Lecture Notes in Mechanical Engineering

Francisco J. G. Silva ·
Luís Pinto Ferreira · José Carlos Sá ·
Maria Teresa Pereira ·
Carla M.A. Pinto *Editors*

Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems

Proceedings of FAIM 2023, June 18–22, 2023, Porto, Portugal, Volume 2: Industrial Management

Springer

Lecture Notes in Mechanical Engineering

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Preface

This volume of Lecture Notes in Mechanical Engineering (LNME) is one of two volumes including papers selected from the 32nd International Conference on Flexible Automation and Intelligent Manufacturing (FAIM 2023), held in Porto, Portugal, from June 18 to 22, 2023. The FAIM 2023 conference was organized by the School of Engineering, Polytechnic of Porto, located in Porto, Portugal.

Flexible Automation and Intelligent Manufacturing (FAIM) is a renowned international forum for academia and industry to disseminate novel research, theories, and practices relevant to automation and manufacturing. For over 30 years, the FAIM conference has provided a strong and continuous presence in the international manufacturing scene, addressing both technology and management aspects via scientific conference sessions, workshops, tutorials, and industry tours. Since 1991, FAIM has been hosted in prestigious universities on both sides of the Atlantic and, in recent years, in Asia. The conference attracts hundreds of global leaders in automation and manufacturing research who attend program sessions where rigorously peer-reviewed papers are presented during the multiple-day conference. The conference links researchers and industry practitioners in a continuous effort to bridge the gap between research and implementation.

FAIM 2023 received more than 400 contributions from over 40 countries and over 220 institutions around the world. After a two-stage double-blind review, the technical program committee accepted 263 papers. From these, 242 papers have been included in two LNME volumes, and 21 extended papers are published as fast-track articles in *Robotics and Computer-Integrated Manufacturing* and *The International Journal of Advanced Manufacturing Technology*. A selection of these LNME articles will be invited to submit substantially extended versions to special issues in ten international indexed journals, such as the *International Journal of Computer Integrated Manufacturing, Journal of Mechanical Engineering Science, Journal of Testing and Evaluation, Sustainability journal, Machines journal, Metals journal, Actuators journal, Systems journal, FME Transactions journal, and Technological Sustainability journal*. We are grateful to the authors for their contributions and would like to acknowledge the FAIM steering committee, advisory board committee, honorary chairs, the scientific committee members, and manuscript reviewers for their significant efforts, continuous support, sharing their expertise, and conducting manuscript reviews. Manuscript reviewers came from various locations around the world, performing 1339 reviews in total. With such effort and toughness, the high standards of the papers included in the FAIM program have been kept.

Special thanks to FAIM 2023's invited speakers: Jiju Antony (*Professor, Khalifa University, Abu Dhabi, UAE*), Daryl Powell (*Chief Scientist at SINTEF, Norway*), Marcello Pellicciari (Professor, *Director of the PhD School "E4E-Engineering for Economics, Economics for Engineering", University of Modena and Reggio Emilia, Modena, Italy*), Rodrigo Martins (*Professor, Nova School of Science and Technology, Lisboa, Portugal*), Alcibíades Guedes (*Professor at Faculty of Engineering, University of Porto, President*

of the Board & CEO at INEGI, Porto, Portugal), and Pedro Carreira (*CEO at Continental Mabor, Lousado, Portugal*).

The book *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems—Proceedings of FAIM 2023* has been organized in two LNME volumes. Volume 1 is mainly devoted to Mechanical Engineering, Robotics, Automation, Manufacturing Processes and Materials Processing, while Volume 2 is mainly focused on Industrial Management, Digital Transformation, Industry 4.0/5.0, Human Factors, Logistics, Sustainability, and related matters. In both volumes, the papers have been organized by topics, providing to the reader an excellent set of papers regarding each topic.

We appreciate the partnership with Springer, ConfTool, and our sponsors for their fantastic support during the preparation of FAIM 2023. Thank you very much to the FAIM 2023 organizing team, whose hard work was crucial to the success of the FAIM 2023 conference.

May 2023

Francisco J. G. Silva
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Maintenance

Maintenance Strategy Selection: An Approach Based on Equipment Criticality and Focused on Components

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Abstract. The selection of appropriate equipment maintenance strategies is essential for avoiding accidents and unnecessary operating costs in companies. This paper aims to propose a methodology which makes use of Decision-Making Grids (DMGs) for classifying and prioritizing the manufacturing assets according to their criticality and, accordingly, selecting the most appropriate maintenance strategy for the analyzed assets components. The ability to support the assignment of maintenance strategies at the component level distinguishes the proposed methodology from the related studies found in the literature, as they define a unique type of strategy for the equipment as a whole or strategies focused on its functional failures. The assets classification and prioritization is performed considering the failure impact and quantitative criteria related to their maintenance history. Therefore, the methodology can also be used as a performance measurement tool for identifying the need of redefining the maintenance plan of specific assets or implementing equipment improvement initiatives. The methodology was successfully applied in a case study performed in a company that produces wood-based panels. Its application enabled to assign maintenance strategies to the six components with higher frequency of replacement of one safety critical equipment in a quick manner. The case study has also shown that the effort and resources required for applying the methodology are low, since it uses mainly data recorded by the current management systems.

Keywords: Equipment criticality · Maintenance management · Maintenance planning

1 Introduction

Maintenance planning involves the selection of the most appropriate maintenance strategies to be applied to a specific equipment or system. Reliability Centered Maintenance (RCM) is a methodology for defining a maintenance plan considering the systems criticality, to establish the most cost-effective maintenance strategies and maximize the overall reliability. However, the complexity and the costs involved in RCM implementation can be high [1]. Emovon *et al*. [2] also highlight the impossibility of ranking maintenance options based on RCM methodology, such that the optimum solution can be easily selected.

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According to Shafiee [3], the maintenance strategy selection is often considered as a complex multi-criteria decision making (MCDM) problem, since there are a great variety of criteria to be taken into account for selecting the most appropriate maintenance strategy. This author classifies the criteria into quantitative (measurable) and qualitative (difficult to measure). Labib [4] use a Decision-Making Grid (DMG) for optimal maintenance strategy selection. The DMG includes two criteria for defining the maintenance strategy: downtime and failure frequency of the system. This method of aggregation is also considered by Fernandez *et al*. [5], Labib [6], Shahin and Attarpour [7] and Rastegari and Mobin [8], using as criteria performance indicators such as downtime, failure frequency, maintenance cost and Overall Equipment Effectiveness (OEE). Nevertheless, in these studies, the severity of the failure impact is not considered to support the maintenance strategy selection. DMGs are also applied for obtaining different groups or categories of equipment. The definition of groups is performed considering that equipment belonging to the same group will be associated with the same maintenance strategy. This is an appropriate method to manage a large amount of equipment, based on their similarities. However, it defines a unique type of strategy for the equipment as a whole, not focusing components.

The maintenance strategy selection is usually preceded by a criticality assessment. The assessment of the equipment criticality is used for defining its degree of importance for maintenance management [9]. The published works frequently use the Analytical Hierarchy Process (AHP) or, less frequently, the additive weighted method for ranking the equipment [10]. These methods have the advantage of being able to aggregate a large number of criteria. However, the time and effort required for their application can increase considerably as the number of criteria and alternatives becomes larger. Santos *et al*. [11] propose a more simple approach which considers the failure effect for classifying the equipment criticality. Nevertheless, the obtained classification is essentially based on a qualitative analysis.

The methods for supporting the analysis of equipment criticality and maintenance strategy selection in companies should be defined considering the existing maintenance records, information technologies and human resources. Moreover, the decision criteria must be aligned with the objectives of the company. Therefore, the definition of methods that can be easily adapted to different contexts assumes a great relevance.

In view of these considerations, in the present study, a methodology for selecting the maintenance strategy to the equipment components is proposed. Unlike the existing maintenance planning methods, the defined methodology can be applied for classifying and prioritizing the manufacturing assets and to recommend a maintenance strategy to the assets components. For this purpose, a set of decision criteria which use data that are commonly recorded by maintenance departments are considered. The proposed methodology was defined to be integrated with the Computerized Maintenance Management System (CMMS) of a manufacturing plant. The paper is organized as follows. Section 2 describes the methodology and the associated criteria and tools. In Sect. 3, the results of the methodology application to a case study performed in a manufacturing plant are presented. Finally, Sect. 4 presents the conclusions derived from the study.

2 Methodology for Criticality Definition and Maintenance Planning

2.1 Equipment Criticality

The defined methodology enables to classify and prioritize the manufacturing assets based first on the analysis of the failure impact that defines its category and, subsequently, on three quantitative criteria which enable to define its subcategory. The combination "category – subcategory" represents a distinct criticality level. This classification is then used for supporting the definition of appropriate maintenance strategies.

The categories for classifying the assets according to the failure impact are:

- Safety (S) – risk of causing injury;
- Environment (E) – risk of causing environmental damage;
- Quality (Q) – generates defective product;
- Production (P) – causes production losses.

These categories were defined based on their relevance to manufacturing companies. Considering the associated severity of the impact, the categories are ranked as follows: S > E > Q > P. The category definition involves assigning a score from 1 to 5 to the failure impact on Safety, Environment and Quality. To facilitate the analysis of the levels of failure impact, the following designation was established: No impact (1), Low (2), Average (3), High (4) and Very high (5). Category S is assigned to assets with a level of failure impact higher than 2 ($S > 2$). If $S < 3$ and $E > 2$, the asset is associated with category E. Category Q is assigned if $S < 3$, $E < 3$ and $Q > 2$. Finally, category P is assigned if $S < 3$, $E < 3$ and $Q < 3$.

The quantitative criteria, used for defining the subcategory, are considered as follows:

- No. of corrective interventions – cumulative number of corrective interventions;
- Downtime – cumulative downtime due to equipment breakdowns;
- Maintenance cost – sum of the corrective and preventive interventions costs.

The values of the criteria should be obtained using data from a CMMS and can be either related to the complete maintenance history of the analyzed assets or to a predefined period. To provide an accurate classification, it was defined that each criterion should be composed of three levels (Table 1).

Table 1. Levels of the criteria considered in criticality definition.

Level	Upper limit	Score
High	MAX	3
Average	$(2/3) \times MAX$	2
Low	$(1/3) \times MAX$	1

For each criterion, the upper limit of the levels was defined to be the maximum value (MAX) registered in the analyzed period, considering all assets from a production line or

section. Afterwards, the assets are associated with a particular level taking into account their individual values (e.g., if the cumulative "No. of corrective interventions" of the analyzed asset is not higher than $(1/3) \times MAX$, the associated level is Low). A score assigned to the criteria levels was defined to assist the assets prioritization.

DMG was the tool defined for enabling the joint analysis of the decision criteria. Figure 1 presents an extract from the proposed DMG1, which includes the subcategories of category S. For categories E, Q and P, a similar grid was defined.

The subcategories are specific combinations of the decision criteria levels. Their criticality is ranked based on the sum of the score associated with the level of each criterion (Table 1). Thus, the sum of subcategory S.1 is 9, since the score associated with the level High is 3. For the subcategories with the same sum, the higher ranking was given to the one that has the higher score in the criterion "No. of corrective interventions" and, in the cases in which the score in this criterion is equal, to the one that has the higher score in the criterion "Downtime". If two or more assets are classified in the same subcategory, priorities can be established based on the score assigned to the failure impact.

For each criticality level, maintenance strategies to be applied to the equipment components intend to be determined. In the column "maintenance strategies" of DMG1, the strategies considered to be assigned in each level are identified. These strategies include Equipment Improvement (EI), Condition-Based Maintenance (CBM), Systematic Preventive Maintenance (SPM) and Run to Failure (RTF). SPM involves the preventive

Category	No. of corrective interventions	Downtime	Maintenance cost	Subcategory	Sum	Ranking	Maintenance strategies	Method	Component selection
Safety (S)	High	High	High	S.1	9	1	EI	RCA	FR > 1 or SPUC > 300 €
	High	High	Average	S.2	8	2	EI	RCA	FR > 1 or SPUC > 300 €
	High	High	Low	S.3	7	5	EI	RCA	FR > 1
	High	Average	High	S.4	8	3	EI	RCA	FR > 1 or SPUC > 300 €
	High	Average	Average	S.5	7	6	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	High	Average	Low	S.6	6	11	SPM, CBM and EI	MPM	FR > 0.5
	High	Low	High	S.7	7	7	EI	RCA	FR > 1 or SPUC > 300 €
	High	Low	Average	S.8	6	12	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	High	Low	Low	S.9	5	18	SPM, CBM and EI	MPM	FR > 0.5
	Average	High	High	S.10	8	4	EI	RCA	FR > 1 or SPUC > 300 €
	Average	High	Average	S.11	7	8	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Average	High	Low	S.12	6	13	SPM, CBM and EI	MPM	FR > 0.5
	Average	Average	High	S.13	7	9	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Average	Average	Average	S.14	6	14	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Average	Average	Low	S.15	5	19	SPM, CBM and EI	MPM	FR > 0.5
	Average	Low	High	S.16	6	15	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Average	Low	Average	S.17	5	20	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Average	Low	Low	S.18	4	24	SPM, CBM and EI	MPM	FR > 0.5
	Low	High	High	S.19	7	10	EI	RCA	FR > 1 or SPUC > 300 €
	Low	High	Average	S.20	6	16	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Low	High	Low	S.21	5	21	SPM, CBM and EI	MPM	FR > 0.5
	Low	Average	High	S.22	6	17	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Low	Average	Average	S.23	5	22	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Low	Average	Low	S.24	4	25	SPM, CBM and EI	MPM	FR > 0.5
	Low	Low	High	S.25	5	23	SPM, CBM and EI	MPM	FR > 0.5 or SPUC > 300 €
	Low	Low	Average	S.26	4	26	Current strategies	-	-
	Low	Low	Low	S.27	3	27	Current strategies	-	-

Fig. 1. Extract from DMG1 for equipment ranking.

replacement of components after a predefined period, whereas CBM includes evaluation through external devices or sensors and also technicians' evaluation.

For each analyzed equipment, to firstly address the components with higher financial impact, constraints were established considering the yearly Frequency of Replacement (FR) and the Spare Part Unit Cost (SPUC) (Fig. 1). To support the maintenance strategy assignment to component, a Maintenance Planning Method (MPM) was defined (Sect. 2.2). The Root Cause Analysis (RCA) was established to assist the definition of improvement actions for the worst performing assets, when EI is the assigned strategy, and contemplates the most frequent failure modes of the covered components. For the assets from categories Q and P, the possibility of performing Autonomous Maintenance (AM) is also considered.

2.2 Maintenance Planning Method (MPM)

The MPM is applied for assigning an appropriate maintenance strategy to the components selected according to the constraints established in DMG1. The aim of the defined MPM is to ensure that RTF is not assigned to components of the most critical categories assets, to analyze if the application of preventive strategies is advantageous and, when they are recommended, to define the most appropriate type of strategy. Thus, it was defined that the maintenance strategy was assigned to components considering the criticality category of the asset in which the component operates, information about the component failure and four additional decision criteria for ensuring lower costs.

The information about the component failure includes:

- Failure classification – indicates whether the failure is Evident or Hidden;
- Hazard function behavior – specifies whether the hazard function associated with the component failure is increasing (degradation failures), or non-increasing (failures which result from random events);
- Symptoms – perceptible changes in measurable parameters caused by the occurrence of the failure (e.g., temperature, pressure, vibration frequency).

The four additional criteria defined for supporting the maintenance strategy selection were the following: "FR" of the component, "Mean Time to Repair (MTTR)", "Inspection Task (IT)/Detection Task (DT) complexity" and "SPUC". The "MTTR" can either be estimated based on the existing maintenance records, or based on experience. The "IT/DT complexity" is assessed qualitatively, taking into account the time and the skills required. Since the IT aims to prevent the failure occurrence, it is recommended when the failure is Evident. In turn, the DT is used to detect Hidden failures. The "SPUC" is analyzed only when the information related to the preceding criteria is considered insufficient for supporting decision-making. This criterion is used to avoid assigning SPM to the failure mode when the associated cost is high, due to the component cost.

If the hazard function is non-increasing, the application of preventive maintenance strategies is not recommended, since the probability of failure cannot be reduced. The symptoms description is considered for analyzing the feasibility of CBM using sensors.

To facilitate the joint analysis of the criteria, two DMGs were defined: DMG2 and DMG3. DMG2 is used if the component hazard function is increasing, whereas DMG3

is applied if the hazard function is non-increasing. Figure 2 presents an extract from DMG2. The development of DMG2 was based on the following assumptions:

- If the IT/DT is effective, CBM is more advantageous than SPM and RTF when the complexity is Low and the "FR" is Low or Average, since it will contribute to extend the usage time and the required inspection frequency is low;
- CBM is not advantageous if the FR is High, or if the FR is Average and the MTTR is Low, due to the time and effort that would be required;
- The maintenance cost is not acceptable, if the "FR" is High and the "MTTR" is High, or if the "FR" is Average or High and the "SPUC" is Average or High;
- RTF is not financially advantageous when the "FR" is Average or High, due to the high costs of failure that would be generated in a relatively short period.

In DMG3, only the criteria "FR" and "MTTR" are considered, as its main purpose is to determine whether the application of RTF is acceptable or not.

Criteria				Category	
				S, E and Q	P
Frequency of Replacement (FR)	MTTR	IT/DT complexity	Spare Part Unit Cost (SPUC)	Proposed strategy	Proposed strategy
Average	High	High	High	EI	EI
			Average	EI	EI
			Low	SPM	SPM
		Average	High	EI	EI
			Average	EI	EI
			Low	SPM	SPM
		Low	High	EI	EI
			Average	EI	EI
			Low	CBM	CBM
		Not applicable	High	EI	EI
			Average	EI	EI
			Low	SPM	SPM
	Average	High	High	EI	EI
			Average	EI	EI
			Low	SPM	SPM
		Average	High	EI	EI
			Average	EI	EI
			Low	SPM	SPM
		Low	High	EI	EI
			Average	EI	EI
			Low	CBM	CBM
		Not applicable	High	EI	EI
			Average	EI	EI
			Low	SPM	SPM

Fig. 2. Extract from DMG2 for strategy assignment to components.

3 Case Study

The defined methodology was tested in a production line of a company which produces wood-based panels. The production line is composed of 838 assets distributed by 18 systems. Each system consists of a group of assets that performs a particular step of the production process. The limits of the criteria considered for defining the assets criticality were determined based on the records performed in the company's CMMS, during a period of 622 days, and organized in a specific form (Fig. 3). Then, a subcategory was assigned to the assets of the system with the higher number of corrective interventions.

Level	No. of corrective interventions	Downtime (h)	Maintenance cost (€)
High	28	13.56	10 334.89
Average	19	9.04	6 889.93
Low	9	4.52	3 444.96

Fig. 3. Upper limits of the criteria considered for subcategory assignment.

The MPM was tested on an asset that uses vacuum suction cups for handling paper surfaces. Since it performs fast and repetitive movements during the production process, it was classified in the Safety category (score 3). Thus, based on its values in the criteria, the subcategory assigned was S.24. The priority components were selected considering the constraints defined in DMG1 for this subcategory (Fig. 1). The information for supporting the maintenance strategy selection and the record of the strategies selected using DMG2 and DMG3 were merged in a unique form, as shown in Fig. 4a. The intervals defined for the levels of the decision criteria are specified in Fig. 4b.

Component	Failure classification	Hazard function	FR (yearly)	MTTR (h)	IT/DT complexity	SPUC (€)	Symptoms	Maintenance strategy
Photocell Leuze	Evident	Non-increasing	2.35	0.25	-	118.88	-	EI
Pipe Flex	Evident	Increasing	2.20	0.5	Low	1.24	Pressure change	CBM
Bearing SY 50 TF	Evident	Increasing	1.61	0.5	Low	43.33	Vibration, noise and temperature changes	CBM
Sensor photoelectric	Evident	Non-increasing	0.88	0.25	-	88.97	-	EI
Timing belt pulley	Evident	Increasing	0.59	1	Low	165.00	-	CBM
Ball bearing 6005 2RS	Evident	Increasing	0.59	0.5	Low	2.72	Vibration, noise and temperature changes	CBM

(a)

Level	FR (yearly)	MTTR (h)	IT/DT complexity	SPUC (€)
High	> 4	> 1.5	High	> 1500
Average	2 – 4	0.5 – 1.5	Average	300 – 1500
Low	≤ 1	< 0.5	Low	< 300

(b)

Fig. 4. Information for maintenance strategy selection and selected strategies (a) and respective intervals defined by the company for the criteria levels (b).

4 Discussion and Conclusion

In this study, a methodology for ranking the equipment, from the most critical to the less critical, and assigning maintenance strategies to improve their performance was defined. The maintenance strategies are assigned to the equipment components taking into account the defined priority. For this purpose, information about the failure is considered together with the values of quantitative criteria obtained from the equipment maintenance history.

From the case study, several findings were observed. The methodology can be used for supporting the maintenance planning dynamically. Furthermore, it enables to analyze the impact of the strategies applied to each asset on the quantitative criteria. Thereby, if the results are not satisfactory, adjustments can be made, taking into account the value of each criterion. However, since the equipment prioritization is influenced by a score

associated with the failure impact, to obtain reliable results, the score assignment should be supported by experienced technicians and records related to failure events.

The methodology was applied to a group of assets from a manufacturing plant. Based on the collected information, the assets were ranked and maintenance strategies were selected for the priority components of an asset whose failure can affect safety. The main purpose was to firstly address the components with higher financial impact. The maintenance strategy assignment was easily performed, since the methodology does not require the application of complex mathematical methods, such as AHP. Moreover, the required quantitative data were acquired from the CMMS records, whereas the qualitative data were obtained in a meeting with maintenance engineers of the company.

The ability to support the definition of maintenance strategies at the component level in a quick manner distinguishes the defined methodology from the methods for maintenance planning identified in the literature. The methodology has also the advantages of using simple and adaptable tools, such as DMGs, and data that are usually recorded by manufacturing companies. Therefore, it can be easily adapted to different contexts and included in a CMMS for updating the values of the quantitative criteria automatically.

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A Model Identification Forensics Approach for Signal-Based Condition Monitoring

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Abstract. Condition monitoring (CM) of machines and robots is vital to improve operational reliability and to avoid occupational incidents. Recently, deep learning (DL) has become popular in CM literature for its outstanding ability of learning fault patterns. However, due to the black box and non-intuitive nature of its layers, the logic behind its decisions is hard to understand. This shortcoming hinders the DL implementation in many critical applications where the user needs to ensure the reliability of the classifier. Hence, in this paper, a new framework for DL-based CM systems is proposed, which consists of four steps (1) Feature extraction (2) Fault diagnosis (3) eXplainable Artificial Intelligence (XAI)-based model optimization (4) Interpretation system. The experimental evaluations on two real-world datasets demonstrate that the proposed XAI interpreter was able to visualize the contributing patterns to fault types. The feature engineering block not only makes it easier for the operator to only observe the contributing features, but also it helps the model optimizer to speed up the runtime. The results show that the proposed model achieved a slightly better accuracy than the other state-of-the-art models.

Keywords: Explainable artificial intelligence · Feature Engineering · Fault Detection · Fault Diagnosis · Interpretable artificial intelligence

1 Introduction

The health of machines and robots significantly impacts operational safety, system performance, and facility lifetime. Ensuring safe and stable operation is critical, as it prevents substantial manufacturing costs, serious injuries, and damages. Condition monitoring (CM) procedures are established to improve quality

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inspection, predictive maintenance, and provide a safe environment for human-robot collaborations [1].

The evolution of CM for machines began with simple circuit breakers on incoming power feeds, progressing to multifunctional electronic relays and Programmable Logic Controllers (PLCs) for more sophisticated protection. Nowadays, due to technological advancements reducing data acquisition costs and increasing computational power, many industrial plants adopt data-driven systems for machinery and robot CM [2].

Deep learning techniques have demonstrated promising capabilities for CM systems. However, their black-box, non-intuitive nature makes it difficult for operators or experts to understand the reasoning behind their decisions, presenting a challenge in convincing them to trust and adopt deep learning-based monitoring systems [3]. This paper aims to address two main open issues in CM literature: (1) feature engineering and model optimization, and (2) the explainability of decisions made by machine learning or deep learning agents in identifying the state of machines or robots.

Various feature types have been proposed for use in CM literature, including statistical features [4], time-frequency analyses such as permutation entropy [5], multi-scale permutation entropy [6], multi-scale entropy [7], and Empirical Mode Decomposition (EMD) [8]. Each feature extraction technique represents the machine's state differently and has its advantages and disadvantages. Some studies have combined these techniques to concurrently benefit from their advantages [9–12]. However, there is no consensus on an optimal feature engineering approach for machinery CMs and having several features can increase the ambiguity of the DL decision.

The remainder of this article is organized as follows: Sect. 2 provides an overview of Shapley values and XAI. Our framework is discussed in Sect. 3. Experiments and discussions are presented in Sect. 4. Finally, the conclusion is reached in Sect. 5.

2 Materials and Methods

2.1 Shapley Values

For simple models, the model itself serves as the best explanation since it is both accurate and easy to understand. However, for complex models like ensemble methods or deep networks, the original model isn't helpful as an explanation due to its complexity. Instead, a simpler explanation model is used, which is an interpretable approximation of the original model [13]. This section discusses how classic Shapley Values led to SHapley Additive exPlanations (SHAP) for explaining deeper and more complex models. Classic Shapley values estimation consists of three phases [14].

Shapley regression values indicate feature importances for linear models in the presence of multicollinearity. This method requires retraining the model using all feature subsets $S \subseteq F$, where F is the set of all features. Each feature is given an importance value, which indicates its impact on the model's prediction. The

Shapley values are computed as feature attributions and represent the weighted average of all possible variations:

$$\phi_i = \sum_{S \subseteq F_i} \frac{|S|!(|F| - |S| - 1)!)}{|F|!} [f_{SU\{i\}}(x_{SU\{i\}}) - f_S(x_S)], \quad (1)$$

Shapley sampling values approximate the effect of removing a variable from a model by integrating over samples from the training dataset. It applies sampling approximations to Eq. 1, eliminating the need to retrain the model and reducing computation of differences to fewer than $2^{|F|}$. As its explanation model form is the same as that for Shapley regression values, it is also an additive feature attribution method.

Quantitative input influence is a more comprehensive approach than just feature attributions. It proposes a sampling approximation to Shapley values similar to Shapley sampling values, making it an additional additive feature attribution approach.

2.2 SHapley Additive ExPlanation Values

To make the classic Shapley values usable on deep networks and feasible in a timely manner, [14] proposed and developed SHapley Additive exPlanations (SHAP) as a method for explaining deep learning models. In more detail, SHAP values are designed to show the feature importance for any input sample that influenced the model's output classification.

The exact computation of SHAP values is challenging. However, by combining insights from current additive feature attribution methods, it is possible to approximate them. Lundberg et al. suggested two model-agnostic approximation methods [14], one that is already known (Shapley sampling values) and another that is novel (Kernel SHAP), for reducing the SHAP values approximation runtime based on the feature attribution methods previously described in the classical Shapley values. Kernel SHAP increases the sampling effectiveness of model-agnostic estimations of SHAP values. However, Lundberg et al. focused on specific types of models and created faster approximation techniques that are model-specific. Consequently, Linear SHAP and Low-Order SHAP are developed for linear models, and Max SHAP and Deep SHAP are developed for decreasing approximation time under certain circumstances. The outcome of all these developed methods can approximate SHAP values in a reasonable time.

3 The Proposed Framework

As discussed earlier, bearing fault detection is a cost-effective task for manufacturers. That is why they need to trust the DL model, which handles detection tasks. To achieve this, the paper proposes a method to enhance the decision transparency, as it can be briefly seen in Fig. 1. Moreover, the framework includes a feature engineering step that can help the practitioners and the model deal with fewer dimensionalities. Fig. 2 illustrate the steps in the proposed XAI-based fault diagnosis framework which comprises the following steps:

1. Feature extraction: Several signal processing techniques, time-frequency domains, as well as Fourier and Wavelet spectra are used to reveal hidden patterns that can improve accuracy and explainability of the DL model.
2. Fault diagnosis/collision detection: A dual-directional Convolutional Long Short-Term Memory (CLSTM) architecture is developed and trained on the extracted features.
3. XAI-based model optimizer: Using SHAP values, uninformative features are removed to reduce the data dimensionality. This part helps the practitioners improve the model performance by decreasing model complexity for online implementations. Additionally, by eliminating the redundant features, the decisions can clearer be seen for the operators.
4. signal-based CM interpretation system: visualizing the model inferences and helping the operators understand the diagnostics decisions made by the DL model.

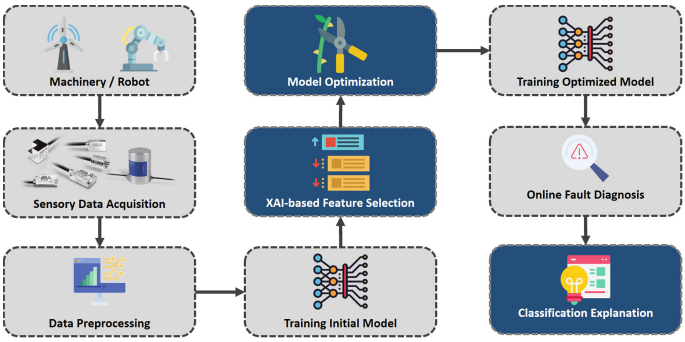

Fig. 1. A schematic overview of the proposed model

The paper uses the SHAP values that were previously discussed to demonstrate how the detection model is working implicitly. To make the ambiguous model clear, there is a need for an informative visualization method to boost the understandability of how the model is performing the classification. To this end, the paper proposes a visualization method similar to Lundberg's terminology introduced for multiple tasks of DL and ML, but a signal data type. The standard solution for visualization in most of the proposed SHAP value visualization methods is color-based. The paper shows details of signal data and patterns along with the blue and red dots denoting how much a specific part of the signal is helping the model to decide about the final classification label. Red dots, higher SHAP values, denoting the higher likelihood of belonging to a class, and blue dots, lower SHAP values, representing the less likelihood of classifying into a class.

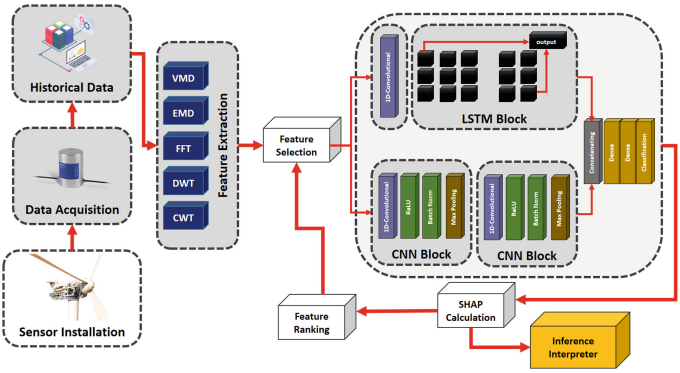

Fig. 2. The proposed XAI-based Fault Diagnosis framework

4 Experimental Results and Discussion

The paper proposes a method to identify how a deep-learning model is performing the classification on signal-based data by developing a visual model interpreter and an XAI-based model optimizer that only takes the contributing features into consideration. To this end, the paper employs Case Western Reserve University (CWRU) bearing dataset that consists of a motor, a torque transducer (/encoder), a dynamometer, and control electronics. The dataset includes a healthy condition and five different fault types, i.e., three different outer race misalignments (outer@3, outer@6, and outer@12) along with the inner race and the ball faults. The faults are grouped according to their severity and range in diameter. The dataset is collected with a sampling rate of 12 kHz with an accelerometer mounted on drive-end of the machine. In the experiments we took signal bursts of 800 timestamps, equal to 66.6 ms, to generate some different datasets of approximately 25,500 signal bursts.

The dataset contains some additional phase resistances equal to 0.099Ω, 0.1485Ω, and 0.198Ω into one rotor phase to get 150%, 225%, and 300% REU, respectively. For the fault class, the study only uses the signals corresponding to 150% REU.

Figure 3 illustrates the proposed visualization method in action on the CWRU dataset for two different classes: Health and Inner race fault. The horizontal axis displays the features (Channels), and the vertical axis displays the possible classes. Each element of the figure contains a full signal annotated with the corresponding SHAP values. The red dots indicate which portions of the signal correspond to the diagnosed class, while the blue dots indicate why the sample does not belong to the other classes. By using this model explanation, the authors considered a second-phase feature selection adjustment to improve efficiency. This example showcases how an operator can visually observe and interpret the model's decision-making process.

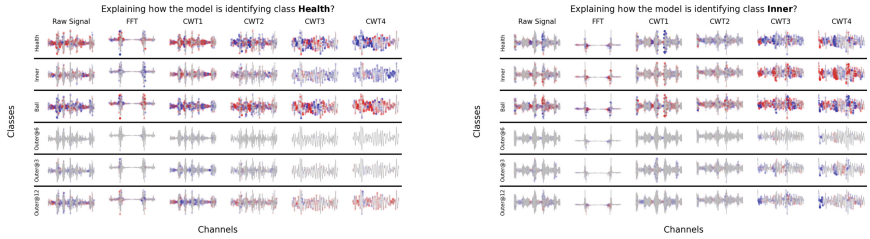

Fig. 3. The SHAP visualization proposed for the fault diagnosis

To understand the effectiveness of the proposed SHAP-based feature selection block, the paper provides a comparison panel composed of several state-of-the-art models: the proposed model (XAI-CLSTM), CLSTM [15], stacked-denoise Autoencoders (sdAE) [16], Convolution Neural Network with two Dropout layers and two Fully-connected layers (dfCNN) [17], CAE-fft [18], and CNN.

The experimental results on both datasets demonstrate that the proposed framework not only helps us to reduce the dimensionality and complexity of the model, but interestingly it can also significantly improve the diagnosis performance on different burst lengths. Figure 4 (left) shows that for the CWRU dataset, XAI-CWRU has an f_1-score up to 7% higher than its rivals. This difference becomes more significant on smaller burst lengths, where the algorithm has fewer data points to understand the nature of the signal and diagnose it. This is crucial when the practitioner strives to prevent the machine fault as quickly as possible and wants the algorithms to diagnose the faults as fast as possible. The same behavior is witnessed in Fig. 4 (right), on the wind turbine dataset, except that CLSTM shows slightly better accuracy on longer burst lengths. The other four algorithms were always inferior to the proposed algorithm in both datasets.

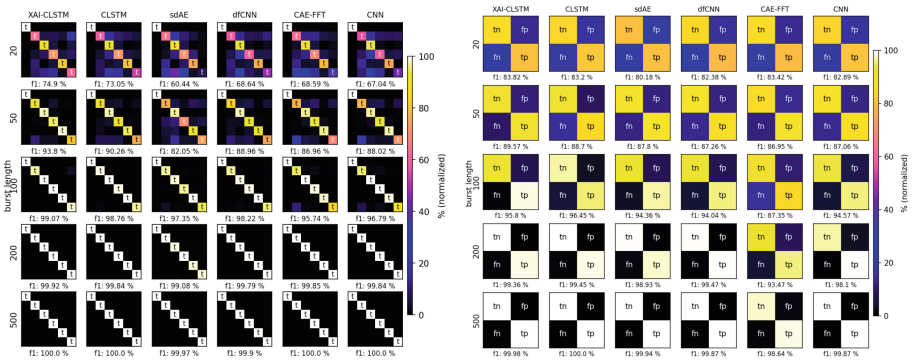

Fig. 4. Classification performance comparison on CWRU (left) and Wind Turbine (right) datasets - t, tn and tp represent the correctly classified samples

5 Conclusions

Machinery and robotic CM play a significant role in industrial production and safety. Signal-based CM methods, especially DL fault diagnosis, have received significant attention in the last decade. This paper proposes a new approach to improve the performance of such models and provide visualization for practitioners to understand the classification inferences. A four-step framework is developed that comprises: (1) Feature extraction, (2) Fault detection based on a dual-path CLSTM DL model, (3) XAI-based feature engineering, and (4) Inference interpretation module.

After extracting a set of features from the signals (i.e., vibration and torque measurements) based on time and frequency domains, as well as Fourier and wavelet spectra, SHAP values are calculated to determine the key features that contribute the most to the CLSTM output. In fact, with this step, practitioners can optimize the input features and dispose of unwanted and redundant input channels in the DL architecture. This helps them reduce the ambiguity of the decisions and a clearer visualization could be obtained. In the classification module, a dual-path DL architecture is adopted that extracts long-term temporal dependencies and shift-invariant patterns using the RNN-LSTM and CNN blocks, respectively. It is also demonstrated that using such an architecture can alleviate the effect of noise on the diagnosis performance. Finally, to cope with the interpretability and explainability of the network, SHAP values are depicted on the selected input channels to illustrate the vibration patterns and signatures that contribute to each class.

Several state-of-the-art algorithms are selected for comparison to evaluate the performance of the XAI-CLSTM algorithm. After extensive benchmarking on two different datasets, it is demonstrated that the proposed XAI-CLSTM improves the efficacy of the diagnosis by reducing runtime and slightly improving accuracy, by at most three percents. This helps practitioners implement a lightweight CM solution suitable for online and budget edge-computing systems.

Future work will focus on domain adaptation and transfer learning associated with methods for model interpretability to improve the applicability of the proposed approach in different industrial scenarios.

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Specification of a Collaborative Platform for Intercompany Maintenance Information Sharing: A Case Study

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Abstract. In the current competitive markets, the possibility to obtain relevant and accurate data and information can make the difference between achieving success or not. A company which has several maintenance technicians in the final stage of their career and plants spread through different countries, can benefit from a collaborative platform that aggregates the maintenance information and knowledge to support decision making. The more accurate the data, the more reliable will be the analyzes and better decisions can be made. This paper presents a study performed in a wood derivatives company which intends to see the knowledge of its most experienced maintenance technicians and all the information related to maintenance department being captured, retained, and disseminated by all elements of the maintenance teams from the different plants. To capture and disseminate the relevant information by all the plants, a collaborative platform and its information architecture were proposed. The platform aims to obtain accurate records for supporting failure diagnosis and maintenance interventions, as well as process the data to carry out benchmarking actions and defining improvement actions. This paper presents the test results of the collaborative platform prototype, developed to validate its specification and information architecture, and the benefits that the company can obtain through its implementation. These benefits are the reduction of the interventions duration, promoting internal Benchmarking actions and establishing priorities in problems solving to improve performance. The proposed novel platform provides helpful information for both technicians and decision-making agents, and considers future integration with holographic solutions.

Keywords: Collaborative platform · Industry 4.0 · Maintenance management

1 Introduction

Since 2011, when the fourth industrial revolution or Industry 4.0 concepts were announced, this industrial revolution has grown and taken shape from a few theoretical concepts to real-world applications, having influenced almost every activity sectors

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[1]. Two of the main objectives for Industry 4.0 applications are to ensure maximum uptime throughout the entire production chain and to increase productivity while reducing the cost of production. As the data-driven economy evolves, companies have started using big data techniques to achieve these goals [2]. The so-called "smartization" of the manufacturing industry came up with the Industry 4.0, a new concept driven by the emergence and progressive maturity of new Information and Communication Technologies (ICT) applied to industrial processes and products. This change of concept allows extracting relevant knowledge from monitored equipment through the adoption of data monitoring strategies [3]. To create knowledge that will be used to make accurate decisions, it is essential to collect and analyze large amounts of relevant data within a reasonable timeframe [4, 5]. The proposed platform intends to improve the decision making based on the created knowledge. According to Sahal *et al.* [2], the process of creating knowledge contemplates four phases: Data Collection, Data Analysis, Data Storage and Data Query [2]. Along with other plant functions, the maintenance function requires knowledge management, which can be considered as a process that integrates several activities in a cycle that includes capturing and/or creating knowledge, sharing and disseminating knowledge and applying it [6]. The capture/creation of knowledge includes the development of new content, or the replacement of the existing content. The sharing and dissemination of knowledge refers to its transfer, and its application refers to its use by an organization to gain competitive advantage. In the area of maintenance management, these activities can be supported by different tools, such as Computerized Maintenance Management Systems (CMMS) or Enterprise Asset Management System (EAM), Augmented Reality (AR)/Augmented and Mixed Reality (AMR) (for knowledge sharing), sensors and mobile devices, and collaborative platforms. According to Ruiz *et al.* [7], problem solving requires searching and sharing knowledge among a group of actors in a particular context. Maintenance actors (technicians and experts) have much expertise (implicit or tacit knowledge) [8]. Aromaa *et al.* [8] propose a model to improve the sharing and understanding of the information by technicians. The data collection was performed based on interviews and observation.

This paper presents the specifications of a collaborative platform for intercompany maintenance information sharing, considering the Industry 4.0 concepts. In opposite to Aromaa *et al.* [8], this work takes in account not only the perspective of technicians and just a specific location, but also the perspective of the responsible for decision making and several locations. The collaborative platform was defined to be applied in a wood derivatives company which has several manufacturing plants located in different countries. In the next decade, some of its most experienced maintenance technicians will reach retirement age and, consequently, will leave the activity, taking with them important technical knowledge. Furthermore, the company intends to implement procedures that facilitate the sharing of information and knowledge, related to the maintenance activities and assets performance, between different plants and to enable collaborative work. For that purpose, a collaborative platform will be developed to integrate records from the different information systems of the company, retain information resulting from their analysis and assist the training of less experienced technicians. The paper is organized as follows. Section 2 describes the current state of company's maintenance data records. In Sect. 3, the requirements and specifications for the collaborative platform, as well as the

information architecture for data storage are described. Section 4 explains the content of the comparative analyzes module and presents some of its dashboards. Finally, in Sect. 5, the conclusions drawn from the study are presented.

2 Company's Information Systems

This study was developed in a company that operates in the wood derivatives sector and has several plants worldwide. In the different plants of the company, a codification composed of the following hierarchical levels is applied: line, area, system, functional location and functional position (position where the asset is located).

To record information related to the assets breakdowns and the maintenance interventions, the company uses different software, namely Zoom Production, EAM and Systems Applications and Products (SAP®). Zoom Production® is used for recording the type of stoppage (e.g., production, electrical, mechanical, etc.), its duration and origin (system or functional location), and complementary information for supporting technicians in performing failure diagnosis. In the EAM, information related to corrective and preventive maintenance interventions is recorded. The information concerning the costs and spare parts consumed during the maintenance interventions is recorded, both in the EAM and SAP using a different format.

The existing records cannot be automatically merged to analyze the complete sequence of events regarding a specific asset. The company expects that, at medium term, all the data will be recorded only in EAM.

3 Collaborative Platform Requirements and Specifications

This section describes the requirements and specifications related to the collaborative platform, which will be integrated with AR/AMR techniques, and the collaborative system works.

3.1 Collaborative Platform Overview

The company intended to improve the records quality and to capture technical knowledge, which is not usually recorded, and to make this information immediately accessible to the employees of the different plants. To meet this need, requirements were defined for the development and implementation of a collaborative platform, between the different manufacturing plants, for assets maintenance management, with the definition of data, information, and methodologies to be shared between the members of the different plants, and its integration with the EAM. The collaborative platform aims to meet the following requirements:

- Retain (capture) the knowledge of maintenance technicians in identifying failure modes, repairing assets and performing preventive interventions;
- Provide (share and disseminate) information to technicians during maintenance activities to support failure diagnosis and repairing interventions based on similar past events;

- Provide (share and disseminate) information to technicians during maintenance activities to support complex preventive maintenance interventions through remote assistance and AMR;
- Retain knowledge for technicians training;
- Provide training to technicians;
- Gather and share information to carry out reliability, availability, maintainability, safety (RAMS) and operability improvement of the assets that the plants may have in common;
- Share assets data to create a meaningful sample of data for further analysis.

These requirements define the information to retain and make available to the employees from the maintenance departments of the different plants. The information will be visualized through AMR or mobile devices. The general specifications of the collaborative work system and its data flow, as well as information between different manufacturing plants, originated the conceptual model of the collaborative platform, presented in Fig. 1. In order to guide future work and developments, detailed specifications were defined and divided into two main modules which are addressed in Subsects. 3.2 and 3.3.

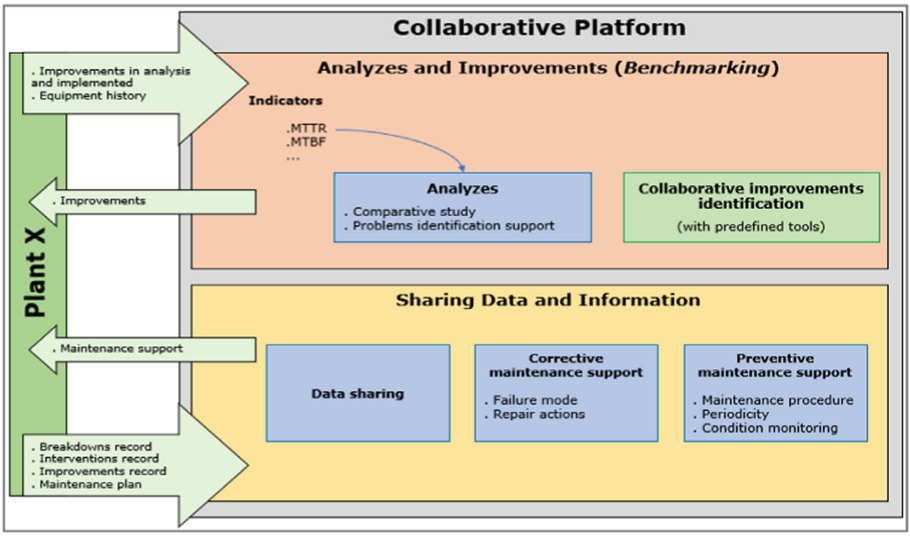

Fig. 1. Collaborative platform's modules and flow of information between them

3.2 Analyzes and Improvements (Benchmarking)

This module uses transformed data from the assets history, namely the records associated with breakdowns, interventions and improvements. This module aims, on the one hand, to provide comparative studies and assist on the identification of the origin of low performance and, on the other hand, to support the collaborative identification of

improvements actions. The module will be available mostly to the company's employees involved in decision-making. The outputs will be presented in dashboards. These joint analyzes can result in improvements to be implemented using appropriate tools.

Comparative Study. Comparative analyzes of the assets performance will be carried out in different plants and within the same plant, with the objective of helping to identify significant differences from the outputs of the calculated maintenance indicators for each hierarchical level. The comparative analyzes will be presented in dashboards using PowerBI® software.

Problems Identification Support. Based on the comparative analysis of assets of the same type in different plants, it is intended to identify the possible existence of values/situations that do not correspond to expectations or significant differences between them. This aims to prioritize problem solving for improving performance and identifying the cause of lower performance of the asset of a particular plant. In these cases, an analysis will be carried out to understand the reason for the non-expected values.

Collaborative Improvements Identification. This information concerns the collaborative identification and implementation of improvements, using RCA methodologies. A RCA form would be completed online, using a common language, on the collaborative platform, which will make them available to all plants. The platform must include search mechanisms, such as keywords, correspondence tables and standardized lists of expressions, allowing any user to search for useful information to solve the problem.

3.3 Sharing Data and Information

This information refers to Raw Data, which means, all the history related to breakdowns, interventions and improvements, as well as to the information that will support the corrective and preventive maintenance actions. The information for supporting interventions will be provided by mobile solutions that were defined according to what is more appropriate to each type of maintenance intervention. This information will be organized and divided into three sub-modules: "Data sharing", "Support for corrective maintenance interventions" and "Support for preventive maintenance interventions", as shown in Fig. 1. The sub-module "Data sharing" includes history of breakdowns, interventions and improvements.

Part of the data shared in this module will be processed to support the calculation of the indicators defined for the analysis performed in the first module.

4 Prototype Development and Exploration

In this section, some dashboards are presented in PowerBI® regarding the comparative analyzes, using the indicators Mean Time Between Failures (MTBF) and Mean Downtime (MDT), to test their functionalities. The considered records belong to the period from December 29, 2020, to April 28, 2022. If it is possible to calculate the Mean Time to Repair (MTTR), it should be used instead of MDT.

4.1 Data Preparation

In order to obtain reliable data to carry out comparative analyzes between different lines and plant locations, the need of a table to establish the correspondence between assets of the same type and identical lines, within the same plant and also between different plants, was identified.

To enable the development of the dashboards, Excel files were defined, to be later imported into PowerBI®. These files include the records from the company's systems after processing, such as data sheets from Zoom Production and from EAM (information related to the Work Orders (WOs) and aggregate records related to consumptions and costs). The MTBF and the MDT were determined by combining the records from Zoom Production with the records from EAM. Therefore, the records from Zoom Production which do not have an associated WO code were not considered.

4.2 Data Exploration

The comparative analyzes include the calculation of technical and economic indicators within the same plant and/or considering information from different plants. In this case study, dashboards related to MTBF and MDT are presented. These indicators were used due to their importance in the maintenance management area.

The charts in Fig. 2 allows performing a comparative analysis between the MTBF values for the different systems, functional locations and positions of one line of the prototype plant, and then allows to identify the most critical situations in a more visual and intuitive way. In all the charts, the presence of records without an associated location was identified and highlighted with the red squares. This observation demonstrated to the company the importance of having complete records.

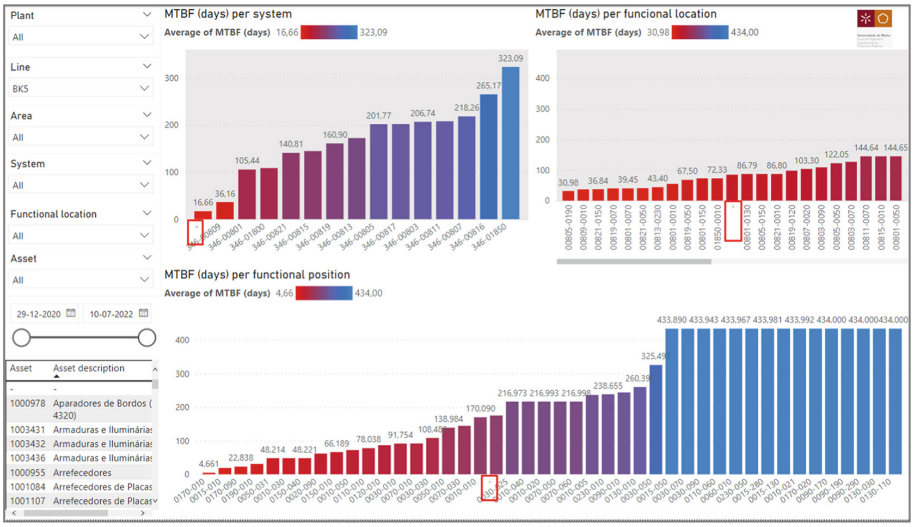

Fig. 2. MTBF values for different levels

Figure 3 presents the charts that were developed to allow performing comparative analyzes, regarding MDT, between lines (first chart), systems of all lines (second chart), functional locations of all lines (third chart), functional positions of all lines (fourth chart), assets families of all lines (fifth chart) and all assets of all lines (sixth chart). Thus, the user can verify, for each level, the location, type of asset or specific asset, which has the most critical value, and whether the difference is significant in relation to the others. Again, the presence of columns without an asset and an associated location is noted.

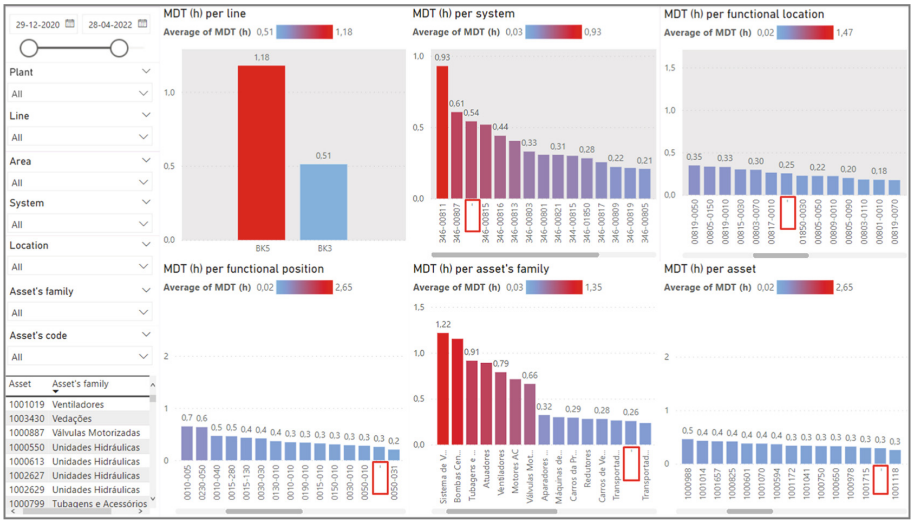

Fig. 3. MDT values for different levels

5 Conclusion and Future Work

In this study, the requirements and specifications for supporting the development and implementation of a collaborative platform were defined and validated. The platform will be used to capture, retain and disseminate, in a standardized way, all the data and the information related to the maintenance management of a wood derivatives manufacturing company. The defined architecture will enable the search for relevant information regarding a particular type of failure and promote the collaborative work. Thus, employees from different departments and plants can take part in the identification of the causes of relevant problems and participate in the definition of corrective and/or improvement actions. From this collaborative analysis, contributions will be obtained to solve similar problems in different locations.

The proposed collaborative platform will have a positive impact in the company's knowledge management, as it provides organized and standardized data and information provided by predefined lists, avoiding the presence of empty registers or inaccurate

data that originate unreliable results in the calculation of performance indicators. This factors, along with the collaborative work, will bring advantages in problems detection, prioritization and solving them.

During the prototype development, the short data sample and the quality of the records turned out to be a limitation, originating dashboards with non reliable values and several columns with absence of data. The platform already proved its utility as the developed prototype made the decision-making agents and technicians aware of the importance of the records and the usefulness of the developed dashboards. Therefore, this new platform contemplates the data and information that is not only for the technicians, but also for the decision-making agents. The developed work aims to surpass the existing shortcoming, promoting the collaboration between all the company members from different locations. Another characteristic of the platform is the ability to integrate holographic solutions, namely Hololens 2®, to provide information to the technicians during their tasks.

The following step for this project consists in the implementation of procedures to improve the quality of the data, and the development of a server that will collect the raw data from the different information systems and process it into information.

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Development and Implementation of Autonomous and Preventive Maintenance in the Rubber Area of a Cork Industry

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Abstract. The project described in this paper was developed in a rubber area of a cork company, where maintenance activity was weak or non-existent. The main objective was to implement a maintenance philosophy, based on the principles of Total Productive Maintenance (TPM). The methodology adopted was based on action-research. The autonomous maintenance (AM) and preventive maintenance (PM) plans created and implemented are described and the results are presented considering the number of intervention requests and the availability of critical equipment before and after the implementation. Intervention requests were reduced by 40% and the availability of critical equipment increased with this project due to an efficient implementation of TPM principles.

Keywords: Total Productive Maintenance · Autonomous Maintenance · Preventive Maintenance · Action Research

1 Introduction

The maintenance department of any organization plays an important role in increasing productivity, product quality and in ensuring on-time deliveries. However, the existence of considerable waste in the maintenance department is a common and frequent reality. Waste occurs in the form of idle workforce and machines, problems in work equipment, products that are rejected due to lack of quality, and mainly an inefficient and resource-poor maintenance activity. Maintenance must be seen as a strategic function to obtain organizational gains. It must support management and be involved in solving production problems, leading the company to competitive levels of quality and productivity. The implementation of an equipment maintenance management system is crucial to increase its useful life and, consequently, increase its availability.

Total Productive Maintenance (TPM) is intended to maximize the efficiency of the equipment, establishing a comprehensive system of productive maintenance, which covers its entire useful life [1]. Its implementation must span the entire organization and is typically divided into short-term and long-term actions. In the short term, efforts are

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focused on AM and PM plans and on developing the skills of operators and maintenance team. In the long-term, they are focused on new equipment, corrective maintenance plans, when equipment is at the end of its useful life, and on eliminating wasted time [2]. Its application has had goods results [3–5].

This paper describes the work developed in the maintenance department of a cork factory to develop and implement AM and PM plans in the rubber area, aiming to demonstrate the application of TPM principles. Initially, the only maintenance activity in this area of the factory was corrective maintenance. AM and PM activities were introduced to improve the availability of critical equipment in these two production lines and reduce the number of intervention requests.

The paper is organized as follows. First, a background section is presented, in which the importance of the maintenance function is addressed, and autonomous and preventive maintenance are introduced as main pillars of the TPM philosophy. Then, the methodology is presented, and the case study is described. The results relating to the availability values of critical equipment achieved with this project and the number of intervention requests are presented. Finally, the main conclusions, limitations and suggestions for future work are presented in the last section.

2 Background

2.1 The Importance of the Maintenance Function

After a long period in which maintenance was seen as the necessary evil of any organization, it is currently recognized as one of the most important and crucial departments of industrial activity, due to its contribution to good performance of production, safety of equipment and workers, product quality, good interpersonal relationship, as well as its contribution to the company's image, the economic profitability of the production process and the preservation of investments [1].

The maintenance activity encompasses management, technical and economic decisions applied to assets, aiming to optimize their life cycles and increase their reliability and availability [6]. In other words, maintenance is a set of activities aimed at maintaining equipment in the physical state considered necessary for the fulfillment of its function or restoring it to its original state [7]. The objectives of maintenance activity within an organization are to ensure the equipment availability and reliability, the quality of products, guarantee that the equipment reaches its maximum useful life, the safety of the equipment and the cost-benefit ratio in operations and maintenance [6].

The availability of equipment is considered a basic condition for the commitment of everyone within the organization and must come with their involvement. The term availability suggests a notion of time during which certain equipment will be available for operation [8]. This indicator is calculated based on the mean time between failures (MTBF), the mean time to repair (MTTR) and the mean waiting time (MWT). Greater availability of the equipment results from an increase in MTBF and a decrease in MTTR and MWT.

2.2 Autonomous and Preventive Maintenance: Two Pillars of TPM

TPM is a maintenance approach that optimizes equipment efficiency, eliminates equipment downtime, and promotes AM tasks, which must be performed by employees through daily activities [7]. TPM advocates a partnership between production and maintenance so that basic maintenance operations (cleaning and inspection) are carried out by machine operators [2]. TPM seeks to minimize all potential losses in the production area and allows workers to have the equipment operating at full capacity [9]. The implementation of TPM may sound simple, but it requires strategy, engagement, and a systematic approach for successful implementation. Many organizations have tried to implement TPM, but only 10% of them successfully implemented it [10].

AM is one of the most important pillars of TPM, as it allows basic maintenance care to be carried out by the operator. AM plans must involve production and maintenance teams and describe the daily activities to keep the equipment in good condition. Cross training must be provided to improve operator skills and attract production operators to maintenance activities [1]. Over time, the operator will acquire more experience dealing with the equipment daily and will become responsible for it, assuming self-control in the connection between him and the equipment. A good implementation of an AM system increases the useful life of the equipment and the motivation of the operators, as they see their role more valued and acquire new technical skills.

PM is another of important pillar of TPM and aims to avoid the occurrence of malfunctions and ensure the safe and efficient operation of the equipment. PM is a programmed intervention, prepared and executed in an equipment, before the probable date of failure. It consists of repeated maintenance activities, at a certain time interval, and can be based on a calendar or number of hours of use. In a first instance, the equipment is analyzed to assess its operational performance, critical equipment is identified, and the current maintenance costs are reviewed. To implement a PM program, it is necessary to know the history of breakdowns and the multiple causes possible for their occurrence. This is a difficult, if not impossible, task and therefore the answers are necessarily an approximation of the reality [11].

3 Methodology

The work described in this paper followed an action-research methodology. It involved a constant presence on the shop floor of one of the authors and, therefore, the main method used was participatory observation. This method is based on strong data collection and provides a privileged access to behaviors in the environment where the study is carried out, as the observer becomes part of the process, observing and immersing himself in the environment in which he is inserted [12]. As a participatory observer of all production and maintenance processes in the factory's production lines, he not only observed the activities and the workers, but also engaged in the activities, solving and facilitating the development of AM and PM activities.

In order to establish a knowledge base on the day to day of the factory and plan the next steps, the observer began by characterizing the initial situation in the production lines regarding AM and PM. In a first instance, data was collected on the existing equipment in the production lines, production flowcharts, the breakdowns of each equipment and

respective analysis, as well as the user manuals and technical sheets. Based on the data collected, the next steps were established. With the help of the maintenance department and production and by observing the processes on site, knowledge was acquired about the operation of the equipment and the production process. After that, the specifications and maintenance activities of each equipment were listed, consulting user manuals and technical sheets and talking to the head of maintenance, and critical equipment was identified through the collection and analysis of intervention requests. Then, AM and PM plans were developed and implemented. During implementation, training and support was offered to workers. Finally, results were monitored by calculating and analyzing the availability of critical equipment.

4 Implementation of AM and PM Plans in the Rubber Area

4.1 Equipment Coding

During the observation of the production lines and the collection of data on the existing equipment, it was found that most of the equipment had no assigned code and could not be identified. Some problems may arise when the equipment does not have a code assigned. The maintenance team cannot identify which equipment needs to be intervened and a data history containing data on intervention requests cannot be created. Thus, the development of maintenance plans in the future would be incomplete.

The coding of the equipment of the production lines in the rubber area was carried out. A list of all equipment was created, and new codes were assigned, ensuring that none of them were repeated. Subsequently, in collaboration with the management control department, data was collected, if available, on the equipment supplier, whether the equipment was new or used, the year of manufacture, serial number, code, and model.

All equipment in the production lines of the rubber area was identified with a code. The coding carried out resulted in many advantages for the operators and the head of the maintenance department. Now, operators can make their intervention requests to the maintenance team in a clearer and simpler way as they can quickly identify the equipment that needs to be intervened and the head of the maintenance department has more data available for further analysis.

4.2 Autonomous Maintenance

In a factory that runs 24 h a day, first level maintenance is often neglected in detriment of increasing productivity. This was observed a few times during the project. Another obstacle to the efficient implementation of AM plans is the lack of a person responsible for verifying compliance with the list of activities in the plan.

The first stage of the implementation of AM was the identification of the equipment in the rubber area that already had AM plans. It was found that there were AM plans in only three pieces of equipment out of the twelve existing in three production lines in the rubber area. In a fourth production line, there were old AM plans divided by area and not by equipment, which did not meet maintenance needs and requirements. With this project, they would be improved and adjusted to the line's equipment.

The second stage of the implementation of AM was the identification of operators working on the production lines and the attribution of responsibilities for the execution of the AM plan. The shift manager became responsible for verifying the correct execution of the AM plans. He bridges the gap between management and workers in the rubber area. He is also primarily responsible for the organization of the work and the way in which it should be carried out, as well as responsible for time management in the greenhouses and refrigeration lines and assists colleagues in any other tasks, when available. The remaining workers are responsible for carrying out the AM plans on the equipment they work with daily, as they know how the equipment should work.

AM plans have a list of activities that operators must perform. As they do not have much time to carry out them, they were assigned simple tasks, such as cleaning, visual inspection of equipment operation and, in some cases, equipment lubrification. As it is a productive area whose raw material generates a lot of dirt, which can contaminate the final mixtures and cause breakdowns, a specific weekly cleaning must be implemented, at the end of each week, on Friday. However, as one day may not be enough for cleaning, two additional measures were implemented: Saturday will be used for cleaning activities and two elements from each work shift will dedicate two hours a day to cleaning activities on the following shift. Furthermore, as it is a large company, which frequently receives external visitors, the concern with cleaning and hygiene of equipment is important for the company's image.

For the elaboration of the checklists of the AM plans, the components of each equipment and its history of breakdowns were considered, trying to understand what the main problems could be. However, involve the main actors in the four production lines, such as the rubber area engineer, heads of the production and maintenance team, workers, and the maintenance team, were essential to implement the best possible AM plan.

4.3 Preventive Maintenance

PM in a factory that runs continuously is indispensable to ensure that equipment is functioning properly until the next scheduled maintenance. The equipment in the rubber area was not included in the factory's annual PM plan nor did it have its own PM plan. PM activity only covered a small part of the factory, not including the rubber area, where the project was carried out. The large number of requests for intervention was explained by the fact that the rubber area was recently transferred from another factory of the group and due to the antiquity of the equipment, some manufactured in 1955.

In order to reduce the number of requests and increase the availability of equipment, PM plans were developed for all equipment in the four production lines in the rubber area. With this project, all equipment was included in the annual PM plan. The record of the execution of the PM checklist is made by an element of the maintenance team assigned to the work, on a secondary sheet, which is archived for future consultations. All problems detected by this element are reported to the head of maintenance, who must schedule maintenance work with the production team to eliminate the problems detected.

In the annual plan, the families of equipment are identified, as well as the number of pieces of equipment in each family and the number of times they must be inspected per year. In the case of families that were already on the plan (because they already exist in

other areas of the factory), the number of equipment was updated. In the other cases, it was necessary to add new families to the plan.

Three main criteria were used to develop the annual preventive plan. First, critical equipment was identified for each production line, as it need to be inspected more frequently. Secondly, there was an effort not to overload the months of August and December, due to the lack of internal monitoring by the maintenance team and because the purchase of tools and materials from suppliers becomes more difficult, as most companies close for holidays in these months. Thirdly, the development of the preventive plan took in account the importance of preventing the occurrence of breakdowns, carrying out PM work so that the production process is not interrupted. For instance, there are many sluice ways, most of them are located outside, subject to adverse weather conditions. Therefore, PM has been scheduled for this equipment before and after winter, to ensure that it works properly in the winter months.

4.4 Results

In order to assess if the maintenance plans developed were adequate for the equipment and if they would result in advantages for the company, the availability of the equipment identified as critical was calculated. During the project, data were collected monthly on the failure rate, as well as the MTBF, the MTTR and the MWT. Table 1 presents the availability before and after the implementation of the maintenance plans for the three equipment that had the most intervention requests.

Table 1. Availability before and after the implementation of AM and PM plans

Equipment	BAM 001		PRE 052		MAB 001	
Indicators	Before	After	Before	After	Before	After
Failure rate (failures per hour)	62	24	56	26	19	26
MTBF (hours)	18,0	41,5	19,9	38,3	58,7	38,3
MTTR (hours)	1,9	1,2	1,8	2,1	1,8	1,1
MWT (hours)	1,2	0,7	1,3	0,8	1,2	0,5
Availability (%)	85	96	86	93	95	96

Despite the difficulties encountered in determining the real value of availability, the first clear evidence of post-implementation of maintenance plans is the decrease in intervention requests made to the maintenance team. Before the implementation of AM and PM plans, there were registered 278 requests for intervention in three months, while after the implementation 168 requests for intervention were registered during the same period, which represents a reduction of 110 requests (about 40%). Operators were able to avoid calling the maintenance team and resolved some of the breakdowns on their own. Another aspect that can help to explain these numbers is the fact that the production engineer realized the importance of first-level maintenance, which must be carried out

by the people working on the production lines. Many first level maintenance activities are focused on cleaning equipment and the surrounding space (Fig. 1).

Fig. 1. Examples of first-level maintenance activities

An important result achieved with this project is the constant concern of workers to keep the work area clean and tidy. It also contributed to strengthen the communication between production and maintenance departments.

5 Conclusions

The work developed showed the advantages and gains of applying the principles of the TPM philosophy. The results already achieved in this short period of time with the implementation of AM and PM plans for the equipment of the production lines in rubber area allow to conclude that this is the path that the company should follow, such as studied in previous works [3–5]. Knowing the operation of each piece of equipment and its components, as well as the assignment of codes to the equipment, proved to be fundamental to start a successful path. It resulted in deeper knowledge of the environment to develop the best maintenance plans. One of the factors that contributed most to achieving the objectives was the awareness of workers about the importance of the project for the protection of their jobs. Working with equipment with few breakdowns results in greater productivity. The importance of encouraging workers to carry out AM activities is highlighted as a way of reducing non-productive times.

Some limitations were found during the implementation of the project. Some of the maintenance activities were neglected, mainly due to the excess of unfinished orders. Another difficulty observed during the project was the lack of human resources in the maintenance team to deal with the many intervention requests, resulting in long waiting times. A final difficulty has to do with the calculation of the real value of availability, as the numbers presented may not correspond to what is experienced daily on the production lines. Non-productive time records were not available, and it was not possible to follow production lines 24 h a day to obtain reliable data.

The implementation of AM and PM plans resulted in a significant decrease in requests for intervention and increase of availability of equipment. However, there is still a long way to go in the pursuit of perfection in the implementation of TPM across the organization. For the TPM philosophy to be ingrained in the organization, top management must be aware of the advantages that can be obtained, delegate specific functions of monitoring and systematic inspection of maintenance activities and take measures to ensure that AM work is never neglected. More time is needed to measure the real improvements

achieved with the implementation of AM and PM plans. In addition, values of availability can be used to calculate the Overall Equipment Effectiveness indicator to derive more meaningful information regarding the general state of maintenance in the rubber area. The company may also consider implementing an improved maintenance policy, carrying out preliminary studies and projects with the aim of reducing or eliminating maintenance tasks that may be unnecessary.

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Analysis and Improvement of the Maintenance Activity in the Molding Process of a Company in the Cork Industry

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Abstract. This article describes the work carried out with the objective of analyzing and improving the maintenance activity in the molding process of a company in the cork sector. Regarding the research design, an analysis of the production and maintenance process was carried out, which allowed an initial diagnosis with the identification of existing problems and the calculation of main maintenance Key Performance Indicators (KPIs). After, improvement actions were identified, planned and implemented in the molding process. A set of standards and best practices was established, and maintenance documentation updated. Additionally, equipment was changed, and the principles of Total Productive Maintenance (TPM) were incorporated, according to the Lean Production philosophy, promoting collaboration between the production and maintenance teams and autonomous maintenance. The post-implementation results revealed an improvement trend in the previously analyzed KPIs.

Keywords: Maintenance · TPM · Lean · Cork Industry

1 Introduction

The maintenance function works to keep the organization's assets in the required conditions for as long as possible. Thus, maintenance is considered as a strategy to improve equipment availability and performance rather than a necessary downside. The objective of this study was to propose and implement improvement actions in the agglomerate sector of a cork company, through TPM and Lean maintenance approaches and principles, and to evaluate their impact on maintenance KPIs. Among the various stages of the manufacturing process of agglomerated cork stoppers, crushing, molding, and grinding are those that require more complex maintenance work. This paper focuses on the improvement of maintenance activities in the molding phase. The main challenges involved improving preventive maintenance operations, standardizing work procedures,

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making workers responsible for the care and maintenance of equipment and eliminating efficiency losses, with the aim of increasing availability and reliability of molding equipment. The research methodology used in this project was the case study, suited to organizational problems and creation of improvement practices for the detected problems [1]. This included several stages, from obtaining initial information to analyzing results, including proposing and implementing improvements.

The paper is organized as follows. After a background section, the case study is described, starting with an initial diagnosis, followed by the presentation of the implemented improvement actions and the comparison of pre and post-implementation results for various maintenance KPIs. Finally, a conclusion section is presented with the main results, limitations and opportunities for future improvements.

2 Background

The maintenance function involves all activities that contribute to the normal operation of equipment, systems and devices and to improve their reliability and availability [2]. Maintenance activities have direct implications for production and quality, so they should be treated as an investment and not just as a cost [3]. Their main objective is to make the equipment more efficient so that production has the ideal conditions to achieve its objectives. For equipment to operate efficiently, it is necessary to reduce the number of failures, minimize equipment repair time and act before failures occur to properly carry out scheduled maintenance activities. All maintenance tasks must be carried out in safe conditions, seeking to maintain the quality of the equipment and reduce costs [4]. A maintenance strategy includes corrective, preventive or condition-based maintenance activities, in which predictive maintenance is included [5]. There are different perspectives on how to choose the appropriate maintenance strategy [6].

TPM is a methodology and philosophy for the strategic management of equipment maintenance, focused on product quality, by maximizing equipment effectiveness [7]. Initially, TPM activities were limited to departments that use the equipment, such as production, but support and administrative departments, which actively support production, are also important to improve the results of TPM activities [8]. TPM has six key elements, which include: improving equipment effectiveness by targeting large losses; involving operators in the daily maintenance of their equipment; improving maintenance performance and effectiveness; training all stakeholders; equipment lifecycle management and preventive maintenance planning; and, achieving goals with teamwork focused on common goals [9]. The eight-pillar TPM implementation plan proposed by the Japan Institute of Plant Maintenance (JIPM) consists of a 5S foundation and eight supporting pillars: autonomous maintenance, planned maintenance, quality integration, focused improvement, early equipment management, training and education, safety, health and environment, and TPM in administration.

Lean production has also changed the compromise between productivity and quality, which has led to a rethinking of a wide range of manufacturing methods and service operations with a significant impact in both academia and industry. The Lean concept quickly spread to many industrial sectors beyond the automotive sector, where it has its roots [10]. However, for its implementation to be successful, the existence of a continuous

process flow must be ensured, as a prerequisite of Lean systems, as it helps to reduce production time, improve quality, minimize operating costs, and reduce production and delivery times [11]. Lean tools can be used to identify waste in the value stream and then find an appropriate way to remove, or at least reduce, that waste.

Furthermore, KPIs can play an important role in the monitoring of the impact of maintenance activities. KPIs are mostly quantitative information that helps to monitor the structures and processes of a company. In order to ensure that the plant achieves the desired performance, maintenance managers need to track performance of the maintenance process and its results. This can be achieved through the development and implementation of a rigorously defined performance measurement system and indicators capable of measuring important elements of maintenance behavior [12].

3 Case Study

3.1 Initial Diagnosis

In the molding phase, the raw material takes the form of granules, coming from the crushing phase, which are transformed into cork stoppers. At this stage, whenever a non-compliance is detected, it is checked whether this is due to the equipment. If so, for reasons such as mechanical failures or poor tuning, the operator reports the situation to the technicians who analyze the failure and carry out the diagnosis. The technicians analyze the problem and assess the possibility of carrying out the repair, considering the need for replacement parts and the existence of stock, if applicable. Depending on the complexity of the problem, technicians can carry out the repair or, not having the capacity to do so, assign maintenance to an external company. One of the difficulties in carrying out some preventive maintenance actions is the fact that molding machines do not have a manual and almost no information from the manufacturers. In addition, these machines underwent improvement actions that were not registered.

During the diagnosis phase, some problems that lead to poor equipment maintenance were identified. Examples of material leaks during the process were observed, mainly due to blockages in the pipes. In molding, where cork is mixed with other products, such as glue and water, the glue tends to accumulate next to the equipment causing greater wear and tear. Sometimes, there was some lack of motivation regarding compliance with work methods. Another problem found was communication failures between operators and maintenance technicians, as well as failures in the maintenance record, with equipment without any record or maintenance plan. In addition, there was a lack of maintenance routines and maintenance was postponed due to the lack of capacity of the maintenance team. To better characterize the initial situation, data were collected so that it was possible to calculate some indicators such as OEE (Overall Equipment Effectiveness), Mean Time Between Failure (MTBF) and Mean Time Between Repair (MTBR). Availability, performance and quality data were used to calculate the OEE, using Eq. (1).

$$OEE = \text{Availability} * \text{Performance} * Quality \tag{1}$$

In order to have quantitative data on the overall performance of the molding equipment before the implementation of improvement actions, data available from January 1,

2021 to November 30, 2021 was used to calculate availability, performance and quality indices. For instance, the cycle time (*i.e.,* the time the machine takes from one demolding to the next) was collected to calculate the performance of molding machines and data on the quality of the cork stoppers was provided by the product quality department. Furthermore, data were collected on the number of stops and the time that each machine took to be repaired to obtain the MTBF and MTTR values for each machine. Equation (2) was used to calculate the MTBF and Eq. (3) to calculate the MTTR. MTBF can be defined as the predicted time between inherent failures of a system during its operation. In turn, MTTR is a basic measure of the maintainability of repairable items and represents the average time required to repair a failed component or device [13].

$$\text{MTBF} = \text{Total operational time}/\text{Total number of failures} \tag{2}$$

$$\text{MTTR} = \text{Total maintenance time}/\text{Number of repairs} \tag{3}$$

The values for these indicators are presented in Table 1. It should be noted that the molding machine 3 was divided into two because they work partially independently, with different production and stop times. Analyzing the data obtained, the molding machine 1 was the one with the lowest OEE, in contrast to molding machine 2, which had the highest value. This difference can be explained by the wear of the molds, as it is known that it greatly impacts the quality of the final product. For the remaining equipment, the values varied between 56% and 69%. The molding machine 5 was the one with the lowest availability value of all, as it is the molding machine that manufactures a wider range of products and, therefore, has more stops to change recipes and granules, which can justify this value.

Table 1. Initial values of OEE, MTBF and MTTR for each molding machine

Molding Machine	OEE (%)	MTBF (h)	MTBR (h)
1	46	63,39	4,49
2	79	49,90	3,17
3 A	59	71,83	3,56
3 B	58	79,21	3,76
4	64	59,51	3,72
5	56	99,41	4,44
6	69	48,58	4,58

Regarding the MTBF values, the maximum value of 99.41 h was found for the molding machine 5 and the minimum value of 48.58 h for machine 6. The MTTR values obtained were similar for the different pieces of equipment, with a minimum of 3.17 h for machine 2 and a maximum of 4.58 h for machine 6.

Once the problems were identified and the initial diagnosis was made, improvement actions were implemented to respond to problems identified, increase the MTBF values

and reduce the MTTR values, improving the conditions for the maintenance team to carry out repairs in less time. These actions are described in the next section.

3.2 Improvement Actions Implemented

Improvement actions were implemented, some of which involved changes in existing equipment and changes in maintenance documentation. Others, such as the layout change, are more general in nature and are described here because they are believed to also have an impact on maintenance activity.

Creation and Standardization of Equipment Maintenance Plans. One of the problems common to all stages of the process was the lack of clear and up-to-date information on the preventive maintenance carried out. Most of the equipment did not have maintenance plans visible and accessible to both technicians and operators, and for the equipment that did, maintenance plans were either outdated or incomplete. To solve this problem, a standard plan template was created that can be applied to all equipment. In molding machines 3, 4, 5 and 6, maintenance plans have been added, containing information regarding planned maintenance actions that are carried out by maintenance technicians and operators. For this type of equipment, the maintenance plan was divided into three groups: (1) shift maintenance (autonomous maintenance), which is performed by the operator; (2) weekly and monthly maintenance, which is performed by the operator and the maintenance technician; and (3) lubrication that is also performed by a technician. As lubrication is essential for good equipment maintenance and there were some difficulties in carrying it out during the technicians' weekly work routine, Monday was established as the day on which the molding machine is stopped for lubrication, to start production on this day.

Provisional Maintenance Sheet. One of the difficulties encountered was the communication between operators and maintenance technicians to report equipment problems. To solve this problem, a provisional maintenance sheet was designed. The function of this tool is to facilitate operator-technician communication, recording the problem found as well as the solution given by the technician.

Change of Glue Injection System in Molding Machines 1, 2 and 3. The glue injection system in the mixer of molding machines 1, 2 and 3 has been changed. Unlike the system used in the most recent molding machines (4, 5 and 6), in which only the injection nozzles are inside the mixer, in molding machines 1, 2 and 3 the injection system is incorporated inside the mixer.

Automatic Mold Cleaning System for the Molding Machine 3. During the mold filling process, a small amount of mixture falls into a tray, which is cleaned by the operator. To solve this problem, an automatic cleaning system similar to the one existing in molding machines 1 and 2 was created.

Factory Layout Change. The layout was changed due to the company's growth and some difficulties in balancing the cork agglomerate production process. Grinding equipment was centralized in the same area. Thus, the manufacturing process of agglomerated cork stoppers has become more linear and the product travels shorter distances between

the different stages of the process. The space now available in the molding area is used to place the carts that store the bodies that come out of the molding machines for the 48-h stabilization time, which were often located in areas where people and forklifts passed.

3.3 Post Implementation Results

After the implementation of improvement actions, data were collected, and the indicators related to molding were evaluated. Availability, MTBF and MTTR were calculated for all molding machines for the month of May 2022 and compared with the values obtained previously (Table 2).

Table 2. Pre and post-implementation results

	Pre-implementation			Post-implementation		
Molding Machine	Availability (%)	MTBF (h)	MTTR (h)	Availability (%)	MTBF (h)	MTTR (h)
1	80	63,39	4,49	83	70,33	4,5
2	88	49,90	3,17	85	52,20	3,56
3 A	83	71,83	3,56	85	70,15	3,23
3 B	80	79,21	3,76	82	85,20	3,59
4	83	59,51	3,72	85	59,60	4,16
5	76	99,41	4,44	80	89,78	3,78
6	83	48,58	4,58	83	70,69	3,70

Although assessing the impact of implementing actions to solve maintenance problems normally requires a longer analysis period and is expected to have a greater impact in the medium and long term, it was possible to verify an improvement trend in all indicators. There was an increase in MTBF for all equipment, except for molding machines 3A and 5. Regarding MTTR, there were no considerable differences, with repair times similar to those previously calculated. Availability improved by 1.43%, comparing the two periods under analysis. Only molding machine 2 had a worse availability rate.

4 Conclusion

Over the last years, the implementation of TPM principles in many organizations has demonstrated that significant improvements can be achieved through it. TPM concepts and philosophy can be used effectively to make fundamental improvements in the performance of companies, thereby leading them to success in a highly competitive environment. Its implementation may involve the participation of all departments of the organization.

The work developed and described in this paper involved the creation and updating of maintenance plans for equipment in the molding area, as well as the creation of a

maintenance record and visual support tools that allow the involvement of operators and technicians in maintenance activities, a better transmission of information between the two parts and a better execution of maintenance activities. Changes to existing equipment and factory layout also aimed at eliminating some inefficiencies in the production process, with an impact on maintenance activities. In general, the implemented improvement actions made it possible to promote a cleaner and more organized environment. It is proven that, when correctly implemented, the TPM methodology allows a progressive reduction of maintenance losses, as well as production losses. Furthermore, communication between teams from different departments and their alignment with the organization's objectives are essential for the maintenance function to be performed effectively. The information provided by the employees of the company under study was very important to make the initial diagnosis and propose improvement actions in order to respond to the identified problems. Operators, maintenance technicians and managers actively collaborated at all stages of the project and contributed with new ideas and changes to improve the proposals and implement them.

Some limitations were found throughout the study, namely with regard to data recording and the assessing the impact of implemented actions. The data were recorded in a production support system and it would be preferable to have dedicated software for maintenance, which is planned for next year, with the introduction of a new ERP system. With the implementation of a new ERP system with a maintenance support system, it will be possible to track in more detail the problems with the molding equipment, to perform a Failure Mode and Effect Analysis (FMEA) for each piece of equipment and, then, update and improve maintenance plans.

Visual management tools such as One Point Lessons (OPLs) and lubrication points can also help prevent errors in task execution, especially by employees who are not used to working with equipment. The company should continue to implement these tools, creating lubrication points for the remaining molding machines and creating OPLs for other tasks, such as changing the screens in the mills. Finally, KPIs must continue to be monitored. As mentioned, although the results indicate an improvement trend in most equipment, it will only be possible to assess the real impact of the implemented action in the medium term.

The main aim of the paper was achieved. Using simple tools, it was possible to increase availability and reliability of molding equipment. In this sense, and related to the academic contribution and novelty statements, it was possible to add a good example of Industry-University relationship best case, not related to radical innovations support from Universities but in incremental and societal challenges, having been achieved good results using simple tools applications.

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Using Process Mining as a Tool for Process' Digital Twin to Perform Strategic Maintenance Decisions

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Abstract. Process mining (PM) and digital twin (DT) present synergy in the context of Industry 4.0 era, as data-driven approaches are leading the way. With this relation, some design principles of DT are accomplished by applying PM techniques in order to extract knowledge from industrial processes. This knowledge can range from singular metrics of indicators through complex process analyzes (comprehension of paths, deviations, frequency, simulation and among others). In this context, the motivation of the work comes from using factory floor process data in a process' digital twin environment as inputs in the decision layer to make assertive choices in the industrial and/or maintenance environment considering different scenarios of actions. Therefore, the main goal of this paper aims at integrating those fields of study (i.e., process mining, process' digital twin and decision-making) in an industrial maintenance area to choose or indicate a strategic maintenance action that best fits the evaluated scenario.

Keywords: Process mining · Process' digital twin · Decision-making · Smart industrial maintenance · Data-driven decisions

1 Introduction

In the current digital and modern era, data-driven decisions are getting attention to academia but, specially, for companies because it could overall increase business performance [1]. According to [2], data-driven methods, considering the decision-making in manufacturing maintenance role, rely on data analytics and/or machine learning algorithms to make assertive decisions about maintenance and operational actions.

Since data is used to drive the assessments, digital twin (DT) concept fits and helps companies by providing ways to create closed loop of interactions such as modeling the system according to the five dimension of digital twin (*i.e.*, physical space, virtual space, services, data, and connection of different parts) [3]. Furthermore, DT concept has

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increased its relevance for industries of several sectors because it brings real advantages to industrial processes and, specially, for industrial maintenance [4].

Thus, in this context, data-driven decision-making can be implemented following the framework presented by [5], which has five steps to perform it (*i.e.*, data collection, data validation, knowledge extraction, model development, and model validation). The last three tasks can be performed by applying the process mining (PM) technique, which consists of extracting information from event logs to capture process models (path, behavior, deviation, etc.) as it is being executed [6, 7].

Therefore, considering the integration of the main fields of study, the main goal of this paper is to use PM technology as a tool to extract metrics of an industrial model process in order to provide insights and/or knowledge for the decision-making procedure into a digital twin context. In order to accomplish it, a framework is proposed to guide the steps regarding the acquisition and consumption of a synthetic event log to support decision-making based on multicriteria decision-making (MCDM) methods. Changes of scenarios of simulations are made, and the results are analyzed, specially, in terms of criteria weight changing for the MCDM method assessment.

To this end, the subsequent sections are structured as follow. Section 2 presents a brief literature review related to the fields of study. In the Sect. 3 some discussion is made to contextualize the paper towards the framework proposition. Section 4 dedicates to the assessment of the proposal into a case of application by using different tools. The final section dedicates to the conclusion of the paper and suggestions of future work.

2 Literature Review and Contextualization

The following subsections will briefly cover the connection of the proposed main fields of study: process mining, process' digital twin and industrial maintenance decision-making.

2.1 Process Mining and Process' Digital Twin

Process' digital twins can be understood as the core which connects the product design and manufacturing processes by linking three-dimensional subjects, including manufacturing procedure model, process attribute information and asset digital twins [8]. It also covers the integration of active software systems to another cyber physical system by using data and models during its runtime in order to optimize its behavior [9].

The classical definition of process mining includes the ability of discovering, monitoring, and improving real processes by extracting knowledge from event logs readily available in information systems [10]. Nowadays, in the context of digital twins and smart manufactories, PM goes beyond this concept since it does perform not only the one-time execution (*e.g.*, discovering the process model) but it is used as supporting continuous process management by applying active and imperative ways [11].

In this vein, PM techniques can leverage the massive amount of data by merging process-level models with low-level event data [9], or monitor deviations in operational processes and, automatically, trigger actions based on the monitoring results [12]. In other words, PM provides tools to extract real process models, being the combination of PM and digital twin ways of producing several and different scenarios [13].

2.2 Process' Digital Twin and Industrial Maintenance Decision-Making

Digital twin can be applied to improve several processes including maintenance and decision-making. Having a model that replicates a process and emulates it is essential to detect deviations in KPIs (Key Performance Indicators) [14] and simulate possible scenarios as consequence of an action.

Related to maintenance, according to [4], there are applications of DT in the following areas: improvement of the maintenance process, optimization of the proposed maintenance strategy, calculation of the costs and/or the remaining useful life, etc. Therefore, digital twin creates new development of opportunities for maintenance team, as for example, by implementing DT technologies to build a picture of factors to perform prediction maintenance decision-making [15].

In sum, digital twin models can provide additional decision-making information for optimizing future operations, forecasting degradation mechanisms, and predicting future failures and it also helps to create a more qualified workforce and reduce the decision-making time in the industrial sector [16], as well as in maintenance.

2.3 Process Mining and Industrial Maintenance Decision-Making

As commented, process mining for the maintenance sector can be considered a useful tool to provide knowledge from process. Furthermore, some competitive advantages rise in favor of this technology, since combining an information system with PM techniques turn out to be a differential in the industrial environment, giving support for decision-making process [17].

Additionally, PM can assist at all four levels of decision making, which are design-time, configuration-time, control-time, and run-time decisions [18]. Therefore, in general, one of the goals of PM in maintenance area is to provide insights and to let users choose better and assertive decisions [19].

3 Framework: Using Process Mining in a Decision Support System Under a Digital Twin Concept

The hybrid architecture of digital twin with a decision support layer for maintenance includes the use of a tool to support the decisions [20], since trade-offs may occur between the KPIs set. In this vein, MCDM methods are ways to help with this step.

One of the methods that suits the case of study is the PROMETHEE, since it supports the possibility of applying different weights to the criteria, it could work with qualitative and/or quantitative value, it reflects several properties of attributes, and there is no need to process raw data [21, 22].

Nevertheless, a previous step is needed, which relates with a methodology that extracts KPI metrics from process' logs. As explained, in the industrial maintenance sector, one of the approaches that best fits this step is the process mining because it provides the knowledge needed to analyze the entire process.

The proposed framework is shown in the Fig. 1. As could be seen, among several layers that DT covers (*i.e.*, monitoring, measuring, analyzing, simulation, understanding,

and decision [20]), the framework focuses only on the decision layer and their steps. Note that process mining techniques could be used within the decision layer to extract KPIs from process models, but its implementation also could discover the model – as presented in the left side of the image.

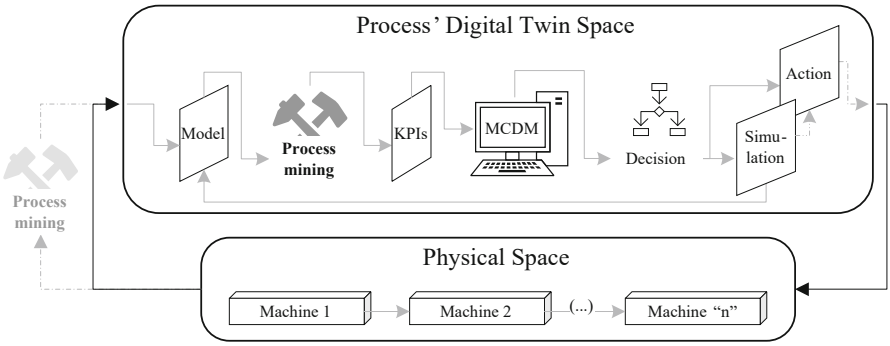

Fig. 1. Framework of implementing process mining technique into a digital twin context.

Explaining the framework, the proposal aims at: 1) using process mining to discover the model and extract metrics in order to fill in the indicators; 2) utilizing multicriteria decision-making method to selection or ranking; 3) using the output of the decision to simulate (in order to create different scenarios of execution for analysis, and a posteriori, a decision) or choose an action (based on simulated scenarios, electing a real action to be applied in the physical space).

4 Case of Application

In order to examine its functionality, this framework was put into a validation step. Therefore, the database used to test it consists of a synthetic log created from an industrial process of a discrete manufacturing with the aid of Petri Net's modeling.

In our context, since we want to use process mining techniques as much as possible, the log was submitted to PM techniques to discover the path/behavior of the process model (represented by the arrows direction and quantity of frequency (numbers over the arrows)), to detect its repeatability (shown as numbers within the boxes), and to identify the time spent in each activity. The result is presented in the Fig. 2 with a fitness index given by the Genetic algorithm (from software ProM) of 0.9815, *e.g.*, almost all the tasks of the synthetic log are covered with this model, therefore, a high fidelity process' modeling with a 98.15% of accuracy.

From this step, some other process mining algorithms was used to extract KPIs metrics from the log. It is important to mention that some indicators are directly extracted from the database, and others are indirectly collected (*i.e.*, for example, by applying a formula), but all the data comes from the log.

In the current paper, the criteria elected to test the framework are: OEE (C_1), total operation time (C_2), number of stops (C_3), mean time to repair (C_4), and mean time

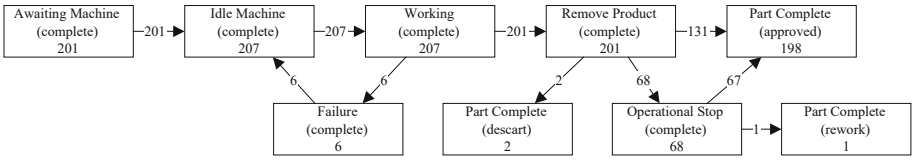

Fig. 2. Process model result after applying a process mining technique (fitness = 0.9815).

between maintenance (C_5). Those criteria were selected considering their relevance for maintenance area and availability of data in the event log, besides, it should be noted that all the weights are equally distributed, *i.e.,* the sum of them is equal to one ($\sum_i^n w_i = 1$). The metrics' values are present in the *'Action 1'* line of the Table 1. Furthermore, this table also present other scenarios of analysis in order to compare all of them with the support of a MCDM method.

Table 1. The PROMETHEE decision-making matrix.

KPIs Settings	Indicator	C_1	C_2	C_3	C_4	C_5
	Unit of measure	%	Time	Absolute	Mean time	Mean time
	Type	max	max	min	min	max
	Pref. Function	Linear	Linear	Linear	Linear	Linear
	Weight	0.2	0.2	0.2	0.2	0.2
Alternatives	*Action 1*	0.6947	275.6	66	5.00	61.58
	Action 2	0.7631	355.7	54	6.69	105.34
	Action 3	0.7475	329.8	43	8.86	148.27

Since we are in a digital twin context, changes could be made in the model to analyze the output before implementing an action in the real process. Therefore, *'Action 2'* and *'Action 3'* lines are execution of the same synthetic log, but with different set of variables (*i.e.*, criteria). In other words, since we are promoting changes virtually, the practice of metric's reading will find different values for the KPIs, and, as consequence, different scenarios of execution is made for analysis.

These *'Actions'* are generic decisions related to the process, for example they could be understood as: maintenance strategic activities, prioritization of industrial machines to perform maintenance actions, selection of production lines, scheduling of product manufacturing, among others. The generic term used (*'Action #'*) was coined on purpose to present a wide range of possibilities of implementation being suggested to use accordingly to the company issue, however it is important to consider that the criteria will change according to this problematic.

As said, the metrics extracted with the support of the process mining algorithms, was input of the PROMETHEE decision matrix aiming at assisting the operator with a decision, since some the indicators are conflicting with one another. Therefore, as also

shown in the Table 1, the matrix presents additional information related to the decision-making step, among them are weight of each indicator in the decision procedure, type of the metric, unit of measurement, and preference function to perform the analysis.

The output of this step aims to show which *'Action'* is more recommended given a set of variables, and, as consequence, a given indicators' reading. This MCDM method presents several result interpretations. For example, it could show the recommendation straightforward, but it also allows some analysis, as following presented.

Figure 3 shows how the suggestion is affected by the using different weights for each indicator. As example, in the image we can note that the indicator Mean Time to Repair (MTTR) could significantly change the result by just modifying its weight. This criterion was chosen because it was the one that showed more than one variation among the other four. Additionally, this sensitivity analysis can be made punctually by electing just one criterion and make the others fixed respecting the same variation (*e.g.*, increasing 1% of MTTR, will decrease by 0.25% the other four), or wide by applying a specific weight for each criterion.

As presented by the light blue lines in the image, the ranking of the recommended actions could be: 3, 2 and 1 (weight range: [0, 17]), or 2, 3 and 1 (weight range: [18, 40]), or 2, 1 and 3 (weight range: [41, 59]), or, and finally, 1, 2 and 3 (weight range: [60, 100]).

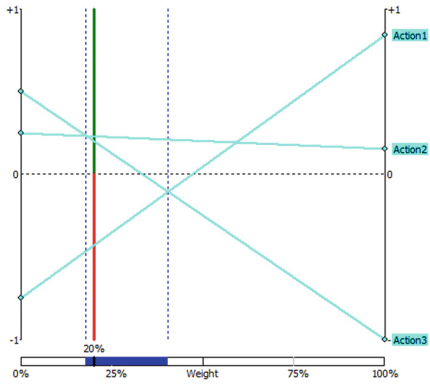

Fig. 3. Different results just by changing weights for the MTTR indicator.

As can be observed, different results can be reached with considering different scenarios of execution and, therefore, this is the one of the purposes of the digital twin technologies, *i.e.*, providing possibilities of analysis before applying the action in the physical space. As shown, the decision layer helps the operator by delivering a wide view of options virtually in order to prepare the team when the real action is needed.

5 Conclusion and Discussion

The main idea of the paper aimed at presenting an integration of process mining and industrial decision-making into a process' digital twin context to help operators in the industrial maintenance area. In order to accomplish it, a briefly overview was made by interconnecting those fields.

Additionally, the paper presented a framework of a decision support layer in a digital twin environment and, therefore, proposed the use of different tools and technologies – for example: process mining algorithms for model discovering and metrics reading, multicriteria decision-making method to analyze the recommended action given different scenarios, and closed-loop analysis, among others.

In order to validate the applicability of the framework, a synthetic log was used, and the result showed that different scenarios bring different actions, and some actions are directly affected by the weight considered for a given criteria.

Related to the process' digital twin, the positive characteristic refers to the ability to run scenarios of applications before a real implementation. On the other hand, the negative side relates to the difficult to replicate the entire physical space (*i.e.*, all the industrial process) in a real-time context.

In sum, all the results are in line with one or more of the digital twin purposes, which consists of predicting actions on the physical space by executing/simulating scenarios in a virtual space, reducing the amount of time, cost and resources put in that activity. Nevertheless, the limitation of the framework lays in the fact that not all the industrial processes could use a process mining technique because of its intrinsically difficult, such as continuous manufacturing, or related to the incapacity of measuring variables due to sensor restrictions, or even the data recorded in the log and its pre-processing.

For future work, we propose the online integration of the steps (as mandatory in the digital twin environment) and, also the testing of the framework considering a real process of discrete manufacturing.

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Interoperability Assessment Model in Industrial Maintenance According to Digital Twin Concept Based on Multicriteria Decision Support Methods

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Abstract. Industry 4.0 (I4.0) refers to recent technological advances where the internet and supporting technologies serve as communication for integration between systems, thus raising the level of maturity of the company. This context is intrinsically linked to Industrial Maintenance, which is greatly impacted by the characteristic of distribution and volume of information imposed by the requirements of I4.0, suggesting a review those models and strategies for a more predictive characteristic based on reliability. In this direction, the Digital Twin (DT) concept emerges expressively, which encompasses functional and technological scopes associated with Industrial Maintenance. Based on these elements, a diagnostic evaluation can suggest Industrial Master Plans, allowing a clearer view of the elements involved, restrictions, risks and better application of resources. Under this focus, the interoperability assessment, a strong requirement of I4.0, represents a relevant diagnostic tool guiding both the requirements and specifications aimed at the integration of supervision and industrial maintenance platforms. The objective of this article is to present a diagnostic evaluation model of interoperability in maintenance, under the requirements of I4.0, through the use of multicriteria decision support methods (MCDM) and to provide an evaluative and directional basis to implement the DT concept.

Keywords: Industrial Maintenance · Digital Twin · Interoperability · Industry 4.0

1 Introduction

Industry 4.0 (I4.0) refers to recent technological advances where the internet and supporting technologies serve as a backbone for the integration of physical objects, human actors, intelligent machines, production lines and processes across organizational boundaries to form a new agile, intelligent and networked value chain [1]. As one of the key

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concepts of I4.0, the smart factory consists of smart machines, so-called cyber physical systems (CPS) [2], storage systems and production facilities capable of autonomously exchanging information, triggering actions and independent controls. Based on the Internet of Things (IoT), CPS communicate cooperatively between themselves and the human element in real time [3, 4].The concept of interoperability means that two or more systems are able to exchange information with each other and take advantage of the received information. Interoperability is indispensable in I4.0, especially in the Industrial Maintenance scenario, since the integration of machines and, consequently, their exchange of information, allows us to move from a preventive and/or corrective maintenance model to a predictive model, which proves to be much more efficient in preventing defects, reducing maintenance time and cost.

With the advancement of interoperability and information systems, the concept of Digital Twin (DT) becomes applicable [5], bringing many benefits to companies that adopt them, such as providing dynamic models of the system according to the physical characteristics, environment and production, failure prediction and simulation of improvements, and the possibility of running tests that would not be able to be carried out without a virtual model. This concept of DT can be expressed in a five-layer architecture [6], and with the objective of optimizing industrial maintenance in search of the predictive model, thus bringing real advantages to industrial processes [7].

However, for the application of the DT it is necessary that the company has a good financial reserve and employees prepared to receive and interact with the necessary technologies for the ideal functioning of the DT. However, the number of articles that indicate the main barriers to be broken and the technologies that are necessary to enable the use of DT are still scarce, which makes the task of finding an evaluative form that presents a high rate of assertiveness to indicate the degree of maturity of a company.

Therefore, this project aims, through the study of multicriteria decision support methods (MCDM) and the requirements of I4.0 and DT, to build an enterprise interoperability assessment model in the field of Industrial Maintenance that is capable of guiding the decision of what should be adopted to enhance the company's capability in this domain, following the requirements of I4.0 and DT.

Then, Sect. 2 will explain the scientific scenario and the theoretical dimensions that underlie the proposed solution. Furthermore, Sect. 3 explains the structure and Sect. 4 discusses the results. Finally, Sect. 5 concludes and suggests improvements.

2 Scientific Scenario and Theoretical Dimensions

This section describes the main concepts that cover this research, like interoperability, industrial maintenance, I4.0, DT and MCDM, addressing its main characteristics and definitions. According to [8] establish interoperability is to relate two systems by removing their incompatibilities. The Framework for Enterprise Interoperability (FEI) [8] is barrier-driven and relate three barriers as technological, conceptual and organizational. The development of interoperability allows companies to exchange information in pursuit of the same goal [9].

Industrial maintenance could be divided in five categories that is reactive, preventive, condition-based, predictive and prescriptive maintenance where the last two types of

maintenance have the best potential for digitization because these strategies reduce production downtime, breakdowns, costs and energy waste, improve productivity, facility security and customer service and reputation, discard ambiguity and expend equipment life [7]. Considering system downtimes as opportunities to maintenance helps to reduce downtime costs [10]. A decision support system (DSS) application that helps maintainers to enjoy machine downtimes to preventive maintenance could be performed with the concept of DT-driven [11].

With the growing importance and impact generated by I4.0, the Reference Architectural Model for Industry 4.0 (RAMI 4.0) was created to help I4.0 initiatives, bases on a vision that seeks the integral understanding of the manufacturing process [12]. Based on RAMI 4.0 and the DT concept, that could be described as a physical entity with your digitized representation which mutually communicate with each other through bidirectional interactions [6] the concept of DT as a service (DTaaS) emerges as a visualization of DT characteristics on the layers of RAMI 4.0 [6]. Both DTaaS as RAMI 4.0 has a tree dimensional map, but RAMI 4.0 works with six layers that are asset, integration, communication, information, functional and business [13] while DTaaS works with five layers that are physical, communication, digital, cyber and application [12].

MCDM emerged in the search for solutions to complex and difficult-to-measure problems, already demonstrated in the maintenance domain[14]. This strategy is used as a tool for more assertive decisions in adapting systems, also following some reference research that applies decision-making to the evaluation of interoperability dimensions. Four elements characterize MCDM: set of alternatives, set of criteria, preferences and result. In literature, different methods are presented in the industrial scenario. For the evaluative purpose of this research, the analytic hierarchy process (AHP) [15] and preference ranking organization method for enrichment evaluation II (PROMETHEE II) [16] stand out. The AHP is used to evaluate the enterprise interoperability maturity [17] starting from the RAMI 4.0, evaluating its layers and the PROMETHEE II method is used to evaluate the degree of relationship existing between the Functional Requirements (FR) present in the layers of RAMI 4.0, with the layers of a similar DT architecture model.

3 Maintenance Architectures in Relation to the Digital Twin

With the theoretical foundation, the next stage of the project was the evaluation, by the AHP method, of the attributes and FR to achieve interoperability in industrial maintenance, where the degree of importance of the attributes in relation to the others present in their respective layers was established, and the importance that a functional requirement has over the others present in their respective attributes. For this, a survey was used where these evaluations were carried out. Then, a study was carried out on the DT, observing the architecture models, their concepts, their application in the industrial maintenance area and their requirements and implementation barriers. There is the RAMI 4.0 reference model [13] that describes the architecture in six vertical layers that refer to the flow and data of the industrial production process, its interfaces and forms of use and the DTaaS model [12] that presents a DT reference architecture, describing the five layers of the DT comprising an interconnected set of physical, communication, digital, cyber and application layers. Figure 1 shows how the architectures fit into an overall DT model and which are their layers with similar characteristics.

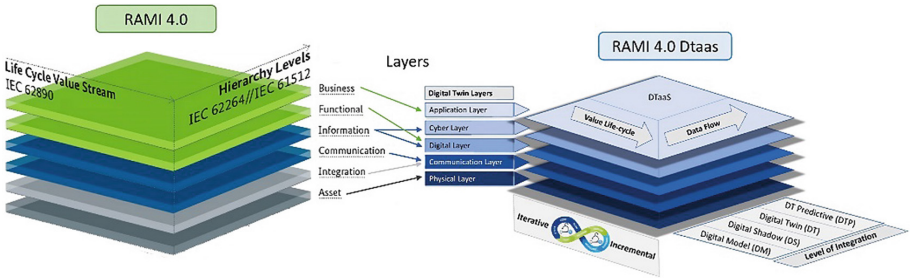

Fig. 1. A Relationship between layers RAMI 4.0 and RAMI 4.0 DT.

After evaluating the "compatibility" between the two models, an evaluation of the relationship between the layers of RAMI 4.0 [13] and the layers of RAMI 4.0 DTaaS [12] was carried out. The values assigned to the indices were: 'Very High', 'High', 'Medium', 'Low' and 'Very Low', as shown in Fig. 2. For this step, the PROMETHEE II method was not used, since there were few relationships.

Then, a more extensive evaluation was carried out, involving the 62 FR [18] evaluating both models to find the FR that have greater adherence to the models. In the Table 2, the FR that most adhered to the DTaaS concepts are presented [19] as explained next.

		RAMI 4.0					
		ASSET	INTEGRATION	COMMUNICATION	INFORMATION	FUNCTIONAL	BUSSINESS
RAMI 4.0 DTaaS	PHYSICAL	5	2	1	1	1	1
	COMMUNICATION	1	5	5	2	1	1
	DIGITAL	1	2	2	3	3	1
	CYBER	1	2	3	4	3	2
	APPLICATION	1	1	1	1	3	4

RELATIONSHIP	
5	VERY HIGH
4	HIGH
3	MEDIUM
2	LOW
1	VERY LOW

Fig. 2. A Relationship between layers RAMI 4.0 and RAMI 4.0 DT.

4 Results

To generate the results, a new evaluation was performed, involving the 62 FR in relation to the layers of RAMI 4.0 and the layers of the DTaaS model, in a way where we can see more clearly the reason why the layers have a higher or lower similarity between each other, by showing the most relevant FR to all different layers. Table 1 presents the results of this evaluation. The results for each Layer are presented below.

Starting with the Physical Layer, which showed the greatest relationship in the topic above, the FR most closely related to this was the following: 'Compare purchases with models and patterns already specified' (FR1), 'Perform the monitoring of several parameters in parallel' (FR2), 'Establish abnormality conditions' (FR3), 'Interpret the relevant parameters on the equipment' (FR4), 'Preserve the integrity of the equipment in the purchase of data'(FR5), 'Supervise equipment performance' (FR5), 'Ensure updated information in the monitoring of data' (FR6) and 'Quality sensors and properly installed' (FR7). It is observed that both have a high degree of importance with the Physical Layer,

Table 1. Functional requirements rank

Rank	Functional Requirement	Phi	Phi+	Phi-
1	Use a data access middleware for direct connectivity between apps and databases	0.761	0.807	0.046
2	Use robust network protocols	0.607	0.738	0.131
3	Adjust the data in different levels	0.489	0.646	0.157
4	Use point-to-point connections between the database and the applications	0.446	0.613	0.167
5	Allow connection capacity with different industrial protocols	0.393	0.574	0.180
6	Use validated gateways by networks	0.295	0.521	0.226
7	Record Failure Prevention Learning based on maintenance historic	0.292	0.512	0.220
8	Allow connection capacity with different industrial protocols	0.279	0.508	0.230
9	Use information correctly to avoid uncertain stops of the machine	0.279	0.538	0.259
10	Ensure updated information in the monitoring of data	0.253	0.482	0.230

all of which refer to the Asset Layer of RAMI 4.0, justified by the relationship between the definition of these layers, since both have a similar function.

Analyzing the Communication Layer, a greater number of FR with strong relationships to it is expected, since from the relationship table between the layers, this one presented strong similarity with two different layers of RAMI 4.0. A total of 15 FR with a high degree of relationship were observed, belonging to the Integration and Communication Layers. The Communication Layer of the DTaaS model assumes the function of integration. The Digital Layer did not present an expressive number of FR that had at least a strong relationship with it. The chance of the current situation occurring with any of the layers presented in the DTaaS model turns out to be moderate/high, since, despite having "equal" structures, they deal with different subjects, even if related. Note that there was only one FR occupying the first place and having a Phi higher than all other FR present in the evaluation. Thus, it is concluded that although the Digital Layer does not have many FR with a 'Very High' relationship, there are similarities with the Communication and Integration Layers of RAMI 4.0.

Moving to the Cyber Layer, once again there were not many "Very High" relations observed with the FR, but in return, it also presented the least amount of "Very Low" relations and the biggest amount of "Medium" or higher ones, making it the most "flexible" layer in the DTaaS model, since even though there is not a great number of really strong relations, a lot of the FR will help in some way to achieve its necessities.

Lastly, the Application Layer also presented a small amount of highly related FR, but when we look at which ones had the better evaluations, it's possible to observe that they come from the Information, Functional and Business layers, where the use of

information, the operation of the process and support for decisions and stages of the process are the main functions, which matches the layer in question.

Table 2. Relationship between RAMI 4.0/RAMI 4.0 DTaaS layers and functional requirements

				DIGITAL TWIN LAYERS									
				PROMETHEE					WALKING WEIGHTS				
RAMI 4.0 LAYERS	ATRIBUTES	FR	FUNCTIONAL REQUERIMENTS	PHYSICAL	COMMUNICATION	DIGITAL	CYBER	APPLICATION	PHYSICAL	COMMUNICATION	DIGITAL	CYBER	APPLICATION
ASSET	RELIABILITY IN DATA ACQUISITION	FR1	Compare purchases with models and patterns already specified						0,885	0,000	0,098	0,312	0,557
		FR2	Perform the monitoring of several parameters in parallel						0,885	0,623	0,098	0,803	0,557
	IDENTIFY FUNCT. FAILURES	FR3	Establish abnormality conditions						0,885	0,410	0,869	0,721	0,557
		FR4	Interpret the relevant parameters on the equipment						0,885	0,000	0,098	0,312	0,557
	EQUIPMENT HEALTH	FR5	Preserve the integrity of the equipment in the purchase of data						0,885	0,623	0,754	0,803	0,557
		FR6	Supervise equipment performance						0,885	0,000	0,754	0,312	0,557
	TELEMETRY	FR7	Ensure updated information in the monitoring of data						0,885	0,771	0,525	0,721	0,148
		FR8	Quality sensors and properly installed						0,885	0,623	0,754	0,803	0,557
INTEGRATION	FLEXIBILITY	FR9	Devices with updated firmware						0,689	0,410	0,098	0,312	0,557
		FR10	Connected elements have knowledge about other elements connected to the network						0,393	0,771	0,098	0,803	0,557
	CONNECTIVITY	FR11	Ensure a proper data transmission rate						0,689	0,771	0,525	0,803	0,557
		FR12	Certify the range of the communication band required						0,393	0,771	0,098	0,803	0,557
		FR13	Use robust network protocols						0,689	0,771	0,869	0,721	0,754
	INTEROPERABILITY	FR14	Allow connection capacity with different industrial protocols						0,426	0,771	0,525	0,721	0,148
		FR15	Use a data access middleware for direct connectivity between apps and databases						0,689	0,771	0,869	0,721	0,754
		FR16	Use validated gateways by networks						0,689	0,771	0,869	0,721	0,754
	SECURITY/ STABILITY	FR17	Operational reliability						0,426	0,771	0,098	0,312	0,148
		FR18	Encrypting data transmitted by gateways						0,426	0,410	0,525	0,312	0,557
		FR19	Use confirmation protocols						0,426	0,410	0,098	0,312	0,557
COMMUNICATION	SCALABILITY	FR20	Limit the amount of requirements around the network at a time						0,393	0,410	0,754	0,312	0,557
		FR21	Use protocols that allow exclusive identification of elements in the network						0,689	0,771	0,869	0,721	0,754
	MOBILITY	FR22	Real -time interactivity and operability						0,426	0,771	0,869	0,312	0,557
		FR23	Allow the connection and exchange of information on furniture devices						0,426	0,771	0,525	0,721	0,148
	HETEROGENEITY OF DATA SOURCES	FR24	Adjust the data in different levels						0,426	0,771	0,869	0,230	0,148
		FR25	Allocate services and applications in different layers						0,393	0,771	0,754	0,230	0,557
		FR26	Relate different types and cloud architectures						0,393	0,771	0,525	0,721	0,557
	SECURITY AND PRIVACY	FR27	Ensure device access control						0,885	0,771	0,525	0,721	0,148
		FR28	Duly projected access authorization policies						0,393	0,771	0,098	0,230	0,557
INFORMATION	VARIETY	FR29	Create a data profile to solve inconsistencies and discover data relationships						0,393	0,000	0,525	0,984	0,557
		FR30	Establish a filter to avoid repeatability of data						0,885	0,410	0,869	0,721	0,557
	FUSION OF INFROMCTIONS	FR31	Ability to prioritize and differentiate data						0,393	0,410	0,525	0,230	0,148
		FR32	Create data models about maintenance and compare them						0,393	0,000	0,098	0,312	0,148
		FR33	Data overload prevention						0,393	0,262	0,098	0,230	0,557
	UTILITY	FR34	Filter information to make them more useful and accurate						0,393	0,000	0,754	0,230	0,492
		FR35	Ensure the quality of recorded information						0,885	0,771	0,525	0,721	0,148
		FR36	Interpret and map only the important parameters in the equipment						0,885	0,000	0,098	0,312	0,557
	VELOCITY	FR37	Design architectures that balance the latent, requirements and cycle of data decline						0,393	0,623	0,098	0,721	0,148
		FR38	Use point-to-point connections between the database and the applications						0,689	0,771	0,869	0,721	0,754
		FR39	Check the ideal data processing speed						0,426	0,000	0,098	0,721	0,557
	VOLUME	FR40	Ensure data storage capacity						0,885	0,771	0,525	0,721	0,148
		FR41	Monitor data use to identify unused and discard it						0,393	0,000	0,525	0,230	0,754
		FR42	Reduce certain analytical structures to a percentage of statistically valid sample data						0,393	0,623	0,525	0,721	0,148
FUNCTIONAL	INTELLIGENCE	FR43	Enhance the precision of the algorithms that reproduce human decision -making						0,393	0,623	0,869	0,312	0,492
		FR44	Use hybrid intelligent systems that learn to identify and predict maintenance situations						0,689	0,771	0,869	0,721	0,754
	RESOURCE VISUALIZATION	FR45	Present diagnosis in a friendly and intuitive way to responsible						0,393	0,623	0,098	0,721	0,967
		FR46	Present characteristics of failures, monitored parameters, possible causes						0,393	0,000	0,525	0,230	0,754
	DIAGNOSIS	FR47	Create a database with a history of faults and follow -ups of the health of the equipment						0,393	0,623	0,869	0,984	0,148
		FR48	Define the tasks to be performed and the time spent based on the state o the equipment						0,393	0,623	0,525	0,312	0,148
		FR49	Identify deficiencies in the process						0,393	0,623	0,098	0,721	0,148
	EFFICIENCY	FR50	Assimilate several parameters and indicators to strengthen the confidence of results						0,393	0,623	0,098	0,230	0,754
		FR51	Optimize the proactivity of real -time information integration						0,393	0,000	0,525	0,230	0,754
		FR52	Record Failure Prevention Learning based on maintenance historic						0,393	0,623	1,000	0,721	0,754
BUSINESS	COSTS	FR53	Strategically evaluate the viability of implementing the technologies necessary						0,393	0,623	0,754	0,803	0,148
		FR54	Optimization with intelligent methods sharing resource						0,393	0,623	0,754	0,803	0,492
	AVAILABILITY	FR55	Use information correctly to avoid uncertain stops of the machine						0,426	0,000	0,525	0,312	0,754
		FR56	Use stop time indicators to define the planning and programming of maintenance						0,393	0,623	0,754	0,312	0,492
	RESOURCES	FR57	Early availability of the necessary tools based on the preachers performed						0,393	0,623	0,754	0,803	0,492
		FR58	Explore mobility solutions to facilitate the performance of tasks and changes						0,393	0,623	0,754	0,803	0,492
		FR59	Possess specialist with know-how in predictive maintenance						0,393	0,623	0,754	0,803	0,754
	DECISION -MAKING	FR60	Easily and quickly assist in the individual decision -making						0,393	0,623	0,098	0,312	0,967
		FR61	Supply and structure information about the problems encountered						0,393	0,623	0,754	0,230	0,967
		FR62	Use statistical tools for the support of decisions						0,393	0,623	0,754	0,230	0,754

After individually observing each layer of the DTaaS model, giving them 100% importance in the Walking Weights function, the weights were distributed equally among the five layers, that is, with 20% of the total for each one. In this way, it becomes possible to assess which are the FR present in the RAMI 4.0 model, for interoperability in industrial maintenance, that best fit the concepts of the layers of the DTaaS. Table 2 presents the FR that have the greatest importance in a whole for the DTaaS.

5 Conclusion

With the emergence of new technologies, the industrial environment undergoes a transformation again. In this scenario, connected CPS provide benefits such as increased productivity, changes in the workforce profile and increased competitive potential. Interoperability is a crucial element within organizations, enabling communication between two or more systems in order to use shared data and access external functionalities. From this point of view, maintenance has become highly valued and, in order to achieve business objectives, it needs to evolve with technologies in order to absorb new features of I4.0.

According to the results obtained with the evaluative approach between the RAMI 4.0 and the RAMI 4.0 DTaaS layers, Integration and Communication layers present greater "compatibility" with DT layers. All FR contained in the RAMI 4.0 layers were evaluated for their similarity with the definition of the DTaaS layers, with emphasis on the Integration and Communication layers. When it comes to meeting the description of the DTaaS layers, these layers showed a high number of "Very High" relationships between their FR and the DTaaS layers. According to the FR rank, provided by the PROMETHEE II method, it contains all the FR of RAMI4.0 in an order that gives the FR that have the strongest relationships with the DTaaS layers. Of the top ten ranked FR, three came from the Communication Layer and four from the Integration Layer. If we restrict ourselves to the top five ranked FR, where the FR have the most relevant Phi values, it can be seen that four of them belong to these same two layers.

It is suggested that companies that are going to implement RAMI 4.0 DTaaS, prioritize the Communication and Integration functions, which have a higher degree of maturity in relation to maintenance.

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The Implementation of Preventive Maintenance in a Product-Service System (PSS) Business Model

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Abstract. The commoditization initiatives triggered in manufacturing companies the concern with the rigidity of their offers, and the appeal of their offers to their customers, leading to servitization strategies. This research highlights the importance of preventive maintenance, and builds on the extraction and processing of data for a PSS business model. Data from https://www.kaggle.com was used to analyze the performance of a production process with three products with differentiated levels of quality. Data analysis was of exploratory nature using descriptive statistics and Pearson's correlation through, using Python via Google Collaboratory. The main failures were exposed allowing the elaboration of a preventive maintenance plan. Through multivariate statistical analyses, we demonstrate that in a PSS business model, having machine suppliers at your disposal that combine the sale of the item with the provision of predictive maintenance services is a differential that will help to make assertive a preventive d skillful decision, avoiding maintenance unnecessary and waste of time.

Keywords: Business Intelligence · Big Data Analytics · Servitization · Fault Identification

1 Introduction

The concepts of Servitization and Product and Service Systems (PSS) emerged in the 1980s, as a business model that unites the offer of products and services, where the aggregation of the offer of services became a differential, facilitating the acceptance of products existing ones offered [1]. The commoditization of products has made manufacturing companies face great competitive pressure in recent decades. As a result, manufacturing companies began to see the provision of services as a differentiator, adding customized solutions to their portfolio as a way to gain competitive advantage [2]. The inclusion of services has led companies to acquire and exploit external knowledge to achieve business innovation [3].

Management and innovation are directly linked in the implementation of the Servitization business model, where management seeks to capture and develop the knowledge

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necessary for the implementation and commercialization of innovation, and this knowledge must overcome the organization's barriers and be shared with network partners of service provision. The knowledge to be captured and developed encompasses both the technical aspects of combinations between services and products and knowledge about market characteristics, customers, delivery and sales strategy [4]. The evolution of digital technology resulting from the fourth industrial revolution allowed great advances in the integration between physical and digital systems, facilitating the collection of data from different machines located in different locations in the production environment, contributing to the construction of a model of preventive maintenance [5]. The difficulty in capturing and storing Big Data (BD) is overcome by offering technological components (software and hardware) that make such actions possible. To extract information and knowledge for future actions, requiring advanced processing and analysis tools in practically real time [6].

Big Data Analytics (BDA) can be defined as a set of large and complex data that is difficult to be analyzed using traditional data management and processing technologies. Faced with this complexity, Business Intelligence (BI) can be considered an important tool to help BDA with regard to recommending the best data analysis options to accurately predict results [7]. In a preventive maintenance scenario whose objective is the pursuit of machine integrity, the production process and cost reduction, maintenance should be performed only when necessary [8]. Given this context, the following question addressed in this report is presented: What is the importance of servitization for preventive maintenance operations in a PSS business model? Preventive maintenance is understood to be preventive actions carried out through technology and in a timely manner in the production process whose objective is to reduce failures, productivity, profitability, and improve the safety of operators in the production process [9]. Preventive predictive maintenance is understood as preventive actions carried out through technology and in a timely manner in the production process, whose objective is to reduce failures and increase productivity and profitability, also attributing better safety conditions to operators in the production process [9]. The purpose of this research is to demonstrate the importance of capturing and correctly analyzing data using big data analytics tools, considering descriptive and multivariate statistics to identify production or machine failures in a production process in a PSS business model with the objective of create a preventive maintenance plan.

2 Literature Review

The behavior of manufacturing companies has changed in recent years in relation to the portfolio they offer to their consumers; the emphasis has shifted from a product-only offering to one that includes both products and services. This process is called servitization and is also known as a solution. Remote monitoring is enabled by hardware, data collection and analysis are performed by middleware, and presentation tools are in charge of creating the visualization and interpreting it, while big data analysis, digital platforms, information technology and communication and the so-called Internet of Things (IoT) are strong allies in management, control and generation of insights. This ecosystem is widely used and is being recognized as one of the most important resources in the context of servitization [10].

BDA is crucial to influence how decisions are made in companies [11]. BDA refers to datasets and analytical methods used in applications that are so complicated and massive that they require state-of-the-art and distinctive technology for visualization and administration [12]. Agility and resilience are crucial qualities for decision making. In a procedurally rational decision-making and problem-solving technique (also known as comprehensive or analytical), pertinent data is located, gathered, evaluated, and interpreted to help decision makers find the optimal answer based on certain decision criteria specific decision [13]. Preventive maintenance is essential in maintenance management because it safeguards the state of the facilities before they fail, according to [14]. In this regard, it becomes even more crucial to be able to gather, combine, organize and evaluate data in order to gain insights and concepts for the benefit of the business. "It is essential to have an effective strategy that efficiently coordinates the prediction or detection of failures and the maintenance schedule to ensure optimal operation and productivity" [15].

3 Methodology

This report has a quantitative experimental nature, based on data analysis through descriptive statistics and Pearson's correlation. The adoption of the method is justified by the existence of a well-defined problem and information and theories regarding the studied object [16]. Pearson's correlation was used to measure the direction and linear strength between two or more quantitative variables [17].

3.1 Data Collection and Analysis

The analyzed data were collected from the Kaagle website, an online community that brings together a collection of more than 50,000 public domain datasets that can be used as a basis for conducting studies. The data used to carry out this report were collected from a machine during the production process of three products. It consists of collecting and storing ten thousand data points with fourteen features described in columns [18], described as follows:

UID: unique identifier from 1 to 10,000; Product ID: identified by the abbreviations L, M and H, where L means low quality products (50% of all products); M means medium quality products (30% of all products) and H means high quality products (20% of all products). Abbreviations were used as product quality variants and are linked to a specific series number. Air temperature (K): generated through a random path process later normalized to a standard deviation of 2 K around 300 K; Process temperature [K]: generated using a random path process normalized to a standard deviation of 1 K, added to the air temperature plus 10 K; Rotation speed [rpm]: calculated from 2860 W power, superimposed with normally distributed noise; Torque [Nm]: torque values are normally distributed around 40 Nm with Ï$f = 10$ Nm and no negative values; Tool wear [min]: H/M/L quality variants add 5/3/2 min of tool wear used in the process; "Machine Failure" Label: Indicates if the machine has failed at this specific data point so any of the following failure modes are true; Target: whether there is a failure or not and Type of Failure: type of failure that occurred. Data analysis was carried out using the Python

programming language via Google Collaboratory, as it is a high-level, oriented, free and cross-platform language developed in the nineties [19], making it possible to identify the existence of five types of independent failures [20], described and explained as follows.

3.2 Heat Dissipation Failure

Failure arising from heat dissipation when air temperature and process temperature differ less than 8.6k, and rotation speed less than 1380 rpm (Fig. 1).

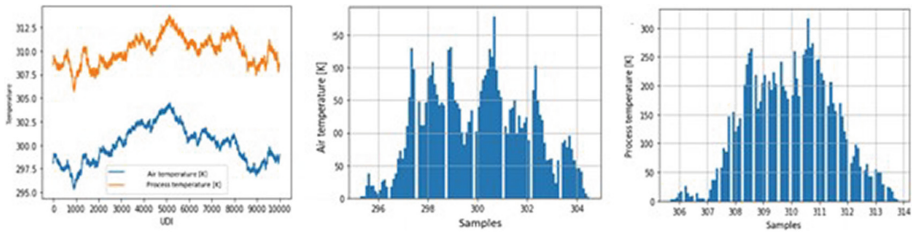

Fig. 1. Histogram of distribution between failure in heat dissipation and temperature. Source: Python.

3.3 Failure in the Production Process

Out of 342 failures, 70% are related to low quality product (L), 23% to medium quality product (M) and 7% to high quality product (H) (Fig. 2). Evidencing that the low quality product (L) requires much more of the production process for representing 5,000 of the 10,000 units produced. Where the most failures occur.

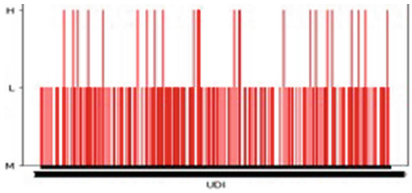

Fig. 2. Failure in the production process by type of product.

3.4 Tool Wear

The tool must be replaced or it will fail between 200 and 240 min. This happened in 120 data points demonstrating the ideal timing of parts and pieces, making it possible to schedule effective maintenance, avoiding unexpected machine stops that affect productivity and incur higher costs (Fig. 3).

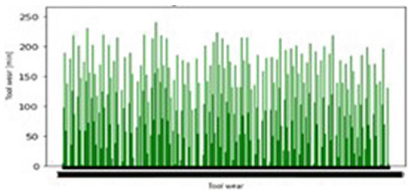

Fig. 3. Tool wear failure.

3.5 Types of Failures

The highest number of failures occurred in the production range between 2,000 to 7,500 units. The largest number of failures are related to problems in heat dissipation (32%), as previously explained in Fig. 2, 27% of the failures are related to energy problems and 22% related to process overload (Fig. 4).

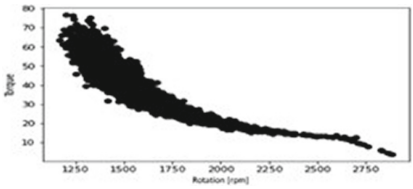

Fig. 4. Types of failures.

3.6 Overload Failure

If tool wear occurs and the torque exceeds 11,000 min Nm for product variant L, 12,000 for M and 13,000 for H, process failure will occur due to overload of the production process. This occurred for 98 data points (Fig. 5).

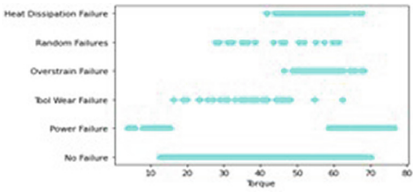

Fig. 5. Rotation x Torque.

3.7 Energy Failure

The product of torque and rotational speed (in rad/s) equals the power required for the process. If the power is below 3,500 W or above 9,000 W, the process will fail, which occurred in 95 data points (Fig. 6).

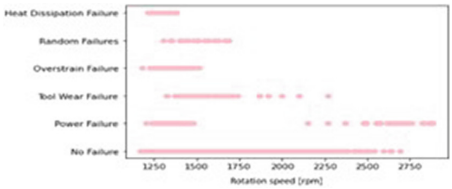

Fig. 6. Energy failure.

3.8 Random Glitch

Random failure occurred at 19 data points, representing 0.1% of the process failing regardless of its operating parameters (Fig. 7).

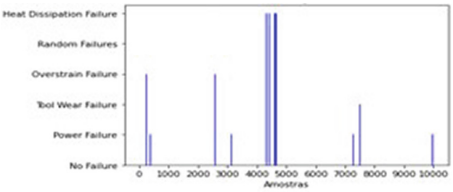

Fig. 7. Random glitch.

4 Multivariate Analysis

Figure 8 demonstrates the correlation between two or more variables and the correlation can be positive or negative [21]. There is a strong and positive correlation of 88% between the variables "air temperature" and "process temperature", explaining problems in heat dissipation. The variables "rotational speed" and "torque" have a strong negative correlation, indicating that with increasing rotational speed, torque decreases. There is a weak and positive correlation between target and failure type.

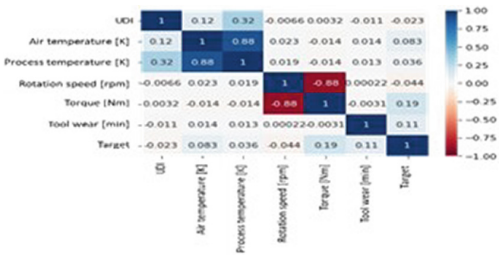

Fig. 8. Pearson correlation.

5 Preventive Maintenance Plan

Scheduled interventions that stop damage and decrease the likelihood of failure while equipment is running are actions that describe preventive maintenance. The recent advances of computerized control, information techniques and communication networks have made possible collecting huge volumes of operation and process's conditions data to be harvested in making an automated Fault Detection and Diagnosis (FDD) and developing more efficient approaches for intelligent preventive maintenance activities, also termed as predictive maintenance (Borgi et al. 2017). Preventive maintenance is crucial in maintenance management because it protects the good state of facilities before they fail. (Razali et al. 2021).

Creating a plan is the first step in putting a preventive maintenance strategy into action. All tasks must be well described and clear, taking into account the necessary tools, components, and staff and even the use of specialized external services. Subsequently, the construction of an inventory containing all the machines will be of great value for the organization and for future corrective or preventive actions. After preparing the inventory, setting up a table containing information about the services and procedures required for each machine is recommended, and then creating a preventive maintenance schedule or a work plan where it is possible to relate each activity of each equipment with each person in charge will bring historical information to managers to adjust or take new initiatives. After these actions, a financial maintenance budget is prepared, containing values for labor, spare parts and costs with specialized services and some amount reserved for surprises that may occur while a machine is dismantled or in case of any unforeseen event., is an essential action for preventive maintenance to be successful. The last step is follow-up. Defined indicators showed whether the plan is being executed as planned or not and needs adjustments. It is an essential action for preventive maintenance to be successful. The last step is follow-up. Defined indicators showed whether the plan is being executed as planned or not and needs adjustments. It is an essential action for preventive maintenance to be successful. The last step is follow-up. Defined indicators showed whether the plan is being executed as planned or not and needs adjustments.

6 Conclusion

In a PSS business, the provision of preventive Maintenance service together with the sale of the machine is a differential in terms of capturing and analyzing data during the production process for decision-making in carrying out maintenance at the appropriate time, avoiding failures and costs. It is important to highlight the import of the relationship between BDA (data collection, storage and analysis) and Business Intelligence (BI), which acts as a facilitator in choosing the best tool to be used for data analysis. Programming in Python for quantitative analysis using descriptive statistics and construction of multivariate analysis using Pearson's correlation proved to be efficient in identifying the main failures that occurred during the production process and highlighting their reasons. Which makes it possible, in a real scenario, to generate insights that can solve specific problems of production failures and improve the preventive maintenance plan.

This research contributes to the theory by emphasizing the methodological issues inherent in the structuring of processes and problem solving and also with the practice

contributing with effective insights on tools for data analysis capable of generating important information that may be useful for the construction of a maintenance plan solid and also suggests choosing suppliers that offer repair services for their products to optimize preventive maintenance steps and preserve important business resources.

As a research agenda, studies are suggested that consider the use of Artificial Intelligence (AI) in conjunction with BDA for real-time data analysis, collaborating with the performance of assertive preventive maintenance, contributing to the gain of the production chain of manufacturing companies. Different analyzes and technologies can also contribute to the creation of new reports that consider the adoption of preventive maintenance in PSS business models.

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Anomaly Detection with a LSTM Autoencoder Using InfluxDB

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Abstract. In the manufacturing industry, anomalies are an unfortunate but inevitable reality. If left unaddressed, they can lead to costly production defects and halted production lines. However, with the rise of Industry 4.0, many industrial machines are now equipped with sensors that can be used to detect anomalous behaviors, allowing for early identification and prevention of defects. Therefore, this study presents a solution using a Long Short-Term Memory (LSTM) autoencoder to detect abnormal behavior in an industrial machine temperature sensor dataset. The algorithm is compared with conventional methods, further demonstrating its capabilities in anomaly detection. Additionally, an implementation architecture is proposed using InfluxDB and Telegraf software, providing a simulated real-world application of the proposed solution.

Keywords: anomaly detection · deep learning · LSTM autoencoder

1 Introduction

Nowadays, the sustainability of the manufacturing industry is increasingly important and the highly competitive landscape makes anomaly detection and error prevention in production paramount for companies. Due to this fact, algorithms are increasingly applied to detect in real-time abnormal behavior to potentially avoid defects, halted production lines, and reduce costs which improve overall efficiency and productivity. There are several methods for such classifications, the traditional ones are statistical based but they do not capture the complex temporal relations present in machine time-series data which deep learning methods can achieve especially a LSTM autoencoder [1] which works by learning to reconstruct normal time-series behavior and determine the reconstruction error to detect abnormal data. This type of deep learning model has proven capabilities in various time-series data such as in the medical field with the ECG (Electrocardiogram) analysis [2] or classroom CO_2 levels [3] and even an anomaly detection for a multivariate dataset of an engine [4]. Moreover, this

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models can achieve real-time anomaly detection [5] which is required for the manufacturing industry.

The current study focuses on the development of an anomaly detection solution for industrial machines based on an LSTM autoencoder and a possible industrial implementation architecture. The LSTM method is compared with a variety of statistical-based and machine-learning methods using an open-source sensor dataset from an industrial machine. Since the goal is to detect abnormal behavior in real-time, the algorithm was implemented in a python script that is managed by Telegraf to continuously analyze new data and ultimately detect anomalies. Finally, a data flow is proposed and tested where the data is stored in InfluxDB.

2 Methodological Approach

In order to develop the anomaly detection algorithm, first a dataset that is representative of an industrial machine is selected. Then, the data is processed followed by exploratory data analyses (EDA) to extract relevant characteristics. Moreover, the dataset is applied to different statistical-based models and machine-learning models, and the target LSTM autoencoder to compare their ability to detect anomalous behavior on the dataset. Finally, the model is implemented in a simulated real-time anomaly detection. The generalized process described is represented in Fig. 1.

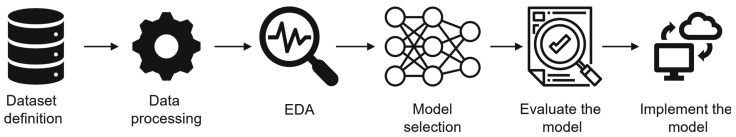


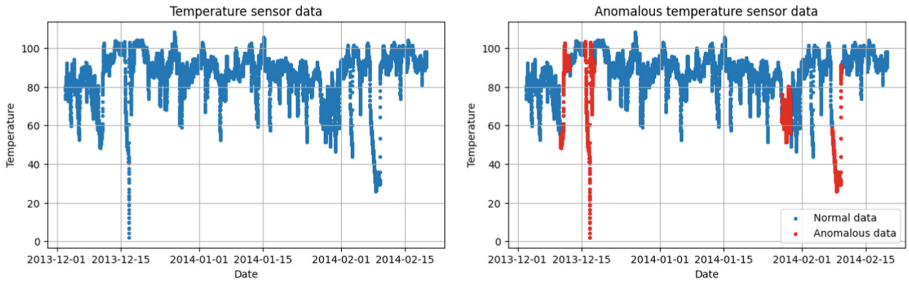
Fig. 1. Pipeline of an anomaly detection system.

2.1 Dataset

The dataset should be a good representation of an industrial machine with some anomalous labeled data to apply the models, so the Numenta Anomaly Benchmark (NAB) dataset [6] was selected which is composed by data of a real-world temperature data from a sensor of an internal component of a large industrial machine. This data is shown in Fig. 2a.

2.2 Pre-process Data

The initial dataset was unlabeled but with the information of the time periods of the machine abnormal behavior we labeled these datapoins as anomalous as presented in Fig. 2b.



(a) (b)

Fig. 2. Dataset of the temperature sensor (**a**) unlabel data (**b**) labeled data.

2.3 EDA

The data analyzed is obtained from a temperature sensor on a machine that runs continuously. It is observable that the data fluctuates around a mean value that may be due to the machine's duty cycle or external temperature. Therefore, and supported by Fig. 3, the sensor data (without anomalies) approximates to a normal distribution but with some skewness. From Eqs. (1) and (2) we calculated a 88.36 mean and a standard deviation of 9.79.

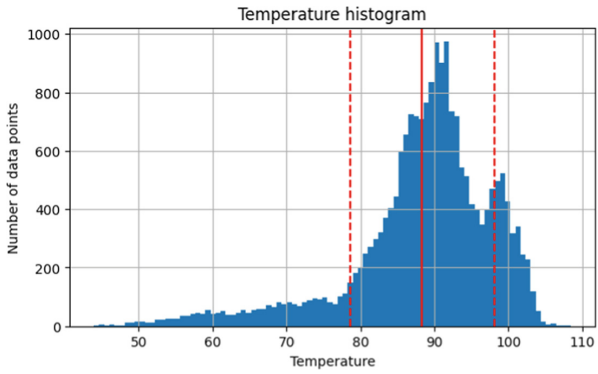


Fig. 3. Histogram of the normal temperature data.

$$\mu = \frac{\sum_{i=1}^{n} x_i}{n} = 88.36 \tag{1}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} = 9.79 \tag{2}$$

Another important characteristic to analyze is the correlation of the temperature data to their past values so the autocorrelation function (ACF) was analyzed which gets the correlation between a variable and a lagged version of itself. It is useful to identify any patterns or trends in the data. Figure 4 shows high values of correlation to the lag temperature data. This means that a model to detect anomalies can use the past values to make inferences.

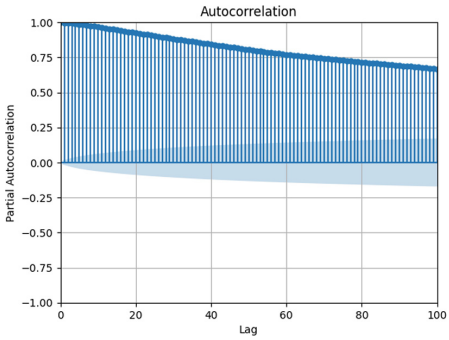


Fig. 4. Autocorrelation function for the temperature sensor dataset.

3 Model Selection and Evaluation

Before applying any algorithm, the dataset was divided into a train and test set with 30% and 70% of the data respectively. As observed before, the data is highly correlated with past values so this division was done with continuous data and without shuffling. Afterward, different statistical-based and machine learning-based algorithms were applied and evaluated to serve as a baseline to the target LSTM network in order to efficiently detect anomalies in the industrial machine. The metrics used to evaluate the models were precision, recall, and F1-score that were calculated using the Eqs. (3), (4) and (5). The F1-score was given more importance since it combined the other 2 metrics and the dataset is imbalanced.

$$Precision = \frac{True\ Positive}{True\ Positive + False\ Positive} \tag{3}$$

$$Recall = \frac{True\ Positive}{True\ Positive + False\ Negative} \tag{4}$$

$$F1\ Score = 2 \times \frac{Precision \times Recall}{Precision + Recall} \tag{5}$$

Initially, two statistical-based methods of variance thresholding were applied since the data approximates a normal distribution. First, the mean and standard deviation were calculated for the train normal data. Then, the first method (Variance 1) used the 3 standard deviations rule as the threshold and the other

(Variance 2) recursively found the best threshold to get the best F1-score. The first method achieved an F1-score of 0.655 and the second 0.750.

Additionally, a machine learning-based algorithm for anomaly detection called isolation forest [7] was tested. This method works by recursively splitting the data randomly into 2 parts to eventually isolate individual observations. The shorter the path in the tree to an observation, the more abnormal it is considered to be. This method showed an F1-score of 0.733.

Finally, a novel LSTM autoencoder network [8] was applied to learn to reconstruct the data from defined time periods, and then the error was calculated and a threshold was selected for anomaly detection. The window of data for reconstruction was selected as 108 data points which corresponds to 9 min. The architecture of the autoencoder which is represented in Fig. 5 includes 1 LSTM layer and 1 dropout layer for the encoder and decoder. The dropout layer prevents overfitting and improves the model's generalization capacity. Also, to train the model we used as the loss function the Mean Absolute Error (MAE) and the Adam optimization algorithm.

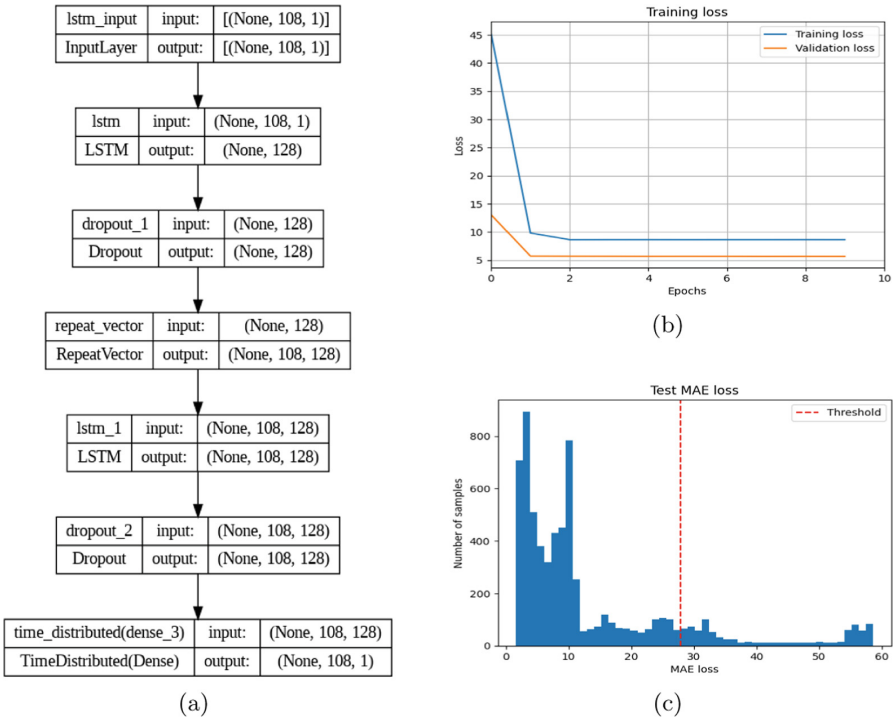


Fig. 5. LSTM autoencoder (**a**) architecture (**b**) training loss (**c**) test MAE loss.

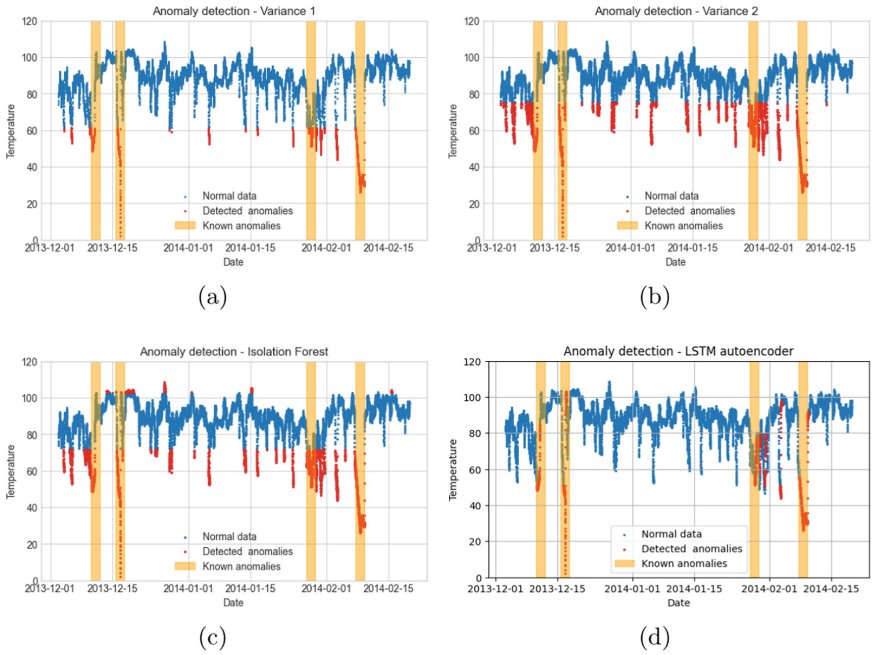


Fig. 6. Anomaly detection for the entire dataset. (**a**) Variance 1 (**b**) Variance 2 (**c**) Isolation forest (**d**) LSTM autoencoder.

After training the model, the error threshold was selected as the maximum train MAE. The result of applying this threshold to the test set was a F1-score of 0.885 which is the highest of the methods analyzed.

Table 1. Models performance comparison.

	Variance 1	Variance 2	Isolation forest	LSTM
F1-score	0.655	0.750	0.733	0.885
Precision	0.681	0.622	0.624	0.825
Recall	0.631	0.944	0.886	0.954

By analyzing the metrics evaluated in Table 1 we conclude that The LSTM autoencoder has the best precision and recall, and by far the best compromise between the two metrics with a higher F1-score. Additionally, Fig. 6 shows anomalies detected with the different methods compared to the regions where are the known anomalies. It's possible to conclude that the LSTM method is the only method that detects well the regions where the industrial machine presents problems demonstrating that this deep learning method reproduces well the temporal dependency of the data. The main drawback of the other methods is the

frequent anomaly detection when the machine is behaving normally which in the industrial context can be contra-productive because it can stop production lines, increase stop time and costs.

4 Model Implementation

Furthermore, an implementation was developed to detect abnormal data in real-time using the previously selected algorithm. The InfluxDB and Telegraf were utilized as the software for acquiring, storing, and analyzing the data, using an architecture illustrated in Fig. 7. The algorithm was implemented in a Python script that Telegraf runs continuously, which gathers sensor data and processes it to detect anomalies. The data used to test this architecture was the same dataset used to trained the LSTM model.

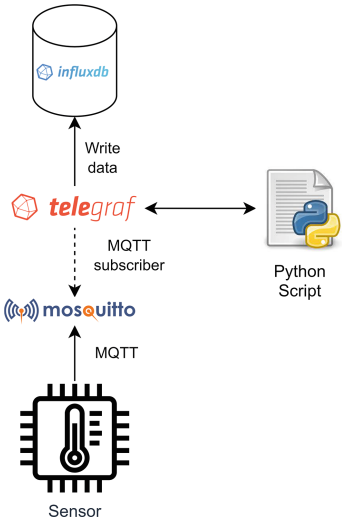


Fig. 7. Architecture of the data acquisition, process and storage of the anomaly detection process.

5 Conclusion

This study revealed that using an LSTM autoencoder is effective in detecting anomalies in time-series data, particularly when there is high autocorrelation of the data. This is particularly relevant for industrial manufacturing, where undetected errors and machine defects can have significant consequences in production quality and costs. Moreover, the LSTM autoencoder's ability to reconstruct normal data makes it capable of detecting previously unseen abnormal behavior, resulting in better performance than conventional algorithms, as demonstrated

by its higher F1-score. Although the study focuses on a specific dataset, this solution can be applied to other use cases with the retraining of the LSTM model. Additionally, this study also demonstrates the potential for real-world implementation by using the InfluxDB and Telegraf software.

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Selecting the Method for Setting the Calibration Intervals of Metrological Devices

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Abstract. Nowadays, and regardless of the activity sector, ensuring product quality and customer satisfaction is the main focus of organizations. In this sense, and since measuring and monitoring equipment (MME) are essentially used in product conformity assessment, an efficient management of the calibration process of these instruments becomes crucial for organizational performance. Although there are several methods for defining calibration intervals, there is a lack of guidelines for selecting the most appropriate method for each situation. Therefore, this paper has as its main goal to present an approach to assist in the management of calibration intervals for MME. This approach is intended to identify, considering a set of factors associated with the characteristics of the measuring instrument and its condition and use environment, which method for setting calibration intervals has the greatest potential for each case. A case study was performed, using data from a set of measuring instruments of an organization that produces cork stoppers, which allowed conclusions to be drawn for each method under study. In the end, with the development and application of the approach, it was concluded that an appropriate choice of the method for defining calibration intervals allows a more efficient management of the measuring and monitoring equipment, in terms of aptitude and adequacy of its metrological capacity within the productive sector.

Keywords: Calibration · Optimal Calibration Intervals · Methods for defining calibration intervals

1 Introduction

To meet the ever-increasing expectations of customers, product quality assurance is crucial in every company. Thus, to ensure the quality of products, organizations seek the reliability of their measurement systems, since measuring equipment are used to assess product conformity and to control and monitor production processes, making the management of this equipment an important factor for organizational performance. Consequently, the MME used shall be calibrated and monitored on a regular basis.

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However, if an adequate periodicity of calibrations is not determined, uncertainties in measurements may increase, which, consequently, may affect the main objective of organizations. By optimizing the period between calibrations, unnecessary calibrations are avoided, there is control of uncertainty as well as measurement reliability, and risks and costs are limited.

In the literature, several methods are proposed for the definition of calibration intervals. However, depending on certain factors associated with the characteristics of measuring equipment and its condition and use environment, the methods suggest different values for the calibration interval, and the selection of the most appropriate method may be conditioned by the impact of that set of factors.

Consequently, it is necessary to define an approach that helps in the decision-making about the method with the highest potential for each case; i.e., an approach that helps in the management of the calibration intervals. This approach is the main goal of this work and it will use, as inputs, data that make it possible to assess the factors, in order to select the most appropriate method for each case.

The paper is organized as follows. The next section presents the literature review, followed by a section presenting the developed approach. Subsequently, the application and validation of the approach are made and, finally, the main conclusions reached are described.

2 Literature Review

2.1 Calibration Intervals

Calibration is a confirmation process used to verify the operational status of any measuring instrument and to characterize its metrological properties, which suffer degradation, requiring periodic application of calibration procedures [1].

Although regular calibrations guarantee the quality of the measurements, if the interval between calibrations is not adequate, unnecessary costs will be incurred [2]. In this way, to reduce the risk of errors – more prone at longer intervals – but also the costs associated with the calibration process, normally higher at shorter intervals, it is fundamental to determine optimal calibration intervals. Optimal calibration intervals are established to ensure that measuring equipment are operating within tolerance limits at the time of use, between adjacent calibrations [2]. Considering this, the main motivations to study the calibration frequency are the direct impacts it may have on costs and on the preservation of the metrological reliability of measuring equipment [4].

For the identification of the appropriate calibration interval, several methods can be applied (such as the Automatic Adjustment method, the Control Chart method, the "Black-Box" method, and the statistical approaches), and typically the method with the most potential can be derived from a combination of several techniques, depending on the quality objective, calibration and maintenance budgets, risk management criteria, and the potential return on investment [3].

In the context of defining calibration intervals, there are three relevant papers to be mentioned. Oliveira and Jesus [4], who propose a modified SWOT analysis to select the most appropriate calibration interval method, Portella and Frota [5], who propose

a metrological parameter to calculate calibration interval and Pashnina [6], who used ultrasonic to illustrate the calculation algorithm, which was developed based on the general guidance on the risk-based approach to maintenance. If on the one hand, Portella and Frota [5] and Pashnina [6] propose a method for calculating the interval; on the other hand, Oliveira and Jesus [4] propose something that resembles the one intended in this paper. In Oliveira and Jesus [4], the authors proposed a method that compares the methods for defining calibration intervals and selects the method with the highest potential for each situation. In their study, four methods for defining calibration intervals were compared taking into account a set of 13 criteria distributed into strengths, weaknesses, opportunities and threats and to which a weighting was attributed. This method relates exclusively to intrinsic characteristics of each method (namely, facility of application, time of sample collection, robustness, etc.), excluding the premise that the selection of the most appropriate method is conditioned by the applicability, expressiveness and impact of a set of factors related to the characteristics of the MME, as well as to the condition and environment of use. This, consequently, points to the relevance of this work, which aims to assist in the identification of the most appropriate method for each situation, through an approach that takes into account the intrinsic characteristics of the methods and a set of factors related to the MME characteristics, condition and environment of use. What differentiates this work from those presented in the literature, is the fact that it combines the characteristics of each method with a set of factors related to the MME characteristics, condition and environment of use, which makes the selection of the method for defining calibration intervals more conscious and reliable.

3 Development of the Approach

Among the various methods and procedures proposed in the literature for estimating optimal calibration intervals, this work considers three different statistical approaches – Adjustment of the interval by drift; Adjustment of the interval based on the last three calibrations; and the Schumacher Method. These methods have been selected to constitute the approach since methods based on statistical analysis have gained increasing prominence, especially when used in combination with appropriate software.

In order to understand in which situations each method is more appropriate than the others, a comparative analysis of the three methods was performed, through the analysis of data from an organization's equipment. Thus, in order to carry out a comparative analysis of the methods, data including the verification/calibration history, the current verification/calibration interval and the Acceptance Criteria (AC) from 30 measuring equipment (randomly chosen) of a company dedicated to the production of cork stoppers was used. It is important to mention that these instruments are only submitted to internal verifications, with the exception of Medcork[1], which is submitted to external calibrations. Verifications occur quarterly and calibrations annually. These data together with the calculation formulas of each method allowed the understanding of what the response of each method would be in relation to the equipment calibration interval. The three methods were applied to each equipment and in the end, the changes suggested by each

[1] Medcork is an intelligent and integrate system, fully automatic, used for the measurement of length, diameter (dimensions), weight and moisture of cork stoppers.

of them, for each equipment, were obtained. Consequently, generic but also concrete conclusions about each method were drawn. So, it was concluded that the drift-based interval adjustment method is the riskiest of the three methods, not considering the previous verification/calibration interval. The fact that it is quite risky is not advisable because suggesting very large calibration intervals is not taking into account increases in the drift caused by factors not intrinsic to the equipment, making it very likely that at the end of the interval the AC is not being respected. On the other hand, the other methods are more cautious, with a slow convergence to the optimal calibration/verification interval. Thus, in cases where the initial interval is ill-defined – too large or too small – these methods will have more difficulty and take longer to indicate the optimal interval.

Consequently, it can be concluded that in situations where the equipment is not very critical in terms of use and quality characteristics, the Schumacher's method is the most appropriate; and that in more critical situations the fitting method based on the last three calibrations is the most appropriate. It was also possible to verify through this comparative analysis, comparing the current calibration/verification intervals and those suggested by the three methods and analyzing the history of verifications/calibrations, that for non-compliant equipment the methods suggest a reduction of the interval, and for compliant equipment an increase.

Besides this, a cost analysis was also performed. From the results obtained by applying the methods to the MME together with data relating to the time available for equipment verifications, the cost of manpower and the price charged for external calibrations, the gains that the organization would have with the adoption of one of these methods were estimated.

Although the methods have intrinsic characteristics that distinguish them (mentioned above) when deciding which method to apply other factors should be considered, as they also influence this decision. It is the combination between the conclusions drawn from the comparative analysis performed and a set of factors (mentioned bellow) that allows determining which method has the greatest potential for each situation and equipment. So, in order to understand, according to certain factors, which method is the most appropriate, a decision tree was developed. To this end, the set of criteria (factors) and classes (methods), that made up this tool, were defined and presented in Fig. 1. The above methods were considered for two temporal measurement units – calendar time and time "in use". This division was made taking into account the criterion "ease of monitoring measurements", which explains why the division was necessary. The definition of the criteria was based on the importance that each one has for the decision to be taken.

Frequency of use and Ease of monitoring measurements – Frequency of use is an important criterion since it will determine whether the method selected should be governed by calendar time or by "time in use" – which can be expressed either in number of uses or in time of use. This criterion should be complemented by the criterion of ease of monitoring measurements to understand whether the time "in use" should be considered. This is because in cases where monitoring the measurements is not automatic, it is not viable to use "time in use" due to the unnecessary costs it incurs.

Importance of use – Depending on the workstation in the production process where measuring equipment is used and the quality characteristic that the instrument has to measure (whether it is more or less important for the quality of the end product), the

measuring equipment will show different criticalities of use. Thus, the more critical in terms of use the instrument is, the more rigorous its control should be.

Equipment stability – The stability of measuring equipment is an important criterion insofar as a more unstable instrument requires more regular and rigorous control.

Calibration costs – The costs involved in the calibration and/or verification processes have a significant weight when deciding on the frequency of these procedures. It is necessary to balance the frequency of calibration/verification considering the costs involved, which makes costs an important criterion.

In this work, only three methods were analyzed, which are only applied when equipment is treated individually and if there is a history of calibrations/verifications. Consequently, for the development of this decision tree, only situations where there is a history of calibrations/verifications and cases where, with respect to the type of management policy, the equipment is treated individually were taken into account.

Hence, once the conditions for the development of the decision tree were met, it was built and presented in Fig. 1.

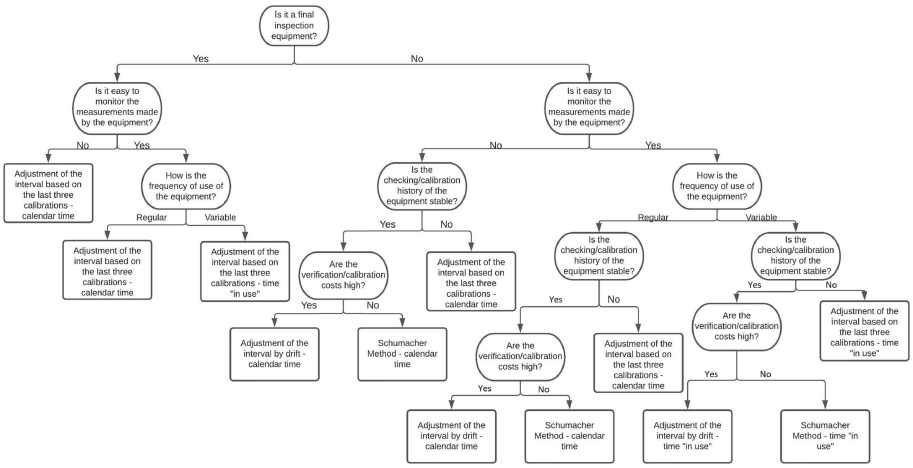

Fig. 1. Decision tree on which method is the most appropriate.

4 Implementation and Validation of the Approach

The approach was applied to a real case so that it could be validated – the case study used in the comparative analysis of the methods.

For this, and in order to classify the MME of the organization according to the factors that constitute the decision tree, further information about each type of equipment was collected, namely information regarding the stability of each one, the susceptibility to the environmental conditions where they are used, the criticality and frequency of use and, finally, the costs associated with the calibration/verification process of some of the

equipment. Thus, three of the equipment – a comparison table, a caliper and a Medcork – that made up the initial sample were randomly selected, subjected to this classification, and, consequently, assigned the method with the highest potential, according to Fig. 1.

The caliper and the comparison table represent non-critical situations, i.e., they are equipment whose importance of use is reduced, they are stable and present reduced calibration costs. Therefore, according to the developed approach, Schumacher's method is the most suitable. On the other hand, Medcork represents the most critical situations, i.e., situations in which the equipment presents a high criticality of use. Consequently, the most appropriate method for this case is the Adjustment of the interval based on the last three calibrations method. In all three cases, the methods should be governed by calendar time.

Once the methods were assigned and applied to the equipment, the company approved the results, which showed the suitability of the methods for each case, taking into account the characteristics of the equipment, condition and environment of use. It was verified that through the new calibration intervals, proposed by the assigned methods, the company could reduce the costs related to these procedures, without jeopardizing the quality of the measurements, i.e., according to the cost analysis previously performed, there would be an annual cost reduction of 2,5€ in the cases of the comparison table and the caliper; and a reduction of 18,18€ in the case of the Medcork.

5 Conclusion

This paper describes an approach that helps decision making about the method, for defining calibration intervals, with the highest potential for each case, i.e., an approach that assists in the management of calibration intervals. This approach, which includes three methods – the interval fitting method based on the last three calibrations, the Schumacher's method and the drift-based interval fitting method –, has as inputs a set of factors that influence the selection of the most appropriate method for each case – importance of use, frequency of use, ease of monitoring measurements, equipment stability and calibration costs.

Consequently, this approach, compared to the studies published on this theme, presents something new, i.e., besides considering the intrinsic characteristics of the methods under study, it combines those characteristics with a set of factors related to the characteristics of the MME, as well as with the condition and environment of use.

For its development, a case study was used – company dedicated to the production of cork stoppers – which allowed conclusions to be drawn regarding each method under study. In the end, these conclusions together with the selected factors made it possible to understand in which concrete situations each method is better than the others.

Hence, it was concluded, through the application and consequent validation of the approach, that besides being easy to apply and quick to respond, an adequacy of the methods assigned to the case study equipment was verified. Furthermore, it was also concluded that the application of this approach allows an efficient management of the MME and respective calibrations, besides providing other advantages, such as the reduction of costs associated to these procedures.

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Production

Identifying Dependency Relationships Between Events in Production Systems

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Abstract. Industry 4.0 is directly related to the digital transformation of organizations. One of the main characteristics of this transformation is the ability to analyze and manage data to obtain relevant and previously unknown information from it. Specifically, in the context of operational risk management, an efficient analysis of the data that typically come from occurrence records, can support decision-making. This paper presents a new algorithm to identify dependencies between events in productive environments, such as equipment failures, defects, or safety and environmental incidents, supporting the decision-making process in the context of analyzing and managing operational risks. The algorithm was developed based on association rule mining algorithms, then tested with data from a Portuguese metalworking company, and finally validated. The test results show that the developed algorithm is capable of identifying dependencies, which have to be confirmed by specialized staff to conclude if they are causal relationships.

Keywords: Association Rule Mining · Data Analysis · Frequent Pattern Mining · Risk Management

1 Introduction

The fourth industrial revolution or Industry 4.0 is characterized by the ability of organizations to take advantage of technological development for industrial applications [1]. The integration of information and communication technologies with the various components of production systems results in a huge amount of data. Therefore, new technologies need to be used in the best way to process data efficiently and thereby improve the management of processes, including the process of operational risk analysis and management [2].

Operational risk analysis and management focus on the uncertainty inherent to the execution of activities that an organization needs to carry out to achieve its goals [3]. In most companies, operational risk is the most common form of risk and should be

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seen as the most dangerous and the most difficult to understand because it results from losses related to failed or inadequate internal processes [4]. Thus, inefficient operational risk analysis and management can lead to the loss of customers, limitation of productive efficiency, and inefficient resource allocation [5].

One way to improve operational risk analysis and management is to discover previously unknown information to improve decision-making. For this purpose, the application of association algorithms can be a useful tool, because they are based on a technique called Frequent Pattern Mining, which is characterized by the ability to locate the repeating relationships between different items in a data set and represent them in the form of association rules. As an example of its usefulness, Wang *et al.* [6] presented a data-focused approach based on association algorithms and frequent pattern mining that allows the extraction of relevant information from historical records, such as association rules between keywords of each record and their conditional probability. As shown in a literature review carried out by Chee *et al.* [7], several algorithms have been developed over time to find frequent patterns, however, they assume that the data set must be explicitly in the form of transactions, restricting its application variability and increasing the possibility of losing potentially relevant relationships in certain scenarios. Antomarioni *et al.* [8] propose an approach to support the analysis of failures in production processes, using an association rule mining algorithm, but which presents the limitation of not considering the temporal dimension to extract association rules.

This paper presents a new algorithm that aims to relate disruptive events in production systems related to different areas such as quality (i.e., defects), safety (i.e., work accident), environment (i.e., gas leak), production (i.e., production stoppage) or maintenance (i.e., machine failure). This algorithm was developed based on existing association rule mining algorithms to achieve the intended results and overcome the aforementioned limitations, calculating similar metrics. The methodology used was CRISP-DM, explained in detail by Huber *et al.* [10]. The need to relate events from different areas arises since sometimes these events have a common root cause and therefore must be treated collaboratively by the various departments [9]. For instance, if the occurrence of a non-compliant product ends up being related to work accidents may indicate that there is a common and potentially unknown root cause for these events. Thus, realizing that two events are related makes it possible to approach them more effectively.

This paper is organized as follows: Sect. 2 presents the proposed algorithm to identify relationships between events, Sect. 3 includes the testing and validation of the algorithm using real data from a Portuguese metalworking company and Sect. 4 refers to the conclusion and future work.

2 The Association Rule Mining Algorithm

The proposed algorithm was developed from existing association rule mining algorithms. To overcome the fact that the dataset is not in the form of transactions, time windows are considered to search for possible dependency relationships.

The algorithm is triggered by the introduction of a dataset, containing the records of events and their times of occurrence (t_oco), combined with a user input regarding the analysis window (u_input) that he considers appropriate for the algorithm to find

possible dependency relationships (e.g., 5 days or 100 000 units). That is, for each instance (event) of a given dataset, the algorithm will try to find "who" (previous events) has the potential to have caused it considering the window defined by the user.

With this purpose, the algorithm was designed to perform a set of steps to identify possible relations between two events, an antecedent and a consequent event, and count their number of occurrences to identify an association rule depending on the value of the calculated metrics, as shown in Fig. 1.

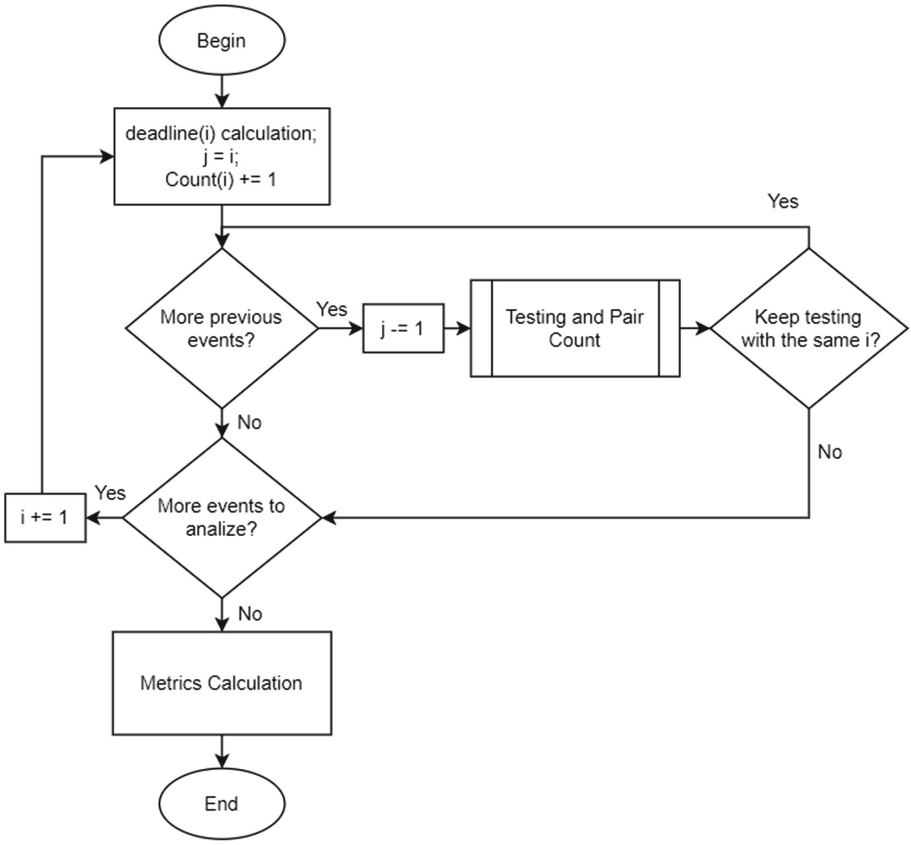

Fig. 1. Algorithm flowchart

For a given row of the dataset (event occurrence), the associated event is considered as the event under analysis (i) and its count is incremented by one (count(i) += 1), representing the number of times the event was registered in the dataset.

The calculation of the deadline (t_lim) for the event under analysis is then performed, representing the moment when a given event can no longer produce effects on others.

$$t_lim = t_oco + u_input \tag{1}$$

In the next step, it is checked which of the previous events (j) has the potential to have triggered the event under analysis (i).

To this end, a reverse search is started, testing the previous events based on three main conditions, where all of them must be satisfied for the pair count to be incremented.

1. The previous recorded event must have a deadline (t_lim) greater or equal to the time of occurrence (t_occ) of the event under analysis, ensuring that the former has the potential to have triggered the latter, being potentially considered the antecedent event.

$$t_\mathrm{lim}(j) \geq t_oco(i) \tag{2}$$

   If the result of this condition is false, the test for the event under analysis (i) is stopped, advancing to a new event (i += 1) if it exists.
2. To be considered an antecedent event, the previous event must be different from the event under analysis.

$$event(j) \neq event(i) \tag{3}$$

   If this condition is not checked, the test for the event under analysis (i) is stopped, advancing to a new event (i += 1) if it exists. Additionally, this previous event record is put into inactive mode by using a binary variable "flag" that by default presents the value of 0 and assumes, in these cases the value of 1 (Flag (j) = 1). Its usefulness is explained in condition 3.
3. The previous event record must be active at the time of the test to be potentially considered the antecedent event.

$$Flag(j) = 0 \tag{4}$$

As indicated in the second condition an event record may become inactive, causing it not to be considered thereafter. The goal is to avoid counting the same pair of events more than once based on the same previous event record. If this condition is not checked, the testing proceeds with the same event (i) as the possible consequent event.

With the three main conditions tested and checked the count of the pair (j → i) is incremented by one, representing the number of times that two given events were recorded in a time interval less than or equal to the analysis window.

However, a fourth condition has been defined indicating that a particular pair will also be counted in the opposite direction (i → j) in the case when both events occur at the same time since it is impossible to know which of the events is the antecedent.

4. That is, if the previous recorded event has a time of occurrence (t_occ[j]) equal to the time of occurrence (t_occ[i]) of the event under analysis.

$$\mathrm{t_oco(j)} = \mathrm{t_oco(i)} \tag{5}$$

   In the last step for each of the pairs, metrics are calculated to provide the end user with greater knowledge about them.

- **Confidence:** Two metrics are considered: C1 and C2. Both are conditional probabilities.

$$C1 = \frac{Count(j \rightarrow i)}{Count(j)} \tag{6}$$

$$C2 = \frac{Count(j \rightarrow i)}{Count(i)} \tag{7}$$

C1 means how likely event i occurs after event j (within the time window), given that event j has occurred. C2 means how likely event j occurs before event i (within the time window), given that event i has occurred. They indicate the level of certainty that the pair presents.

- **Average time:** Displays to the end user the average time that normally occurs between the two events of a given pair, indicating the time he may have at his disposal to prevent the consequential event from occurring.

$$\overline{T}_{j \rightarrow i} = \frac{\sum (t_{oco(i)} - t_{oco(j)})}{Count(j \rightarrow i)} \tag{8}$$

3 Testing and Validation

To test and validate the developed algorithm, data from a Portuguese metalworking company were used, specifically the history of corrective maintenance actions related to a machine tool from a progressive stamping process, whose main components are punches and die inserts. The data were collected through forms filled in by machine operators and maintenance technicians, during a period of approximately a year and a half. The records are related to failure occurrences, where each failure is a specific damaged component through wear. Thus, in this case, each event is identified by the name of the damaged component.

Analyzing the data associated with the machine tool, 109 occurrences were recorded during the production of 6 191 466 parts. The data were then prepared to serve as input to the algorithm and an analysis window (user input) of 100 000 production parts was defined. Additionally, to form association rules and increase the probability of a given pair representing a dependency relationship between two events a filtering condition was defined.

$$(Count \geq 10 \cap (C1 > 90\% \cup \mathrm{C2} > 90\%)) \tag{9}$$

Subsequently, the algorithm was executed, and the results presented in Table 1 were obtained.

The evaluation from a computational and algorithmic perspective was positive since the algorithm can identify possible dependency relationships between events of a given data set.

As an example, through the output of the algorithm, the user can obtain the following information about the pair (4H → 20D):

- 4H can be the cause of 20D.

Table 1. Testing Output

Pair	Count	$\overline{T}_{j \to i}$	C1	C2
20D → 4H	18	5490	40.9	100
4H → 20D	17	84	94.4	38.6
20C2 → 20C1	10	8647	90.9	66.7
20D → 20C2	10	21897	22.7	90.9

- The occurrence of this pair, considering an analysis window of 100 000 production parts, was checked 17 times.
- On average, 20D occurs 84 production parts after 4H has occurred.
- 94.4% of the time 4H was registered, 20D was recorded during the production of the next 100 000 production parts.
- 38.6% of the times 20D was recorded, it was after the 4H registration, based on a 100 000 production parts analysis window.

The results presented were also analyzed and evaluated by the company's technical managers. The objective was to understand whether the pairs of events proposed by the algorithm are somehow representative of what happens daily in production regarding machine wear and failure.

In this sense, the following conclusions were drawn over the pairs suggested by the algorithm:

- **(20D → 4H/4H → 20D)** – This combination of events has been suggested both ways by the algorithm. This is because they occur or at least are recorded at the same time, leaving the question of which of them will be the trigger of the other. However, from a procedural and mechanical perspective, the pairs presented for this tool should be in the direction of "4 → 20", therefore the pair considered as correct and that makes sense in practice is the (4H → 20D), whereas 4 is a die insert and 20 is a punch, and it will make more sense to be a damaged matrix to damage the puncture and not the other way around.
- **(20C2 → 20C1)** – They are two components that work in parallel and perform the same function under identical conditions, when one of them fails is common the other also fails. Thus, it was deduced that this pair of events presents an association relationship, but not causality.
- **(20D → 20C2)** – Initially, no physical justification was found for the pair, so it seemed to make no sense. Since these are two punctures that perform apparently unrelated operations at different stations. It may eventually be reevaluated in the future regarding a temporal relationship (time between failures) if the algorithm continues to suggest it. However, the low confidence value reinforces the pair's lack of logical sense.

With the test performed it was noticed that the result of the algorithm can be conditioned by the user's choice regarding the time window of analysis, which can be seen as a limitation.

Also, the pairs presented by the algorithm have a suggestive character since they always require final validation by the user and the relationship between two events of a given pair may come from a causality (4H → 20D), an association based on work conditions (20C2 → 20C1), or merely temporal (20D → 20C2).

4 Conclusions

The ability to use data to support decision-making should be seen as the new standard for the future of organizations. In operational risk analysis and management obtaining previously unknown information regarding how events relate to each other can improve resource allocation and increase productivity.

Thus, in this article, an association algorithm was developed capable of suggesting dependency relationships between two events, introducing a new way to apply association algorithms, where it is not necessary to have transactional databases as input thus allowing the inclusion of the temporal dimension in the discovery of frequent patterns. More specifically, with the application of the proposed algorithm, the end-user is presented with a set of pairs of events, which should be analyzed to understand whether they make sense and, based on this conclusion, make it possible to make decisions efficiently.

The test performed with the data from the Portuguese metalworking company allowed an understanding of the limitations and the algorithm validation since it was able to find some relationships between the recorded events. Later, the algorithm is intended to be implemented in collaborative software to be used in the most diverse industrial scenarios.

For future work, the objective is to mitigate some of the limitations of this algorithm as its subjective adjacent to human intervention in the choice of the analysis window and the suggestive character of the pairs presented.

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How to Prioritize Replenishment Orders in Demand Driven MRP: A Simulation Study

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Abstract. Demand Driven Material Requirements Planning (DDMRP) assumes that a production order is generated for replenishment when the inventory position, given by the net flow equation, is below a given level. Literature on this production planning and control system suggests prioritizing open orders on the shop floor based on the inventory buffer status. However, the performance of buffer-oriented priority dispatching largely remains unknown. Using discrete event simulation, this study suggests that buffer-oriented dispatching based on the net flow equation outperforms due date-oriented dispatching rules and first-come-first-served. The performance impact depends, however, on the reorder quantity associated with the production orders. These results have important implications for industrial practice.

Keywords: Production Planning and Control · DDMRP · Priority Dispatching

1 Introduction

Flexibility, efficiency, and effectiveness are important competitive requirements for industrial companies to survive in the current market environment characterized by volatility, uncertainty, complexity, and ambiguity (VUCA). Traditional Production Planning and Control (PPC) systems, such as Materials Requirements Planning (MRP), which are still widely used in industry, were not developed to operate properly in this context. Demand-Driven Material Requirements Planning (DDMRP) can be seen as a PPC system that can respond to these new challenges.

Given its importance, a large literature on DDMRP recently emerged (e.g., Miclo et al. 2019; Lee and Rim 2019; Dessevre et al. 2019; Thürer et al. 2022 and Azzamouri et al. 2022). Most of this literature focuses on comparing DDMRP with alternative PPC systems. Only a subset focuses on its actual parametrization. For example, Lee and Rim (2019), focused on different methods to calculate safety stock levels, Azzamouri

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et al. (2022), assessed the impact of continuous and periodic buffer replenishment, and Dessevre et al. (2019), studied the dynamical adjustment of the decoupling lead time (DLT).

One important parameter that is widely neglected is the rule used to prioritize replenishment orders on the shop floor. The literature suggests that these should be prioritized based on the inventory buffer status. But no study to date assessed the actual impact of the choice of the dispatching rule on DDMRP performance. As a contribution to fill this gap, this study uses discrete event simulation to assess the performance of different dispatching rules in a multi-stage assembly system controlled by DDMRP, where demand for product parts depends on the market-driven demand for end products. Using different control factors and performance measures, we seek to identify which priority dispatching rules to use in this omnipresent industrial scenario, which is of high practical relevance.

The remainder of this study is structured as follows. Section 2 shortly introduces DDMRP and the dispatching rules evaluated. Section 3 presents the simulation model used to evaluate performance before the results are presented and discussed in Sect. 4. Finally, conclusions are summarized in Sect. 5, where managerial implications, limitations, and future research directions are also put forward.

2 Background

DDMRP is a multi-echelon planning and execution system introduced by Ptak and Smith (2011, 2016) that combines elements of MRP, Kanban, and Drum-Buffer-Rope (DBR) to protect and promote flow. DDMRP seeks to reduce delivery times while aligning production with demand. It has five sequential components or phases (Ptak and Smith 2016), namely: (1) strategic inventory position, which determines where the decoupling points are placed; (2) buffer profiles and levels, which determines the amount of protection at decoupling points and is usually divided into three zones (green, yellow and red); (3) dynamic adjustment, which defines how this amount varies depending on the operation parameters, market changes, etc.; (4) demand driven planning, which defines how purchase and manufacturing orders are generated; and (5) visible and collaborative execution, which manages open orders. The first three phases, essentially determine the initial configuration of the system and its evolution, while the remaining two phases focus on day-to-day operational aspects, specifically the scheduling of orders and their execution.

Buffers in DDMRP are divided into three zones: green, yellow, and red. Each zone has a specific purpose. The green zone is at the heart of the order generation process, determining the order frequency and the order size. The yellow zone is at the heart of the demand coverage, which is determined by the demand during the DLT. The red zone is the safety factor embedded in the buffer; the higher the variability the larger this zone. Execution priorities in DDMRP are focused on the current state of these buffers. Buffer status alerts for the current on-hand and the projected on-hand inventory are used to protect and promote the flow. This scheduling of open orders and their execution is the focus of our study.

The execution priority in complex systems is usually managed through dispatching rules. Reviews of priority dispatching research found hundreds of dispatching rules (e.g.,

Panwalker and Iskander 1977; Blackstone et al. 1982), from very simple rules, such as First-Come-First-Served (FCFS) to much more sophisticated rules, including due date oriented dispatching rules. One such class of powerful priority dispatching rules are Operation Due Date (ODD) oriented rules, which have been shown to perform well in complex shops (e.g., Kanet and Hayya 1982). In this study, we will therefore use a rule based on operation due dates (or authorization dates), and FCFS as a baseline.

DDMRP is a relatively new PPC system that showed much promise in VUCA environments. A key element of DDMRP's execution logic is priority dispatching based on the inventory buffer status. While this information is important from the customer's perspective, it overlooks the need for order progress coordination. Order progress coordination is provided by time-based dispatching rules, such as ODD. In response, the objective of this study is to answer the following two research questions (RQs):

RQ1: Is the performance of DDMRP affected by the execution priority given to orders?
RQ2: Should the buffer status be used to prioritize orders in DDMRP?

3 Method

Discrete event simulation is used as a research method to answer our two research questions. A simulation model of a multi-stage assembly system was developed using ARENA® software. The model is based on Thürer et al. (2022) and Jodlbauer and Huber (2008). It represents an assembly shop, where demand for product parts depends on the market-driven demand for end products. To create a balanced situation, the part quantities per product have been adjusted. Moreover, we use stochastic processing times and stochastic demand inter-arrival times to capture the impact of VUCA aspects in the system.

3.1 System

The assembly system contains six stations, where each station is a single, constant capacity resource. There are eight different end products (P1 to P8), as summarized in Fig. 1. Each product requires six assembly operations to be completed, each one taking place at a different station (starting at station 1 and ending at station 6). Raw materials at gateway station 1 are assumed to be not restrictive and always available.

Processing times follow a 2-Erlang distribution (see e.g., Thürer et al. 2022) with a mean of 1.0-time units at stations 1, 2, 3, and 4 and of 0.5-time units at stations 5 and 6, resulting in a balanced shop.

As in previous studies (e.g., Thürer et al. 2022; Jodlbauer and Huber 2008) demand occurs at fixed periods. Our study considers an average demand arrival rate of 9 end products per period of 10-time units. The demand rate follows a Poisson distribution, as in Thürer et al. 2022 and Jodlbauer and Huber 2008, with an equal probability of arrival for all end products. This resulted in an average utilization rate of 90% at all stations.

Customer due dates are assumed to be set endogenously, i.e., by the company. A constant allowance is therefore added to the order entry time. Two levels for the due date allowance are tested, tight, and loose. In our study, tight refers to 30-time units after the order arrival, while loose to 40-time units. These values are based on the realized average throughput times in preliminary simulation experiments.

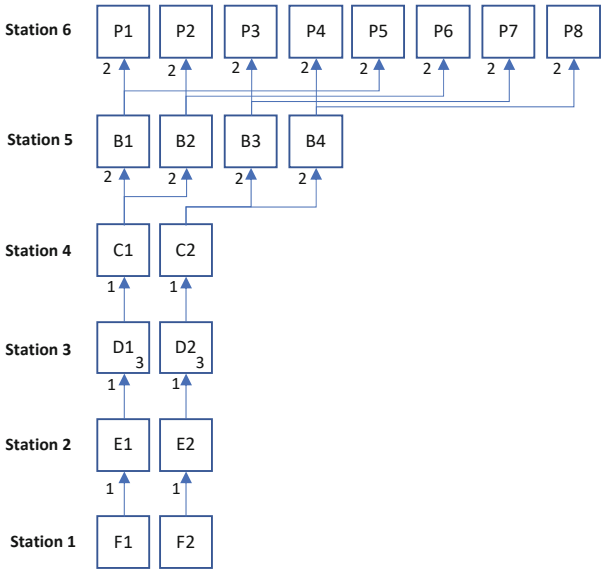

Fig. 1. Assembly stations and end products structure.

3.2 Production Control

Demand (D) is only satisfied at the order due date. This means that end products wait in a finished goods buffer (FGB) until the due date. We recognise that at least part of the demand can be immediately fulfilled if there is an FGB, and this may be an advantage when dealing with customer tolerance time. Therefore, as in Azzamouri et al. (2022), DDMRP has been implemented with two buffers, one for raw parts (RPB) and the other for finished goods (FGB), as illustrated in Fig. 2.

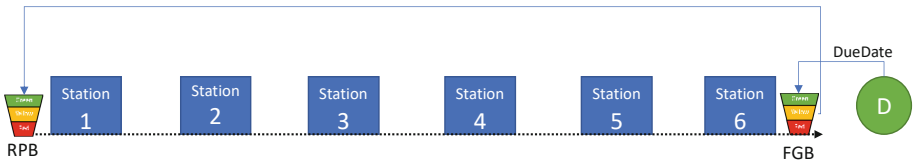

Fig. 2. DDMRP assembly system.

If the inventory position in the FGB falls to the re-order point, then a production order for the replenishment of a specific end product is generated. This production order triggers the release of parts to station 1 to produce the required end product. We use a re-order point inventory policy with three levels for the re-order point (3, 4, and 5) and two levels for the re-order quantity (1 and 4). The inventory position, given by the net flow equation (*on-hand inventory* + *open orders* – *customer orders*), is assessed continuously.

On the shop floor, an order is scheduled as soon as it is generated. This involves defining authorisation dates based on MRP logic, which are calculated for each part by backward scheduling from the due date using the station's lead times. Allowances for lead times at each station are given by the average of all throughput times realized until the decision time.

Finally, three dispatching rules are considered in this study: lowest net flow position (LNFP), earliest authorization date (EAD), and FCFS. LNFP acknowledges that the lower the inventory buffer of an end product, the higher the threat to maintaining flow, and consequently the higher the execution priority. EAD uses the authorisation dates to determine the sequence in which orders are considered for processing at each station. It recognizes the need for coordination of order progress on the shop floor. Finally, and in addition to EAD, priority dispatching based on FCFS is used in our study as a benchmark.

3.3 Experimental Design and Performance Measures

We used a full factorial design for the experiments, which results in 36 ($3 \times 2 \times 2 \times 3$) scenarios. This includes three levels for the re-order point, two for the re-order quantity, two for the due date tightness, and three for the dispatching rule. Each scenario was replicated 100 times. Results were collected over 30,000-time units following a warm-up period of 20,000 time units.

The following performance measures are considered: the service level (SL), the customer waiting time (CW), the finished goods inventory (FGI); the delivery time (DT), i.e. the mean time between the customer order arrival and its satisfaction from the FGB; the total throughput time (TTT), i.e. the mean time between the production order generation and the production order delivery to the customer; and the shop floor throughput time (TT), i.e., the mean time between production order generation and production order completion on the shop floor.

4 Results

In this section, we assess the performance of the experimental control factors, namely the DD tightness, the re-order point (ROP), the re-order quantity (ROQ), and the priority dispatching rule, on the performance of DDMRP. Simulation results under FCFS are summarized in Table 1. The following can be observed from the results:

- Due Date Tightness: As expected, the due date tightness mainly impacts the delivery time (DT) as demand is satisfied from the FGB. It has no impact on shop floor throughput times (TT). Since products wait in the FGB until the customer's due date, the due date tightness impacts the time products are in the FGB and thus the total throughput times (TTT). In general, a looser due date leads to a higher FGB, which in turn leads to higher service levels.
- *Re-order Point System Parameters*: There are two main parameters for the Re-order Point system: ROP and ROQ. The service level is largely determined by the ROP - if the ROP is higher, then the probability of stockouts is lower. But it is also determined by the ROQ. A higher ROQ leads to a higher FGB and thus to a higher service level.

ROQ also impacts TT, a higher ROQ leads to a higher TT. However, the negative impact of a higher TT on the availability of products in the FGB, and thus on the service level, seems to be offset by the positive impact of the ROQ on the FGB, which leads to a higher service level.

Table 1. Experimental results for FCFS dispatching (95% confidence interval).

Controls			Performance Measures					
ROP	ROQ	DD	TT (time)	TTT (time)	DT (time)	FGI (units)	SL (%)	CW (time)
3	1	tight	38.1±0.80	67.0±0.23	31.5±0.26	26.0±0.55	88.8±0.68	11.3±0.82
3	1	loose	38.1±0.80	76.2±0.15	40.7±0.16	34.3±0.61	94.7±0.50	9.2±0.78
4	1	tight	38.1±0.80	75.3±0.16	30.9±0.18	33.5±0.61	93.3±0.53	10.3±0.77
4	1	loose	38.1±0.80	84.8±0.11	40.4±0.10	42.0±0.65	97.0±0.36	8.2±0.70
5	1	tight	38.1±0.80	83.7±0.13	30.5±0.12	41.1±0.65	96.1±0.39	9.2±0.70
5	1	loose	38.1±0.80	93.5±0.11	40.2±0.07	49.9±0.68	98.3±0.25	7.2±0.64
3	4	tight	39.9±0.71	79.7±0.13	30.8±0.14	35.8±0.55	93.3±0.41	10.2±0.65
3	4	loose	39.9±0.71	89.3±0.10	40.3±0.08	44.4±0.59	97.0±0.28	8.4±0.61
4	4	tight	39.9±0.71	88.3±0.12	30.4±0.09	43.5±0.59	96.1±0.30	9.3±0.62
4	4	loose	39.9±0.71	98.0±0.11	40.2±0.05	52.2±0.61	98.3±0.20	7.5±0.56
5	4	tight	39.9±0.71	97.0±0.12	30.2±0.06	51.3±0.62	97.7±0.22	8.4±0.58
5	4	loose	39.9±0.71	106.8±0.13	40.1±0.03	60.1±0.62	99.0±0.13	6.5±0.57

Table 2. Experimental results for EAD dispatching (95% confidence interval).

Controls			Performance Measures					
ROP	ROQ	DD	TT (time)	TTT (time)	DT (time)	FGI (units)	SL (%)	CW (time)
3	1	tight	38.2±0.79	67.0±0.23	31.5±0.26	26.0±0.54	88.9±0.67	11.3±0.85
3	1	loose	38.2±0.79	76.2±0.15	40.7±0.16	34.2±0.60	94.7±0.50	9.3±0.82
4	1	tight	38.2±0.79	75.2±0.17	30.9±0.18	33.4±0.60	93.3±0.53	10.3±0.80
4	1	loose	38.2±0.79	84.7±0.12	40.4±0.11	42.0±0.64	97.0±0.36	8.2±0.75
5	1	tight	38.2±0.79	38.2±0.79	30.5±0.12	41.0±0.65	96.1±0.39	9.2±0.75
5	1	loose	38.2±0.79	93.4±0.11	40.2±0.07	49.8±0.67	98.3±0.25	7.2±0.68
3	4	tight	40.1±0.71	79.7±0.13	30.8±0.14	35.6±0.55	93.3±0.39	10.4±0.68
3	4	loose	40.1±0.71	89.2±0.10	40.3±0.08	44.2±0.58	96.9±0.28	8.6±0.64
4	4	tight	40.1±0.71	88.3±0.21	30.5±0.09	43.3±0.59	96.0±0.30	9.5±0.65
4	4	loose	40.1±0.71	98.0±0.11	40.2±0.05	52.0±0.61	98.3±0.20	7.8±0.58
5	4	tight	40.1±0.71	96.9±0.12	30.3±0.06	51.1±0.61	97.7±0.22	8.6±0.62
5	4	loose	40.1±0.71	106.8±0.12	40.1±0.03	60.0±0.62	99.02±0.14	6.8±0.60

Simulation results for the EAD rule and the LNFP rule are summarized in Tables 2 and 3, respectively. The following can be observed from the results:

- *Earliest Authorization Date*: This dispatching rule has a negligible impact on performance when compared with the benchmark rule (FCFS).

Table 3. Experimental results for LNFP dispatching (95% confidence interval).

Controls			Performance Measures					
ROP	ROQ	DD	TT (time)	TTT (time)	DT (time)	FGI (units)	SL (%)	CW (time)
3	1	tight	38.1±0.80	88.8±0.68	31.5±0.26	26.0±0.55	88.8±0.68	11.3±0.82
3	1	loose	38.1±0.80	76.2±0.15	40.7±0.16	34.3±0.61	94.7±0.50	9.24±0.78
4	1	tight	38.1±0.80	75.2±0.16	30.9±0.18	33.5±0.61	93.3±0.56	10.3±0.77
4	1	loose	38.1±0.80	84.7±0.11	40.4±0.10	42.0±0.65	97.0±0.36	8.2±0.70
5	1	tight	38.1±0.80	83.7±0.13	30.5±0.12	41.1±0.65	96.1±0.39	9.2±0.70
5	1	loose	38.1±0.80	93.5±0.11	40.2±0.07	49.9±0.68	98.3±0.25	7.2±0.64
3	4	tight	39.6±0.64	79.4±0.12	30.4±0.09	35.8±0.54	96.4±0.44	9.7±0.69
3	4	loose	39.6±0.64	89.1±0.11	40.2±0.05	44.5±0.55	98.4±0.28	9.0±0.68
4	4	tight	39.6±0.64	88.1±0.13	30.2±0.05	43.6±0.56	98.2±0.31	8.3±0.69
4	4	loose	39.6±0.64	97.9±0.12	40.1±0.03	52.5±0.56	99.2±0.19	7.5±0.76
5	4	tight	39.6±0.64	96.9±0.14	30.1±0.03	51.5±0.58	99.12±0.21	6.9±0.76
5	4	loose	39.6±0.64	106.8±0.14	40.0±0.02	60.4±0.57	99.62±0.12	5.6±0.87

- *Lowest Inventory Position*: If the ROQ is one, then this dispatching rule has a negligible impact on performance compared to both FCFS and EAD. However, if the ROQ is higher, i.e., four, this rule outperforms the other two. This effect originates from having different priority values for jobs of the same type, depending on the inventory position at order generation.

5 Conclusions

DDMRP is a Production Planning and Control system that extends MRP logic to VUCA environments. Inventory buffers that act as decoupling points are strategically placed to ensure the availability of key items that are considered important. The net flow equation then monitors the virtual stock levels at these decoupling points. In this study, we compare the performance of three priority dispatching rules on the performance of DDMRP using a discrete event simulation model of a multi-stage assembly system, where demand for product parts depends on the market-driven demand for end products. Answering our research questions – Is the performance of DDMRP affected by the execution priority given to orders? and should the buffer status be used to prioritize orders in DDMRP? – results indicate that using the net flow position to prioritize orders on the shop floor outperforms due date and first-come-first-served priority dispatching rules. However, if the reorder quantity is unitary, prioritizing orders based on the buffer status performs identically to the other two rules. This suggests that the advantage of this rule essentially originates from the different priorities that are given to orders of the same type when the reorder quantity is greater than one.

Future research work should extend this study to consider real production scenarios and other buffer status priority rules given the promising results of the net flow position rule tested here. For example, the execution priority may be determined by the amount of on-hand divided by the top of the entire red zone (i.e., the safety embedded in the buffer) as suggested in the DDMRP literature. Additionally, it would be of interest for

future work to explore how this rule and others perform in more complex production environments.

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DDMRP as Production Control Policy in a Two-Product Closed-Loop Supply Chain

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Abstract. Recently, closed-loop supply chains (CLSCs) are receiving growing attentions by the academic world since they represent a sustainable network for circular economies. However, the impact of production control policies (PCPs) on the performance of CLSCs is still unexplored. Then, this paper investigates the role of the Demand-Driven Material Requirements Planning (DDMRP) as a PCP in two-product CLSCs. The normal flow of the CLSC consists of factory and retailer nodes. The factory is characterized by a production line subject to failure events and product changeovers. The retailer issues orders to the factory through the Smoothing Order-Up-To policy and meets the customer demand. The reverse flow is represented by the remanufacturer that collects and restores the two product types coming from the customer. DDMRP is adopted by the factory node to decide what product type has to be processed. A full-factorial Design of Experiments was defined, and ANOVA was carried out to investigate the impact of remanufacturer and control parameters of DDMRP on the fill rate of the whole closed-loop supply chain. This paper allows investigating how the parameters regulating the DDMRP bias the responsiveness of two-product CLSC with capacity restrictions.

Keywords: DDMRP · Supply chain management · Production control

1 Introduction

Recently, Demand-Driven Material Requirements Planning (DDMRP) is keeping growing attention from both academics and practitioners. Several companies implemented this new production strategy and achieved significant performance improvements in terms of on-time delivery and internal operational efficiency [1]. DDMRP was developed by Ptak and Smith [2] and can be considered a hybrid approach since it embraces the principles of Material Requirements Planning (MRP), Theory of Constraints (TOC) and Lean Manufacturing (LM) [3]. DDMRP usually consists of three main steps. The first step regards the positioning of buffers in the manufacturing system. The aim is to identify the optimal position of each buffer (or inventory) to reduce lead times and variability. The second step concerns sizing the inventory levels. To do this, DDMRP

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makes use of three inventory areas, denoted as red, yellow and green zones. The scope is to maintain positive inventory levels to avoid any risk of stock-outs. Finally, the last step deals with dynamically adjusting the buffer levels to promptly react to uncertainties. The effectiveness of this production strategy was demonstrated by Miclo et al. [1] and Thürer et al. [4] since they compared DDMRP with other strategies, such as MRP II or Lean Production. Velasco et al. [3] showed the applicability of DDMRP in complex manufacturing systems to avoid stock-outs or over-stocks and reduce inventory levels. Azzamouri et al. [5] used a discrete event simulation model to evaluate how the continuous and periodic assessments of inventory levels perform in DDMRP. Cuartas et al. [6] developed an interesting hybrid approach that combines a reinforcement learning algorithm and DDMRP. The work aims to identify an optimal policy for deciding when and how much to buy a certain product. Recently, Damand et al. [7] pointed out that DDMRP is characterized by several control parameters and only general rules were previously provided to set their values. They proposed a multi-objective optimization algorithm to maximize delivery on-time to the customer and minimize the inventory level. Finally, Corsini et al. [8] were the first to adapt DDMRP as a production control policy (PCP) in a two-echelon supply chain with production capacity constraints. In their work, DDMRP was used to make decisions about product changeovers based on the inventory levels of two product types.

In summary, DDMRP was tested in one-echelon manufacturing systems or two-echelon supply chains. However, the closed-loop structure is preferable since it sustainable for the circular economy. In fact, closed-loop supply chains (CLSCs) are receiving growing attentions by the academic world to enhance and support circular economies. To our knowledge, the impact of DDMRP on a two-product CLSC is unknown and, therefore, the scope of the present paper is two-fold:

1. Proposing a novel two-product CLSC model with the production capacity constraint, which characterizes the factory node. DDMRP is adopted as PCP of the factory to manage the decision-making on product changeovers;
2. Evaluating the impact of the two main control parameters of DDMRP, namely lead-time factor and variability factor on the dynamics of the CLSC. Since we assume that the CLSC under investigation is customer-focused, then the fill rate is considered as a single (or unique) key performance indicator. Also, the influence of the remanufacturer on the performance of the CLSC was investigated.

The structure of the paper is the following. Section 2 presents the simulation model used to emulate the dynamics of the two-product CLSC. Section 3 describes the rationale of DDMRP. Section 4 shows the experimental campaign and reports the analysis of results. Finally, Sect. 5 deals with the conclusions of the paper.

2 Problem Statement

A simulation model based on discrete-time difference equations and coded in Matlab r2021® is used to emulate the dynamics of the two-product CLSC model. The CLSC model consists of normal and reverse flows, and the position of each node is indexed as follows: $i = 1$ factory; $i = 2$ retailer; $i = 3$ remanufacturer. In the whole CLSC, the

product type and the time unit are indexed with p and t, respectively. Figure 1 shows the material and information flows between each node of CLSC under study. Precisely, the material flow is represented with continuous lines, while the information flow is with dashed lines. The normal flow of the CLSC is composed of two echelons, *i.e.*, the factory and the retailer, and is modelled in accordance with the multi-product EXPO model of Corsini et al. [8]. The reverse flow of the CLSC is characterized by a remanufacturer and is modelled in accordance with the work of Dominguez et al. [9].

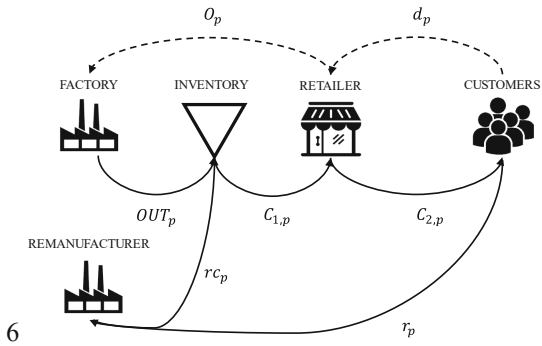

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Fig. 1. The material and information flows in the closed-loop supply chain model

The factory node consists of a failure-prone manufacturing system able to process two different product types. The two product types cannot be manufactured simultaneously; then, changeover operations are needed to switch from one product type to another. The decision on product changeovers is made by DDMRP, which acts as PCP. The product type under process is indexed with p, while the product type in waiting to be processed is indexed with p'. The input quantity $INP_p(t)$ at time t is the amount of raw materials of product type p that feeds the production line and is equal to the nominal production capacity χ_p. However, $INP_p(t)$ can be reduced due to the changeover operations or failure events as follows:

$$INP_p(t) = \chi_p \cdot (1 - CO_{p'p}(t)) \cdot (1 - tr(t)) \tag{1}$$

where $CO_{p'p}(t)$ is the residual changeover time to switch from p' to p, while $tr(t)$ is the time to repair a failure event. When a decision on product changeover is made by DDMRP, then $CO_{p'p}(t)$ is equal to the changeover time δ. On the other hand, $tr(t)$ is derived from U(0,1) when a random failure occurs with a failure rate denoted as λ [9]. Then, the number of finished products at time t of product p is represented by $OUT_p(t)$ and is calculated as:

$$OUT_p(t) = INP(t - F) \tag{2}$$

where F is the flow time. $OUT_p(t)$ fills the factory inventory level, which is computed as follows:

$$I_{1,p}(t) = \max\{I_{1,p}(t-1) + OUT_p(t) - O_p(t-1); -k \cdot \mu_{d_p}\} \tag{3}$$

where $O_p(t-1)$ is the order issued by the retailer at time $t-1$, while $-k \cdot \mu_{d_p}$ is the threshold of lost sales used to limit the backlog level (k is the threshold of lost sales factor and μ_{d_p} is the mean customer demand of product type p). The inventory level is used to meet the orders quantity arising from the retailer as follows:

$$C_{1,p}(t) = \max\{\min\{I_{1,p}(t-1) + OUT_p(t); O_p(t-1)\}; 0\} \tag{4}$$

where $C_{1,p}(t)$ are the units of product type p delivered by the factory to the retailer at time t. $C_{1,p}(t)$ fills the retailer inventory level $I_{2,p}(t)$ after a non-negligible delivery lead-time LT. $I_{2,p}(t)$ also depends on the customer demand $d_p(t)$, , which is derived from N(μ_{d_p}, σ_{d_p}), as follows:

$$I_{2,p}(t) = \max\{I_{2,p}(t-1) + C_{1,p}(t-LT) - d_p(t); -k \cdot \mu_{d_p}\} \tag{5}$$

The units of products delivered by retailer to the customer $C_{2,p}(t)$ are:

$$C_{2,p}(t) = \max\{\min\{I_{2,p}(t-1) + C_{1,p}(t-LT); d_p(t)\}, 0\} \tag{6}$$

In this case, the delivery lead-time is neglected. The retailer issues orders $O_{2,p}(t)$ to the factory following the Smoothing Order-Up-To (S-OUT) replenishment policy:

$$O_{2,p}(t) = \max\{\widehat{d}_{2,p}(t) + \beta \cdot \left(TW_p(t) - W_p(t) + TI_p(t) - I_{2,p}(t)\right); 0\} \tag{7}$$

where $\widehat{d}_{2,p}(t)$ is the demand forecasted by the exponential smoothing method, β is the proportional controller, $TW_p(t)$ is the target delivery work-in-progress, $W_p(t)$ is the delivery work-in-progress and $TI_p(t)$ is the target inventory (for the sake of brevity, please see Corsini et al. [8]). As shown in Fig. 1, a percentage of the customer demand of product type p, denoted as return quantity $r_p(t)$, is sent to the remanufacturer at time t with a non-negligible delivery lead-time LT_c in order to be restored. $r_p(t)$ is calculated as follows:

$$r_p(t) = y_p(t) \cdot d_p(t - LT_c) \tag{8}$$

where $y_p(t)$ is denoted as the return rate and is derived from N($\mu_{a\%}$, $\sigma_{a\%}$) and limited in the range [0,1]. The remanufacturing operations are characterized by a remanufacturing capacity constraint ψ_p, which is calculated as:

$$\psi_p = CoC_r \cdot \mu_{a\%} \cdot \mu_{d_p} \tag{9}$$

where CoC_r is the coefficient of remanufacturing capacity. Then, the units of product can restored by the remanufacturer $rc_p(t)$ with a remanufacturing lead-time LT_r. If the units of product to be restored exceed the remanufacturing capacity constraints, then, they are recorded as remanufacturing backlog $rb_p(t)$. $rc_p(t)$ And $rb_p(t)$ are calculated as follows:

$$rc_p(t) = \min\{r_p(t - LT_r - 1) + rb_p(t-1); \psi_p\} \tag{10}$$

$$rb_p(t) = \max\{r_p(t - LT_r - 1) + rb_p(t-1) - \psi_p; 0\} \tag{11}$$

3 Demand-Driven Material Requirements Planning

As stated in the introduction, DDMRP is composed of three steps. The first step of DDMRP, *i.e.*, the positioning of buffers, is disregarded since only the inventory of finished products is considered in the factory node [8]. As for the other two steps, DDMRP defines at each time unit t three different inventory thresholds, *i.e.*, threshold of red zone $TOR_p(t)$, threshold of yellow zone $TOY_p(t)$ and threshold of green zone $TOG_p(t)$. The red zone indicates a dangerous scenario in which the inventory level may assume negative values. The yellow zone points out the need of increasing the inventory level to avoid the red zone. The green zone is the ideal inventory level for the factory node. The thresholds, *i.e.*, $TOR_p(t)$, $TOY_p(t)$ and $TOG_p(t)$ are calculated as follows:

$$TOR_p(t) = [(\widehat{d}_{1,p} \cdot F) \cdot Flt] \cdot (1 + Fvar) \tag{12}$$

$$TOY_p(t) = TOR_p(t) + (\widehat{d}_{1,p} \cdot F) \tag{13}$$

$$TOG_p(t) = TOY_p(t) + [(\widehat{d}_{1,p} \cdot F) \cdot Flt] \tag{14}$$

where Flt and $Fvar$ are two control parameters denoted as lead time factor and variability factor, respectively, while $\widehat{d}_{1,p}$ is the demand forecasted by the factory through the exponential smoothing methodology. To make decisions about changeovers, DDMRP thresholds are compared with the forecasted inventory level $\hat{I}_{1,p}(t)$ [9]. There are two different conditions to decide on product changeovers. The former is that the forecasted inventory level $\hat{I}_{1,p}(t)$ of the product type under process p is higher than $TOG_p(t)$. In this case, the inventory reaches its ideal level and there is no need to further process the product type p. The latter condition is that the forecasted inventory level $\hat{I}_{1,p}(t)$ of the product type under process p is higher than $TOY_p(t)$ and, at the same time t, the current inventory level $I_{1,p'}(t)$ is lower than its threshold of yellow zone $TOY_{p'}(t)$. In this case, the inventory level of the product type in waiting p' risks collapsing in a stock-out scenario; then, a product changeover is suggested by DDMRP.

4 Experimental Results

To investigate the impact of DDMRP in the CLSC under study, a full-factorial Design of Experiments (DoE) is devised in which the variables related to the remanufacturing capacity constraint and the DDMRP control parameters are considered as experimental factors, *i.e.*: *i*) the mean of return rate $\mu_{a\%}$; *ii*) the coefficient of remanufacturing capacity CoC_r; *iii*) the lead-time factor Flt; *iv*) the variability factor $Fvar$. The factors related to the remanufacturing capacity constraint vary at four levels, while the DDMRP control parameters vary at three levels. Then, $4^2 \cdot 3^2 = 144$ different configurations are considered in this research. Since 10 replicates were included, 1440 simulation runs were launched. In accordance with the literature [8–11], the other variables of the problem were set as follows: $LT = 2$; $F = 2$; $\alpha = 0.3$; $\beta = 0.3$; $\varepsilon = 1$; $\delta = 2$; $\chi_p = 3$; $k = 2$; $\lambda = 0.1$; $LT_C 32$; $LT_r = 4$; $\sigma_{a\%} = 0.3$. It has to be specified that α is the forecasting

factor used to compute the forecasted demand $\hat{d}_{i,p}(t)$, while ε is the safety stock factor used to compute the target inventory $TI_p(t)$ (see Corsini et al. [8]). The two product types can be identified with A and B and the related customer demands are derived from N(100,10) and N(50,5), respectively. However, there is no significant difference in the results of A and B; then, the analysis of results concerns the first product A. The response variable is the Fill Rate (*FR*) indicator. *FR* measures the ability of the supply chain to meet the customer demand [10, 11]. It is calculated as the ratio between the average units of product delivered by the retailer and the average customer demand:

$$FR_p = \frac{\overline{C_{2,p}}}{\overline{d_p}} \tag{17}$$

The average values $\overline{C_{2,p}}$ and $\overline{d_p}$ are computed without considering the warmup period Tw, which is set to 200 time units (while the time horizon, T, is of 2000 time units). The values of T and Tw are in accordance with the relevant literature [8, 9]. The Analysis of Variance (ANOVA) at 95% confidence level was accomplished by means of Minitab®2017 to evaluate how the experimental factors bias the *FR* of the CLSC. The assumptions of the ANOVA analysis, *i.e.*, independence of residuals, homogeneity of variances and normality of residuals were verified. As shown in Fig. 2, the effectiveness of the model is also demonstrated by the R^2 values, which is equal to 99.17%, and the difference between adjusted and predicted R^2, which is less than 20%. Figure 2 also reports p-values and F-values of the experimental factors and the 2-way interactions. All the experimental factors are statistically significant on *FR* since p-values are equal to zero. Looking at F-values, $\mu_{a\%}$ is the factor with the highest impact on the response variable. However, the other factors also have a notable influence in terms of *FR* since they present high F-values. As for 2-way interactions, all the interactions composed by $\mu_{a\%}$ have an important impact on *FR*. In particular, the combination $\mu_{a\%}$*Flt presents the highest F-value. Figure 3 depicts the Main Effect Plot. The influence of the mean return rate demonstrates the benefit provided by the remanufacturer in CLSCs. In fact, high values of $\mu_{a\%}$ positively impact *FR* performance indicator. However, it can be noticed that $\mu_{a\%}= 0.6$ can be identified as a critical point. In this scenario, the mean *FR* value is close to 100% and higher $\mu_{a\%}$ cannot provide any further benefit to the CLSC in terms of customer satisfaction. Also, the coefficient of remanufacturing capacity positively biases the performance of the CLSC. However, the magnitude of its impact seems to be lower than the influence of $\mu_{a\%}$. As for the DDMRP control parameters, the results demonstrate that high values of *Flt* and *Fvar* are required to enhance the performance of the CLSC. Moreover, it can be noticed that *Flt* has a notable influence in terms of *FR*. In fact, moving from $Flt = 0.4$ to $Flt = 1$ involves an improvement of about 10% on *FR*. To conclude, the impact of the remanufacturing capacity constraint in general respects the findings arising from the literature (see e.g. [9]). However, this is the first study that investigates the impact of DDMRP in the CLSC's performance. The experimental results revealed that defining the optimal set of DDMRP parameters is needed to enhance the CLSC's performance.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	56	18.5189	0.33070	2942.82	0.000
Blocks	9	0.0025	0.00027	2.43	0.010
Linear	10	16.0988	1.60988	14326.14	0.000
μa%	3	13.2670	4.42233	39353.81	0.000
CoCr	3	0.4279	0.14265	1269.41	0.000
Flt	2	2.1323	1.06614	9487.46	0.000
Fvar	2	0.2716	0.13579	1208.42	0.000
2-Way Interactions	37	2.4177	0.06534	581.48	0.000
μa%*CoCr	9	0.2206	0.02451	218.08	0.000
μa%*Flt	6	1.8967	0.31612	2813.14	0.000
μa%*Fvar	6	0.2581	0.04302	382.84	0.000
CoCr*Flt	6	0.0343	0.00571	50.83	0.000
CoCr*Fvar	6	0.0054	0.00090	8.00	0.000
Flt*Fvar	4	0.0026	0.00065	5.81	0.000
Error	1383	0.1554	0.00011		
Total	1439	18.6744			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0106006	99.17%	99.13%	99.10%

Fig. 2. The results of the ANOVA analysis

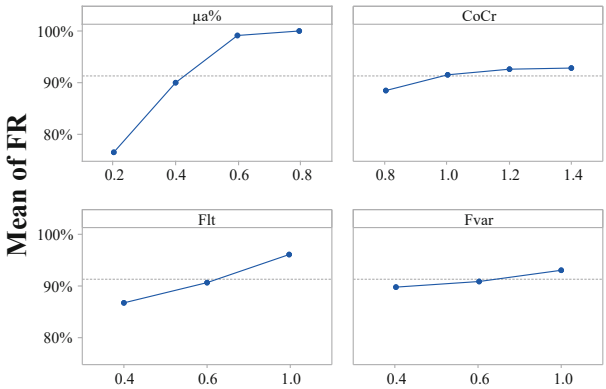

Fig. 3. The Main Effect Plot

5 Conclusions

CLSC is one of the main topic in supply chain management since it represent a sustainable business network. The aim of our work is to investigate the relation between the PCP and the performance of CLSCs. In fact, this paper investigates the impact of DDMRP as a PCP on the fill rate of a novel two-product CLSC model. The factory node is characterized by a failure-prone manufacturing system that has to manufacture two different product types. The two product types cannot be processed at the same time and DDMRP is needed to decide on product changeovers. A full-factorial DoE was devised to investigate how four experimental factors affect the performance of the whole CLSC in terms of fill rate. Two experimental factors are related to the remanufacturer node, *i.e.*, the mean of returns rate and the coefficient of remanufacturing capacity. The rest of the experimental factors are the two DDMRP control parameters, *i.e.*, the lead time

and variability factors. The numerical results show that the mean return rate presents the most significant impact on CLSC performance. As for the DDMRP control parameters, the study shows that the lead time factor and variability factors should be set to high values to increase the fill rate of the whole CLSC.

This paper is the first to test the effectiveness of DDMRP in two-product CLSCs. The experimental results revealed the importance of the calibration phase for the DDMRP control parameters, which significantly affect the performance of the CLSCs in terms of the fill rate. However, the influence of each control parameter should be investigated with other response variables, such as indicators related to the inventory and/or backlog levels. Furthermore, optimization techniques (such as metaheuristic algorithms) may be developed to calibrate the DDMRP parameters and enhance the CLSC's performance. Finally, new sources of uncertainties and disruptions in the whole CLSC can be included in the model to evaluate the capacity of DDMRP to react to these adverse events.

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Development of a Production Planning and Control Method Through Productivity Analysis of Bottlenecks

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Abstract. This paper describes the development of a Production Planning and Control (PPC) method implemented in a company that produces shower screens, to respond to problems associated with overproduction. In this system, the daily workload is directly influenced by the productivity presented in the bottleneck. The bottleneck was identified, a database was built to support the calculation of the bottleneck' productivity and the determination of the workload for each day. It is foreseeable that the system will bring considerable improvements in the productivity values. The data collected before and after the implementation of PPC system allowed identifying an increasing trend in the productivity values of the bottleneck resulting from the implementation.

Keywords: PPC · Productivity · Workload · Bottleneck

1 Introduction

The market is becoming extremely competitive, and it is crucial for companies to respond to demand efficiently, effectively and at the lowest possible cost, compared to the competition. Since there are numerous approaches regarding the applicability of Production Planning and Control (PPC) methods, developing the right procedure is a critical decision to successfully respond to customer expectations and requirements [1]. A PPC system is also important for an organization to respond to constant changes and fluctuations in orders, monitoring and adjusting production plans and workload [2]. As productivity is directly associated with the manufacture of products, it is a factor to be considered when developing a PPC system.

This article describes the method developed to solve the absence of a PPC system in a company that develops customized bathroom solutions for the global market. The lack of a PPC system led to overproduction, which contributed to increased inefficiency and waste in the manufacturing process. In order to respond to this problem, a system based on analysis of productivity and bottleneck capacity was developed.

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The paper is structured as follows. Section 2 presents a theoretical background introducing the definition of PPC and productivity. Section 3 briefly describes the methodology used. In Sect. 4, the problem related to the case study is exposed, the development of the method for PPC is described and some issues considered in the implementation of the PPC system are addressed, as well as results obtained with the system. Finally, a conclusion about the case study is presented in Sect. 5.

2 Background

2.1 Production Planning and Control

PPC can be defined as a central control instrument that brings together the organization's productive capacity and its logistical performance with market demand. The main task of a PPC system is to plan, initiate and control the delivery of the product, readjusting the production plan whenever unforeseen events occur [2]. This system also helps to reduce Work in Progress (WIP) as well as Lead Time in the organization [1]. The absence of a PPC system entails some consequences with an impact on the logistical and production process, causing rework and delays in deliveries [4]. The term "rework" concentrates several meanings in the literature, such as deviations and quality failures, nonconformities, and defects [5].

Several approaches to PPC are presented in the literature. The Theory of Constraints (TOC), also called the "Drum-Buffer-Rope" approach, aims to increase the efficiency of a company in terms of market requirements and opportunities, outlining the production process according to the impositions of the bottlenecks, as they dictate the system's capacity. It is important that they do not change, even if there are variable operating ranges and non-repetitive production [1, 6]. In this perspective, a detailed production program (Drum) is instituted for each bottleneck, with the aim of using its capacity. New orders are entered into the system and their development is monitored in the program (Rope). The upstream and downstream stages of the bottleneck(s) are not inspected; however, they are structured taking into account a waiting buffer and the considered cycle time [6], which is the time spent executing a process [7].

2.2 Productivity

Productivity can be considered a way of quantifying the relationship between goods/services produced (output) and resources consumed (input), such as work, capital, material, etc. [8, 9]. It is important to highlight the importance of not confusing the notions of productivity with production (output). If inputs remain unchanged, increases in productivity values are associated with increases in output. However, this correspondence is sometimes not verified, as it is possible to increase productivity without changing production (output) if less inputs are used in the production process. Thus, while the concept of production is attributed only to the art of producing goods and services, productivity is associated with the efficiency in the use of inputs to produce outputs [10].

3 Methodology

For the implementation of a PPC system adapted to the company's reality and that would respond to the identified problems, some steps were followed, starting with the identification of bottleneck in the process. Due to the variety of items produced and their different cycle times, Pareto analyzes were carried out to reduce the sample to the most influential items within the company. A second stage involved building a database with data on the time spent by operators to complete the bottleneck process, excluding all activities that did not add value to the product (*i.e.,* theoretical hours). Then, the procedures for calculating the productivity and determining the workload of bottlenecks were established, considering the values recorded in the database, as well as the time spent by operators in the workstation (*i.e.,* the real time spent at the workstations). Finally, the PPC system was implemented and data on the productivity of the bottleneck were monitored to assess the impact of the PPC system.

4 Case Study

4.1 Problem Contextualization

This study was carried out in the shower screen manufacturing section of a company that develops bathroom solutions for the global market. When observing the manufacturing process, it was relatively easy to identify some Non-Value-Added Activities, *i.e.*, activities that are considered wasteful within the work environment, usually associated with unnecessary actions that need to be eliminated [11]. Transport of heavy parts, defects in some aluminum parts (*e.g.,* scratches, wrong measurements, and holes), excessive movement throughout the entire process, as well as exaggerated waiting times for suspended material upstream of the process are some of the activities identified as waste. Despite all this, the most worrying problem identified was overproduction. The current decrease in demand and consequent decrease in orders has resulted in the unnecessary manufacturing of products in advance. This practice of manufacturing before necessary brings with it several problems for the organization, such as the increase in the consumption of raw materials and inventory levels, as well as the payment of wages to workers for work performed, which is also expendable [12, 13]. This led to the emergence of all other types of waste, as it implies greater movement of operators, large displacements within the shop floor, increased waiting times in subsequent stages, as well as an increase in the number of defects in products. The absence of production management appeared as one of the factors causing the manifested problem. The lack of a PPC system was evident and alarming. The lack of a production manager present resulted in the inability to control workers and manufactured products.

The following section describes the methodology followed to solve the identified problems, proposing a PPC solution, adapted to the company's reality. This methodology is based on planning the daily and weekly workload of bottlenecks in the manufacturing process, being directly influenced by its productivity.

4.2 Development of the PPC System

Identification of the Bottleneck. The first step was to identify bottleneck in the manufacturing process, *i.e.*, the activity with the highest cycle time. Considering the diversity of shower screens in the catalog (approximately 60 different items) and, consequently, their disparities in cycle times at certain stages of the process, it was essential to reduce the sample of items to be considered in the study, focusing on those that may have more influence on the company's results. For this purpose, two Pareto charts were prepared, the first referring to the previous year's revenue and the second considering the produced quantities of each item.

Analyzing the results, it was possible to conclude that only four items corresponded to about 45% of the total revenue, which can be considered a significant value. About 55% of the total number of shower screens produced corresponded to just four items. With a significantly reduced sample of items, with great influence on the financial results of the company, it becomes imperative to consider these items to identify the bottleneck. The cycle times of these items at all stages of the manufacturing process were collected and analyzed. Table 1 shows the relationship between the items identified as most relevant and their cycle times in the different stages of the process.

Table 1. Cycle times analysis of all stages in the manufacturing process.

Cycle Time Analysis (minutes)						
	Card boxes printing	Aluminum cutting	Aluminum machining	Shower screen collage	Shower screen packing	Kit preparation
Item 32	1.02	1.57	1.23	2.50	17.19	8.44
Item 33	3.12	2.11	2.43	4.18	35.40	9.54
Item 52	1.02	1.23	1.01	5.86	10.56	4.56
Item 60	1.57	4.21	5.54	16.73	28.45	7.32
Item 64	1.02	3.06	4.22	13.01	18.17	6.59

It was found that the stage with the longest cycle times in the manufacturing process was the Packing of shower screens. Therefore, the two existing packing stations were identified as bottlenecks in the manufacturing process.

Database Construction. Once the bottleneck was identified, the next step was to build the database, which contains all codes for all items created, with more than thirty thousand different ones. This variety comes from the great diversity and customization of products that the company offers. The codes are generated based on differences in the length and width of the shower screen, color of the aluminum profiles, type of existing serigraphy, inclusion of the side, among other more exclusive factors.In the case of the developed PPC solution, all codes included in the database have an associated "Optimal Packing Time" (OPT), in minutes, which is important for calculating the productivity of the packing stations under study and determining their workloads. This OPT was calculated by summing the time operators take to perform value-added activities and other

necessary but non-value-added activities, in the packing process, for a specific item. Considering the lack of prior documentation on the activities that integrate the process, the first step involved a rigorous observation of the process, with the aim of decomposing it into several iterative activities. Then, the various activities were classified into three categories: Value-added activities; Necessary but non-value-added activities; non-value-added activities [15]. This step was completed when the OPT was determined for all items.

Productivity Calculation. To begin determining workloads, it was necessary to calculate the productivity of the packing stations. For this, a daily study was carried out containing data on the items that were packed each day. As each packed item has an associated code in the database, it is possible to determine the total OPT for a working day. The sum of all OPT's for a given day was called "Theoretical Hours" (TH). Another essential factor in the calculation of productivity is the determination of the "Real Hours" (RH), which correspond to the time that each operator, individually, spends at the workstation, per day. Daily productivity is calculated using Eq. (1).

$$Daily\,productivity = \frac{\sum OPT\ hours}{RH\ hours} \times 100 \tag{1}$$

Equation (1) represents a ratio between TH and RH. The determination of weekly productivity is based on the same assumption, making the sum of the TH of the orders to be produced in the week, on the sum of the RH of the same week. With this data, it will be possible to determine the workload.

Workload Determination. The collection of data on the productivity of the packing stations and the list of orders awaiting production allows the company to start calculating the workload. The list is obtained from the software used in the company. It includes the code of the shower screen ordered, as well as the expected date for closing the order on the shop floor, which depends on the level of customization of the product, purchases from external suppliers, among other factors. As packing is the last step of the manufacturing process, the list provides a deadline for packing, which must not be exceeded or there will be a high risk of delays in delivery.

Equation (2) is used to calculate the time that each item will consume when being packed, *i.e.*, the cycle time, through the ratio between the OPT of a given item over the average weekly productivity of the corresponding workstation. The denominator in Eq. (2) is determined through the average of the weekly productivity values obtained since the beginning of the study.

$$Cycle\ Time\ (hours) = \frac{OPT\,(hours)}{Average\ Weekly\ Productivity} \tag{2}$$

At this point, the production orders on the waiting list and their deadline, as well as their cycle time, are known. The workload planning will be carried out weekly. The number of weekly hours available at each workstation must be known to determine its capacity. This information is obtained using Eq. (3) to calculate the total Time Available per Week (TAW).

$$TAW = \left(\sum Operators\ in\ the\ workstation\right) \times 8 \times \left(\sum Working\ days/week\right) \tag{3}$$

For example, in a week with five working days, the TAW for planning the workload of a workstation, if it was occupied by two workers in that week, would be 80 h. In these 80 h, the cycle time consumed by each order can be calculated using Eq. (2). In this way, it is possible to determine the capacity that each workstation has and manage it in the best possible way to efficiently meet the demand.

4.3 Implementation of the PPC System

Regarding the implementation and evaluation of the PPC method developed on the shop floor, a board was created with the workload of 2 to 3 weeks, divided by days, each one containing a set of cards representing the orders to be completed that day. A pilot study was carried out to determine which, how many and where to place each card, not only concerning the workload and the capacity of each workstation but considering the high degree of customization of a product and the possibility of delays from external suppliers. These cards contain estimated dates for all other steps in the manufacturing process to guide workers. In addition, they have "priority identifiers" differentiated by color. Green means that all processes are within the estimated dates, yellow for any delay that does not compromise de packing estimated date, and red for delays that may compromise the estimated order closing date.

Data on the weekly productivity of the bottleneck were collected before and after implementation (Fig. 1). Although the implementation is very recent, it is possible to observe in Fig. 1 that productivity shows an increasing trend from week 11, when the PPC system was implemented.

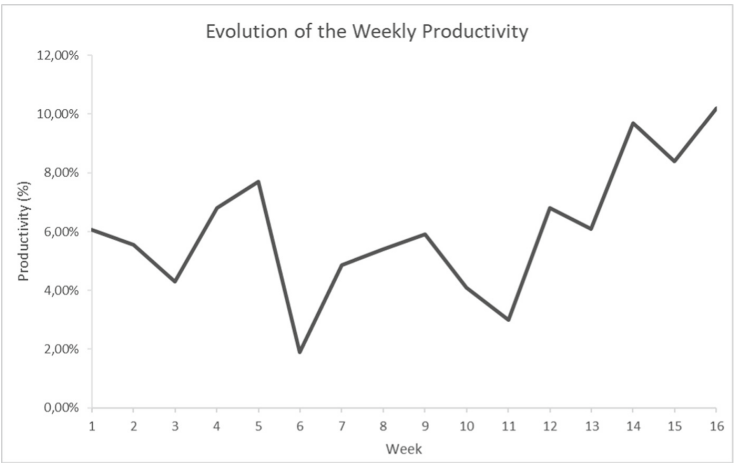

Fig. 1. Chart regarding the analysis of the weekly productivity evolution in the bottleneck resource.

The low productivity values are justified by the fact that they are calculated based on the OPT, in which are only considered value-added activities. However, currently most

of the RH is consumed with activities that do not add value, which means that there is a considerable difference between OPT and RH. For example, the item that generates the most revenue has an OPT about five times less than the time operators spend packing it. Additional measures should be taken to increase these values.

5 Conclusion

The decision to calculate productivity based on an OPT analysis is due the fact that the company is a small/medium enterprise starting to adopt Lean methodologies in its manufacturing process, which means that any future improvement will have a considerable impact on cycle times. If the study included cycle times taken from a stopwatch study and not the ratio between TH and RH, cycle times would be revised whenever an improvement was implemented in the process, which would lead to continuous work to correct the values of productivity. Considering continuous improvement efforts and that there will never be a scenario in which the process does not have any type of waste, using an optimal time to measure productivity means not having to constantly measure and review cycle time, which is a very time-consuming task. There are numerous methods to measure productivity, so there is no consensus on how it should be calculated. In this case study, the focus will not be on achieving high productivity values, but on having a sustained growth over time, which was observed through the preliminary results presented.

The implementation of the new PPC method will be accompanied by the implementation of lean techniques to eliminate waste in the processes, reducing their cycle times. By eliminating non-value-added activities, productivity will increase because it takes the operator less time to do his job, meaning less RH. It is believed that relevant improvements can be achieved in productivity levels not only of the workstations presented, but in the entire process. By providing a very accurate measure of the time required to respond to the workload, it is possible to manage operators in more efficiently, contributing to an increased productivity, even without lean improvements yet implemented. By establishing some rules, such as a time limit for completing the daily workload, better management of working hours will be achieved, influencing RH and improving productivity. It is expected that, with the implementation of this method, the overproduction problem will be eliminated, as there will be no production before necessary. It is also expected that the permanence time of an order on the shop floor will decrease considerably, without long waiting times between adjacent processes as these orders will be placed using new criteria.

This case and the method described for PPC can serve as a reference for similar cases, as this is a problem present in many organizations that share the same characteristics as the company where the case study was carried out.

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Characteristics of Production Scheduling Problems in the Era of Industry 4.0 – A Review of Machine Learning Algorithms for Production Scheduling

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Abstract. Changes in customer demand and technological advances increase production scheduling complexity. A solution to handle the increased complexity is to facilitate machine learning. Current reviews of the research of scheduling algorithms focus on summarizing existing methods. They lack the characteristics of practical implications arising from the increased complexity of the scheduling problem by Industry 4.0 and do not consider how the scheduling algorithms cope with the added complexity. Therefore, we address these issues and synthesize the current literature in a comprehensive literature review and taxonomy. We discuss how they address changeovers, buffers before and after machines, prioritization of jobs, dynamics of production, and transportation on the shop floor. Afterward, we summarize the concepts of scheduling approaches and derive five research gaps.

Keywords: Production Scheduling · Machine Learning · Industry 4.0 · Literature Review · Practical Characteristics

1 Introduction

Production scheduling, the time-related allocation of production jobs to production resources [1], is becoming more complex because customers increasingly demand individualized products reducing batch sizes [2], and they demand shorter delivery times, necessitating faster lead times [3]. These changes in customer demand and technological advances are summarized in the concept of Industry 4.0 [4].

In practice, schedules are created by experts or priority rules. With these methods, scheduling takes too much time to react appropriately to unforeseen situations [2], or it creates a solution that is suboptimal and thus does not meet productivity goals. These effects increase as scheduling becomes more complex [5]. Due to the expanding use of cyber-physical systems in production, real-time data is available, allowing for data-driven decisions [6].

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The availability of real-time data allows machine learning to be used for production scheduling. In research, machine learning methods are already employed for scheduling [e.g., 7], and literature reviews summarize methods used for scheduling (cf. Section 2). These reviews lack the characteristics of practical implications that arise due to the increase in complexity of the production scheduling problem and do not consider how the scheduling algorithms cope with the added complexity. This synthesis is required to show potential directions for future research on this topic. Therefore, we address the following research questions:

RQ 1: *How does current research on the use of machine learning for production scheduling consider characteristics of practical production scheduling problems?*
RQ 2: *How are the machine learning algorithms in current research solving the production scheduling problem?*
RQ 3: *What are the research gaps in machine learning for production scheduling?*

To answer these questions, we first present related research. Then, we introduce the research design before we discuss and synthesize the results and develop a taxonomy of machine learning algorithms for production scheduling. Afterward, we discuss the implications of the results and derive research gaps before we conclude our research and provide an outlook on future research.

2 Related Literature Reviews on Production Scheduling

In recent literature, there are already some structured literature reviews on the application of machine learning in production scheduling. Branke et al. [8] summarize the state of the art of hyper-heuristics to design scheduling rules. Lin and Gen [9] have a broader scope of evolutionary algorithms and present representations, hybridization techniques, and machine learning techniques to enhance evolutionary algorithms. Cunha et al. [10] provide a brief overview of evolutionary algorithms and deep reinforcement learning for job shop scheduling. They propose a high-level architecture for developing deep reinforcement learning algorithms for job shop scheduling.

Fazel Zarandi et al. [11] do not focus on specific algorithms and provide extensive literature for solving the scheduling problem with fuzzy logic, expert systems, machine learning, stochastic local search optimization algorithms, and constraint programming.

There are also literature reviews on the influence of Industry 4.0 on production planning, not having a focused view on scheduling. Usuga Cadavid et al. [12] contribute a methodology to implement machine learning into production planning and control approaches. Luo et al. [13] review the impact of Industry 4.0 on production planning approaches and software and argue for creating data-driven models for decision-making.

These reviews do not focus on the implications of practical scheduling problems and how scheduling in literature addresses these implications. Instead, they focus on the implementation of algorithms and distinguish basic scheduling concepts. These are essential topics, but they leave out the practical side of the increased complexity induced by the demand changes and technological improvements summarized in the idea of Industry 4.0 [4]. Therefore, we address these issues in our literature review.

3 Research Design

To answer the research questions, we conducted a structured literature review [14, 15]. The goal is to systemize the existing literature on the application of machine learning methods on production scheduling, integrate their results, and derive research gaps based on it. We searched scientific and practice-oriented databases not limited to highly ranked journals to also include case studies or smaller studies from a practical view that might contain additional information and constraints from practice. We used the search term "*machine learning" AND "production scheduling"* to find relevant literature. Literature is relevant if the research uses machine learning to solve the production scheduling problem. After the full-text analysis, 114 papers were relevant. Figure 1 summarizes the research design. Extended information is available in the online appendix (http://bit.ly/3ZbGxyX).

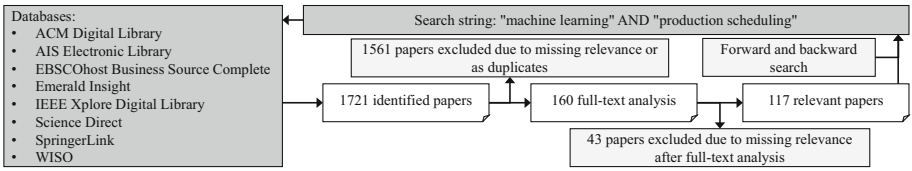

Fig. 1. Research Design

4 Results of the Literature Review

In the following, we present the main results of the structured literature review. The descriptive results and the literature matrix containing all results are available in the online appendix (http://bit.ly/3ZbGxyX). First, we address RQ 1 and summarize and synthesize the scheduling problems' practical characteristics. Afterward, we present how the algorithms solve the scheduling problem, answering RQ 2. Finally, we integrate the results of RQ 1 and RQ 2 by developing a taxonomy.

4.1 Practical Characteristics of the Addressed Problem

Analyzing the literature, we categorized the characteristics of the addressed scheduling problem to answer RQ 1. The standard literature problem was often examined, while other research included constraints and added complexity from practice. The percentages show how often we found the characteristics in literature.

In most cases, the **goal** of the scheduling algorithms was to minimize the makespan of production [16]. Costs are often not considered. Alternatively, research focuses on the tardiness of jobs, and in some cases, on earliness [17]. Some research combines multiple optimization goals, using scalar functions in which the goals are combined [18] or multivariate optimization [19].

The literature mostly ignores **Changeovers** (82%). Especially with a complex shop layout and a variety of products, changeovers allow for scheduling improvements. We found product [20] and sequence-dependent setup times [16] defined for each machine.

The standard literature problem assumes infinite **buffer** sizes (96%), and this assumption holds for small manufactured products or homogeneously designed shop layouts with enough buffer sizes for a typical schedule. The literature also accounts for buffer limits [20] or assumes buffers are non-existing [21] or additionally considers a no-wait condition [19].

In the case of rush orders, **prioritization of jobs** can be helpful. While most literature does not explicitly consider this (90%), some research included job weights in the goal function, e.g., mean weighted tardiness [22]. If prioritization is used within the algorithm, we find discrete priority classes [23] or continuous priority values [24].

94% of the identified papers ignored unforeseen events that invalidate a schedule. In the remaining literature, we found two strategies to deal with the **dynamics** of the shop floor: First, algorithms that can create schedules in near real-time, generate new schedules if events occur, and allow a quick reaction this way. Second, the algorithm can account for uncertainties by planning buffers to have a leeway for minor events [25], integrating the uncertainty as variables, e.g., through fuzzy theory [17], or evaluating the schedules using a simulation engine that includes the uncertainties [26].

Transportation on the shop floor is primarily ignored in literature or viewed as an independent problem (97%). With automated guided vehicles, the vehicle routing and assignment problem may be integrated into the production scheduling problem to allow for detailed planning of the arrival times of jobs on machines [27]. Specialized algorithms combining both problems or independent algorithms that cooperate are used. Alternatively, with simple transportation problems, transportation could be modeled as a production resource and scheduled as operations.

The algorithms are **evaluated** with priority rules or simpler versions of the proposed algorithm [27]. Combined with tailored production scenarios, the evaluation only demonstrates the algorithm's functionality but does not allow for comparison with different algorithms from other research. For this problem, benchmark problems are used [16]. They allow for comparability but represent the standard literature problems, which often do not include the just discussed increase in complexity.

4.2 Implementations of the Machine Learning Algorithms

In the following, we address RQ 2. Across all algorithms, the **scheduling mechanism** can directly [23] or indirectly decide on the job-machine assignments. The latter decides on priority rules [28] or creates custom ones [22]. Indirectly deciding reduces complexity and allows for faster scheduling.

Regarding the type of machine learning algorithm used, we follow Marsland's classification [29]. Most identified publications use **Evolutionary learning**, mainly genetic algorithms [21]. The algorithm can decide the order in which jobs are scheduled [30], determine applicable priority rules [26], or create a new priority rule [31]. Scheduling with Evolutionary learning can be significant due to its iterative nature, making evolutionary learning infeasible for rescheduling and complex environments.

Supervised learning algorithms are used in four publications. In these, a neural network is trained to find priority rules for a situation [32] or calculate a job's priority [33].

We found **unsupervised learning** algorithms in seven papers. Based on historical data, the approaches learn clusters of situations in production where a specific priority rule is advantageous [34] or use a support vector machine to determine the weights of priority rules to create a custom priority rule [35].

The early **Reinforcement learning** approaches used Q-Learning with a Q-table containing the estimated rewards of a decision and decided on a priority rule for a given decision situation [28] or replaced the Q-table with a neural network allowing for a continuous problem representation [36]. The reward function must be designed to represent the scheduling problem's goal correctly. Reinforcement learning combined with direct scheduling must overcome the limitations of a fixed input size into the neural network. Current research only works with fixed problem sizes [7, 37], making the application in practice unfeasible, or they circumvent this issue by using the priority-rule-based scheduling algorithm [38]. Reinforcement Learning can quickly create new schedules because the model is pre-trained.

5 Taxonomy of Machine Learning Algorithms for Production Scheduling

Dimension	**Characteristics**				
Problem class	Single machine	Parallel machines	Flow shop	Job shop	Open shop
Changeovers	Not included	Product-dependent	Sequence-dependent		
Buffers	Not included	Buffer limits	No buffers	No-wait	
Prioritization	Not included	Weighted in goals	Priority classes	Priority values	
Dynamics	Not included	Planned buffers	Integrate uncertainties	Simulate uncertainties	
Transportation	Not included	Integrated algorithm	Separate algorithm		
Algorithm class	Supervised learning	Unsupervised learning	Reinforcement learning	Evolutionary learning	
Scheduling mechanism	Direct	Priority rules	Meta-heuristic		

Fig. 2. Taxonomy of machine learning algorithms for production scheduling

To integrate the results of the previous sections and provide a foundation for discussing the research gaps, we develop a taxonomy following the approach of Nickerson et al. [39], extended by Kundisch et al. [40]. The classified objects are machine learning algorithms for production scheduling, and the target user groups are practitioners and researchers developing or applying production scheduling algorithms. We define "features of machine learning algorithms for production scheduling" as our meta-characteristic and use the ending conditions suggested by Nickerson et al. [39]. The online appendix presents the intermediary results (http://bit.ly/3ZbGxyX).

We chose an empirical-to-conceptual approach for the first iteration, using the dimensions and characteristics discussed in the previous sections as a starting point.

Trying to condense the resulting comprehensive taxonomy, we decided on a conceptual-to-empirical iteration, discussing the taxonomy. We removed the *fast reschedule* from *dynamics* because it depends on the used algorithm class.

For the third iteration, we used the empirical-to-conceptual approach analyzing the literature reviews presented in Sect. 2. Their summaries of the literature on scheduling did not present the need for changes in the taxonomy. Therefore, the ending conditions are met. Figure 2 presents the final taxonomy.

6 Discussion of the Results

In this section, we answer RQ 3. Therefore, we discuss the results of Sect. 4 and derive research gaps based on it. Table 1 lists the identified research gaps.

Research on the open shop scheduling problem is underrepresented, as it is a unique form of manufacturing and job shop representing most manufacturing in practice [1]. Still, open shop is rarely researched in scheduling, representing a research gap [RG 1]. The increased use of reinforcement learning algorithms in recent years represents the advances of reinforcement learning in other areas. However, it is less researched than evolutionary learning, and it offers the possibility for more research on specific variants and scheduling problems, presenting a research gap [RG 2]. Most of the identified literature uses a scalar goal function to evaluate schedules, while multivariate optimization techniques can solve goal conflicts, making it another research gap [RG 3].

The literature mainly focuses on the default literature problem or extends it with one or a few of the presented practical characteristics. A scheduling algorithm implementing all presented characteristics could serve as a starting point for practical implementations, and such an algorithm would propose a general approach for scheduling problems in practice helping cross the bridge from research to practice. Therefore, it is a research gap [RG 4]. Finally, benchmark problems must also include the identified characteristics allowing a comparison between developed algorithms. Without proper benchmark datasets, evaluation sections of scheduling research papers only prove the functionality of the proposed algorithm but not the solution quality compared with other algorithms in different. Thus, creating benchmark problems for evaluating algorithms, including the identified additional characteristics, is a research gap [RG 5].

Table 1. Identified research gaps

Research Gap	Description
RG 1	Development of scheduling algorithms for open shop scheduling problems
RG 2	Further exploration of reinforcement learning algorithms for production scheduling
RG 3	Usage of multivariate optimization in production scheduling algorithms
RG 4	Creation of scheduling algorithms, including the identified practical characteristics
RG 5	Creation of benchmark problems for the evaluation of production scheduling algorithms that include the identified practical characteristics

7 Conclusion

In this paper, using a literature review, we found changeovers, buffers, prioritization, dynamics, and transportation as characteristics of practical problems often neglected and presented these findings in a taxonomy. Finally, we identified five research gaps. However, we acknowledge that our research has limitations. Even though we followed a structured approach, we might not have found all relevant literature. Furthermore, our research focuses on the research perspective, not the practical one. With this work, we contribute to research by synthesizing existing literature and deriving research gaps. For future research, it is most promising to develop general scheduling algorithms, including the identified practical characteristics, as they are required for practical use.

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Improving the Production Process of a Bakery: A Simulation Approach

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Abstract. The present study brings forward a simulation-based study of the production process of a Portuguese bakery. The main goal is to analyse different production processes and propose improvements, through the use of discrete event simulation. A relevant set of data was collected, and four productive processes were selected to be modelled using Simio software (Simulation Modelling based on Intelligent Objects). The analysis of the developed models highlighted the need for improvements and different scenarios were created to this purpose. Among the obtained results, it was found that the adoption of mixed production scenarios allowed the increase of the production level while maintaining the current existing resources. In conclusion, this study highlighted the ability of the simulation technique to analyse manufacturing processes, throughout the creation of different scenarios, providing insights on the production process optimising the companies' productive performance.

Keywords: Manufacturing · Simulation · Bakery · Case study

1 Introduction

Bakery industry has continuously changed over the past 150 years and the common artisan bakeries are being replaced by the technological bakery industry [1]. The constant changes on the market, with the increase of products variety, leded to automation and the need for new manufacturing environments [2].

In the middle 1980's the concept of par-baked frozen bakery expanded and in the early 1990's this technology was improved. A par-baked bread refers to a product fully baked, but without a crust [1]. There are many companies seeking the introduction and modernisation of their production processes, like the par-baked technique, without losing the flavour and tradition of their products.

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Simulation is a powerful technique in decision- making enabling the analysis and evaluation of a wide range of complex scenarios [3]. It can be defined as a method that imitates all the operations and processes of a system, during a time period, allowing to comprehend and analyse the system's behaviour [4]. A simulation model should be as similar as possible to the real system. Thus, it is important to define the problem to solve and collect all the information and required data. Concerning the model itself it is important to: (i) choose the type; (ii) evaluate; (iii) build in some computer language; (iv) validate; (v) perform a sensitive analysis; and (vi) verify if the results are consistent and representative [6].

Because of simulation versatility, many studies are being developed using this technique. This study presents the development of a simulation model to reproduce the manufacturing environment of a Portuguese industrial bakery. The aim is to analyse and improve some of the production processes. In particular, the analysis was performed in order to find alternatives to solve:

- the company is exceeding the production capacity of the daily working shift to meet the demand;
- due to the new production process implemented (par-baked process) and to the new production line configuration, the workers do not have standard times for their tasks;
- with the increasing number of orders it is increasingly difficult to meet the market's demands.

This work is organised into six main sections. The next section presents a brief literature review. Afterwards, in Sect. 3 we present the case study under analysis. A brief description of the company is presented, and the topic is contextualised and the production processes are described. In Sect. 4 we describe the methodology used to the development of the simulation models. Simulation results and a discussion are shown in Sect. 5 and, finally, conclusions are presented in Sect. 6.

2 Literature Review

The use of simulation technique is increasing due to its many benefits. As a result, managers are integrating simulation in their regular operations on an increasingly basis [7]. Simulation optimisation aims to identify the best input system' parameters considering all the possibilities. Its main objective is to minimise the consumed resources and, at the same time, maximise the obtained information in a simulation experiment [8]. Nowadays, computer simulation became a powerful tool for model and analysis of companies' performance [9]. Simulation technique allows to create mathematical and logical models to describe the behaviour of a system during a period of time [10].

Müller et. al [11] used the simulation software Arena to improve a productive real flow. According to the production phases two different scenarios were considered. Both scenarios were simulated and compared with the real system.

Results showed that it was possible to increase the productivity of the production line in both scenarios. Hassan and Abdelsalam [12] conducted a pioneer study using simulation. Using Simio software, the authors analysed the behaviour of a supply chain of the contraception methods for Egypt Ministry of Health. Loaiza, Sarmiento and Correa [13] developed a study using the simulation software ProModel aiming to increase production of an existing system. A flexible manufacturing cell was evaluated, in order to identify the best alternative to maximise the use of the available resources.

There are many possibilities when the subject is software packages and their popularity is increasing because of the many applications in reproducing engineering and management systems [14]. Nowadays, a wide variety of discrete simulation software are available. Among the most used softwares one can mention ARENA, ProModel, FlexSim, Simul8, WITNESS, ExtendSim, Plant Simulation, Simio, etc. [15].

In the next section a case study aiming to optimise the production process through discrete simulation, using real data is presented. The study was performed using Simio software. This simulation tool allows the creation of new objects with complex behaviour and it is possible to model discrete and continuous systems [16].

3 Case Study

The company "Pão de Gimonde" is located in the village of Gimonde, Bragança, Portugal. The company's mission is to recreate the tradition of artisan breads like in the old days. Among the different products of the company it is possible to highlight: wheat bread, rye bread, fig bread, and "bijou" bread.

Nowadays the company works in two working shifts. The first working shift works during the night and produce fresh products (breads) ready for distribution in the early morning. The second working shift starts at 8 a.m. and produces bread according to the new production process of par-baked breads. Nevertheless, on this study only the day shift will be analysed, since it is the one in expansion and with more needs to be improved.

After the introduction of the new par-baked products on the market, the demand have increased substantially, and often the eight-hours workday is not enough to complete the required production. As production cannot be stopped, due to the specific production process, the company use overtime production, resulting in extra hours to be paid.

Taking into consideration the actual production context, a simulation of the production system was performed. First illustrating the current reality, and then, different scenarios were tested with the main focus on adapt the actual production level to one shift of work. If this is not feasible, due to the configuration of the production, finding a solution to maximise production level that may reduce extra hours of work will be required. The four production processes included in this study will be described in the next section.

4 Modelling and Simulation

The development of the simulation model was divided into four main steps:

- Step 1: Evaluation of the manufacturing processes for the different products. The processes were studied and the manufacturing process workflows (flowcharts) were created to detail the activity-level steps that must be completed to produce finished products.
- Step 2: Data collection. Necessary data was collected during some visits to the company, and/or was available in the company.
- Step 3: Development of the simulation model. Taking into account the collected data, and using the developed simulation model, each production process was represented and evaluated.
- Step 4: Validation of the simulation model. The developed model was tested to confirm if it correctly represents the reality of the manufacturing processes. For that purpose outputs were produced and compared with the real activity of the company.

Then, for each product, alternative scenarios have been created in order to identify possible improvements in the current manufacturing process. The scenarios that have been studied will be described in Sect. 5.

4.1 Fig Bread Manufacturing Process and Model

To better understand the production process of the fig bread, a flowchart has been created to identify all the necessary manufacturing steps. Data collection was obtained by observing all the production steps and using the fly back method of a stopwatch time study. Then, processing times have been placed on the respective model equipment's and the entity movement logic was created. The production process of the fig bread was modelled and validated in order to check if the model is functional, and represents the production reality. Model's validation was performed checking all the entity paths, the processes times and sequences, and the entity behaviour during a time period of a working day. Then, it was verified if the created model matched with the observed reality during the data collection time period. After the verification phase the developed simulation model was validated. The production of the fig bread was simulated and the output produced by the model was compared with real production level of 477 units. Multiple replications were carried out and the maximum percentage of error obtained was 0.75%. So, it is possible to conclude that the simulation model may be considered valid and correctly represents the fig bread production process.

4.2 Wheat Bread Manufacturing Process and Model

The wheat bread manufacturing process was also illustrated in a workflow to better describe the production process. For this process, the data for the different processing times were provided by the company. For this reason, they were

considered reliable and representative of the reality of the company. The verification of the model was also performed to attest its functionality. During this step it was possible to certify if the process is being performed according to the reality and if the model works properly. To verify the simulation model, all the entity paths, the processes times and the entity behaviour were checked during a working day period. After that, it was possible to confirm that the model presented the expected behaviour, similar with the reality of the production line. After the verification of the model, the next step was the model validation. The model was simulated and multiple replications were carried out. Again, the model's output was compared with the quantity of wheat bread produced by the bakery. The higher verified percentage error was of 0.74%. Therefore, it is possible to conclude that the model may be considered valid and correspond to a correct representation of the wheat bread production.

4.3 Rye Bread Manufacturing Process and Model

The production process of the rye bread is very similar to the production of the wheat bread. Also, the data processing times for the rye bread were provided by the company. As such, they were considered reliable. The verification of the rye bread model was also performed to certify that the processes is according with the reality and if the model works properly. The model was ran and all the entity paths, the processes times and the entity behaviour were checked during a working day period. It was possible to confirm that the model presented a behaviour similar with the real production level. Due to validation purposes, the model was simulated and multiple replications were carried out. Again the model's output was compared with the real production level. In this case the higher percentage of error achieved was 0.184%. Therefore, it is possible to conclude that the model is valid and correspond to a correct representation of the rye bread production.

4.4 Bijou Bread Manufacturing Process and Model

The bijou bread is a typical bread consumed in Portugal. The production process of the bijou bread is slightly different from the production processes of the wheat and rye breads, since this variety of bread is always packed and shipped fresh. As for the wheat and rye breads the data of the processing times was provided by the company. Consequently, they were considered reliable. This production process was simulated and the verification of the model was performed to verify if the model works properly, and if the process is being modelled according to the reality. It was possible to verify that the developed model has a similar behaviour to that of the real production line. Model's validation was made simulating a daily working shift. In all the performed replications the production level of 1080 units of bijou bread was reached. Thus, the developed model may be considered valid and representative.

5 Simulation Results and Discussion

In this section the results of the developed simulation models are presented and discussed. Our aim is to analyse the production system behaviour and identify new production strategies. First single productions of all the four products were tested (fig bread, wheat bread, rye bred, and bijou bread). Then, simulation models were developed regarding mixed-production scenarios, where more than one product were produced in a daily shift. Six distinct scenarios were considered: (i) bijou and wheat bread; (ii) bijou and rye bread; (iii) bijou and fig bread; (iv) rye and wheat bread; (v) rye and fig bread; and (vi) wheat and fig bread.

The company's working shift is 8 h long. Nevertheless, it can be of 9 h if we consider the lunch break hour. During this time the employees are not working. Nevertheless, this time is useful in the production process, because the products are on the cold chambers. For this reason, in productions scenarios where the final product is frozen (fig bread, wheat bread and rye bread) the working shift is considered to have 9 h and in what concerns fresh products (i.e. bijou bread) the working shift has 8 h long. For the scenarios involving wheat bread we will consider that the shift begins at 3a.m. resulting in a 14 h shift. This is possible because a "fermentation" activity occurs during six hours and without the workers intervention.

The obtained results are shown in Table 1. It is possible to mention that, with exception of Scenario 5, if the company starts using a mixed-production strategy it is possible to, at least, duplicate the daily production in all the considered scenarios without exceed the working shift. Actually, and considering the production of single products, the company produces 500 units of fig, wheat or rye breads, and for the bijou bread 1080 units.

Table 1. Mixed Scenarios Production Level.

Scenario	Description	Production level
Scenario 1	Bijou + Wheat Bread	1580 units
Scenario 2	Bijou + Rye Bread	1580 units
Scenario 3	Bijou + Fig Bread	1580 units
Scenario 4	Rye + Wheat Bread	1000 units
Scenario 5	Rye + Fig Bread	973 units
Scenario 6	Wheat + Fig Bread	1000 units

In an attempt to increase the production level the dough's proportion was increased. Using this approach, six new scenarios (see Table 2) were created, where the dough proportion for each product was incremented. For example, in Scenario 8 it was considered an increment of 40% on the bijou dough and of 20% on the rye bread dough. Simulation's results highlighted the increase of the production level. Scenario 7 is the one with higher production level (2512 units) being produced 1512 units of bijou bread and 1000 units of wheat bread.

Table 2. Mixed Scenarios Production Level: After Increasing the Recipe.

Scenario	Description	Production level
Scenario 7	1.4xBijou + 2xWheat Bread	2512 units
Scenario 8	1.4xBijou + 1.2xRye Bread	2112 units
Scenario 9	1.2xBijou + 1.1xFig Bread	1850 units
Scenario 10	1xRye + 1.4xWheat Bread	1200 units
Scenario 11	0.96xRye + 1.02xFig Bread	990 units
Scenario 12	1.6xWheat + 1.09xFig Bread	1345 units

Note that scenarios where the bijou bread is involved have a final production bigger then the others. This happens due to the fact that bijou is a fresh product and it does not passes through the cold chambers, and also because the recipe of the bijou bread generate more units. Scenarios 10, 11 and 12 have reached lower production levels. This happens due to the fact that both products use the cooling chambers. This process narrows production level because of the smaller capacity of the cooling chambers. Finally, it is possible to highlight that even in Scenario 7, the maximum percentage of the processing time do not exceed 42.74%, which may be considered a low percentage.

6 Conclusions

This work aimed to analyse the production processes of an industrial bakery. The main goal was to study possibilities of increasing the production level to face the external increasing demand. Using Simio software, simulation models were developed to reproduce the production process of four product types: fig bread, wheat bread, rye bread and bijou bread.

A total of twelve scenarios were considered. The outputs of all scenarios showed that it its possible to face the increase of the external demand with the company's actual resources. In fact, it is possible to, at least, double the production level if the company adopts a strategy of mixed-production instead of a single item production.

In summary, the gathered results showed that changing the production strategy, it will be possible to increase the production level to face the external demand using the current existing resources.

As future works, it is possible to expand the developed simulation model, considering mixed-production of new product types, and explore different scenarios. Also new simulation models involving new production processes and or new production layouts may be developed and analysed.

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Making Flow in Machining and Non-machining Processes with Leveling and Small Lot Sizing: A Kaizen Case Study

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Abstract. This paper presents a kaizen case study that aims to create a smooth flow in both machining and non-machining processes, while addressing the inventory problem that arises in these processes. To accomplish this, we developed a model that analyzes the production requirements of various products in the machining process and the cleaning process of machined parts in the non-machining process. The machining and set-up times for each product differ depending on the CNC machine types used, and set-up labor resources are required whenever a machine switches to produce a different product. Meanwhile, the non-machining process involves cleaning batches of machined parts before they are delivered. In this study, we focus on creating an optimal flow between these two processes by considering different batch sizes and their impact on overall inventory. Our results demonstrate that by implementing a leveling and small lot sizing strategy, we can achieve a more efficient and streamlined production process that reduces inventory levels and improves productivity.

Keywords: Inventory · machining processes · non-machining processes · batch size

1 Introduction

In response to the increasing demand for efficiency, quality, and cost reduction in industrial production, many companies are turning to lean production as an approach to optimize their production processes. Toyota Production System (TPS) is a well-known example of lean production, with its two key concepts of "Just in Time" and "JIDOKA" driving the success of many companies that follow its principles (Towill [1]). One important aspect of TPS is Kaizen, which refers to continuous improvement through small, incremental changes (Cannas et al. [2]).

In Taiwan, where over 90,000 factories operate, many companies are still adopting mass production systems. However, some are attempting to transition to lean production to stay competitive in the global market. This paper examines the case of a Taiwan manufacturing company (referred to as Company T) that specializes in producing components and parts for the automobile, medical, electronic, and industrial applications sectors.

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The company faces challenges in managing its inventory due to the high volume of precision metal components produced daily and the use of mass production methods. Additionally, the company's over 100 automatic CNC machines require significant set-up time and labor resources, making scheduling difficult. To address these challenges, this study analyzes the trade-off between inventory and dynamic lot sizing.

A model is developed to analyze the work in process (WIP) between machining and non-machining processes. The machining process involves producing a variety of products with varying machining and set-up times for each product on different machine types. The non-machining process requires the cleaning of machined parts in batches before delivery. The study focuses on establishing a flow between machining and non-machining processes with different batch sizes, considering their impact on total inventory.

Through this case study, the paper aims to demonstrate the benefits of implementing lean production principles, including Kaizen, in a real-world context, providing insights that may be useful to practitioners seeking to optimize their production processes and researchers interested in the application of lean production principles.

2 Literature Review

Towill [1] analyzed the DNA of TPS and highlighted the importance of balancing flow and inventory to achieve efficient manufacturing operations. Cannas et al. [2] applied complexity reduction and Kaizen events to balance manual assembly lines. They proposed a method that integrates the analysis of the time taken for each task and the operator's skill level to improve the balance of manual assembly lines. This approach can be useful for industries that rely on manual labor, such as the garment industry. Bozer and Ciemnoczolowski [3, 4] provided insights into how lean manufacturing can be applied to the milk running system, with a model that focuses on balancing high utilization with achieving the decision-maker's target cycle time and tugger capacity. Their work also considered the impact of the number of Kanban and the physical capacity of the tugger on workstation starvation. Diaby [5] proposed a model for reducing set-up time and batch sizes in dynamic manufacturing environments, which was solved using a heuristic method. Glock [6] studied a model that treated productivity as a variable, with production rate affecting the probability of the production process going out of control. Rau and OuYang [7] developed a mathematical model for minimizing joint costs incurred by vendors and buyers, which generated optimal and unique solutions for increasing and decreasing demands. Chen and Sarker [8] presented a mathematical model for decision-making on lot sizes, delivery frequencies, and vehicle routes of suppliers. Hoque and Bhattacharya [9] proposed an integrated single-manufacturer multi-buyer model that incorporated generic continuous probability distribution of lead time for delivering equal and/or unequal batch sizes of a lot. Li et al. [10] introduced a solution procedure for a single-machine batch scheduling problem with three objectives, including the maximum upper limit of batch sizes and completion time, and minimum flowtime. Park et al. [11] developed a model for finding the optimal batch size with the minimum average cost.

While the above literature focused on solving the problem of the machining process and optimization costs, this paper aims to study the lot sizing and the flow between

the machining and non-machining processes. The impact of batch size on the work-in-progress before the non-machining process will be investigated, with a focus on improving the overall process efficiency. By examining the impact of batch size on work-in-process before the non-machining process, this study aims to contribute to the broader understanding of production systems and improve the overall efficiency of manufacturing processes by identifying the relationship between batch size and inventory levels.

3 Problem Description

In Company T, different precision-machined metal parts are produced every day and the manufacturing process is divided into machining and non-machining processing. In the machining process, there are hundreds of CNC machines running every day, such as turning and milling. In the non-machining process, there is a cleaning room for cleaning all products produced by the CNC machines. The problem Company T faces is the inventory in the factory is too high.

In this paper, one of the orders of Company T will be used as an example to investigate the application of lean production, which includes pull production and levelized production in Taiwanese companies. The manufacturing process of Company T will be simplified into two steps, a machining process and a non-machining process.

First, the factory allocates 20 CNC machines to complete the order ID FFF0001 which requires a weekly production of 6000 pcs of product a, 2000 pcs of product b, and 4000 pcs of product c. Company T categorizes these 20 machines into 4 types, LS, LD, LC and LR with the brands and types (Swiss turning, Horizontal turning, Multi-axis turning, etc.). There are 5 machines of type LS, 2 machines of type LD, 7 machines of type LC, and 6 machines of type LR, and each machine is capable of producing two or more products. The LS-type machine can produce products a and b with a rate of 360 s per pc and 390 s per pc respectively. The LD-type machine can produce products b and c with a rate of 360 s per pc for both. The LC-type machine can produce products a and c with a rate of 420 s per pc and 390 s per pc respectively. The LR-type machine can produce products a, b and c with a rate of 390 s per pc, 420 s per pc and 420 s per pc respectively. Table 1 refers to the processing times of the three products using different machine types.

Table 1. Processing times of the products produced on different machine types.

Product\machine	LS	LD	LC	LR
a	360	N/A	420	390
b	390	360	N/A	420
c	N/A	360	390	420

Second, changing the production items on the same machine requires a set-up time. The changeover set-up times between products a and b, between products a and c, and

between products b and c are eight hours, two hours, and eight hours respectively. Four set-up engineers are present every day and one person can only work on one machine at a time. Therefore, no more than four machines can have set-up procedures at the same time. Table 2 refers to the set-up times for product changeover.

Table 2. Set-up Time

Product\Product	a	b	c
a	N/A	8 h	2 h
b	8 h	N/A	8 h
c	2 h	8 h	N/A

Third, each product has its daily production target pre-determined by the production control manager. For instance, on Monday, the production targets of products a, b, and c are 1500 pcs, 300 pcs, and 800 pcs respectively. On Tuesday, the production targets of products a, b, and c are 800 pcs, 800 pcs, and 1000 pcs respectively. The factory will only operate from Monday to Friday, working 16 h a day. Table 3 refers to the daily production targets of the products.

Table 3. Daily production targets of the products.

Product	Monday	Tuesday	Wednesday	Thursday	Friday
a	1500	800	1200	1300	1200
b	300	800	600	300	400
c	800	1000	800	1000	400

The scheduling is based on the daily production targets and sufficient quantities are produced every week. However, the daily production volume may fluctuate depending on the production targets set for each day. Some days may result in extra production while others may produce fewer quantities than the set target. Nevertheless, the overall weekly production targets are met. Combining the above, a weekly schedule (Table 4) can be arranged manually as follows:
The rules for manual scheduling are as follows:

1) The order with the largest quantity is scheduled first.
2) Products are assigned to the machine with the shortest production time first.
3) The type with fewer machines will be distributed first.

Since Company T uses the “batch-production” at present which results in two “isolated islands”, the clustered CNC machines (for machining processes) and the cleaning room (for non-machining processes), i.e. the machining processes run independently from the non-machining processes. The production schedule for machining processes

Table 4. Weekly production schedule.

Product	Monday	Tuesday	Wednesday	Thursday	Friday
a	1504	800	1196	1300	1200
b	304	736	664	294	400
c	808	997	799	998	403

can be made using some powerful heuristics or different algorithms. However, without considering the non-machining processes, such two islands result in huge excess inventory.

Figure 1 shows the flow of machining and non-machining processes. Inventory 1 (shown as I1 in Fig. 1) stands for the inventory of the non-machining process and only the necessary amount of inventory is left in I1. The batch-processing work in process produced from the machining process will also be stored in I1. Inventory 2 (shown as I2 in Fig. 1) stands for the daily inventory caused by the excess output of the non-machining process. The entire flow is that work in process from the machining process will be sent to inventory 1. Then non-machining process uses the semi-finished products in inventory 1 to do the batch processing and produce finished products. Finished products will be delivered or stored in inventory 2 if extra products are produced.

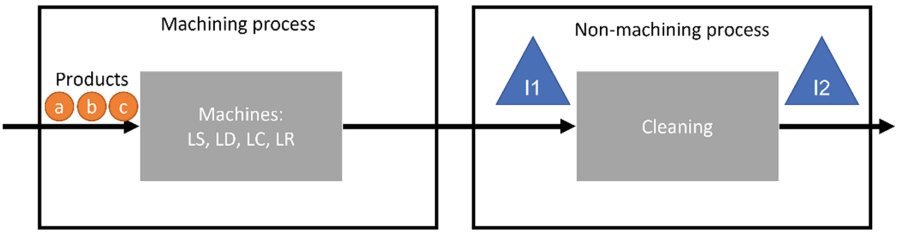

Fig. 1. Flow chart of the machining process and non-machining process

To cope with the daily shipment demand shown in Table 3, the cleaning room will also operate every day in which different products will be collected into a batch for cleaning. In the first scenario, products a, b and c will be in batches of 1000 pcs, 600 pcs and 800 pcs respectively which is likely to generate inventory in I1 and I2 in Fig. 1 every day. For example, the production demand for product a on Monday is 1500 pcs and product a will be cleaned in a batch of 1000 pcs. If the demand for 1500 pcs of product a on Monday is to be met, 2 batches need to be cleaned on Monday in the cleaning room, that is 2000 pcs. During the machining process, 1504 pcs of product a will be produced as shown in Table 4 and then shipped to the cleaning room. Therefore, the necessary inventory of product a in the cleaning room on Monday is 496 pcs, which is I1. After product a is cleaned, the extra 500 pcs of cleaned product a will be produced which will be stored in the finished product inventory, I2, in the cleaning room.

In Table 5, extra cleaned products will be produced on Tuesday and 700pcs of extra product a will be stored in I2 for use on Wednesday. As Wednesday's requirement for product a is 1200 pcs, in order to cope with this quantity, two batches of product a should be cleaned. However, the 700 pcs of product a in I2 on Tuesday resulted in only one batch of product a needs to be cleaned. After the cleaning of 1000 pcs from the production of 1196 pcs of product a produced on Wednesday, 196 pcs of WIP are left in I1 inventory. In adding the 296 pcs on Tuesday, there will be 492 pcs of WIP of product a on Wednesday in I1.

Table 5. Weekly WIP with batching plan scenario 1 (non-machining processes)

Scenario1		Monday		Tuesday		Wednesday		Thursday		Friday	
	Lot size	WIP (I1)	WIP (I2)	WIP (I1)	WIP (I2)	WIP (I1)	WIP (I2)	WIP (I1)	WIP (I2)	WIP (I1)	WIP (I2)
a	1000	496	500	296	700	492	500	792	200	992	0
b	600	296	300	136	100	200	100	104	400	96	0
c	800	8	0	595	600	594	600	792	400	395	0

4 Experiment

4.1 Leveling Daily Production Targets for Machining Process

The above is a simplified version of the actual example of Company T in Taiwan where manual scheduling is used in the machining process and the batch sizes of products in scenario 1{a, b, c}: {1000,600,800} in the non-machining process are used for cleaning resulting in a total WIP of 10684 pcs as shown in Table 5. Since the primary goal is to reduce WIP and shorten lead time, we believe that leveling is the key to improve scenario 1, i.e. the daily shipment demand is leveled while the total weekly shipment volume remains unchanged. Table 6 shows the production targets after levelization and the daily demand for products a, b and c is 1200 pcs, 480 pcs and 800 pcs respectively.

Table 6. Daily production targets of the products after levelization.

Product	Monday	Tuesday	Wednesday	Thursday	Friday
a	1200	1200	1200	1200	1200
b	480	480	480	480	480
c	800	800	800	800	800

A weekly schedule that uses the same rules as before can be arranged manually to satisfy the above daily demands. The related scheduling results are as follows:

1. Monday: 1205 pcs of product a, 480 pcs of product b, and 808 pcs of product c.
2. Tuesday: 1196 pcs of product a, 480 pcs of product b, and 799 pcs of product c.
3. Wednesday: 1205 pcs of product a, 480 pcs of product b, and 799 pcs of product c.
4. Thursday: 1196 pcs of product a, 480 pcs of product b, and 799 pcs of product c.
5. Friday, 1205 pcs of product a, 480 pcs of product b, and 799 pcs of product c.

After levelization of daily production targets of the products, scenario 2 shows the total WIP is 9921 pcs which is less than that of scenario 1.

4.2 Reducing Lot Size for Non-machining Process

The previous experiment shows that the total WIP inventory will decrease as the daily target becomes levelized. In order to reduce the inventory further, we decided to test the effects of batch size reduction and the experimental results for scenarios 3 and 4 are shown in Table 7 for different batch size conditions.

Table 7. Total WIP with scenarios 1–5.

Scenario	Lot size (a, b, c)	WIP (I1)	WIP (I2)	Total WIP
1 (Present condition)	1000,600,800	6284	4400	10684
2 (Leveling daily target for machining)	1000,600,800	6721	3200	9921
3 (Reducing lot size)	500,300,400	2601	1600	4201
4 (Reducing lot size)	250,150,200	1065	800	1865
5 (Reducing and fixing lot size)	80,80,80	51	0	51

In scenario 3, half of the batch sizes of scenario 2 are used, i.e., scenario 3{a, b, c}: {500,300,400}, and the total WIP is 4201 pcs. In scenario 4, the batch sizes are further reduced to half of those of scenario 3, i.e. scenario 4{a, b, c}: {250,150,200) and the total WIP is 1865 pcs. It can be clearly seen that as the batch sizes decrease, the total WIP also decreases rapidly.

4.3 Reducing and Fixing Lot Size for All Products

Combining the results in experiments 4.1 and 4.2 above, we can conclude two important points:

1. The total WIP produced can be improved by leveling the daily production targets.
2. The total WIP decreases as the batch sizes decrease.

In part 3 of the experiment, an attempt is made to find the best batch sizes for reducing the total inventory. Based on experiment 4.2, the highest common factor of the

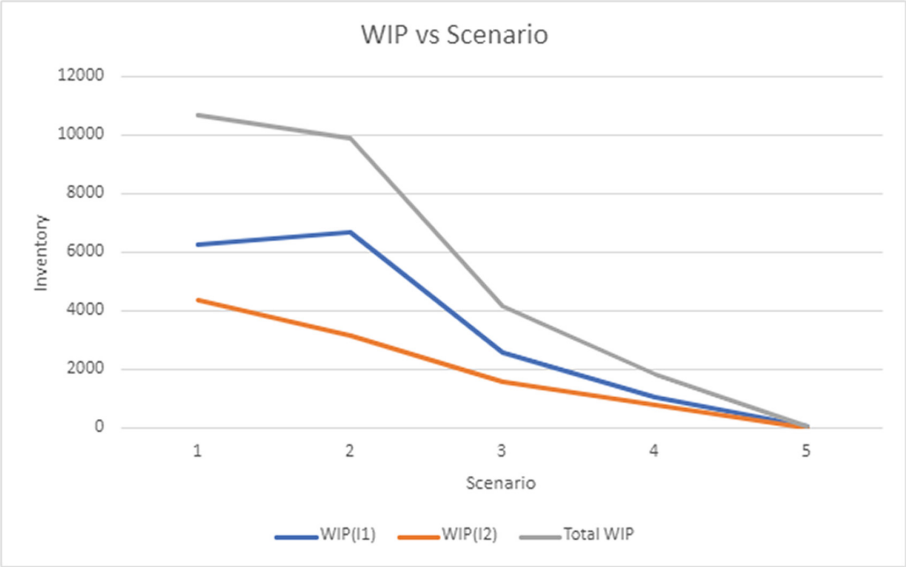

Fig. 2. Line chart of total WIP produced in scenarios 1–5.

daily production targets is used as the batch sizes of scenario 5, i.e., scenario 5{a, b, c}: {80, 80, 80} and the total WIP is 51 pcs which is the best overall.

Figure 2 shows that from scenario 1 to scenario 2, the total inventory decreases slowly while from scenario 2 to scenario 5, the total inventory decline is very rapid. This shows reducing the batch sizes can effectively reduce the inventory.

Conclusions and Recommendations

After examining the non-machining process in Company T, this study has identified several key contributions to reducing inventory from a lean perspective. Our results demonstrate that reducing batch sizes, in addition to leveling daily production targets, can effectively lower inventory levels. Moreover, using the highest common factor of daily production targets as the batch sizes can optimize inventory reduction. These findings are consistent with previous literature on lean production systems, which have emphasized the importance of batch size reduction and production leveling in improving manufacturing efficiency (Bozer and Ciemnoczolowski [3, 4]; Womack et al. [12]).

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Simulation Approach for Solving Production Problems Reducing Total Processing Time

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Abstract. This paper presents an application of computational simulation to a production problem on unrelated parallel machines and dependent setup times, aiming at the reduction of jobs' total processing time (makespan). The scenarios studied by Rabadi, et al. (2014) were used, along with the SIMIO simulation software, to model and conduct experiments to study the impact of a set of sequencing rules. Based on the computational study carried out, it was possible to realize that simulation is a powerful tool to support scheduling processes, as it allows to reach generally good results in a reasonable time to properly support decision-making in the resolution of production problems. These problems are highly complex and dynamically changing in nature, being usually hard to solve. Thus, simulation tools are of particular interest in this field. Moreover, as these problems are characterized by a more or less extensible set of factors, parameters and conditions, it continues to be of primer importance to further explore its resolutions, namely based on simulation tools. This study relies on the base for being used in industrial practice in the context of iFixturing Project.

Keywords: Production problems · Parallel machines · Setup times · Modeling · Discrete event simulation

1 Introduction

One of the most problematic areas in many industrial sectors is the optimal production scheduling. Scheduling methods have a very broad application in solving a wide variety of problems, under varying kind of conditions and manufacturing environments, and by making use of different kind of technology and solving systems [1–3].

Solving a scheduling problem entails two main sub-problems: (1) allocation, assign resources to be available to perform each task; and (2) sequencing, to define when each task will be performed.

The configuration of a parallel manufacturing line or flow shop can be defined simply as the replication of several classic manufacturing ones, i.e., instead of having just a

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classic or a simple manufacturing flow shop (e.g. a permutation flow shop), one can have several lines in parallel, where all of them are integrated into a single production system [4].

The benefits of a good scheduling and sequencing process of a production line are several, namely: better compliance with delivery deadlines, stock reduction, increased productivity, reduction of unproductive stops, and improved customer satisfaction [5].

Minimizing makespan generally implies a good use of production resources, typically machines and workers. According to Lustosa, et al. (2008) [6], production scheduling represent one of the most important management issues.

The constant demand for a reduction in delivery times solicits the developed of new methods, with the main objective of making delivery more efficient. Due to the difficulty of characterizing and solving more complex scheduling problems, along with the urgency of defining a production plan, simulation tools allow to build a simulation model – adapted to the specific production system – and to predict results. Moreover, these simulation models can also be adapted to different scenarios, enabling timely and suitable results for the production line scheduling processes.

Computer simulation refers to methods of studying real or abstract systems, in numerical evaluation models, using dedicated software, through simulation models developed specifically to replicate the behavior of a system under analysis, with specific characteristics, usually for a defined time period [7]. Few methods are as flexible and popular as simulation.

This work builds on a previous work developed by Rabadi, et al. (2014) [8], making use of the scenarios studied and shared by that team. This approach was defined to allow for a direct comparison between the two studies. This paper applies computational simulation to schedule tasks in unrelated parallel machines with dependent setup times. The aim is to reduce jobs' total processing time (makespan). The SIMIO simulation software was used as the simulation tool to model and conduct experiments of a set of sequencing rules. This was followed by the study of the impact of each one.

This paper starts with the present introduction, to frame the reader. It is followed by a literature review on the relevant topics: manufacturing scheduling, sequencing rules, and simulation. On the third chapter the simulation model is presented. Results are presented and discussed on the fourth chapter. The fifth chapter presents the conclusions.

2 Literature Review

2.1 Manufacturing Scheduling

Production scheduling deals with the resource allocation to perform a given set of jobs, which can integrate one or more tasks or operations, during a given period. Its goal is to optimize one or more performance measures, ensuring that tasks are executed at the right time, with the adequate resource [9].

Production systems involve several decisions to be taken at the planning level, especially in cases where there are diverse resources to be managed, and it is important to guarantee not only the delivery deadlines fulfillment, as well as cost and time minimization of the production process for relatively extended set of jobs.

Sequencing usually aims at minimizing the maximum completion time of a set of tasks (makespan), the delay (tardiness), the early completion of tasks (earliness), the total number of tasks delayed (tardy jobs), or a combination of these objectives. Such objectives can be linked to a prioritization factor (weight), which takes the form of an importance factor or a representative cost factor of the task [10, 11].

Scheduling problems are very complex and computationally difficult to solve due to their diversity, dynamic nature, and dimension. They are usually characterized as optimization problems [2]. Schrijver, in 2003 [10], described that Edmonds, in 1960, defended the idea of classifying the method as efficient if its execution time is limited by a Polynomial (P). Later, in 1970, Cook and Karp defended that several other combinatorial optimization problems are more difficult, thus, creating a new class, called Non-Deterministic Polynomial Time (NP). Xiao, et al., in 2016 [11], described that a task sequencing problem in a system with several machines, are treated as complex combinatorial problems of the NP-hard type. In other words, they require a non-polynomial (exponential) processing time to obtain the optimal solution according to the increase of the number of machines and/or tasks.

2.2 Sequencing Rules

A sequencing rule is a rule that assigns a priority to each job, which is waiting to be processed by a machine. Research on sequencing rules has been conducted for decades, and several different rules have been developed and studied by the scientific community [12]. A sequencing rule serves the objective of selecting the task which will have processing priority over the other tasks, based on the production orders (OP) and/or the conditions of the production system [13]. Variations in the arrival time of tasks classify these either scheduling problems or rules as dynamic (tasks arrive at different times) or static (tasks arrive simultaneously, for being processed) [14, 15]. Sequencing methods are considerably easier to implement, however allow several types of solutions. In simpler problems, they can even achieve a good solution. As an example, the Shortest Processing Time rule guarantees the lowest total flow time, while the Early Due Date rule guarantees the lowest maximum delay for some single machine problems. However, when dealing with a more complex problem, sequencing rules will only be useful if incorporated into meta-heuristics, which do not guarantee an optimum result [16].

2.3 Simulation

Computer simulation refers to methods of studying real or abstract systems, in numerical evaluation models, using specific software. In simpler terms, it is the process of creating a computerized model with the objective of carrying out numerical experiments, in such a way that it provides an understanding of the system, subjected to a certain set of conditions [7].

As mentioned by Poça [17], according to Law & Kelton [18] and Paiva [19], simulation models can be classified as follows: open versus closed, static versus dynamic, continuous versus discrete, deterministic versus stochastic.

Simulation has shown increasing use in situations involving discrete events, to assist decision-making, and is applicable to any type of system, since several research methodologies in simulation have been developed, proving its effectiveness in solving problems [20]. Pegden [21] describes that the SIMIO tool is a discrete event simulation software designed around basic object-oriented principles. It allows building and executing varying kind of dynamic 2D and 3D models. This allows the user to visualize their designed models running them before implementing or modifying a real system.

3 Proposed Simulation Model

Rabadi, et al., in 2010 [22], addressed a scheduling problem of non-preemptive tasks on unrelated parallel machines, with machine and sequence dependent setup times. For this problem it is considered that: (a) all jobs are available at time zero, (b) all times are deterministic, and (c) the objective is to minimize makespan. An Ant Colony Optimization (ACO) algorithm was presented and applied for this NP-hard problem.

An extension of earlier work of Rabadi, et al., in 2014 [8] tested their ACO under processing or setup dominant times, where the distributions are different, and the dominant distribution has higher values, thus reaching their ACO II.

The results obtained with the ACO II algorithm were compared with the Tabu Search by Helal, et al. [23], Meta-RaPS by Rabadi, et al., in 2006 [24], Ant Colony Optimization I by Rabadi, et al., in 2010 [22], Simulated Annealing (SA) and Restrictive Simulated Annealing (RSA) by Ying, et al. [25].

For the construction of the model, data on processing time and setup time were collected using Scheduling Research, used by Rabadi, et al., in 2014 [8]. Two conditions were chosen to be analyzed: (1) balanced processing times and setup times (balanced problem), and (2) dominant setup times (setup dominant problem).

For each of these scenarios, the processing times and setup times were randomly generated from the two uniform distributions: U(50,100) and U(125,175), and each machine combination was tested with 15 instances of the problem [8]. Therefore, in the balanced scenario: U(50,100) for both processing and setup times was used; and in the setup dominant one: U(50,100) was used for processing times and U (125,175) for setup times. Moreover, sets of (2, 4, 6, 8, 10, 12) machines and (20, 40, 60, 80, 100, 120) jobs were considered. In total, 72 scenarios were analyzed, 36 with setup dominant characteristics, and 36 scenarios with balanced characteristics, which were divided into 12 sets, considering 15 instances for each scenario.

The sequencing rules proposed in this work are based on well-known ones, namely: the SPT (Shortest Processing Time), the LPT (Longest Processing Time), the SIRO (Service In Random Order) and the SQ (Shortest Queue). For setup times, the proposals are based on the Shortest Setup Time (SST) rule and some details are adaptations based on the heuristics presented by Gupta, et al. [26] and Li [27]. The five sequencing rules for conducting the analysis of these problems are described below.

- S0: Sequence of tasks performed randomly;
- S1: Sequence of tasks in descending order of processing time value;
- S2: Sequence of tasks in ascending order of processing time value;
- S3: Sequence of tasks in descending order of setup time;

– S4: Sequence of tasks in ascending order of setup time.

For rules S3 and S4, the setup time depends both on the task to be processed and on the task executed immediately before it, on the same machine, hence, called sequence dependent. Other parameters must also be considered:

– Machine number is represented by m;
– There is no preemption during sequencing, i.e., tasks cannot be interrupted during model execution;
– Each machine processes one job at a time;
– All jobs are available at time zero;
– All machines are available at time zero;
– Each job has a machine-dependent processing time;
– Each machine has a job-dependent setup time.

The simulation model was verified and validated using the input data from the work developed by Rabadi, et al., in 2014 [8].

4 Results Presentation and Discussion

The five proposed sequencing rules, S0 to S4, were modelled according to the study by Rabadi, et al., in 2014 [8], using the SIMIO simulation software. To decide on the number of replications to ran on experimentation, two scenarios were chosen, and 5, 10, 15, 20, and 25 replications were ran on both scenarios. In both scenarios, all replications maintained the same input values. This was followed by a comparison between the total processing time values, of the sequencing rules used, with the total processing time values of the ACO II results [8], for the same sequencing rules.

For all instances, the average percentage deviation of the sequencing values was calculated and compared to the ACO II values, according to Eq. 1, below:

$$\frac{Cmax(s) - Cmax(ACO\,II) * 100\%}{Cmax(ACO\,II)} \tag{1}$$

It can be seen in both cased (a) and (b) of the Fig. 1 about balanced and the setup dominant scenarios, respectively, the values tend to stabilize after 20 replications.

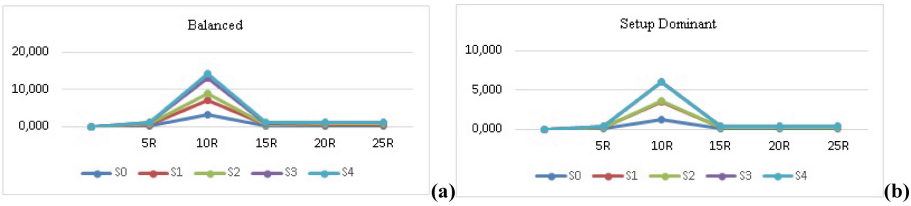

Fig. 1. (a) Balanced and (b) setup dominant problem results comparison.

All obtained results can be viewed at bit.ly/3M2kKpt. Through these results, and considering the five sequencing rules plus the ACO II, it is possible to identify that on

the **balanced** scenarios, the ACO II represents **92%** of the scenarios with the lowest total processing time, while in the S2 sequencing presents 8%. In the **setup dominant** scenarios, the ACO II represents **72%** of the scenarios with the shortest total processing time, while S2 sequencing represents 19%, and in the S4 sequencing it represents 8%. On the **shortest total processing time** it is possible to analyze that it was found ACO II with **82%** of scenarios, followed by S2 sequencing with 14%, and S4 sequencing with 4%; demonstrating the superiority of Ant Colony Optimization (ACO II).

However, the rules used in ACO II follow a different pattern from those present on the sequencing rules proposed in this work. Therefore, by taking out ACO II, a new analysis was carried out, considering only those five sequencing rules proposed. On this new analysis, it was possible to realize that for the scenarios with **balanced times** the S4 sequencing rule represents **75%** of the scenarios with the shortest total processing time, while the S2 sequencing presents 25%. For **setup dominant**, S4 sequencing represents **72%** of the scenarios with the shortest total processing time, while S2 sequencing represents 28%.

The **S4 sequencing rule** presented **74%** of the lowest values of total processing time, and the S2 sequencing presented 26%. Therefore, the sequencing with the sequencing rules Shortest Processing Time (SPT) and Shortest Setup Time (SST) presented satisfactory results for the purpose of this work.

5 Conclusion

The main objective for this work was to study a production problem, taking as reference the studies conducted by Rabadi, et al., in 2014 [8], and analyze the effects of five different sequencing rules with each other, and compared with the ACO II.

The same problem has been previously studied by other authors, using different methods, such as: Tabu Search by Helal, et al. [23], Meta-RaPS by Rabadi, et al. [24]; ACO I by Rabadi, et al. [22]; and Simulated Annealing (SA) and Restrictive Simulated Annealing (RSA) by Ying [25].

Computational simulation was chosen to conduct experiments due to its flexibility in modeling different sequencing rules, while keeping the base model equal, in order to compare results of the five sequencing rules considered in this work. The simulation software SIMIO was chosen due to its modelling capabilities and experimentation features. This approach proved to be well suited for this work.

The simulation modelling was developed considering commonly used sequencing rules, such as S0 - SIRO (Service Random in Order), S1- LPT (Longest Process Time), S2- SPT (Shortest Process Time), S3- LST (Longest Setup Time), and S4 - ST (Shortest Setup Time).

One of the main conclusions is that the total processing time values found by using the ACO II algorithm – developed by Rabadi, et al. (2014) [8] – were quite often smaller when compared with the other five proposed sequencing rules. However, it is important to note that the difference between those values found through ACO II was small compared to the values obtained when using the S4 sequencing rule – which prioritizes jobs with the Shortest Setup Time (SST) through the SIMIO software.

When only comparing the five sequencing rules proposed for this work, it was identified that the sequencing rule S4 – which prioritizes jobs with the Shortest Setup Time

(SST) – continued to obtain satisfactory results, achieving quite often the lowest total processing time values. The exceptions were systematically found in scenarios with the larger number of machines (10 and 12) and with number of jobs (20). On these few exceptions, the sequencing rule S2 – which prioritizes the work with the Shortest Processing Time (SPT) presented the lowest total processing time values.

As future work, it would be interesting to analyze scenarios for conditions where the processing time is greater than the setup time (process time dominant), and define other sequencing rules for the first jobs entering the machine, which are not dependent on the setup time, with the objective of finding the best combination of sequencing rules for reducing the total processing time.

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Realizing Waste-Reducing Potential in Small-Lot Production with Digital Twins

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Abstract. New digital technologies are integrated to improve production. The Lean manufacturing paradigm is the foremost approach to creating efficient processes in the industry. In small-lot production, improvements include optimizing the process and decision-making for controlling the quality of the final product, reducing production time, and saving energy. This research overviews existing combinations of Lean manufacturing and Industry 4.0 technologies by literature review and discusses the potential of the digital twins in lean manufacturing. The objective of this paper is to investigate the potential of digital twins, as a state-of-the-art technology in industry 4,0, in small-lot production in the metal-cutting industry. As a result, a digital twins framework with five layers is proposed to use in the product design and manufacturing phase of a product lifecycle with a lean waste paradigm. The tasks of these layers are to transfer data from the physical space to the virtual space, extract information and knowledge, analyses them to select the appropriate manufacturing parameters, evaluate the results, and predict the status of the production. The framework enables the users to optimize the process planning and make decisions based on the updated data from the physical shop floor.

Keywords: Industry 4.0 · Digital twins · Lean manufacturing · Small-lot production · Small and medium-sized enterprises

1 Introduction

Advanced technologies in the fourth industrial revolution assisted manufacturing factories in shifting toward an innovative manufacturing paradigm with automation and intelligent decision-making to enhance product life cycles [1]. The circular economy assists the manufacturing industry through sustainability intention. SMEs consume a noticeable percentage of energy. Researchers investigate industry 4.0 integration with CE to achieve appropriate energy efficiency [2].

In Finland, small and medium-sized enterprises (SMEs) have a noticeable manufacturing industry share. In 2021, the statistic showed that 1711 SMEs (5–99 employees)

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are active in manufacturing basic metals, fabricated metal products, and machinery and equipment [3]. The focus of this statistical analysis was to understand the level of digitalization in SMEs in Finland. This study discovered the needs of SMEs in applying Industry 4.0 technologies such as cyber-physical space, cloud computing, communication technologies in warehouse management systems, and optimization in production [4, 5].

Optimizing small lot production is complicated due to many factors affecting the output, depending on the human decisions from the designer or operator [6]. Product lifecycle management (PLM) assists enterprises in reducing cost and time and improving product quality. Procurement often uses supply chain management to support the production function [7]. Lean Manufacturing (LM) can be described as a multi-faceted production approach comprising a variety of industrial practices directed towards identifying value-adding processes from the purview of customers and enabling the flow of these processes at the pull of the customer through the organization [8]. Energy and resource efficiency is one of the principles of using Industry 4.0 [9]. Data availability and communication networks increase the efficiency of production planning [10].

Integrating Industry 4.0 technologies into SMEs is challenging and needs more attention. Small-lot production is in high demand in Finland and its effects on the environment and industry such as waste material, waste lubrication, and noise and vibration affect operators and manufacturing equipment are the reasons to develop a system to reduce its negative influences.

This research proposed a digital twins framework to apply to manufacturing small-lot production to reduce waste, resource consumption, time, and cost. In order to make it acceptable for small lot production it is simple, case-independent, and efficient to use. Many articles studied the methods for efficient small lot production. There is no framework to integrate industry 4.0 technology to directly reduce waste in small lot production. The proposed framework uses the Internet of Things (IoT), Big Data analysis, and machine learning to make the optimized production plan and predict the required maintenance. However, the detail of applying these methods is not in the scope of this study. The proposed digital twins framework is widely applicable in reducing waste for various metal-cutting processes.

2 Methodology

This research methodology includes three steps: observation, categorization, and association. In the observations step, a literature review was done to excavate the usage and application of Industry 4.0 in reducing resources such as cost and time. In this section, we present a literature review of product lifecycle management and lean manufacturing integration with Industry 4.0 as two tools concentrating on waste elimination and time optimization. References include journal and conference papers from 2012–2021. Papers includes the study of applying industry 4.0 in lean manufacturing and product lifecycle management. Papers that studied lean tools, or used conventional methods are excluded. The categorizing step identifies SMEs' issues that lead to seven lean wastes which are over-production, over-processing, defect, transport, inventory, waiting, and motion. Finally, the association step proposes a digital twins framework for small lot production in the metal cutting industry.

3 Literature Review

Applying Industry 4.0 to PLM stages assists factories in accelerating product development time, reducing costs, improving quality, visualizing product information, and shortening the communication gaps between the cooperating parties [11].

Lai et al. [12] argued the effect of the Industry 4.0 manufacturing facilities on minimizing the seventh lean waste in mass production. The paper focused on the cyber-physical approach to make more intelligent production planning, decision-making, maintenance, and energy management systems. Varela et al. [13] studied the progress of LM and Industry 4.0 on sustainability in the manufacturing industry in Portugal and Spain. The results show a correlation between Industry 4.0 and sustainability; however, there is no relation between LM and sustainability.

Buer et al.[14] did a literature review on LM and Industry 4.0 relationship in performance and environmental factors. The results demonstrate that Industry 4.0 solutions support lean tools limitations like value stream mapping could use real-time data collection and detect waste in the company information flows. Integration of Industry 4.0 and LM improves productivity and reduces waste and costs. For instance, autonomous Kanban bins eliminate inventory waste by detecting inventory levels automatically [15].

Lean manufacturing tools guide companies to eliminate waste through corrective actions. Just-in-time (JIT) production tool enhances the company to produce the right product in the right quantities at the right time, although sudden changes happen. JIT benefits from Industry 4.0 technologies for instant communication between a product and the machine, increase production speed, smart task allocation, and tracking the location of products in real-time. Cloud technologies, the Internet of things, and Big Data analysis equipped JIT with real-time communication. Augmented reality and real-time simulation solve problems and provide better decisions. Wireless tracking optimizes delivery and transportation by using intelligent sensors [16].

A value stream collects value-added and non-value-added activities from the design phase to the distribution phase. Value stream mapping (VSM) identifies all types of waste in the supply chain [17, 18]. Real-time data communication is the key in VSM, which Big Data and the cloud could update. Virtual simulation analysis the process and optimize it. The result gives the possible interaction between the flow elements and respective cost and time savings [19].

Three maintenance components are essential to track the machine and equipment functions. Although using preventive maintenance, machine failure is not inevitable [19]. Industry 4.0 technologies monitor the machine statutes like load, wear, and defects indexes during operation [20]. Big Data is used to predict defects and simulate machine behaviour based on historical failure data to plan predictive maintenance [21].

Digital twins as a technology based on the CPS consists of digital and physical environments which represent features, performance, and changes between these two spaces [22]. Digital twins in manufacturing is able to perform in various disciplines that are characterized by the synchronization between the physical and digital spaces. Digital twins goal within Industry 4.0 manufacturing system is to estimate and optimise the behaviour of the production system at each life cycle phase in real time [23]. Bazaz et al.[22] proposed a five layers framework which contains the data store, data flow, processing data, analysis and prediction, and interface to connect to the physical space.

Schützer et al. [24] proposed two phases for the digital twins lifecycle. Each phase includes four stages: creation, production, operation, and disposal. The creation stage consists of the initial assessment and design of manufacturing requirements, and the digital twins prototype is implemented based on the simulation results in the first stage. The real-time data exchange is activated in the second stage to verify the behaviour of the designed system in the operation stage. The disposal stage contains artificial intelligence tools to update the previous stages to find the source of unpredictable behaviour.

The digital twin has taken attention in lean manufacturing during the last few years. Yangguang et al. [25] integrated VSM with Efficiency Validate Analysis (EVA)-based digital twins for SMEs for production planning in the reengineering process. This approach uses IoT data to exchange data from the production line and then uses data in EVA simulation to calculate an accurate performance index. Holopainen et al. [26] proposed the digital twins for real-time performance measurement as support to accomplish lean principles. This approach eases control of the process, decision-making, and operations management.

Ito et al. [27] used IoT in a decision support system to achieve dynamic real-time communication for a framework consisting of three stages: collecting data, storing data, and simulation and decision-making. The outcome of the research reduced waiting time, balanced operator workload, and increased labour productivity.

4 Small-Lot Production in SMEs

Problems and wastes in small batch production differ from mass production. Adapting Industry 4.0 technologies in SMEs sometimes costs highly or needs expertise which is not efficient to use. A product life cycle consists of stages before (preproduction), during and after production. This section studies issues of manufacturing small lot production in metal cutting which causes waste and uses more resources.

Incorrect or mistakes in product design and complicated computer-aided manufacturing (CAM) programming increase preproduction time. Selecting cutting tool and machining parameters such as cutting velocity, depth of cut, and feed rate are commonly based on the human experience. Using unoptimized or incorrect parameters affects the final quality, vibration, power consumption, machining time and tool wear. These increase overprocessing, motion and defect wastes. In worst cases, tool breakage may cause additional downtime, which in consequence, boosts the waiting waste.

The rigidity of the machine affects the deviation of the Computer Numerical Control (CNC) machines. The deviation of the CNC machine means the deviation between the actual and desired parameters. For example, deviation in spindle rotation could happen because of the spindle's coaxial error. The positioning deviation causes inaccurate machining. Tool geometry deviation impacts final part accuracy and quality. Workplace stiffness, tool stiffness, and machine tool component stiffness influence the final product, vibration, power consumption, machining accuracy, and tool wear.

Due to the product variety and low volume in small batch production, process planning and set-up time affect the production's waste, time, and cost. This research proposed a digital twins framework for small-batch production. This framework should be simple to use while it is comprehensive, and it avoids including extra data or steps. The

solution should not be time-consuming or limited to one case. For example, simulation or augmented reality is unsuitable for SMEs due to the need for special skills, is time-consuming, and works only for one case study. In Finland, SMEs are successful in reducing transportation and inventory waste. The digital twins focuses on reducing waiting, motion, overprocessing, overproduction and defect wastes by assisting the operator in making a suitable plan for their orders. By selecting optimized cutting conditions, tools, workpieces, and other processes, and set-up parameters to achieve the required product quality and accuracy, reduce machining time, downtime, set-up time, and waste.

5 Digital Twin Framework for Small-Lot Production

Figure 1 illustrates the digital twins framework for small-lot production. This framework is based on the earlier study [23]. The framework consists of a physical environment and a digital environment. The physical environment includes the design and manufacturing phases of the product life cycle. Data and information from the physical environment are collected and transferred in the digital environment through the network in real time. The Internet of things is the bridge between the physical and digital spaces. The digital space includes five layers: cyber-physical data store layer, analysis layer, evaluation layer, prediction layer, and interface layer.

Cyber-physical data store layer is the core of the digital twins. It is responsible for feeding the data and information among digital space layers and physical space. This layer stores the data from the physical space in the database then converts the raw data to meaningful information, and extracts the features to send to other layers. The knowledge base contains the extracted features from the database and the results of the different layers. The decision results could transfer to the physical space to optimize the parameters in real time. Moreover, in the case of the manufacturing machine, IoT tracks the status and rigidity of the machine tool and operation in real time. Different sensors on the machine measure the rigidity of the machine, the force deformation, and the tool or workpiece deviation and send the data in real time to the digital environment.

The goal of the analysis layer is to make a production plan for some product orders to optimize the set-up time, tool usage, accuracy, and shorter machining time. Big Data analysis is suitable due to the variety and massive volume and complex data. Big data analysis techniques decide on production planning according to the product demand, machine tools condition, and available facilities like the tool quality, machine, and process restriction. The decision could be changed if other changes happen in the physical space, like cutting temperature, tool wear rate, vibration, and force. The right production plan reduces the motion, waiting, overproduction, and overprocessing wastes by selecting the proper parameters to maximize the used potential of the production.

The evaluation layer uses the results and parameters from the analysis layer and tool wear to calculate the used and wasted material and production time. Reduction in overprocessing and overproduction happens in this layer, and the outcome of this layer could correct the results of the analysis layer.

Defect waste has crucial effects on small lot production. If a machine breaks, usually there is no other machine to replace it, or maintaining the machine needs experts. Changing a tool in the middle of the process or frequently changing a tool increases the

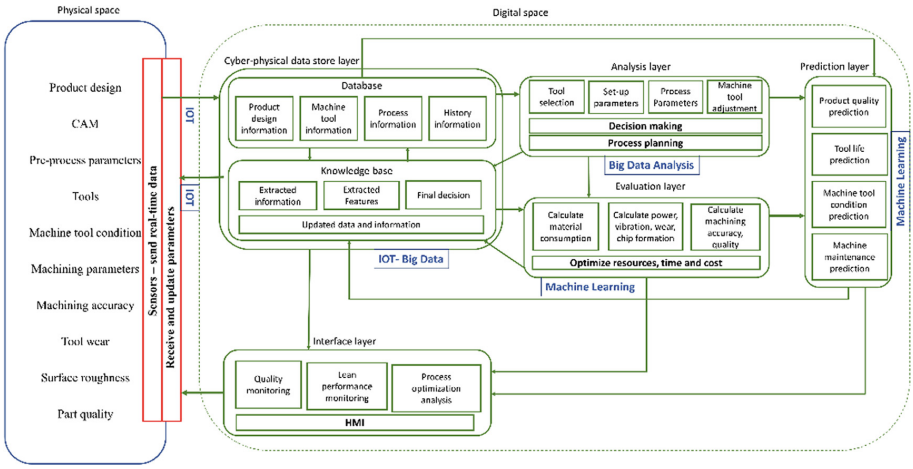

Fig. 1. Proposed digital twins framework for small lot production

production and set-up time, affecting the cost. Predicting the product quality prevents overproduction. This layer predicts the product quality and tool life from the outcomes of the analysis and evaluation layer. The prediction layer tracks the machine tool condition directly from the cyber-physical data layer to avoid failure.

The interface layer contains the results from the other layers to perform in the physical layer. The outcome of this layer could automatically use, for example in preventive and predictive maintenance, making production, and monitor production flow or sent to the manufacturer and experts through a human-machine interface. This layer connects CAM, Enterprise Resource Planning (ERP), or Manufacturing execution systems (MES) to the digital space. Another task of this layer is to measure the lean waste on the shop floor.

6 Discussion and Conclusions

A manufacturing process in SMEs mainly relies on human experience and abilities. Changes in the environment impact production and need to apply improvement. Long set-up time, using an inappropriate tool, frequently changing tool and machine adjustment, downtime, extra moving to provide raw material, tools, and preparing machine are some factors that increase the production time, energy, and consequently cost. Technologies adopted by SMEs should have the following properties: simple and quick to implement and operate, doesn't cost too much, independent of particular cases, dynamic changes in real-time, and intelligent. Industry 4.0 aims to automate manufacturing to make the process faster and more efficient.

The research proposed simplified digital twins to use in small-lot production of the metal cutting process. The approach of the digital twins framework is to minimize the seven lean wastes by making a proper production plan with optimized machining tools and parameters and predicting the state of the machine tools to prevent failure. This solution uses IoT for data exchange, Big Data analysis to analyze data and make decisions, machine learning methods to minimize waste, reduce time and cost, and

maintenance prediction. This method is not as vast as lean tools, but it focuses on the details of the manufacturing phase during the product life cycle. This method provides optimized parameters for production planning in order to reduce lean waste during manufacturing.

The authors will investigate appropriate big data and machine learning methods in detail and suitable standard to transfer data from the physical space to the digital space. Moreover, they will evaluate the framework in laboratory conditions using actual products from industry cooperators. It is essential to inquire about the challenges of using digital twins in SMEs, methods to establish the framework, benefits, cost, and time consumption.

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Scheduling for Flexible Production: A Case Study of Production Leveling Under Volume Constraints

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Abstract. Flexible manufacturing systems in high-mix low-volume segments offer many challenges in terms of planning and scheduling. The complexity of these systems often requires a systemic approach for which humans are the perfect actors. However, computer systems can support scheduling tasks more effectively due to their capacity to synthesize large amounts of data. This paper describes a system developed for the flexible manufacturing of wooden doors with a wide range of product configurations. This paper proposes a rule-based scheduling method for high-mix production. The method was applied and validated at a wooden door producer. Based on the company's production schedule for a given week, a scheduling program was developed that suggested minor rearrangements for production leveling. As the rule-based approach makes the decisions verifiable, the program was validated at the producer, through a case study of production leveling under volume constraints. The results include the complete elimination of changeovers and the stabilization of throughput, which improved the precision of the delivery time. The producer is integrating the program into their production planning and control system. Thus, the results suggest that the proposed method can be useful for scheduling high-mix low-volume production, and merits further validation in similar environments.

Keywords: Production leveling · Production optimization · Scheduling · Explainable AI

1 Introduction

Due to the complexity of modern manufacturing systems, planning and scheduling for production leveling is a difficult task for humans. As more capabilities and constraints are added to the manufacturing system, more dimensions are also added to the scheduling task. Computers can solve multi-dimensional problems such as manufacturing scheduling far easier than humans [1].

On the other hand, the creativity and flexibility of the human mind coupled with tacit knowledge and experience often reveal challenges and opportunities that a computer cannot possibly find unless explicitly programmed to do so. This human touch to scheduling is crucial in flexible manufacturing systems where the design of robust rules

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for computer-automated scheduling may not be feasible. Utilizing the best of both worlds, this paper presents a combined approach to production scheduling where a rule-based system informs an engineer of possible improvements to scheduling. The remainder of this paper is structured as follows: Sect. 2 provides a brief insight into the related theory and larger context before the methodology of the research work is described in Sect. 3. Section 4 introduces the case study, and the results are presented in Sect. 5. A discussion is made in Sect. 6, and finally, conclusions are made in Sect. 7.

2 Production Scheduling

Production scheduling is defined as a set of orders to be performed to best satisfy a set of criteria. The criteria involve tradeoffs between early and late completion of an order and reserving machines for the order and frequency of production changeovers [2].

Production flexibility results from the adaptability inherent in processes. Typically, it is the material handling that limits the flexibility as a result of the finite capacity of storage buffers and transport systems [2].

As product variation and production constraints increase, production scheduling becomes increasingly complex and requires more flexibility [3]. Balancing the production flow throughout the manufacturing system improves production efficiency [4]. When one process takes longer to set up than the others, this process becomes a bottleneck. In manufacturing systems with high product mix, proper scheduling may alleviate the effects of this bottleneck by minimizing the number of changeovers. However, maximum throughput is not the only objective in manufacturing as quality is a prerequisite for success [5]. Thereby, production scheduling must preserve the required product quantity and quality, two notoriously conflicting objectives.

Methods have been developed to handle basic scheduling operations, and these are widely available in commercial computer systems [6]. In academia, heuristics and metaheuristics have been applied to many problems in planning and scheduling [7]. A simulation study by Haeussler and Netzer [8] indicates that rule-based heuristics may outperform optimization-based approaches at high utilization rates, i.e. close to production capacity. The multitude of available information from new technologies adds to the complexity of scheduling in modern manufacturing systems [9]. However, manufacturers operating in environments with high product mix and low volume may struggle with finding an "off-the-shelf" solution for their scheduling tasks, because the problems are non-trivial and often unique. Therefore, scheduling for such environments is often a manual task.

An alternative way to control scheduling in a flexible manufacturing system is to treat the system as a holonic manufacturing system [10]. Holonic manufacturing is a highly distributed control paradigm based on autonomous 'holons' like order holons, product holons, and resource holons. Unlike traditional methods, a holonic system is not constrained to an already established schedule. A holonic system triggers an update when new expectations arise, and was explored further in later publications [11, 12].

3 Methodology

A rule-based heuristic was developed using Python3 in a Jupyter Notebook environment. Besides the Python3 built-in libraries, the packages Numpy and Pandas were used for data analysis, and Matplotlib was used for visualizations. The production schedule for three days from the wooden door company was first used to develop an initial version of the method for proof of concept. Upon acceptance, the production schedules for five days, which the company experienced as particularly challenging, were used to make further improvements. An executable program was generated from the code and validated on real data within the manufacturing environment.

The dataset for the five challenging days is used in this paper to demonstrate the developed method. The dataset contains 130 customer orders, where 64 orders contain painted products. A total of 2131 products are included in the dataset, of which 981 are painted. There are 39 unique colors. Figure 1 shows the number of products and the number of colors in each day in the dataset.

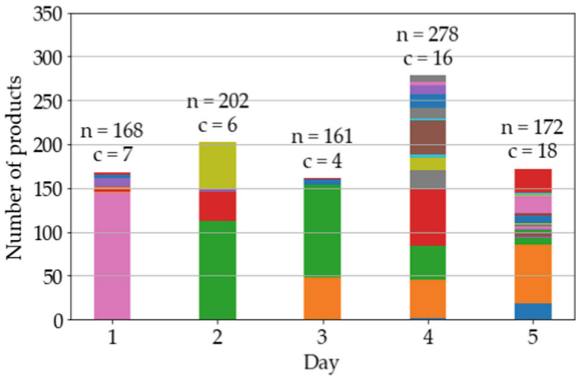

Fig. 1. Number of products of different colors per day (initial schedule). The colors are only a representation of the different product colors and are not the same as the true colors. n signifies the total number of products, and c signifies the number of different colors. (Color figure online)

4 Case Description

The case company manufactures a wide range of door variants. The company is situated in a highly volatile market with large fluctuations regarding order sizes and product configurations. To meet the demand, the company has developed a flexible manufacturing system capable of accommodating most order types with a high degree of automation. This system relies heavily on batching products of similar configurations to limit the number of changeovers at critical bottlenecks such as the painting machine.

The painting machine holds a limited number of colors and requires cleaning for each set-up. It is therefore beneficial to allocate all products of the same color to a single day, however, certain limitations and considerations must be made which complicate this initially simple rule:

- A single order may contain doors of different colors
- All the doors in an order must be painted on the same day, but not necessarily at the same time during the day, thus a mix of orders is allowed
- Maximum capacity of the production line is 500 doors per day
- Maximum capacity of the painting machine is 200 doors per day
- Maximum number of available colors for the painting machine is ten
- At the time of scheduling, the delivery date of each order is estimated based on overall capacity, etc. To avoid large deviations from the estimation given to the customer, orders can only be rearranged within their assigned week.

Currently, the colors of produced products are automatically determined from the overall system capacity without any regard to the painting machine. Consequently, there is a risk of too many different colors being assigned to a single day, leading to large changeover times for the painting machine, and since the painting machine is the bottleneck it will delay the entire production line. Hence, there is a large potential in moving orders to gather all instances of the same color in a single day.

5 Results

The proposed method consists of four steps: (i) collate colors, (ii) reduce the number of colors per day, (iii) reduce the number of products per day, and (iv) final adjustments.

The following sections describe each of these steps and demonstrate their performance on the dataset with five challenging days. Figure 2 depicts the status after the various steps.

5.1 Collate Colors

The first step of the process is to collate the colors. This is done for each color by identifying the number of instances of the color per day. Next, the possibility of moving colors from the day with the most instances (D_{max}) to the day with the least instances (D_{min}) is considered. This will either result in the move being executed, or D_{max} being excluded from further analysis. At this step only the total capacity of the machine is considered, i.e., if there are enough instances of a single color to exceed the capacity of the machine, this color is not moved to a single day, and production is allowed to continue over several days. This is indeed the case for white doors of which there are many.

Thirty orders were moved to other days to collate colors. This procedure reduces the average number of colors per day from 10.2 to 8.4. While 10.2 colors mean that changeover is required during production, an average below 10 means that the set-up potentially can be done before production starts and thereby enabling continuous production through an entire day.

As illustrated in Fig. 2a, the distribution is not better after this operation where day 2 exceeds the daily capacity of the painting line with 117 doors (58%). Furthermore, on the fifth day, the limit of ten different colors is exceeded by 50%, while days 1 and 3 only have three and two colors respectively.

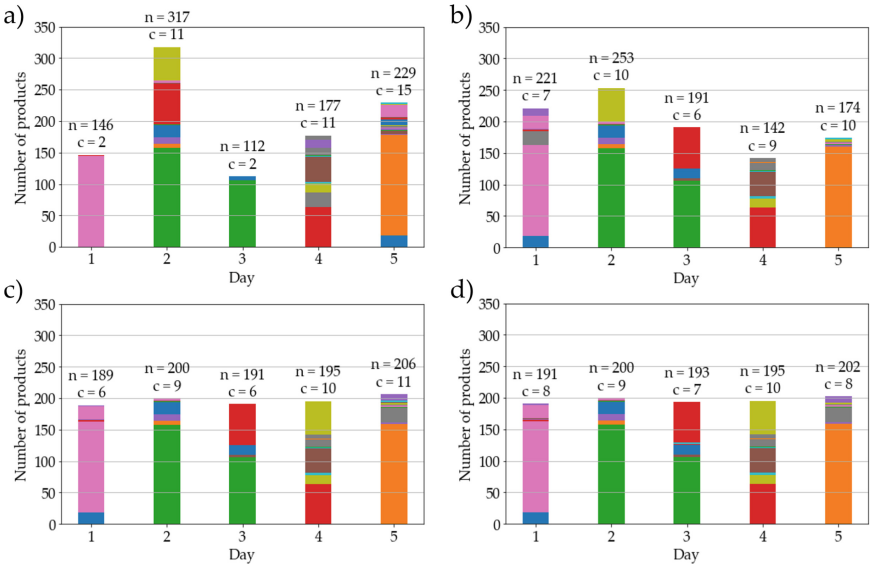

Fig. 2. Number of products (n) and colors (c) each day. (a) after collating colors, (b) after limiting the number of colors per day, (c) after limiting the number of painted products per day, and (d) after final adjustments.

5.2 Reduce the Number of Colors Per Day

To achieve a more even distribution of the colors, the next step reduces the number of colors per day by moving orders from days with many colors to days with fewer colors than the threshold value. This is achieved as follows:

1. Identify the day (D_0) with the largest number of colors
2. Identify the day (D_1) with the smallest number of products
3. Find the free capacity of D_1 (n_{room})
4. Find the color (C) in D_0 based on two conditions: (i) with most instances, (ii) the color C fits in D_1 ($n_C \geq n_{room}$)
5. Move the color C from D_0 to D_1
6. Repeat from point 1 until one of the three criteria is satisfied:
   a. None of the days have more than ten different colors
   b. All days have ten (or more) colors
   c. No days can take on extra products

This procedure proposes to move thirteen orders which reduces the number of different colors per day below the threshold for each day as shown in Fig. 2b. However, the number of painted products per day is not considered during this step. Consequently, the two first days are overloaded by 10% and 25% respectively.

5.3 Reduce the Number of Products Per Day

Another procedure is needed to reduce the number of painted products per day to acceptable levels. Because the total number of products entails production close to capacity, a

soft limit is imposed on the number of products at this point. This procedure moves three more orders and successfully reduces the number of painted products to a maximum of 206, i.e., only 3% above capacity. This result is shown in Fig. 2c.

5.4 Minor Adjustments

To further optimize the production plan, a final production leveling is done. Contrary to the other procedures which target the largest possible orders, this minor adjustment aims at moving only the smallest orders. This change is deliberate to avoid moving orders back and causing a loop. Priority is put on the number of colors per day as violating this limit will imply a changeover during production. The number of painted products, however, only has a linear impact on the total processing time of the day.

Three orders are moved to bring down the number of painted products and the number of colors even further as visualized in Fig. 2d. At this step, only one violation of the initial limits can be observed, which is the 202 painted products on the fifth day. This corresponds to 1% overload and translates to about 5 min of extra work.

6 Discussion

The rule-based method presented in this paper progresses in a manner like a human may approach the study case problem. This serves two purposes: not only will it promote explainability, but it will also make the solution understandable to the person who will utilize this as decision support in a scheduling scenario. By presenting the proposed rescheduling operations to the engineer, an informed decision can be made regarding the entire production system, i.e., the effect the new manufacturing plan may have on other manufacturing processes.

The current production plan of the case company is used as the starting point for the demonstrated scheduling method. The original schedule entailed cleaning out the machine to change colors during production. However, the proposed method eliminates the need for changing colors during production, hence avoiding disrupting the production flow. This saves time in set-up as well as materials with associated costs and environmental impact.

The explainability of the proposed method may come at the cost of effectiveness as a stochastic method or a sequential search method may arrive at a better solution, however, the path to that solution may not be straightforward. The proposed method takes a tentative schedule as input as is the current situation at the case company. Starting from an established foundation ensures minimal changes to existing plans, and consequently minimal changes to original delivery dates. For the case company, the painted doors only make up half of the production volume, and there are also soft limits on the total daily capacity of the factory estimated to 500 products regardless of type and configuration. The distribution of all product categories after production leveling concerning the painting machine is displayed in Fig. 3a, where all days are still within the soft limit of maximum of 500 products per day. By applying the same leveling approach for the other product categories, the distribution in Fig. 3b is achieved by moving only eight more orders. The additional moves may further level out the production and improve

production flow. These changes must however be carefully considered concerning other manufacturing processes.

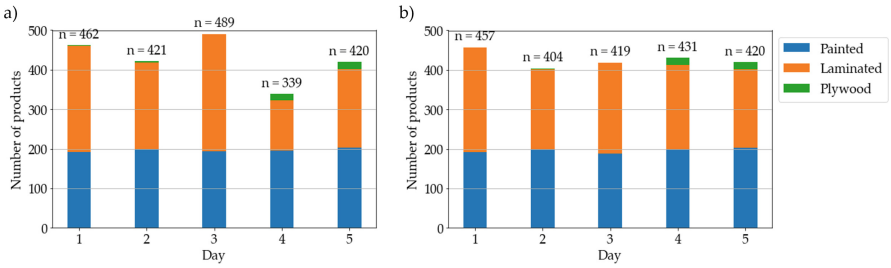

Fig. 3. The number of products scheduled per day per product category. (a) after leveling with respect to the painting machine, (b) after additional leveling of other product categories

An alternative approach could start with a clean slate and assign dates to orders as best as possible from the very beginning. This would however mean that only the expected delivery week, not a date, can be communicated to the customer at the time of the order. A similar scenario could be true with a holonic approach for which flexibility could be gained at the cost of predictability in terms of delivery dates. An evaluation should be made on which alternative is suitable for the context; some may prefer a timeframe narrowing in as the time to delivery closes in, while others may prefer to have a fixed date to consider, and rather be aware that this date may change.

7 Conclusions

This paper presented a rule-based method for scheduling in a high-mix low-volume manufacturing environment. This approach makes the results explainable and comprehensible as decision support in flexible manufacturing systems. The case study demonstrates the feasibility of the method in a real manufacturing environment as a tool to inform decision-making processes. The method was shown to minimize the number of threshold violations. Only one day exceeded the limit on the number of painted products, while none of the days exceeded the limitation on the number of colors per day. Consequently, the proposed method resulted in a complete elimination of changeovers during production.

The results have been validated by the case company where the method is being implemented in the existing manufacturing system. The production leveling of the paint line is shown to not have a negative effect on other product categories. Future work involves evaluating the performance on a larger data set and within the production system. Future work will involve a similar rescheduling of other product categories to further improve production leveling. Furthermore, updates based on real-time production data constitute an interesting avenue for future research.

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Scheduling Chemotherapy Outpatient Appointments: A Self-adaptive Metaheuristic Approach

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Abstract. In this paper, we address the chemotherapy outpatient scheduling problem with the aim of reducing the total patient waiting time. Since the problem is characterized by several sources of uncertainty, a stochastic approach is adopted. A simulation model based on discrete-time recursive equations, which includes all the steps of the oncology process, was developed. In particular, the simulation model emulates the therapy preparation and transportation process. Since the oncology and pharmacy can be located in different buildings, the therapies are collected in batches and delivered by a courier service. The simulation model is embedded in a stochastic metaheuristic algorithm to evaluate the candidate solution for the chemotherapy outpatient scheduling problem. A novel metaheuristic algorithm, namely Self-Adaptive Harmony Search (SAHS), is here proposed and its effectiveness is demonstrated through an experimental comparison with a well-known Harmony Search (HS) and Greedy Randomized Adaptive Search Procedure (GRASP) algorithms. Specifically, non-parametric tests revealed that the difference between the performance of SAHS and HS is not statistically significant. Then, SAHS is preferable since it avoids the time-consuming calibration phase.

Keywords: Scheduling · Healthcare · Flow time

1 Introduction

Despite the complexity and the multitude of tasks to be performed in a chemotherapy ward, reducing the patient waiting time is the leading objective for improving the quality level in outpatient cancer treatment facilities. In this regard, an effective strategy to cope with the chemotherapy outpatient scheduling (COS) problem should positively impact the performance of the chemotherapy outpatient departments.

The COS problem in oncology clinics is stochastic in nature [1], since some parameters of the problems, such as the medical consultation time or treatment time, are

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uncertain and cannot be exactly determined in advance. Then, the deterministic approach should be a strong simplification to use for addressing the COS issue. Usually the works in literature made use of two-stage stochastic programming model to solve the COS problem focused only on the treatment stage, *i.e.*, to assign patients to nurses and chairs [1, 2]. Castaing et al. [3] and Demir et al. [4] encountered high computational time to cope with large-sized instances and, then, developed heuristic algorithms to solve the problem in reasonable times. Garaix et al. [5] were the first to consider both consultation and treatment stages in the stochastic COS problem subject to deferral probability, *i.e.*, the probability that the treatment is postponed due to the patient health status. They proposed a metaheuristic algorithm, *i.e.*, Greedy Randomized Adaptive Search Procedure (GRASP) and considered the makespan as the objective function.

It can be noted that there are no works in literature that included the pharmacy operations in the COS problem. The therapy preparation process starts after the medical consultation and cannot be anticipated since deferrals or patient no-shows may cause expensive waste of drugs. Furthermore, the pharmacy and oncology units can be located in different buildings and, then, the therapy delivery time is not negligible. In this case, the therapies are usually collected in batches and a courier service is employed to deliver the batches from the pharmacy to the oncology unit [6, 7]. Therefore, both therapy preparation and transportation times affect the patient waiting time and should be considered in the COS problem.

The present research is the first in which all the steps of the daily oncology process have been handled as resource-constrained stages since the number of oncologists, pharmacists and nurses affect the service rate of their respective working areas. Furthermore, the paper considers that the drugs are delivered in batches and, as a result, the transportation time may influence the system dynamics and the performance of the clinic as well. A simulation framework based on discrete-time recursive equations has been adopted for modelling the patient flow in the oncology clinic. The simulation model works as an evaluative method embedded into a generative optimization technique consisting of a novel Self-Adaptive Harmony Search (SAHS) with the aim of reducing patient waiting time. The effectiveness of SAHS was tested through a comparison with the well-known Harmony Search (HS) and the GRASP algorithm arising from the relevant literature.

The structure of the paper is the following. The problem statement and the objective function are presented in Sect. 2. Section 3 introduces the novel SAHS proposed in this research. The results of the numerical experiments are shown in Sect. 4, while Sect. 5 reports the conclusions.

2 Problem Statement

In the oncology process, each patient is assigned to a specific oncologist, denoted as the referee oncologist, who follows the patient on the whole therapeutic path [8]. The referee oncologist defines in a protocol all the information regarding the treatment path of the patient (*e.g.*, treatment date and durations, type of therapy). Generally, in this department, the patient flow evolves through the following phases.

Firstly, the patient meets the referee oncologist for the medical consultation. The oncologist assesses the health status of the patient and, in case of a positive response,

he/she sends the drug specifications to the pharmacy. Whether the patient's condition is too weak for receiving the therapy, the oncologist may decide to defer the treatment [5]. The therapy preparation process is carried out by the pharmacy technicians. Each pharmacy technician can prepare only one therapy at a time. Once finished the preparation process, the pharmacy technicians collect the therapies in batches. A courier service is employed to deliver the batches from the pharmacy to the oncology unit. Once the therapy is ready and both a chair and a nurse are available, the patient set-up can start. During the set-up operation, one nurse allocates the patient to a chair and prepares her/him for the treatment. The nurse can prepare only one patient at a time. Then, the patient can undergo the treatment monitored by a nurse. As in the literature, it is assumed that at most four patients can be simultaneously monitored by the nurse during the treatment stage [4, 5]. The objective of the paper is the minimization of the length of stay of each patient, which in turn involves the reduction of the patient waiting time. The total length of stay can be represented by the total flow time (F) and can be calculated as follows:

$$F = \sum_{p=1}^{P} (C_p - S_p) \tag{1}$$

where C_p is the completion time of patient p, i.e., the time in which the patient completes the treatment and leaves the oncology units, S_p is the starting time of the medical consultation of patient p, and P is the total number of patients received by the oncology unit in a day.

3 Self-Adaptive Harmony Search

SAHS is a novel metaheuristic algorithm here proposed as a variant of HS. To assure maximum performance, metaheuristics require a set of control parameters to be preliminarily set, according to the kind of problem to be addressed. An accurate selection of such control parameters allows metaheuristics to find the best balance between exploration and exploitation. During the exploration phase, different solutions are generated to search in the solution space on a global scale, while exploitation consists of a search in a smaller region of a local optimum. To overcome any trial-and-error approach as well as any tedious calibration analysis concerning the selection of control parameters, a Self-Adaptive Harmony Search algorithm (SAHS), inspired by the self-adaptive differential evolution proposed by Brest et al. [9], has been devised.

Different solutions (harmonies) are stored in the Harmony Memory (*HM*). A harmony, denoted as $\boldsymbol{x} = (\mathrm{x}_1, ..., \mathrm{x}_\mathrm{j}, ..., \mathrm{x}_\mathrm{n})$, is a real-coded vector (defined in the domain $[LB_\mathrm{j}, UB_\mathrm{j}] \in \mathbb{R}$) that is converted in a discrete sequence through the smallest position value (SPV) [10]. The number of harmonies in a *HM* is denoted as Harmony Memory Size (*HMS*). The rationale of SAHS is shown in Algorithm 1. The first step consists of initializing the parameters of the algorithms, such as the number of evaluations (*evals*) or the number of harmony improvisations (*iter*). Among the parameters, the values of the exit criteria have to be specified, *i.e.*, the maximum number of evaluations (*Max_ev*) and the maximum number of computational times (*Max_ct*). Then, a random initial population is built and its objective function, *i.e.*, total flowtime, is calculated. To this end, a simulation model based on closed-form equations, which emulates the patient flow in

the oncology unit, is employed as decoding procedure. The simulation model refers to the work of Corsini et al. [8] and, for the sake of brevity, details of the equations and validation phase are not provided in this paper. It is characterized by two steps: Early-Start (ES) and Late-Start (LS) procedure. In ES, the solution is evaluated following the patient flow, *i.e.*, from the medical consultation to the treatment stage. On the other hand, LS adjusts the starting times going backward from the treatment to the medical consultation, so as to avoid any useless idle time between each stage.

To configure a self-adaptive mechanism for tuning the provided control parameters, with exception of the population size, each harmony in the *HM* is extended by three values, namely Harmony Memory Consideration rate *HMCR*, Pitch Adjustment *PAR* and Bandwidth *BW*, as follows:

$$\begin{bmatrix} x_{1,1}\cdots x_{1,n}|x_{1,n+1},x_{1,n+2},x_{1,n+3} \\ x_{2,1}\cdots x_{2,n}|x_{2,n+1},x_{2,n+2},x_{2,n+3} \\ \cdots \\ x_{HMS,1}\cdots x_{HMS,n}|x_{HMS,n+1},x_{HMS,n+2},x_{HMS,n+3} \end{bmatrix} = \begin{bmatrix} x_1|HMCR_1,PAR_1,BW_1 \\ x_2|HMCR_2,PAR_2,BW_2 \\ \cdots \\ x_{HMS}|HMCR_{HMS},PAR_{HMS},BW_{HMS} \end{bmatrix} \tag{2}$$

For the sake of clarity, hereinafter the generic vector of the control parameter $x_{i,n+1}$, $x_{i,n+2}$, $x_{i,n+3}$ will be denoted as $y_i = [y_{i1}, y_{i2}, y_{i3}]$. Each control parameter may vary within a specific domain to be preliminarily defined based on what the literature experienced so far. *HMCR* is chosen in the range [0.5, 1.0], *PAR* can be set in the range [0.40, 0.90], while *BW* is varied in the range [0.001, 0.1].

Then, a new harmony is generated with the following procedure:

```
for i = 1 : HMS
    for j = 1 : n
        if rand < y_i1
            x_ij^new = x_aj,      where a ∈ (1, …, HMS)
            if rand < y_i2
                x_ij^new = x_ij^new ± rand · y_i3
            end
        else
            x_ij^new = LB_j + rand · (UB_j - LB_j)
        end
    end
end
```

The objective function is evaluated for each harmony solution of the new *HM*. Then, the best and the worst harmony memory (*i.e.*, x^{best} and x^{worst}) are saved. The control parameters of each harmony vector are dynamically updated according to a twofold rule. Notably, a sort of global search mechanism drives the parameter updating with an adaptive probability equal to *1-(1/iter)*. The rationale is that the control parameters of the best solution *(*y_1^{best},y_2^{best},y_3^{best}*)* should be able to bias much more than those of the other harmonies as much as the iterations increase. Therefore, for a generic harmony vector x_i, if *rand* $\leq$ *1-(1/iter)*:

for $k = 1:3$
  if $y_{ik} \leq y_k^{best}$
    $y_{ik}^{new} = y_{ik} + rand \cdot (y_k^{best} - y_{ik})$
  else
    $y_{ik}^{new} = y_{ik} - rand \cdot (y_{ik} - y_k^{best})$
  end
end

On the other hand, to avoid being trapped into a premature uniformity of control parameters, a diversification strategy is assured when the aforementioned adaptive probability is not satisfied, as follows:

for $k = 1:3$
  if $rand \leq 0.5$
    $y_{ik}^{new} = y_{ik} + rand \cdot (max_i\, y_{ik} - y_{ik})$
  else
    $y_{ik}^{new} = y_{ik} - rand \cdot (y_{ik} - min_i\, y_{ik})$
  end
end

The Local Search and Reinitialization [11] procedures are included to increase the exploration and exploitation ability of SAHS. Finally, SAHS is stopped if the two exit criteria are respected. Otherwise, a new harmony is improvised.

Algorithm 1 Self-adaptive approach

1	*Step 1*:	Initialization and setting of the control parameters, namely HMS, $HMCR_{max}$, PAR_{min}, BW_{max}, BW_{min},
2		$(LB_j, UB_j)\ \forall\ j=1,\ldots,n$; Max_ev and Max_ct; $evals = 0$.
3	*Step 2*:	Randomly generate HM and calculate the objective function of each harmony.
4	*Step 3*:	Compute the fitness function of SPT and LPT solutions and replace with 2 harmonies.
5	*Step 4:*	Randomly generate a vector of control parameters related to each harmony vector:
6		$y_{i1} \in U\,[HMCR_{min}, HMCR_{max}]$; $y_{i2} \in U\,[PAR_{min}, PAR_{max}]$; $y_{i3} \in U\,[BW_{min}, BW_{max}]$.
7	*Step 5:*	Improvise a new harmony $\boldsymbol{x}^{new}$. Compute the objective function $f(\boldsymbol{x}^{new})$.
8	*Step 6:*	Save $\boldsymbol{x}^{best}$ and $\boldsymbol{x}^{worst}$. Set control parameters associated to the best solution: $\boldsymbol{y}^{best}$.
9	*Step 7:*	Update control parameters and HM.
10	*Step 8:*	Local search and Reinitialization. Update *evals* and *iter*.
11	*Step 9:*	**If** $evals \leq Max_ev$ **or** $time \leq Max_ct$ **then** return the best harmony vector $\boldsymbol{x}^{best}$ and $E(F_{best})$.
12		**Else** Goto *Step 5*. **End**

4 Experimental Analysis

This section deals with the experimental comparison between the proposed SAHS and the other two metaheuristics, *i.e.*, HS and GRASP. Three classes of problem were identified based on the number of patients received by the oncology unit: (*i*) $P = 15$; (*ii*) $P = 40$; (*iii*) $P = 70$. For each class of problems, a full-factorial Design of Experiments (DOE) was devised wherein the experimental factors, which vary at two levels for each class, are the number of oncologists (O), the number of chairs for treatment (C), the therapy batch size (B_{size}) and the stochastic distribution of the therapy transportation time (TD).

Precisely, the values of O and C depend on the class of problem as follows: (i) O in [2,3] and C in [5,10] when $P = 15$; (ii) O in [4,6] and C in [10,15] when $P = 40$; ii(i) O in [6,9] and C in [15,20] when $P = 70$. On the other hand, B_{size} and TD vary in [2,4] and [U(8,12), U(18,22)], respectively, regardless of the problem size. Each configuration of the full-factorial DOE is characterized by ten different instances. As for the other parameters, the number of pharmacist technicians (D) depends on the class of problems (*i.e.*, $D = 1$ when $P = 15$; $D = 2$ when $P = 40$ and $D = 3$ when $P = 70$), while the number of nurses (N) depends on C as follows: $N/C = 4$. In order to handle the stochasticity of the problem, the Sample Average Approximation (SAA) approach is adopted. Each instance of each DOE combination is characterized by a number of scenarios (Ω) in which the stochastic variables assume different values. The stochasticity of the problems arises from six variables: medical consultation time $\mathrm{Dc}_{\mathrm{p}}^{\omega}$ in N(22.83,3.19); deferral probability $\lambda_{\mathrm{p}}^{\omega}$ equal to 0.2; drug preparation time $\mathrm{Dt}_{\mathrm{p}}^{\omega}$ in U(3,7); batch transportation time $\mathrm{TD}_{\mathrm{b}}^{\omega}$ as in DOE; set-up time $\mathrm{Ds}_{\mathrm{p}}^{\omega}$ in U(5,15); treatment time $\mathrm{Di}_{\mathrm{p}}^{\omega}$ in Γ(1.9, 52.37). It must be specified that p is the patient, b stands for the batch and ω is the scenario. Ω was set equal to 300. Table 1 presents the results of the comparison between SAHS, HS and GRASP. The Relative Percentage Deviation (RPD) was used as a key performance indicator and is calculated as follows:

$$RPD = \frac{E(F)_{alg} - E(F)_{best}}{E(F)_{best}} \tag{3}$$

where $E(F)_{alg}$ is the expected total flowtime achieved by an algorithm in a configuration, while $E(F)_{best}$ is the best expected total flowtime obtained by the three algorithms in that configuration. RPD was also used to establish the values to be assigned to Max_ev and Max_ct. To this end, we used a specific data set composed by 10 instances for each class of problems. Problem size and level of each factor related to each instance have been randomly selected conforming to DOE. The rationale to determine Max_ct is to launch the SAHS many times, by adopting a stopping criterion that varies with the maximum number of evaluations, and then to identify the value of Max_ev which assures the convergence of SAHS. Particularly, we used a parameterized exit criterion based on $Max_ev(\gamma) = \gamma \bullet P$, where γ is varied in the set {30, 60, 90, 120, 150, 180, 210, 240, 270, 300}. Once Max_ev is known, we determine Max_ct by rounding the maximum computational time down to the lowest integer value. Then, the values of Max_ev and Max_ct identified for each class of problems are adopted as exit criteria for each metaheuristic algorithm. Based on the outcomes, γ is set to 210 for $P = 15$ and 240 for $P = 40$ and $P = 70$, while we set Max_ct to 272, 1154 and 2674 s for the small, medium and large classes of problem, respectively. As for the comparison between the three algorithms, Table 1 reports the RPD values of the algorithms for each configuration and class of problem, the median and the maximum values (RPD_{med} and RPD_{max}, respectively) of the $RPDs$ of each algorithm. The bold numbers, which point out the minimum RPD values between the algorithms for each configuration, highlight the outperformance of SAHS and HS in respect to GRASP. This outcome is confirmed by the values of RPD_{med} and RPD_{max}. Moreover, both SAHS and HS achieve an RPD_{med} value equal to zero for each class of problems, revealing that the major target of SAHS to achieve at least the same performance of HS has been reached. Looking at the RPD_{max} values it is clear that the SAHS algorithms slightly improves its performance as the

problem size increases. To infer about the statistical difference between SAHS and HS a series of non-parametric tests have been performed through Minitab17®. The outputs from a Mann-Withney test on the median RPDs related to the small, medium and large classes of problems confirm that there is not a statistical difference between the two algorithms.

Table 1. Median RPDs and global indicators to compare SAHS, HS and GRASP.

Class	Small			Medium			Large		
Conf./alg	SAHS	HS	GRASP	SAHS	HS	GRASP	SAHS	HS	GRASP
1	**0.00%**	**0.00%**	0.65%	**0.00%**	0.01%	0.91%	0.02%	**0.00%**	2.86%
2	0.02%	**0.00%**	0.28%	**0.00%**	0.01%	0.85%	0.01%	**0.00%**	1.77%
3	0.02%	**0.00%**	0.79%	**0.00%**	**0.00%**	1.11%	**0.00%**	**0.00%**	1.92%
4	**0.00%**	**0.00%**	0.55%	**0.00%**	**0.00%**	1.21%	**0.00%**	0.03%	1.30%
5	**0.00%**	0.01%	0.18%	**0.00%**	**0.00%**	0.11%	**0.00%**	**0.00%**	0.12%
6	**0.00%**	**0.00%**	0.16%	**0.00%**	0.01%	0.12%	**0.00%**	**0.00%**	0.09%
7	**0.00%**	**0.00%**	0.23%	0.02%	**0.00%**	0.24%	**0.00%**	**0.00%**	0.31%
8	0.01%	**0.00%**	0.29%	0.02%	**0.00%**	0.19%	**0.00%**	**0.00%**	0.23%
9	**0.00%**	**0.00%**	0.18%	**0.00%**	**0.00%**	0.52%	**0.00%**	0.03%	0.89%
10	**0.00%**	**0.00%**	0.05%	**0.00%**	**0.00%**	0.56%	0.01%	**0.00%**	0.79%
11	**0.00%**	**0.00%**	0.09%	**0.00%**	**0.00%**	0.51%	0.02%	**0.00%**	1.01%
12	**0.00%**	**0.00%**	0.14%	**0.00%**	**0.00%**	0.65%	**0.00%**	**0.00%**	0.75%
13	**0.00%**	**0.00%**	0.11%	0.01%	**0.00%**	0.11%	**0.00%**	**0.00%**	0.32%
14	0.02%	**0.00%**	0.09%	**0.00%**	**0.00%**	0.12%	**0.00%**	**0.00%**	0.74%
15	0.01%	**0.00%**	0.15%	**0.00%**	**0.00%**	0.15%	**0.00%**	**0.00%**	0.43%
16	**0.00%**	**0.00%**	0.16%	**0.00%**	**0.00%**	0.18%	**0.00%**	0.01%	0.69%
RPD_{med}	**0.00%**	**0.00%**	0.19%	**0.00%**	**0.00%**	0.27%	**0.00%**	**0.00%**	0.63%
RPD_{max}	0.02%	**0.01%**	0.79%	0.02%	**0.01%**	1.21%	**0.02%**	0.03%	2.86%

5 Conclusions

This research aims at addressing the COS problem with a stochastic approach. The patient flow in the oncology unit is affected by several sources of uncertainty, such as deferral probability or variable treatment time, and, then, a deterministic approach is not appropriate for the problem at hand. Differently from the literature, the present paper is the first to consider the pharmacy stage in the problem. In fact, the works concerning the stochastic COS issue focused only to the treatment stage. Garaix et al. [5] were unique in considering also the uncertainties arising from the medical consultation. In this paper,

we included the therapy preparation process carried out by the pharmacist technicians and the therapy transportation time. Since the pharmacy can be located far from the oncology unit, a courier service is needed to transport the therapies, which are collected in batches.

We propose a novel Self-Adaptive Harmony Search, named SAHS, so as to minimize the total patient waiting time. The novelty of the algorithm consists of the self-adaptation procedure, which allows to auto-calibrate the control parameters during the evolutionary path. The effectiveness of SAHS is demonstrated through an experimental comparison with other two metaheuristic algorithms, *i.e.*, HS and GRASP. The RPD performance measure was used to compare the outcomes of each algorithm with respect to the best solution in terms of total patient flowtime. Firstly, an experimental campaign was executed to define the exit criteria of the metaheuristic algorithms. Then, the comparison was carried out based on a full-factorial DoE with three class of problems depending on the number of patients. For each class of problem, the experimental factors are the number of oncologists, the number of chairs for treatment, the therapy batch size, and the stochastic distribution of the therapy transportation time. The results show that both SAHS and HS achieve the best performance in respect with the GRASP algorithm proposed by the relevant literature. Furthermore, non-parametric tests demonstrate that there is no statistical difference between SAHS and HS. Therefore, it is preferable to use SAHS since it allows us to avoid the time-consuming calibration phase. For future works, new sources of uncertainty can be included in the problem such as appointment cancellations or patient no-shows. Moreover, new algorithms can be tested in comparison with SAHS here proposed.

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Sample Size Analysis for a Production Line Study of Time

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Abstract. Setting labor standards is an important topic to operational and strategic planning which requires the time studies establishment. This paper applies the statistical method for the definition of a sample size in order to define a reliable cycle time for a real industrial process. For the case study it is considered a welding process performed by a single operator that does the load and unload of components in 4 different welding machines. In order to perform the time studies, it is necessary to collect continuously data in the production line by measuring the time taken for the operator to perform the task. In order to facilitate the measurements, the task is divided into small elements with visible start and end points, called Measurement Points, in which the measurement process is applied. Afterwards, the statistical method enables to determine the sample size of observations to calculate the reliable cycle time. For the welding process presented, it is stated that the sample size defined through the statistical method is 20. Thus, these time observations of the task are continuously collected in order to obtain a reliable cycle time for this welding process. This time study can be implemented in similar way in other industrial processes.

Keywords: Statistical Analysis · Sample Size · Time studies

1 Introduction

Time studies are commonly used in several companies, since they are required to set labor standards [1]. These have a major importance since they facilitate the understanding of a process [2,3], being necessary for the development of improvement methodologies inside Toyota culture such as Hoshin Kanri [4,5]. This method combines short and long term problem solving [6], building a link

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between operational and strategic management by demanding commitment to develop solutions for previously set targets and priorities [7,8].

Nevertheless, it is required to recognize that time studies establishment is a vital task, once it works as input for strategic planning, estimating labor costs, designing incentive systems and other tasks inside companies [9]. Any work in an industrial area could be classified into two categories, value added work and non-value added work or Muda. Value added work includes the operations that indeed generate results [10]. Muda consumes time and resources and must be reduced whenever possible, once it makes the production more expensive [11,12]. While defining a proper way to develop time studies it is necessary to consider the time and resources needed, once Muda must be avoided.

A concept that needs to be introduced inside time studies is the standard time. That is the time that a qualified operator uses to accomplish a task under a constant pace and typical conditions, considering all the parameters involved in a process. Those could be the layout of the workplace and the actions that the worker does periodically, for instance, some change of tool inside a machine [1,9].

According to [1], the standard time is calculated following a sequence of steps. First of all, it is defined the task that will be studied inside a production line, secondly, the chosen task will be divided into measurement points (MP), which are the precise elements of the same task in study [9] to facilitate their visualization for each operator. Thirdly, the sample size will be defined by deciding the number of time observations (n) to measure the task in order to give the highest reliability to the analysis. Once every parameter is decided, one can record the time between the successive start and end points for each MP and calculate the statistics. The sum of the times between MP's of the task results in the cycle time, that is measured and calculated for each observation n. Finally, some observations in which the operator did some unplanned thing due to, for instance, a machine problem or any other interruption, should not be considered in the calculation of cycle time [1].

This paper intends to contribute to the sample size definition that corresponds to the third step of standard time calculation. In order to identify the sample size, a statistical method has been presented on the literature [1,9]. This is an iterative method that requires preliminary sample size, from which a new sample is calculated. In the literature, there is a scarcity of studies that apply the statistical method to the sample size definition in the context of real study of time. In fact, no studies were found, reporting practical applications of this method to a real industrial case. To fill this gap, this paper intends to apply the statistical method to the sample size definition by using a typical task of a company used as case study. This case study involves a single operator that performs a task in 4 different machines to produce welded parts. Thus, the measurement points of the task that the operator performs are delimited by the moments when the operator presses the cycle start button of each machine.

This paper is organized as follows: the next section presents the literature review concerning the core concepts behind time studies; Sect. 3 describes the

statistical method adopted; Sect. 4 applies the statistical method to the case under study; Finally, Sect. 5 presents the conclusions and further work.

2 Literature Review

This section aims to present some important topics regarding time studies. First, it is intended to briefly introduce the concept of Hoshin Kanri and its relationship to labor standards; next it is showed the importance of time studies in labor standards; afterwards the method to define a sample size inside time studies in order to guarantee its reliability is discussed.

The literature review for time studies started with the search for "Hoshin Methodology" in Scopus platform. [6–8,13] present the Hoshin Kanri method in a clear manner, showing its basis on the relationship between operational and strategic management. At operational management level, it is important to create the labor standards, which can be defined during the daily activities performed by the operators. Those standards should support the labor content definition, costs estimating, workers efficiency measurement and staff size definition. In turn, these topics are important to carry out long-term planning, associated with strategic management [1,7].

As it is introduced by [1], time studies are a way of setting the labor standards, by timing a worker's performance during the execution of a task. According to [2], time studies provide basis for improving processes and organizational productivity in several areas. It is needed to assure that the time studies have reliability which means that it is necessary that the duration of the task should be reproducible, in the standard working conditions [2,14,15]. According to [1], the reliability of time studies is dependent on the sample size, that corresponds to the number of time observations collected for a task performed by the worker [16,17].

[14,17,18] describe the statistical method to define the sample size based on a preliminary one. Additionally, [16,17] present a good overview about the statistical method. Thus, in each iteration, the sample size definition is based on the mean and standard deviation of the time observations collected on production line [1,9].

Since a time study requires a sampling process, it is necessary to take into account the sampling error in the average observed time, once it varies inversely with the sample size. Thus, it is required to consider the variability of each element of the task in order to determine how many "cycles" should be timed. Three factors need to be taken into account in order to choose an appropriate sample size, accuracy, level of confidence, and the variation that exists within the elements of the task. Thus, a larger sample will be required if there is significant variation within the elements of the task [1,9].

Despite the statistical method is one of the most reliable ways to define the sample size, some weaknesses have been identified. According to [18], the susceptibility to subjectivity in the time observations collected is one of the main disadvantage of statistical method, once it depends on the worker pace,

the observer who is measuring the time of the task and the workstation condition during the time observations collection.

3 Methodology

This section describes the statistical method used to calculate the sample size in which the sampling error should be taken into account. Thus, to determine how many time observations n should be collected, it is necessary to consider the variability of each element in the task [1].

Considering the task under study, it is necessary to identify in a clear manner, the j elements or measurement points (MP) of the task. The start and end points for each MP_j must be clearly visible during the measurement of time, and they can be when the operator touches some part, some button or any other movement that is clearly visible to the observer, [1,9].

The method begins with a preliminary sample size and iteratively calculates the sample size based on the normal distribution [14]. The method enables to calculate the ideal sample size concerning the number (n) of time observations required to collect for each element of the task. Setting the value of each observation x_{ij}, that corresponds to the recorded time between the start and end points for each MP_j, and x_i is the sum of the j time elements x_{ij} of the task. Thus, the following notation is considered to calculate the sample size.

$\overline{x}$: mean of the k observations $x_i,\ i = 1, \ldots, k$ collected in each iteration.
s: standard deviation of time from the k observations, calculated by $s = \sqrt{\frac{\sum_{i=1}^{k}(x_i - \overline{x})^2}{(k-1)}}$
z: number of standard normal deviate (or z-score) corresponding to the desired level of confidence selected.
p: desired precision or accuracy.

Thus, the number of observations is given by equation (1).

$$n = \left(\frac{z.s}{p.\overline{x}}\right)^2 \tag{1}$$

This equation indicates that for a defined level of accuracy and desired level of confidence, a larger variability in data requires a larger sample size. [14] referred that the most used value of accuracy is 5%, that corresponds to the acceptable error desired, in the sample size definition inside time studies.

Thus, the statistical method starts with the preliminary sample size k. In each iteration, before calculating the mean and standard deviation for the sample size, it is necessary to eliminate outliers [1,9,19], once there are times in which the operator is interrupted or performs uncommon actions. According to [19], for the consideration of outliers, limits to consider or disregard values in the collected data should be established from knowledge of the sampling properties. Assuming, that the time measured for each task follows a Normal distribution,

the general practice is to consider an outlier if it is three times the standard deviation limit above or below the mean.

Once the outliers are eliminated, the mean and standard deviation of the preliminary sample size are recalculated and a new value of n is calculated, using Eq. (1). If the n is greater than the preliminary sample size, it means that one more iteration is needed, by collecting a new sample size. The iteration sequence ends as soon as the resulting n is smaller or equal than the sample size obtained in the previous iteration [1,9], indicating that the stop condition is reached.

It is important to highlight that, in order to reduce the influence of subjectivity into the time observations collection referred by [18], it is necessary to collect them continuously, from x_1 to x_k, making sure that working conditions are maintained as constant as possible over the measurement process.

4 Results

This section applies the statistical method described in the previous section to determine the sample size for determining the time of the task under study, considering a confidence level equals to 95%, using $z = 1.96$ and an accuracy p equals to 5%. The task under study includes 4 different welding machines and it is decomposed into 4 elements. Each welding machine has a button that enables to divide the task into $j = 4$ different measurement points. These measurement points are set in order to facilitate the measurements, and are divided according to the small tasks that the operator does in each machine. Considering a sample size equals to k, the measurement process is applied to measure the 4 different MP_j of the task performed by the operator, according to the following steps:

(i) he stopwatch start button is pressed as soon as the operator presses the cycle start button on machine 1, marking the start point of MP_1;
(ii) When the operator presses the cycle start button on machine 2, the lap button is pressed on the stopwatch, thus, marking the end point of MP_1 and the beginning of MP_2. Thus, the time between the start and end points of MP_1 for the first observation is obtained, x_{11}. This time observation, in practical terms, represents the unload of the part generated by welding machine 2 and the load of new components to be welded in the machine 2;
(iii) When the operator presses the start cycle button on machine 3, the lap button is pressed on the stopwatch once again and it marks the end of MP_2 and the start of MP_3, thus, the time between the start and the end points of MP_2 for the first observation is obtained, x_{12}. This time measured, represents the unload and load of the parts of machine 3;
(iv) When the operator presses the start cycle button on machine 4, the lap button is pressed on the stopwatch, marking the end of MP_3 and the start of MP_4. Thus, the time between the start and end points of MP_3 for the first observation is obtained, x_{13}. This time observation represents the unload and load of the components of machine 4;

(v) When the operator presses the start cycle button on machine 1 again, the stopwatch lap is pressed, marking the end point of MP_4 given by x_{14} and the beginning of MP1 of the second observation x_{21}. Practically, x_{14} represents the unload and load time of machine 1. Thus, $x_1 = \sum_{j=1}^{4} x_{1j}$;

(vi) The steps (i)–(v) are continuously collected until x_{kj} observations are obtained for each MP_j of the task, keeping constant the working conditions.

Thus, the Fig. 1 schematizes the described measuring process for each time observation x_k of the task performed by the operator.

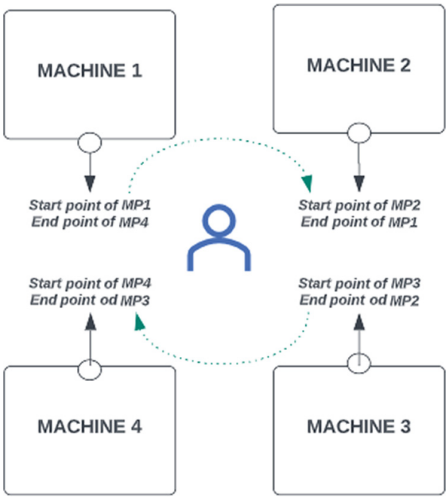

Fig. 1. Scheme of measuring process for each time observation x_k of the task

The preliminary sample size to be considered was k=10 time observations. Thus, the task was continuously measured, 10 times from the cycle start button on machine 1 to the cycle start button on machine 1 again. These time observations (measured in seconds) are presented on Table 1, in which the first column represents the measurement points, numbered from 1 to 4, the first row shows the number of time observation (x_{kj}) collected for each MP_j, and the last row corresponds to the total time for the 4 elements of the task corresponding to the cycle time. For example, the last line of the second column of Table 1 corresponds to x_1, which is the sum of the times to perform the 4 elements of the task (MP_1 to MP_4) which represents the first cycle time.

After the 10 cycle time observations have been collected in the preliminary sample (Table 1), it is checked if there is any outlier. Thus, no observation is eliminated from the analysis, once all the data range in the acceptable interval. Afterwards, sequentially: (i) the mean ($\overline{x} = 128.0$) and the standard deviation ($s = 11.5$) of the cycle time (last line of the table), are calculated; (ii) the

Table 1. Data for $k = 10$ measurements (in seconds)

	x_{kj}									
MPj	x_{1j}	x_{2j}	x_{3j}	x_{4j}	x_{5j}	x_{6j}	x_{7j}	x_{8j}	x_{9j}	x_{10j}
MP1	29.3	29.8	25.7	42.7	24.1	37.7	23.2	29.0	23.4	23.6
MP2	34.9	38.4	34.5	38.1	47.7	34.0	47.6	39.0	37.0	34.5
MP3	25.0	25.4	27.9	34.1	38.7	24.1	28.8	24.6	24.4	33.2
MP4	30.7	36.6	28.8	39.1	33.7	32.3	37.4	33.1	48.5	30.5
Cycle Time	**119.9**	**130.2**	**116.8**	**153.9**	**144.2**	**128.1**	**137.0**	**125.7**	**133.3**	**121.9**

equation (1) is used to determine the new sample size for the second iteration, obtaining $n = 11.8$. Since, it is bigger than the preliminary sample, it is required to collect $n = 12$ time observations for each element of the task, by using the same measurement process previously described.

Table 2. Data for $k = 12$ measurements (in seconds)

	x_{kj}											
MPj	x_{1j}	x_{2j}	x_{3j}	x_{4j}	x_{5j}	x_{6j}	x_{7j}	x_{8j}	x_{9j}	x_{10j}	x_{11j}	x_{12j}
1	22.9	31.7	22	24.6	22.5	21.6	26.4	23.4	23.9	25.8	24.0	27.6
2	39.3	43.6	36.9	35.4	35.0	41.5	37.1	58.9	34.3	43.7	34.6	36.6
3	24.7	23.7	24.9	23.0	24.0	21.2	25.0	22.3	24.3	24.8	70.0	23.7
4	33.6	38.5	38.8	33.5	37.0	31.7	31.8	37.0	39.2	31.7	36.1	32.3
Cycle Time	**120.4**	**137.3**	**122.7**	**116.5**	**118.5**	**115.9**	**120.3**	**141.6**	**121.6**	**125.9**	**164.7**	**120.2**

The data collected for the second iteration are presented on Table 2, in which no outliers are identified. The same sequence of calculations is performed: (i) the mean ($\overline{x} = 127.0$) and the standard deviation ($s = 14.2$) of the cycle time are calculated; (ii) the Eq. (1) is used to determine the new sample size, obtaining the $n = 19.2$. Once again, this sample size is bigger than the one achieved on the second iteration, and a new iteration is necessary.

In the third iteration, it is required to collect $n = 20$ time observations for each element of the task, by using the same measurement process. The data collected for this iteration are presented on Table 3, in which an outlier 176.1 is identified and eliminated, resulting in a sample size of 19. For this sample, the following calculations are achieved: (i) the mean ($\overline{x} = 131.1$) and the standard deviation ($s = 13.7$) of the cycle time; (ii) the Eq. (1) enables to determine the new sample size, $n = 5.7$. Once, this sample size is smaller than the one used on the third iteration, indicating that the stop condition of the method is reached.

Table 3. Data for $k = 20$ measurements

	x_{kj}																			
MPj	x_{1j}	x_{2j}	x_{3j}	x_{4j}	x_{5j}	x_{6j}	x_{7j}	x_{8j}	x_{9j}	x_{10j}	x_{11j}	x_{12j}	x_{13j}	x_{14j}	x_{15j}	x_{16j}	x_{17j}	x_{18j}	x_{19j}	x_{20j}
MP1	23.9	24.2	22.8	23.7	28.1	25.6	22.1	25.8	22.9	21.5	27.1	22.8	24.1	31.2	24.9	23.9	23.8	24.9	27.3	23.5
MP2	38.7	45.1	34.8	37.8	52.6	86.7	38.4	37.5	36.7	35.8	37.4	35.7	46.0	44.2	37.8	48.1	40.9	36.7	38.2	35.7
MP3	25.6	23.1	24.8	23.5	24.0	26.6	24.5	23.1	26.3	29.0	27.6	27.9	27.8	26.9	24.6	22.9	23.2	25.9	22.6	23.8
MP4	39.1	32.4	30.7	39.5	35.9	37.3	36.4	37.6	32.1	35.0	36.3	33.4	39.0	33.7	29.1	39.2	41.0	32.8	40.8	31.1
Cycle Time	**127.0**	**125.0**	**113.0**	**125.0**	**141.0**	**176.0**	**121.0**	**124.0**	**118.0**	**121.0**	**128.0**	**120.0**	**137.0**	**136.0**	**116.0**	**134.0**	**129.0**	**120.0**	**129.0**	**114.0**

Analysing the results, it is observed that the statistical method used to calculate the sample size is affected by the variability of the data over the iterations since higher variability in data requires a larger sample size. However, it must be taken into account that as the number of observations increases, the probability of uncommon actions may also increase such as operator fatigue can affect the measurements.

5 Conclusion

For the case study presented, in which an operator performs his task along 4 different welding machines, the applied statistical method provides a sample size of 20 time observations as enough to obtain a reliable cycle time of this process. The statistical method enables to determine a sample size value through iterations that take into account a number of time observations in order to reduce sampling error and avoid the needless usage of bigger sample sizes that also increase susceptibility to variability in terms of uncommon activities.

The time observations are continuously collected and the division the task into Measurement Points with visible start and end points facilitated the time measurements, enabling to reduce any susceptibility and subjectivity. These results can be developed further, aiming the definition of labor standards.

This paper describes the practical implementation of the statistical method to define a sample size in order to obtain a reliable cycle time for a task of an industrial case study, filling the gap in the literature related to the matter.

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Asset Administration Shells and GAIA-X Enabled Shared Production Scenario

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Abstract. Increasing the flexibility of production environments and the resilience of value chains are major challenges of Industry 4.0. Multi-enterprise manufacturing networks can be a solution to create dynamic supply chains and to make product manufacturing more flexible. To enable the concept of manufacturing networks, vendor-independent and data-secure solutions are required. This includes automated bidding procedures and cross-company interpretation of information. Existing approaches to data exchange between companies are based on proprietary concepts. An industrial data space should support vendor-independent solutions to facilitate data exchange, participation in multiple data spaces, and offers the freedom not to be dependent on a single software company or marketplace provider. The paper focuses on existing technologies and describes a Shared Production scenario based on the decentralized GAIA-X architecture, the Asset Administration Shell and the Industry 4.0 language. In this way, uniform semantics can be achieved, the Industry 4.0 language defines the structure of text messages as well as the communication flow, and GAIA-X provides technologies for secure and data-sovereign information exchange. The focus is on the possible identification of supply chains in the machining industry.

Keywords: Cloud Manufacturing · Shared Production · Asset Administration Shell · Industry 4.0 · GAIA-X · capabilities · skills

1 Introduction

Volatile markets, individual products and shorter life cycles will require more dynamic production environments [1]. The corona pandemic has shown that a sudden change in demand of certain goods leads to a global supply problem due to rigid production and supply chains [2]. The ability to adapt to unexpected changes in the production process and to serve more individualized and personalized requests is increasingly required in new production systems. In the course

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of this development, it becomes necessary to automate factories more flexible in order to serve customer-specific requests [3]. Digital marketplaces are expected to be established in the long term as part of the development of the 4th Industrial Revolution [4,5]. One way to network companies individually for the production of a component is based on the concept of offering production services on digital marketplaces and is called Production as a Service (PaaS) [6]. The same concept is also defined as Cloud Manufacturing (CM). Liu et al. analyze existing concepts of CM and defines CM as "a model for enabling aggregation of distributed manufacturing resources [...] and ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing services that can be rapidly provisioned and released with minimal management effort or service operator and provider interaction" [7]. The current concepts of CM and PaaS lack Industry 4.0 (I4.0) compliant solutions. As a result, there are currently only proprietary solutions for using manufacturing marketplaces. These solutions lock a company into a specific vendor. Through an I4.0-based approach, it should be possible to use defined or standardized solutions for communication and to easily change data spaces or participate in different data spaces. Technologies are also needed to support authentication and secure data management between partners. Upcoming legislation, such as the Digital Product Passport regulation, also requires interoperable data exchange with access restrictions between manufacturing companies, product users and recycling companies [8,9]. In the case of flexible production environments, *Plattform Industrie 4.0* defined a Shared Production (SP) scenario which "[...] focuses on flexible production configuration not only inside one factory but also including cross-site optimization and cross-company collaboration to enable a fast reaction on changing markets which results in hard to predict long-term volume of incoming order" [10].

This paper discusses vendor-independent technologies for SP as defined by the Reference Architecture Model Industry 4.0 (RAMI4.0) [11] based on services, capabilities and skills. To define a common vocabulary between partners, information is defined in Asset Administration Shells and existing standards in machining are discussed. The I4.0 language specifies the structure of messages and communication processes. GAIA-X connectors are used to exchange data in a secure, decentralized and confidential manner.

2 State of the Art

2.1 Services, Capabilities and Skills

A working group of the *Plattform Industrie 4.0* discussed and defined a consolidated information model for capabilities, skills and services (CSS) with focus on flexible I4.0 production [10,12]. In this model, a service is defined as a "description of the commercial aspects and means of provision of offered capabilities" [10]. A capability is the "implementation-independent specification of a function in industrial production to achieve an effect in the physical or virtual world", while a skill is the "executable implementation of an encapsulated (automation) function specified by a capability" [10]. The model enables concepts such as

SP, the flexible adjustment of production resources or the individual manufacturing of products. Here, the model is used as a basis for a marketplace. The cited paper suggests technologies to use, but does not show technology-specific solutions. Section 3 therefore describes a technology-specific approach to SP.

2.2 GAIA-X

GAIA-X is an open, transparent, and secure digital ecosystem that meets the highest standards of digital sovereignty. The GAIA-X concept aims to create a trusted data space through the connection of previously separated data spaces [13]. Thus, data can be made available, aggregated and shared in a secure and trustworthy manner through GAIA-X. The data owner retains control over his own data and decides where it is stored and for what purposes it may be used.

2.3 Asset Administration Shell

A central concept of I4.0 is the so-called Asset Administration Shell (AAS). The AAS is an I4.0 specification designed to improve interoperability between systems from different vendors. An asset with an AAS is referred to as an I4.0 component [11]. The meta model of AAS is published in [14]. It specifies a set of elements that are used to create so-called submodels (SMs). An SM represents specific information about an asset. The use of standardized SMs ensures interoperability between companies. Examples of such standardized SM templates are e.g. the nameplate, the capability description, or the control component that specifies the skill interface [15]. However, currently there is no product SM template or service SM template to describe products or services in an SP scenario [15]. In this paper, the concept of AAS is used to exchange information about services and products between the participants.

2.4 The VDI/VDE 2193 I4.0 Language

To enable vendor-independent communication between I4.0 components, the participants must be able to speak a common language. The specification VDI 2193-1 proposes a concept for such an I4.0 Language (I4.0L) [16]. It is specified to define a vocabulary, a message structure, and semantic interaction protocols. VDI 2193-2 defines a semantic interaction protocol for bidding procedures [17]. The bidding procedure envisions that commercial services provided by autonomous I4.0 components (in this case an enterprise in the data space) can be tendered and offered. In terms of the paper, I4.0L should be used to ensure a vendor-independent communication in bidding procedures.

3 Vendor-Independent Marketplace for Machining

This section describes the scenario where an SP Platform acts as a partner in a data space. The SP platform matches product requirements to registered

production services. To guarantee vendor-independence and data security, the architecture is based on GAIA-X connectors, AAS and I4.0L. In the SP scenario, there are three types of participants:

- The **customer** who provides the product requirements and requests an individual product. The customer acts as service requester.
- The **manufacturer** providing his production resources to perform production services on the product. The manufacturer acts as service provider.
- The **SP Platform** which identifies suitable manufacturers based on the product requirements. It manages communication between the customer and manufacturers.

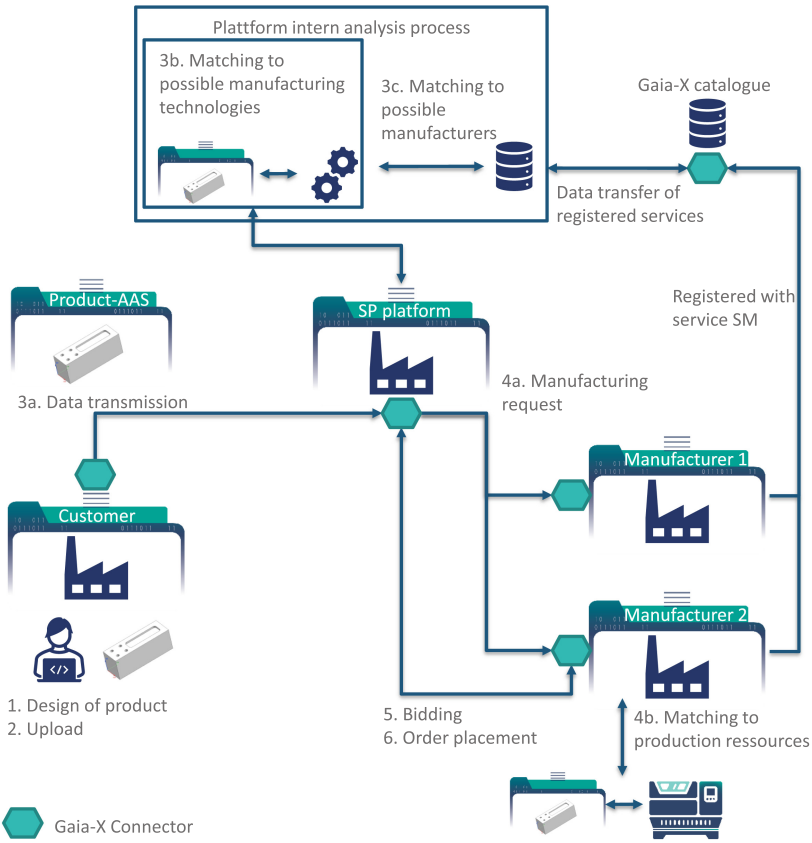

Fig. 1. A product AAS is shared between partners in the data space to identify potential supply chains

Figure 1 shows the SP scenario. The product AAS contains all important product information. Relevant SMs of the product AAS are exchanged between the

participants. The services of a manufacturer are described in a standardized service SM in the AAS of an enterprise. The service SM is used to register in the GAIA-X catalog of the data space. With the information of the catalog, the SP platform is able to retrieve all available services in the data space. In this case, the SP platform can be an independent company that specializes in identifying specific supply chains (e.g., machining supply chains). The I4.0L is used for communication between the participants. It provides clear sequences for a bidding process and allows the exchange of AAS SMs in the message. This preserves the semantics of the AAS. The SP scenario consists of the following steps.

Step 1: The production order begins at the end of the design process. On the one hand, a customer can upload his CAD model, including an optional technical drawing, to a platform via a web-based interface after the design process. On the other hand, the part can be designed directly in a cloud environment using Software as a Service (SaaS). Ideally, the designer stores all relevant product manufacturing information (PMI) in the CAD model. PMIs include e.g., tolerances, surface finishes, fits, threads, and the required material. Optionally, these can also be defined in an attached technical drawing. The designer's responsibility to check the part for manufacturability increases in an automated manufacturing process. In an input mask, the customer has to specify mandatory as well as optional production information to the order. Mandatory information includes the contact information, quantity, payment terms and the relevant information about the part to be manufactured. Other information that may be required includes additional material or strength specifications, surface alloy or roughness specifications, tolerance information, or restrictive specifications such as maximum delivery time, CO_2 emissions, or costs. Required certificates or warranties may also be specified.

Step 2: The entire requirements and files (CAD, technical drawings) are extracted into a product AAS. For this purpose, all necessary information about the customer and precise information about the product must be stored. The creation of the AAS can be done directly from the CAD system or by a specialized service provider (e.g. the SP platform). The possibility of automatically generating product information based on features for storage in an AAS and necessary SMs is discussed in detail in Sect. 3.1.

Step 3: The customer transfers his CAD data, including the information from step 1, to the SP platform (3a). The SP platform automatically analyzes the supplied data. Based on the product AAS, the required manufacturing technologies and manufacturing companies are determined. The SM for services of manufacturing companies is stored in a GAIA-X Federated Catalog. In this way, all necessary information is accessible to the participants of the data space. For example, if the manufacturing platform identifies an individual milling order for a certain material of a certain size, it starts filtering potential contract manufacturers (3b). Companies offer services in the manufacturing network based on their enterprise AAS. A service can be based on a very general description, e.g. available manufacturing technologies constrained by limiting factors such as quantities or component sizes. For example, a contract manufacturer could offer

as a service the milling of an individual component in the material aluminum and a size from $50 \times 50 \times 10$ mm up to max. $400 \times 400 \times 300$ mm. Possible standards for describing services are discussed in Sect. 3.2. The next step is to define technology chains and process steps to create the product. In this case, a technology would be the milling process and a process step could be a manufacturing feature like drilling a hole. The result can be used to identify needed manufacturing technologies or process steps as a service offered by a company. The features (product description), manufacturing technologies (services), and specific manufacturing steps (capabilities) should follow a standard, if possible. In this manner a semantic interpretation of the data becomes possible. The information from the part analysis extends the product AAS and describes the required services (e.g., milling). Contract manufacturers that meet the requested services, as well as initial filter criteria such as materials and quantities, receive a request for the desired product. The product AAS is sent to a service provider. This allows the information to be matched to specific resources.

Step 4: The request for quotation can be processed by a contract manufacturer at three different levels of automation (4a):

- Level 1: The quotation process is performed "by hand". An employee creates a rough production plan based on his experience and a cost calculation based on internal cost tables.
- Level 2: The employee is assisted by software in selecting manufacturing resources and calculating costs. There are several software that provide these functions, like Spanflug[1] or up2parts[2] For this purpose, relevant information such as the manufacturing resources, raw materials and cost parameters are stored in a database by the contract manufacturer and matched to CAD part.
- Level 3: The creation of a manufacturing plan and cost calculation is fully automated. Production resources are included in the planning process to perform a manufacturing review and cost analysis.

The fully automated creation of a quotation is described (4b). In the matching process, the material defined in the product AAS and the stored component size are first compared with the available raw material. If the required raw material is not available, the material order would have to be checked first. Material orders can also be triggered via the cloud connectors. Time delays and additional costs should be included in the quote process. The next step is to verify that the features can be manufactured with existing production resources. This is done by mapping the geometric features to capabilities and manufacturing skills. The capabilities should be described as manufacturing features (compare to Sect. 3.2), so geometric features from the CAD and available manufacturing features are mapped. A software identifies manufacturing resources with the required capabilities and skills and performs a feasibility check whether the feature can be manufactured by a corresponding resource [10,18]. If the check is true, the expected

[1] Spanflug: https://spanflug.de/en/.
[2] up2parts: https://up2parts.com/en.

processing time, estimated cost and estimated energy consumption for executing skill are calculated. The resources eligible for manufacturing are collected with their respective manufacturing step (skill) and associated manufacturing information (duration, cost, energy consumption). A scheduling algorithm can plan the manufacturing steps and costs based on the previously planned machine utilization. A proposal is automatically generated. If the manufacturing process is not possible, the proposal is cancelled.

Step 5: On the one hand, quotes can be collected on the manufacturing platform and made available to the customer or sent directly to the customer. The customer can select a suitable quote. When the order is triggered, the contract manufacturer receives a production release. A rejection of the quote can be sent to the competitors via the cloud connectors. The connectors should also delete design data from the companies that have not received a quote approval.

Step 6: One or more serially connected contract manufacturers receive the order to produce a component. The detailed scheduling and use of specific resources is determined. A human operator should still have the opportunity to check and change the processing sequence. In this way, the human operator provides the final decision-making authority. If several subcontractors are involved in the production process, possible time dependencies among the supply chain must be taken into account. In the companies, the corresponding skills of the resources and transport systems can be triggered to execute the production process defined in product AAS as described in [19]. Information about the production process can be stored in the product AAS. In case of delays, the involved subcontractors should be informed in time by an automated message. In this way, process steps can be postponed in time. The customer should be provided with information about the sub-steps of the manufacturing process.

3.1 Description of the Product

Literature already exists that deals with the semantic description of products using features, e.g. [20,21]. In order to be able to identify the required services and capabilities to manufacture a product, the goal is to extract form features with the required parameters from the CAD. Form features are defined as "structure-oriented groups of geometric items [...] within a product model (frequently reduced to geometric characteristics), which under a common name can be created, stored, modified and deleted" [22]. The form features to be produced are to be assigned to services in the service matching and later to a production machine in the capability matching [10]. For feature recognition concepts like design by feature, feature recognition (interactive or automatic) and feature mapping can be used [23]. The goal is to implement automatic feature recognition to automatically generate a product AAS with the list of features to be manufactured after the design process. The designer is not bound to any predefined design features in the design process by the automatic feature recognition and can keep and apply his usual design methodology. STEP-AP 242 [24] is a vendor-independent CAD standard and contains a definition of form features. However, when searching for a tool to extract features and parameters, no

suitable tool was found. This is confirmed by the research of [25]. Therefore, we examined the API NX open of the CAD/CAM software NX to extract product parameters automatically. Required information in the sense of manufacturing the product is the geometry, product size, material, weight, form features, feature parameters relevant to manufacturing and PMI's such as tolerances. In a test, it was verified that the standard features defined by NX can be searched and automatically output, and that it is possible to access relevant parameters using the NX open API (Fig. 2).

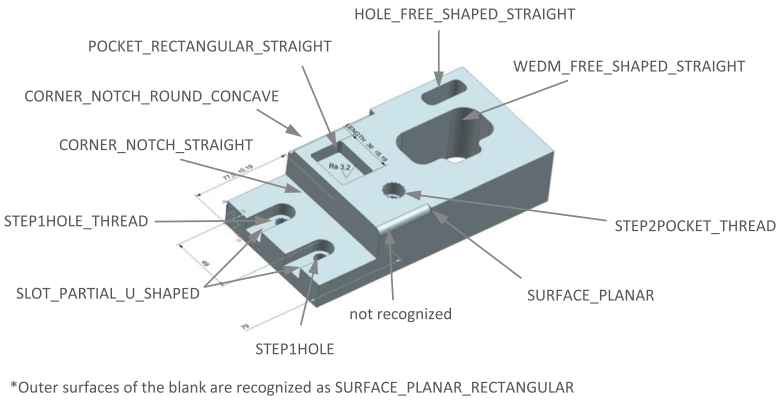

Fig. 2. Feature extraction using a self-designed test component

Therefore, the software should be used in further implementation to create the product AAS. Most of the features contain all relevant parameters needed for manufacturing. The following manufacturing relevant parameter can be exported from a POCKET_RECTANGULAR_ STRAIGHT. Depending on the global coordinate system of a part, the position is thus clearly defined. The length, width and depth of the pocket are available, including general tolerances. If PMI's with additional tolerance information are added, this information must be extracted separately. Furthermore, important parameters such as corner and bottom radii are defined. A few exceptions, such as the WEDM_FREE_SHAPED_STRAIGHT feature, cannot be manufactured using the parameters. The feature does not contain geometric information about the outer shape of the contour.

In the next step, a product AAS was modeled with different SMs to represent all relevant product information for the SP use case. The following SMs are added to the product AAS (Fig. 3). The *ProductIdentification* SM contains general information such as an ID, the product name and type, and a reference to the customer. The company of the customer is described in the *ContactInformation* SM (see SMs of IDTA [15]). The *DesignOfProduct* SM contains the versioning of the design process. The *CommercialProperties* SM describes

all of the customer's organizational manufacturing requirements, such as standardization to be met, necessary non-disclosure agreements (NDA), and delivery criteria. Under the delivery criteria, more detailed information can be provided on the desired delivery date, the CO_2-limit for the production of the component, the number of pieces, the desired delivery of the batch sizes, or even a desired price range for the product can be specified.

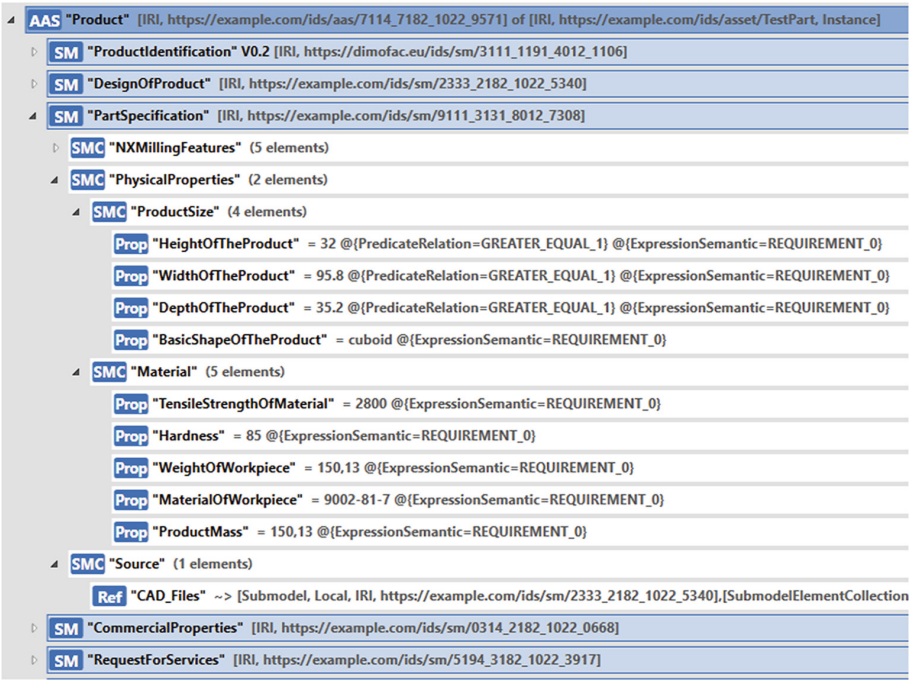

Fig. 3. Product AAS with different SMs to safe relevant product information

The part specific information is stored in the SM *PartSpecification*. The SM contains a collection of several *SubElementCollections (SMC)*. The source file (CAD file) used to generate the SM *PartSpecification* is referenced under Source. To analyze the manufacturing requirements, the external dimensions of the part and the geometry are saved in the SM. This data is stored in the SMC *PhysicalProperties* as *ProductSize*. The material, weight and other physical parameters are stored in the *Material* submodel collection (SMC). All extracted features and the feature parameters are saved in the *Features* SMC. The name of the feature and the feature parameters should be taken directly from the CAD software during extraction. Since there are many different vendors of CAD systems, it is to be assumed that there are many different descriptions and definitions of features. Therefore, it is important to specify the software and version of the software used to extract the features. All relevant information of the product

AAS is included for the transfer to the manufacturing platform (step 2). To match possible services and capabilities, a clear description of them is necessary.

3.2 Possible Standards to Describe Services, Capabilities or Skills in Machining

The AAS of an enterprise lists the services to be offered. In this case, the focus is on contract manufacturers in the field of machining. The services offered by a contract manufacturer can be described in an abstract or specific way. A more abstract description of a service would be, the description of a manufacturing technology, according to DIN 8580 [26]: *Cutting → Machining with geometrically defined cutting edge → Milling*. Furthermore, ECLASS offers a possibility to describe services in group 25: *General Services → 25-09 Subcontracting → 25-09-07 Chip removal (subcontracting)* [27]. Even more specific would be a description of manufacturing features, such as milling a pocket, or the ID of a specific product (Fig. 4). The more specific the description of a service, the less effort the subcontractor will have to identify a suitable manufacturing process. Further information included in the service description should be indication of the approximate number of pieces and component sizes that an order may comprise, location of the provider, input factors like CAD data or technical drawings, Standards to be complied with, further Agreements, qualitative information like tolerances, terms of delivery and payment as well as cost information.

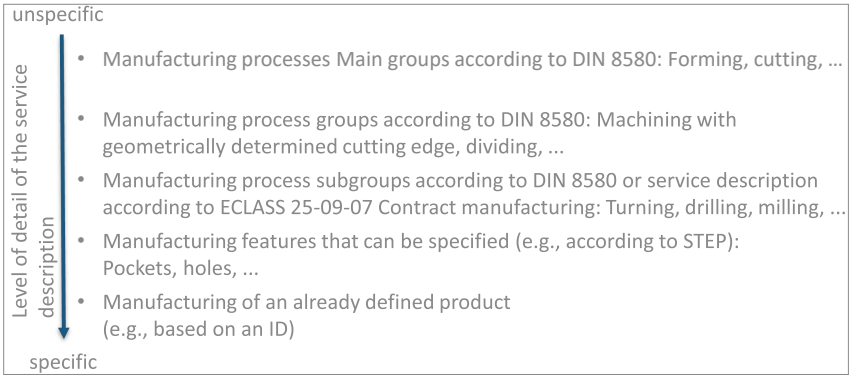

Fig. 4. Description of services or capabilities

Capabilities describe the possibilities in the company to manufacture a product. To describe capabilities, the description forms shown in Fig. 4 can also be used. In general, capabilities are described more specifically than a service. For example, [28] suggests the using DIN 8580 to describe capabilities in machining. However, this would increase the matching effort considerably, since a feature of a product can be completed by different processes defined in DIN 8580. The

most useful way to describe capabilities is to use manufacturing features as the description. "Manufacturing features are primarily determined in terms of shape and topology by the manufacturing processes concerned [...]" [22]. The use of a more product-specific description, as opposed to a process-specific description of capabilities, makes it possible to match a capability and a product feature in a one-to-one relationship. The capabilities should be described by standards and be applicable across manufacturers. In this case, different feature description standards can be mapped to a capability that refers to the skills of the manufacturing machines. Therefore, the naming of skills can be freely chosen by the manufacturers. This reduces the complexity of the matching algorithms. In [29,30] the machining of a product with skills is described after the skill sequence is identified.

4 Conclusion

The paper describes a Shared Production scenario in the sense of RAMI4.0 and outlines a first idea of an Industry 4.0 data space to connect companies on the business level. Actual CM and PaaS concepts lack vendor-independent technologies. This concept is necessary to define flexibly and resilient supply chains in data spaces and to reduce processing time in the preparation of quotations. Furthermore, the digital product passport, for example, makes it necessary to exchange information about the entire supply chain and the further life cycle on the basis of manufacturer-independent communication methods. At the same time, a manufacturer should still be able to participate in different data spaces or easily change a data space. The concept supports independence from a software company through vendor-independent, decentralized communication. In the described scenario AAS, GAIA-X and the I4.0L are the basis for a vendor-independent manufacturing network. The AAS provides standardized SMs to define a common vocabulary for the data to be exchanged. Standards and information needed to be described in a product AAS are discussed. CAD systems are able to automatically generate a product AAS with form features. The product information can be matched with service and capability descriptions. The most effective way to describe machining capabilities is as manufacturing features (product-specific). The I4.0 language defines the structure of the messages sent as well as the steps of communication processes. AAS information AAS can be embedded in the I4.0 language. For bidding procedures in I4.0 language, there is VDI 2193-2, which defines the steps of the communication process. GAIA-X offers connectors and rules for authentication as well as secure and data sovereign exchange of information. In future work the needed product AAS will be generated automatically from CAD to be offered on a marketplace. I4.0L will be used to transfer SMs between the participants of the data space. The concepts will be implemented into a GAIA-X connector e.g. the Eclipse Dataspace Component (EDC).

In order to enable vendor-independent shared production, some standardization work is initially necessary. The SMs of the product AAS and the content

of the SMs must be standardized. Capabilities must be defined to enable the matching of different features to capabilities. The existing I4.0L standards must be checked for completeness and expanded if necessary. Then the function of exchanging SM and communication via I4.0L must be technically integrated into GAIA-X connectors. It is also conceivable that the AAS will receive a plug-in that is GAIA-X compatible. The connectors must be easy to use so that they can be used by small and medium-sized enterprises. Complex processes must be encapsulated.

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Asset Administration Shell Modelling and Implementation Enabling Plug and Produce Capabilities for Modular Production

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Abstract. Mass customization approach requires low-volume, high-mix production schemes, leading to the creation and industrial uptake of highly flexible and modular production lines capable of processing a wide range of products. Towards that end, flexibility of reconfiguration and responsiveness of production plants needs to be increased. Digital technologies can make a significant contribution in making production systems more flexible for modular production. Reconfigurability and interoperability between automated industrial systems and Cyber Physical Systems (CPS) can be achieved by implementing a Digital Twin based on Asset Administration Shell (AAS) and formal definitions found in the I4.0, IIoT and IDTA standards. The AAS modelling containing a machine-readable, semantically unambiguous self-description metamodels needs to be supported by a software infrastructure capable to orchestrate the different assets. This paper presents an implementation of AAS modelling based on the relation of the main production assets –Product, Process and Resources (PPR model)– allowing the dynamic creation of process chains and reconfigurations, as well as up-to-date virtual representation of the Product by deploying a Digital Thread able to trace and orchestrate the data generated along the product lifecycle.

Keywords: Asset Administration Shell · Plug and Produce · modular production

1 Introduction

With a growing demand for customized products tailored to customer demands, manufacturing industries need to develop innovative strategies towards mass customization [1], which leads to adoption of modular solutions capable of processing a wide range of products. Towards that end, flexibility of reconfiguration and responsiveness of production lines need to be increased. This reconfiguration leads to the implementation of Plug and Produce (PnP) concept in manufacturing, which requires an infrastructure based on a service-oriented-architecture (SoA), enabling the digitalization and integration of manufacturing resources on the IoT as adaptive, secure and on demand services, leading on a vertically and horizontally integrated manufacturing ecosystem [2] with minimal

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manual intervention. The PnP concept is accomplished by bringing existing production modules to current standards containing a machine-readable, semantically unambiguous self-description of their properties and capabilities by encapsulating the production models and the different assets as Industry 4.0 components, i.e. the asset and their Asset Administration Shell (AAS) [3].

The concept of the Asset Administration Shell has originally been defined by RAMI4.0 and its specification standardized by Platform Industrie 4.0 [5]. The AAS is the model with the highest degree of maturity for mapping product and process information across the entire lifecycle of industrial goods [6] and is the standardized self-description of a technical component in production [7]. But there is a lack of formal standardization when implementing AAS regarding standards and technologies, as well as the need to address the semantic interoperability between assets [8]. This lack of stablished AAS models increases when it comes to immaterial and non-machine assets [9] (e.g., process or the product). Moreover, all the steps for AAS modelling must be carried out manually requiring intensive programming [10]. For that, in the literature can be found some software implementations for production management [11] that allows an AAS to be formed in a user-friendly manner, especially as regards the specifications of the AAS modelling utilizing relevant standards.

In this paper a methodology to create and deploy Asset Administration Shells in a modular scheme production is presented using as demonstrator one of the production modules of H2020-DIMOFAC project [4]. A methodology for AAS modelling of non-physical assets as well as the relation with the production assets is presented. The modelling of all involved assets in the product lifecycle, as well as its relations, not only allows orchestration of the production systems but also the traceability of the product lifecycle resulting on an implementation of a Digital Thread. The paper is organized as follows: in Sect. 2, a brief overview on the methodology for AAS modelling is presented. Section 3 presents a proposal of Asset Administration Shell implementation and modelling. Lastly in Sect. 4 some conclusions and future work are introduced.

2 Methodology: Product-Process-Resources Model

For Industry 4.0, an asset is any object which has a value for an organization and can take almost any form, i.e., a production system, a product, a software or even human resources, and can be a single component but also an assembly of components [12]. The asset's information is described in the AAS as *Submodels* [13] and describes technical functionality exposed by the Administration Shell or respective assets [14]. Below the submodel level, there are the submodel elements for storing specific data related to the submodel.

Taking in consideration the description of the 3 types of AAS [7], in type 2 and 3, the AAS is composed of a passive and active part. The passive part composed by properties which are readable and/or modifiable. On the other hand, the active part consists of functions performed by the asset and the AAS, providing service-oriented communication *capabilities* and decision-making functionalities [15]. This active part is mainly represented by the specific submodels: *Capabilities* and *Skills*. Although the AAS meta-model provides a generic approach of modelling, the definition and standardization of the implemented submodels is essential for interoperability. This is part

of Industrial Digital Twin Association (IDTA) [16] and ZVEI SG [14] provides a list of potential common submodels: *Identification*, *TechnicalData*, *ConfigurationData*, *OperationalData*. But the definition of specific submodels for describing the capabilities offered by the asset depends on the granularity of the model, level of abstraction and the use case [17].

For Platform Industrie 4.0 the functions performed by an asset can be seen as some kind of abstract process step that is not yet tied to a specific resource but has a description of its inputs and achievable effects. These effects typically have an impact on the processing state of products [18]. The resulting conceptual model of the asset with its functions is an extension of the well-established Product-Process-Resources (PPR) representation paradigm extended by the notions of capability and skill [19]. The definition of the interconnection of the three views allows the dynamic creation of process chains and reconfigurations. This paper presents the AAS modelling of the Product, Process and Resources and how the relations between these assets allows the reconfigurability of the production line as well as the traceability of the product by demonstrating a Digital Thread. Figure 1 shows the dataflow needed to carry out the orchestration of the production systems: first, the product AAS includes the process needed for the manufacturing; secondly, for the execution of the process some capabilities are needed; then, an orchestrator will search for the resources that have these capabilities. Finally, the resources are linked to the product for having traceability of its manufacturing.

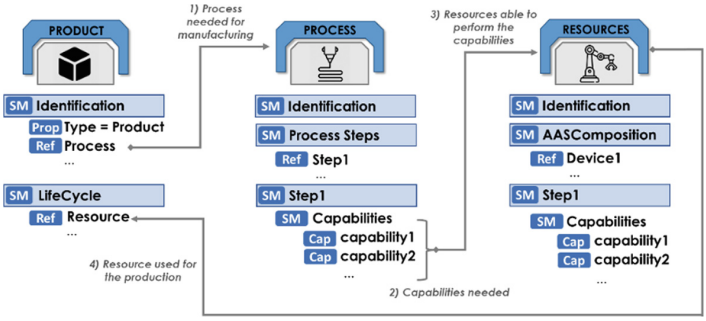

Fig. 1. AAS modelling methodology based on Product-Process-Resources (PPR) model.

3 Implementation of Asset Administration Shell for Achieving PnP Capabilities

The Industry 4.0 components' lifecycle is supported by a digital infrastructure that is able to support real-time connectivity (e.g., based on OPC UA or MQTT) and basic data storage, monitoring and security enabling a horizontal integration. For that, the work presented is based on the digital *DIMOFAC Platform* developed by Netcompany-Intrasoft developed under DIMOFAC project. The selected use case to apply the AAS approach is one of the production modules of DIMOFAC that focus on a multi-material component manufacturing by Automated Tape Laying (ATL) process.

3.1 Architecture Definition and Assets Identification

The first step for implementing AAS is the identification of the different assets [20], the architecture and communication protocols that could or will be used. This ATL module is composed by a movement system (FANUC robot) and heat system (ATL head), which can be composed by infra-red system or laser source. The whole module will be represented by a central unit (i.e., industrial PC). The information gathered by the central unit (Operation Technology) is available in the DIMOFAC platform (Information Technology) as well as the product information related to the design and/or simulation (Engineering Technology). The software in charge of taking the decisions and allowing PnP capabilities is named *Orchestrator*. While the software in charge of registering all the information related with a specific product is the *Digital Thread*. Figure 2 depicts the aforementioned considerations.

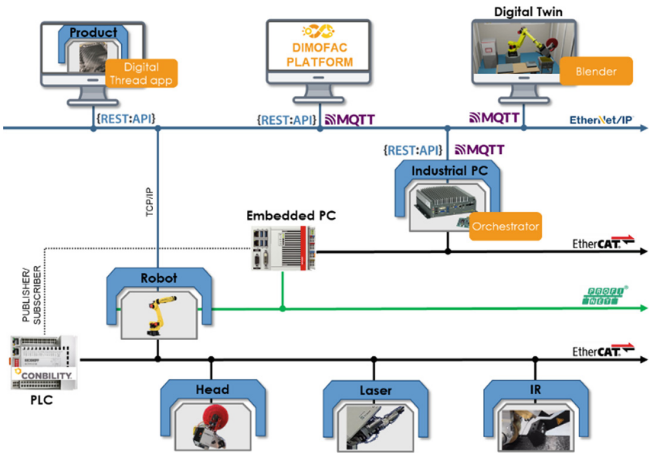

Fig. 2. Assets identification and architecture.

3.2 AAS Modelling

Resources Modelling. The type 2 assets modelled for this use case are the robot, heating system, whereas the type 3 is the *Orchestrator* software. All type 2 AAS follows the same modelling methodology, containing the same submodels, but with different property values. The submodels will be presented taking the robot (without tooling) as example; but for a comprehensive reading the AASx file are also available in Zenodo (link) [21]:

- *Identification* and *TechnicalData*: submodels to identify the physical asset with static information.
- *Capabilities*: this submodel specify the tasks that the asset is able to perform. For instance, the robot AAS *moves* to perform the process and *communicates* for the process monitoring.

- *Communicate*: specify the communication protocol and it has a relation with a specific submodel ConfigurationEthernet in which the details for this communication are specifies. For instance, the IP, port and data format.
- *OperationalData*: is one of the common submodels defined by Platform I4.0 and it defines the output data of the asset. This data will be sent to DIMOFAC platform and updated in real-time. The values are considered data in motion.
- *Parameters*: defines the data needed for performing the capabilities. In the robot example, the reference system and the Tool Centre Point (TCP) information.
- *AASComposition:* the whole manufacturing cell/module is represented by the AAS of the module. In this AAS, the main submodel is the *AASComposition* that specify the assets that compound the module (i.e., robot and heating system). The *Capabilities* are inherited from the assets that compound the module.

Product and Process Modelling. These assets are needed for linking the information gathered in the shopfloor with the data coming from other production steps (i.e., design, simulation, quality). The *Product AAS* is created using the *Digital Thread* application and the main submodel is the *LifeCycle* which references the physical assets used for manufacturing the product. On the other hand, for *Process AAS* the main submodels are the *ProcessSteps* (i.e., additive manufacturing, cutting, …) and the *Capabilities* needed for executing a specific step. The *Process AAS* information is managed by the *Orchestrator* and it will be used for searching the physical assets needed for the manufacturing.

3.3 Hardware and Software PnP Capabilities: Orchestrator Overview

The *Orchestrator* and the *Digital Thread* software are the responsibles of managing the AAS information in a user-friendly manner. That software were developed based on PyI40AAS [22] libraries to manage AAS models. The Digital Thread is used for visualize the product lifecycle information, whereas the Orchestrator decides what physical assets are available, start the communication with different devices, and it is also able to decide the assets/modules needed for manufacturing a product.

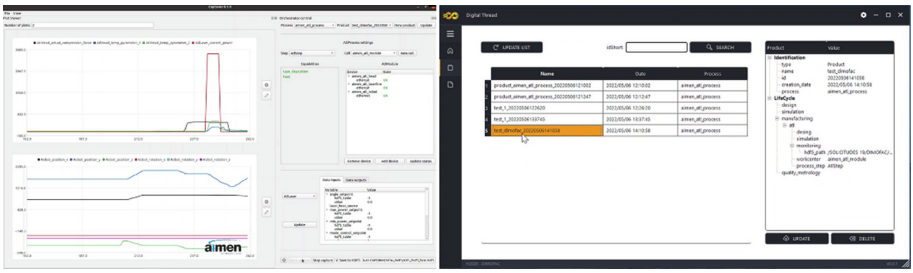

Fig. 3. Software user interfaces (Left: Orchestrator, right: Digital Thread)

Figure 3 shows the interfaces of these software, but a demonstration is shown in a video [23]. Whereas Fig. 4 shows the sequence and interaction that the user has to

do with the different software. The user starts with the creation of a product using the *Digital Thread* application selecting the processes needed for the manufacturing. Then, for starting the manufacturing, the user selects from a list the specific product to be manufactured, and the *Orchestrator* checks the modules available for this manufacturing. During manufacturing, the user can also see real time information of the different assets. Once the manufacturing finished, the user could check in the Digital Thread application that the information related to the manufacturing is automatically linked with the product previously selected.

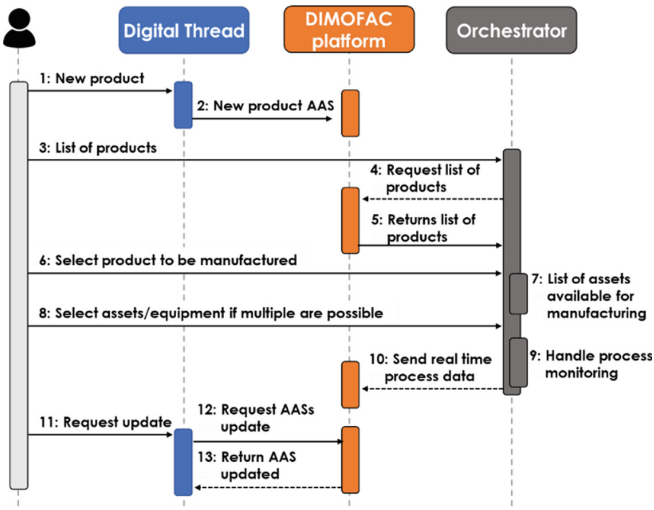

Fig. 4. Dataflow scheme between user, Digital Thread, Digital Platform and Orchestrator.

For hardware PnP capability, the *Orchestrator* will try to stablish the communication with the physical assets that compound the module checking the *AASComposition* submodel. For each asset, the software will take the configuration specified in the Submodel *Communication* and execute the corresponding method with the attributes specified in the submodel. If the asset is not physically connected to the central unit, the software will not allow start the production. Whereas for software PnP capabilities, the *Orchestrator* makes the decision of what module is needed for manufacturing a specific product. The *Product AAS* has a reference to the processes that need to be performed as it was shown in Fig. 1 (i.e., *aimen_atl_process*). Then, the *Orchestrator* will search into the different processes available in DIMOFAC platform the capabilities needed for executing the process (i.e., *tape_deposition* and *heat*), and the module that can perform these specific capabilities (i.e., *AtlModule*). Finally, the Orchestrator starts the communication with the individual assets.

4 Conclusions and Future Work

A video was published (link) [23] to show an overview of the work presented. A practical AAS-enabled PnP implementation using standardized technologies was presented and some AAS models were uploaded in the open repository Zenodo [21]. Some of the main results of the implementation process can be summarized as follows:

- Thanks to the PPR AAS model the information related to a specific product along the entire value chain can be traced implementing a Digital Thread. The Product AAS can be used for implementing a Digital Thread application and it can be the base for a Digital Product Passport implementation.
- The orchestration of the different physical assets for enabling a PnP solution is done through the definition of specific submodels that nowadays are not standardized (i.e., *Communication* of the assets). Some examples can be found in Zenodo.
- Specific use case implementations can be found in the literature, but the PnP system and the software presented in this work is process- and product- independent, so it could be applicable and deployed in another use case. Nowadays, this work is being deployed and tested in different manufacturing domains for checking the interoperability of the AAS models and the benefits of the PPR model.

Future work will focus on the update of the different AAS models according to the new templates provided by IDTA; so, the final solution is compliant with the standard and interoperable with the production systems that are digitized through the implementation of AAS. A further step will be to add artificial intelligence to AASs, which will allow the orchestration of different production lines and minimize human intervention in the decision-making [24]. For instance, not only the decision-making is based on the availability of the assets, but also taking in consideration some sustainable and circularity indicators.

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An Algorithm for the Assignment and Scheduling of Tasks in Human-Robot Collaboration

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Abstract. To face the challenge of increasing productivity while having flexibility, collaborative robots can help manufacturing or assembly systems. However, it is essential to assign and schedule tasks between humans and robots to provide a successful Human-Robot Collaboration while considering the agents' potential and limitations. Thus, the main goal and contribution of this paper is to present an algorithm inspired in the GRASP metaheuristic for the assignment and scheduling of tasks in a collaborative workspace composed of a human worker and a collaborative robot. The algorithm is first tested with a fabricated data instance and then using data from six practical jobs from a published paper. The comparison with the dataset from the literature showed that the developed algorithm can provide good-quality solutions.

Keywords: Human-Robot Collaboration · Task · Scheduling · Assignment · Heuristic

1 Introduction

The current technological challenges that industries face are characteristic of the Fourth Industrial Revolution or, also called, Industry 4.0 (I4.0) and to overcome them, industries must have flexibility and a greater focus on the human being in their processes. Moreover, the changing production and demand patterns, along with the increasing attention to the worker's conditions, boost the transition towards more human-care solutions built upon synergies between robots and humans [1]. In addition, maintaining competitiveness against the background of globalized markets is also an ongoing challenge. Therefore, high-quality requirements, the capability to respond quickly to market changes, and the control and reduction of production costs are important known strategies for organizations to survive [2]. One of the brand-new technologies that I4.0 brings are the collaborative robots or also called cobots. Thus, to face the challenge of increasing productivity while having flexibility, collaborative robots represent a clear added

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value as they promise to increase production rates when compared to manual operations and provide flexibility to industrial environments [1, 3]. Interestingly, assembly systems have a high proportion of manual work which bring drawbacks such as low productivity. Whereas, through the ability of robots to work in collaboration with humans, new applications in automation have appeared over the last years [2].

The main purpose of these technologies is not to replace human jobs. Conversely, human workers will find support from these innovative robots for improving the efficiency of processes [1]. Therefore, Human-Robot Collaboration (HRC) enables the combination of the strength and accuracy of a robot with the intelligence, adaptability, and dexterity of a human worker [4, 5].

Hashemi-Petroodi et al. [6] stated that the relevance of collaboration between humans and automated systems is rising productivity and flexibility and in terms of ergonomics, safety and reconfigurability of production systems, which is setting up new challenges to industries. Therefore, to provide effective HRC, one important factor is the correct assignment and scheduling of tasks. Thus, decisions must be made regarding which tasks should be allocated and scheduled to the cobot and which tasks should be left to the human workers while respecting changeover times, temporal and spatial safety distances, and precedencies [7]. Thus, one intelligent approach, for instance, is a skills-oriented task allocation [2]. In fact, humans and robots have different qualities and limitations. Therefore, there are tasks that are more suitable for each type of agents, and others that both can perform. For that, in this paper, will be presented an algorithm for the assignment and scheduling of tasks between a human operator and a collaborative robot. The algorithm aims to help engineers to decide the best schedule for a specific job.

The paper is structured as follows. In Sect. 2 related works are briefly presented. In Sect. 3 the problem under study is described. Then, in Sect. 4 the approach to computing task assignments and schedules is explained. In Sect. 5, the algorithm results are shown. Finally, Sect. 6 is dedicated to the conclusions.

2 Related Works

Different approaches have been proposed to study allocation and/or scheduling problems in human-robot teams. Solution methods include heuristics, metaheuristics, exact methods, simulation or even hybrid approaches. While task allocation is a general problem and has been discussed intensively, less effort has been devoted to the factors that should be considered in allocating tasks among a heterogeneous team. For this reason, [8] investigate the agent characteristics that should be considered in the task allocation problem in industrial assembly processes. Hari et al. [9] present an approximation algorithm with a greedy heuristic for the Task Allocation, Sequencing and Scheduling Problem involving a team of humans and robots. The problem is a generalization of the single Traveling Salesman Problem and aims to find a schedule of tasks for each robot while minimizing the maximum mission time. Bogner et al. [7] propose two approaches to optimally distribute tasks between humans and robots in a realistic production process of printed circuit boards (PCB), where the objective is the minimization of the completion time: an order-based heuristic approach and a matheuristic applying a truncated variant of the

integer linear programming (ILP) model. The computational evaluation is based on a real-world use case from the PCB industry. Scheduling problems are very much explored in assembly scenarios. A much less explored application concerns the disassembly of electric and electronic devices. Kinast et al. [10] use a real-world data set and propose a genetic algorithm with a biased random-key encoding for a collaborative assignment combined with the job shop scheduling problem for the disassembly of electric vehicle batteries. In fact, it is difficult to program traditional industrial robots for these tasks since there is a huge variance in the batteries. Cobots, by contrast, can be assigned to many tasks of disassembly and by working closely together with a human, they provide a reduction of costs and risks. Kinast et al. [11] study the job shop scheduling problem with the assignment of a cobot aiming to maximize the normalized sum of production costs and makespan. To solve the problem, a hybrid genetic algorithm with a biased random-key encoding and a variable neighborhood search is proposed which combines the exploration aspects of a genetic algorithm with the exploitation abilities of a variable neighborhood search. Then, the algorithm is tested using real-world data and artificially generated data.

Characteristic differences between humans and robots bring challenges to collaboration task scheduling. For instance, in terms of flexibility, humans are naturally flexible and adaptable, able to deal with unforeseen situations and quickly adjust their actions. Robots, on the other hand, usually have a limited range of motion and operate on a pre-programmed set of actions. Other difference is related to the capacity of judgment. Humans have the ability to make complex decisions based on limited or uncertain information. Robots are usually programmed to follow a set of rules or instructions and can have difficulty making decisions in ambiguous or unusual situations. Zhang et al. [12] propose a genetic algorithm aiming to minimize the job cycle while having human fatigue as a constraint, to study the task scheduling of an HRC assembly cell to achieve a trade-off between job cycle and human fatigue by integrating microbreaks inside job cycles.

Despite the number of papers that studied scheduling problems in collaborative robotics, the majority do not use real-world data which widens the gap between academic and practice problems. For instance, in job shop scheduling problems, most of the papers focus on method development and only 8% address real-world industrial applications [10]. Several contributions can be mentioned regarding the investigation here presented: 1) the developed algorithm used for the assignment and scheduling of tasks between a human worker and a collaborative robot which was inspired in the Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic, 2) testing the developed algorithm using real data from [13]; and 3) the algorithm enables the assignment of a task to a human worker and a cobot, in a fully collaborative scenario which most previous researches do not enable.

3 Problem Description

The problem under consideration in our research was inspired by three real-world use cases. Before the presentation of the problem definition, it is important to first clarify some notation that will be used in order to fully understand the problem under study. The definitions were inspired by Radwin et al. [14]:

- A job, J, consists of several tasks that may have precedencies between them. Therefore, job J can be divided into a set of N tasks, such that J = {T1, T2, T3,…,TN};

- A task, T, is an operation that cannot be subdivided like, e.g. pick, place, and reach.

Consider a single workstation, in other words, a collaborative cell, where two agents, a human operator H and a robot R, have to cooperate during a work shift in order to perform S jobs (J1,…, JS).

The allocation and scheduling of tasks between a human and a robot is designed as a multiagent assignment and scheduling problem as in [13]. Each task is associated with an execution time pi(A), where A ∈ {H, R} represents the agent that executes the task. The duration of the tasks will depend on the agent that performs them. Moreover, each task has a strain value. This parameter is extremely important in order not to allocate tasks that are repetitive, heavy, or dangerous to the human worker to improve the quality of the human job. Precedence relations among tasks are also considered. Because of the capabilities required for some operations (e.g. analytic skills, visual inspection, or high flexibility) and agent-limited capabilities, only a set of operations can be performed by the robot, and there could also exist tasks that cannot be done by the human. A human and a robot can perform different operations simultaneously or collaborate on an operation, in other words, there are tasks that can only be executed when the human and the robot work in close collaboration. Each agent can only perform one task at a time (no overlapping) and preemption is not considered, in other words, for task T2 to begin, task T1 has to be finished first, if there is a precedence relation between tasks T1 and T2. It is important to state that T1 and T2, in the previous example belong to the same job, as the program only runs one job at a time.

The solution of the scheduling algorithm will be a set of assigned tasks to the human and to the robot, its sequence, and times, and the total makespan. The objective of the scheduler is to distribute tasks to the agents and determine the sequence of tasks that minimizes the makespan, considering human strain. The ergonomic risk is inputted as a constraint. The input to the scheduler consists of the ergonomic risk for each task along with the time to complete each task for both agents and its precedencies. The scheduler also has a set of constraints that represents which tasks cannot be done by the robot or by the human.

4 Algorithm Presentation and Description

For many years, heuristics have been studied to solve combinatorial optimization problems. By definition, heuristics are search methods that take advantage of the characteristics of the problem to be explored, making it easier to try to find a global minimum in the search space [15]. The algorithm presented in this section was inspired in GRASP [16] and was coded in java in the software of IntelliJ IDEA Community version. The pseudo-code of GRASP can be found in [16]. Regarding the way of working of the algorithm, its main steps can be described as follows:

Firstly, the algorithm begins with the greedy construction function where it will order all tasks taking into consideration their duration, in other words, the tasks will be ordered increasingly by duration, considering the robot time and the human time. In case there are tasks with equal duration, the algorithm takes into account the difference

between the human's time and the robot's time, and it will prefer tasks with a smaller difference. Secondly, the algorithm will create a Restrict Candidate List (RCL), with 80% of the fastest tasks. However, this parameter can also be modified according to the trade-off between greediness and randomness pretended. After the creation of the set of candidate tasks, one task will be chosen randomly. Thirdly, the chosen task will be assigned randomly to one of the agents (to the robot or to the human worker) but taken into consideration if each agent can indeed perform the task and if the task can be assigned to the human, in other words, if the ergonomic risk of the task is not higher than the maximum defined. Once the selected task is incorporated into the partial solution, the RCL is updated and the incremental costs (in this case the duration of the task) are reevaluated which is the adaptive aspect of the algorithm. This process will be repeated until all tasks are assigned to an agent. The process of selecting another task to be assigned works as follows: the algorithm will always look for the task with the lowest duration, taking into consideration both durations (the human and the robot). The best task represents the one which will increase less the makespan. The selection of the next task for incorporation is determined by the evaluation of all candidate tasks according to a greedy evaluation function, which represents the incremental increase in the minimization time function due to the incorporation of the task into the solution under construction. The incremental costs in time will be updated after each assignment. A feasible solution for the job schedule is constructed. The solution will always be feasible as the constraints of capability matters and ergonomic risk and precedencies are already considered when assigning each task, so there is no need to apply a repair procedure to achieve feasibility.

The process will be repeated 100 times, which is the number of iterations defined, whereas this parameter can also be modified. Finally, after iteration number 100, the best solution, in other words, the solution which respects all the constraints and has the lowest makespan, is kept as the result.

5 Results

5.1 Generated Data

In order to test all the enabled functionalities of the developed algorithm, an instance was generated, consisting of one job, eight tasks, a human worker and a collaborative robot. The precedencies were defined by considering groups of tasks. The tasks between groups were supposed to not have precedencies, in other words, there can be parallelization of tasks between groups. Inside each group there is a precedence. Finally, to test all the functionalities of the algorithm, there is one task which is collaborative (T5) and task 7 (T7) and task 8 (T8) cannot be assigned to the human and to the robot, respectively. Firstly, the problem was solved without constraining the ergonomic risk. In this instance, the classification of the ergonomic risk did not follow any specific method, so further on, the values for ergonomics will be designated as ergonomic risk (ER). The higher the value for the ergonomic risk the higher the physical strain for the human worker. The best solution found by the algorithm resulted in a total makespan of 82 s. Secondly, in order to understand the influence of the ergonomic risk in the makespan, the ergonomic risk was decreased, step by step. Along with the reduction in the maximum accepted

ergonomic risk it is expected that the human will be assigned to fewer tasks. A summary of the results is presented in Table 1.

Table 1. Created instance makespan impact when reducing the ergonomic risk.

ER	15	6	5	3	2	0
Makespan	68 s	68 s	102 s	122 s	122 s	122 s

5.2 Real-Word Data

The algorithm was also tested using data from [13] in order to understand the performance of the algorithm and to enable the comparison of the results. Six real-world-based processes executed by human workers were considered, including three observed during a visit at Steelcase, Inc., a furniture manufacturer based in the USA and three chosen from the NIOSH video database [13]. The three processes from Steelcase included a quality-control process (Job 1), a packaging process (Job 2), and an assembly process (Job 3). The other three processes from the NIOSH database consist of a stocking process (Job 4), a parts-assembly process (Job 5), and a metal-cutting process (Job 6) [13]. Again, our aim was to analyse the effect on the total makespan with the changing of the maximum limit allowed for the ergonomic risk, and the same conclusion could be achieved, i.e., as expected the makespan increases along with the reduction of the maximum value for SI; and the human idle time increases with the reduction of the maximum value for SI while robot idle time will decrease.

Despite Pearce et al. [13] used a different method to analyze the trade-off between time and ergonomics it is still interesting to compare the results because the authors referred that their solution had a gap to optimality of 1%, Therefore, it can be inferred how close the algorithm was from the optimal solution. Thus, the values obtained for the makespan for the six processes when a higher importance is given to the time can be seen in Table 2. The comparison between the values when a higher importance is given to ergonomics will not be made because [13] study ergonomics as a component in the objective function, and in our developed algorithm ergonomics is integrated as a constraint, therefore, the results are not comparable.

The baseline values represent the solution when all tasks are performed by the human worker. Analyzing Table 2, for jobs 5 and 6, the best solutions when higher importance is given to time, our algorithm managed to reach the values of [13]. On the other hand, for jobs 1,3 and 4, the solution of the presented algorithm is near, but it was not able to reach the near-optimum solution. However, for job 2 the algorithm could even find a better solution than [13], probably the optimal solution.

Table 2. Makespan for jobs from [13] method and the developed algorithm.

	Baseline	Pearce et al. (2018)	Our algorithm
Job 1	38 s	28 s	33 s
Job 2	25 s	25 s	24 s
Job 3	55 s	36 s	46 s
Job 4	422 s	370 s	413 s
Job 5	38 s	38 s	38 s
Job 6	65 s	57 s	57 s

6 Conclusions and Future Work

In this paper, it is proposed and tested an approach that considers time and ergonomics for integrating a collaborative robot into a set of manufacturing processes. Trade-offs between time and ergonomics are discussed by modifying the constraint of the maximum value for the ER or SI allowed. The resulting set of schedules enables process engineers to balance these parameters in the most convenient way for the organization. Overall, the algorithm showed to be successful as good results were found for the jobs presented by [13].

As future work it would be interesting to improve the graphics of the algorithm program when the user is introducing all the necessary inputs in order to make it more appealing. Moreover, one limitation of the program is that the algorithm does not take into consideration human fatigue over time which could influence the performance when executing certain tasks. Also, it will be interesting to explore in the future some improvements to the RCL list, namely, including the study of alternative approaches to the RCL list dimension and also the study of alternative incremental costs.

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Influence of Finishing Colour on the Efficiency of Automated Production Line for Wooden Doors

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Abstract. Porta KMI Poland S.A. company has implemented a fully automated intelligent technological line TechnoPORTA for customized mass-production of technical door leaves. Each door leaf is provided with a unique QR code. It allows the line modules to individually adjust the machining parameters to the currently processed element according to the IT controlling system. Before entering the TechnoPorta line, the door leaves are not sorted, although the high capacity characteristic of mass production is required. Therefore, the aim of this short test was to verify the influence of leaf segregation by colour on the efficiency of the TechnoPorta line. Three groups of door leaves – white, black anthracite and mixed – were tested. The test included measurements of the time interval between successive door leaves, which is the tact of the line. The test showed that each time the machining parameters are changed due to colour changes, the tact of the line is approximately twice as long. The colour segregation of door leaves influences the efficiency of the production line. In the case of a single-color set, the tact of the line is half that of a mixed set. The less frequent the colour changes, the greater the production time savings.

Keywords: Door Manufacturing · Multi-Product Production · Customization

1 Introduction

In the international market, Poland is one of the countries leading the production of doors, windows, and furniture. The popularity of these products can be attributed to high quality in relation to relatively low production costs. Technology allowing the automation of production and easier access to fabricated goods is the main driving force of progress. Robotization of such processes as gluing the door edgebands streamlines the work, decreases the risk of an error and lowers the costs borne by a producer.

Optimal planning and control of automated production lines plays a key role in modern manufacturing systems. This is especially true for the production many varied products. PORTA company, the largest Polish manufacture of wooden doors, has a wide

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portfolio of products distinguished by functionality, purpose, construction, dimensions and colour. A limited number of production lines requires frequent retooling of the machines to process a specific type of product. The problem of controlling the manufacturing in the conditions of many products has been known and tested for a long time [1–3]. Nowadays, in order to find an optimum solution, modern tools compliant with the idea of Industry 4.0 are being used [4]. A producer who follows these principles can count on lower fabrication costs even if their product is customized. Digital twins of the factories [5, 6], application of artificial intelligence [7] including deep learning models considering sequential information on the production process [8], multi-agent models based on the fractal theory [9], knowledge graphs [10] and blockchain technology [11] are becoming increasingly popular. The problem of the control policy described in reference [12] concerned the production of doors in a car assembly plant. Analytical research resulted in the introduction of closed formulae for the key efficiency indicators. Also, the indicator of overall equipment efficiency (OEE) is used as an indicator of its condition and utilisation [13]. Analysis and modelling of the OEE values received from the factory allow the formulation of the Association Rule Mining (ARM) which in a dynamic manner facilitate the decision making process within the production line. Another technology is Transmission Control Protocol (TCP) for the optimization of the setting time, that is, using the Time Series model for the algorithm of clustering and Parallel Job technology in Single Minute Exchange of Die (SMED) [14]. On the basis of these principles, actions taken by a company cause increased reliability and increase the efficiency of reaction, as well as time and cost efficiency [15].

Research indicate that within the whole service life of such a product as doors, the production stage is the most significant in terms of the impact on the environment [16]. Therefore, the optimization of the production has a significant meaning also on this account. Due to the variability of construction and finish of such products as door leaves, there are numerous factors influencing the efficiency of the production equipment. Identification and quantitative definition of the influence of various factors on the achieved efficiency have crucial meaning for planning and controlling production lines, especially automated ones [17]. The strongest influence on the efficiency of door leaves production is exerted by technological operations associated with the linear feed and requiring a repeated passage connected with the need of machining three edges of the product. In an automated production line for door leaves, such a solution is exemplified by a technological line for machining narrow surfaces. Operation control of such lines is parametrized and the operation of specific machining modules of the line depends on the parameters of the machined products. The most important parameters of the door leaves include their dimensions, presence or absence of the weather stripping and the finishing colour. All these parameters can constitute factors which, to a various extent, influence the efficiency of the technological line. Therefore, it is necessary to measure their individual influence in order to be able to correct the course of production for limiting the resources, mainly time. This is why the objective of this paper consisted in conducting a short test to indicate the influence of the finishing colour of the door leaves on edge machining time in softforming modules of the technological line. The approach proposed in the paper is an innovative one, not yet seen in wooden door factories.

2 Materials and Method

2.1 General Assumptions of the Experiment

Tests were conducted on currently produced door leaves of panel doors with a frame made of glued laminated coniferous wood. The colour scheme of wide and narrow surfaces included anthracite black and white. The narrow surfaces of the door leaves were finished with a 1 mm thick Polyacrylonitrile-Butadiene-Styrene (ABS) type edgeband attached with hot-melt glue.

The difference in the production process for white and anthracite black doors consists in different settings of the heating lamps. For brighter colours, the lamps heat up to a higher temperature. When interchangeable feed of elements whose colours are extremely different, such as white and anthracite black, occurs, the machining tool needs time to adjust the temperature of the lamps to the specific colour of the edgeband. Eighteen door leaves of various colours were used in the test.

2.2 Technological Line Control

The technological TechnoPorta line for machining narrow surfaces of door leaves consists in two sub-lines dedicated for machining narrow surfaces using softforming and postmorfing methods. The tests involved softforming due to the fact that the majority of the produced door leaves is subjected to this type of machining. Figure 1 presents a schematic drawing of the line setup.

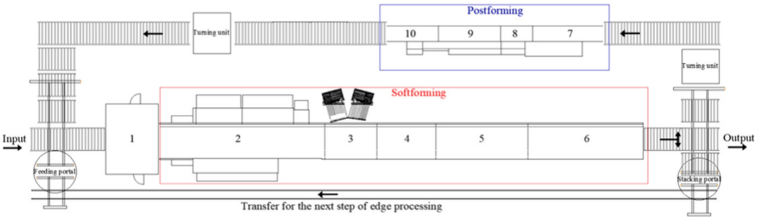

Fig. 1. Schematic drawing of TechnoPorta line.

The line structure includes the following modules and sections (subsequent numbers comply with the numbers in Fig. 1):

Softforming: 1 – Milling the reference edge module; 2 – Pre and finished milling of the edge (preparing the edge to stick edgeband on) module; 3 – Edgeband application module; 4 – Pressdown section; 5 – Corners and edge finishing module; 6 – seal's grooves milling module.

Postforming: 1 – pre-wrapping milling profile module; 2 – Glue applying module; 3 – Pressdown section; 4 – Edge finishing module.

From the point of view of such a parameter as the finishing colour, module 3 is the most decisive on the line efficiency. This is where thermal activation of the applied edge band occurs along with heating the glue to its working temperature. The information on the set temperature is coded in the code characteristic for each door leaf.

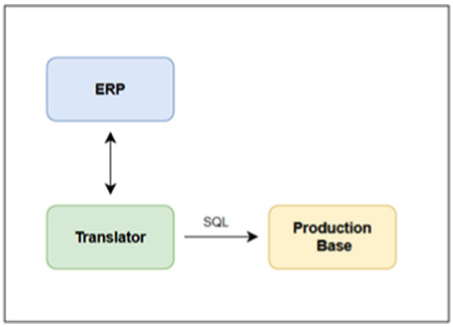

Fig. 2. Data transfer.

Communication between Porta and the automated TechnoPorta line for forming and wrapping the door leaves is realized with the aid of **Translator** application created by the Porta company. Translator takes fragments of data regarding the machining process from an ERP system and the remaining data are generated from the application using the appropriate filters. This allows translating the information from the language used by Porta in their systems into the language understood by the machine. Generated data package is being sent to the machine. The machine queries its database and launches the appropriate macros which carry the information regarding the scope of machining that needs to be done in a given product (Fig. 2).

In the Porta company's IT system, each door leaf is specified by a 21-character symbol containing all technological data. Laminate colours is 12th in the code and it is a 2-character symbol. Examples for tested Agat (BM) door leaves with white (Barcode 130846397) and anthracite black (NC) (Barcode 130846393) laminate (Fig. 3).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
S	P	E	A	0	P	0	L	0	8	2	BM	0	S	P	3	0	0	0	0	0

Production_Barcode_ID	Cycle	MaxCycle	Comment1	Comment2	Comment3	Printer	Etikett	Order_No	Serial_No	Part_No	Product_Item_ID	Logistic_Trans_ID
130846397	1	3	Agat	EPF3L08A0PMM0C00		1	1	26111167	*	SSWZS	SPEA0P0L082BM0SP300000	ZPL1000089/5/1
1	9	5	20	1		9	8	1	1	1	1	1
130846397	2	3	Agat	EPF3L08A0PMM0C00		0	0	26111167	*	SSWZS	SPEA0P0L082BM0SP300000	ZPL1000089/5/1
1	10	5	20	1		10	9	1	1	1	1	1
130846397	3	3	Agat	EPF3L08A0PMM0C00		0	0	26111167	*	SSWZS	SPEA0P0L082BM0SP300000	ZPL1000089/5/1
1	11	5	20	1		10	9	1	1	1	1	1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
S	P	E	A	0	P	0	L	0	8	2	NC	J	S	D	3	0	0	0	0	0

Production_Barcode_ID	Cycle	MaxCycle	Comment1	Comment2	Comment3	Printer	Etikett	Order_No	Serial_No	Part_No	Product_Item_ID	Logistic_Trans_ID
130846393	1	3	Agat	EPE3L08A0PMNIC00		1	1	26136545	*	SSWZS	SPEA0P0L082NCJSD300000	R//959203/4/1
1	9	5	20	1		9	8	1	1	1	1	1
130846393	2	3	Agat	EPE3L08A0PMNIC00		0	0	26136545	*	SSWZS	SPEA0P0L082NCJSD300000	R//959203/4/1
1	10	5	20	1		10	9	1	1	1	1	1
130846393	3	3	Agat	EPE3L08A0PMNIC00		0	0	26136545	*	SSWZS	SPEA0P0L082NCJSD300000	R//959203/4/1
1	11	5	20	1		10	9	1	1	1	1	1

Fig. 3. An example of processing data for the tested door leaves, taking into account the used colour of the laminate – view from the Translator.

On the basis of symbols and the family of a given product, the Translator decodes all the parameters and finds appropriate filters, yielding the machine macros. The parameter that governs the colour, type, thickness and width of the applied edgeband is macro “EdgeCode” (Fig. 4).

35	33	RebateDepth2_X	Wymiar 2 wrębu w osi X	tak	float	Od 0 do 35		pokaż
36	34	RebateHeight2_Y	Wymiar 2 wrębu w osi Y	tak	float	Od 0 do 60		pokaż
37	35	EdgeCode	Softforming. Makro obrzeża.	tak	nvarchar	Od 0 do 30		pokaż
38	36	GrooveMacroRightSide	Softforming, prawa strona maszyny. Makro frezowania uszczelek dolnych.	tak	nvarchar	Od 0 do 30		pokaż

Fig. 4. List of processing parameters, including Edgecode.

For the previously mentioned test door leaves, the machine imported appropriate filters from the Edgecode parameter no. 2475 for white laminate and no. 24 for anthracite black laminate, yielding specific macros reflected in the machine database such as A100058E_BIALYRAL9003 (white) (Figs. 5 and 6).

2474	%	S		W;T;E;X						0;Ć;B		2;7	BI					0;K					1;2;3	A100058E_BIALY
2475	%	S		W;T;E;X						0;Ć;B		2;7	BM					0;K					1;2;3	A100058E_BIALYRAL9003
2476	%	S		W;T;E;X						0;Ć;B		2;7	PO					0;K					1;2;3	A100058E_POPIEL
2477	%	S		W;T;E;X						0;Ć;B		2;7	NC					0;K					1;2;3	A100058E_ANTRACYT

Fig. 5. View of filters from the parameter EdgeCode – Translator level.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
S	P	E	A	0	P	0	L	0	8	2	BM	0	S	P	3	0	0	0	0	0

Production_Barcode_ID	Cycle	Thickness	OversizeHeight	OversizeWidth	OverhangSurface	RebateDepth1_X	RebateHeight1_Y	RebateDepth2_X	RebateHeight2_Y	EdgeCode
130846397	1	40.1	8	8	0	13	26	0	0	A100058E_BIALYRAL9003
1	9	65	4	6	1	26	53	6	18	2475
130846397	2	40.1	8	8	0	13	26	0	0	A100058E_BIALYRAL9003
1	10	65	4	6	1	26	53	6	18	2475
130846397	3	40.1	8	8	0	13	26	0	0	A100058E_BIALYRAL9003
1	11	65	4	6	1	26	53	6	18	2475

Fig. 6. Processing data for white doors showing loaded filter 2475 from parameter EdgeCode.

It is imperative that the machine database contains macros whose names are exactly the same as the ones sent by the Translator, otherwise the door leaves machining process will not be launched. When laminate colour changes, the production line needs time to allow the heaters to reach the set temperature and percentage values from a given macro. Differences between the particular machine programs depending on the type of the EdgeCode have been presented in Fig. 7.

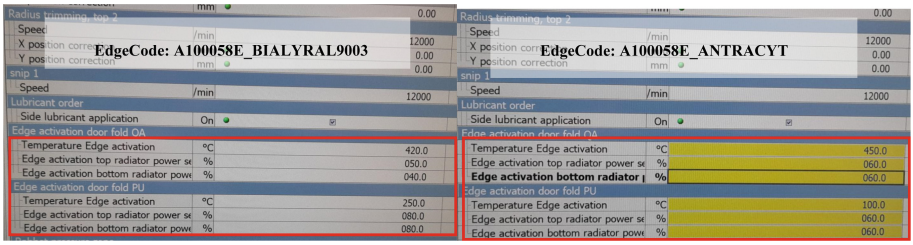

Fig. 7. Heating parameter settings in processing programs.

2.3 The Course of the Test

The measurements of the time interval between the start of the machining of another leaves, defined as the tact of the line, were conducted during the machining of elements on module 3 of sub-line for softforming. The line features Edge Banding Machine HOMAG with the feed of 20 m/min at this point (Fig. 8).

The process of finishing the door leaves consists in a triple passage of the element through the line. In the first cycle top edge of the door is being machined and in the next two cycles side edges undergo machining. The time gap between the entrance of the subsequent door leaf to the technological line was measured. This time gap is defined as the line tact. Two sets of door leaves were prepared for the test. One set contained sequentially placed white and anthracite black door leaves separated by a grey door leaf to obtain technological separation. The second set consisted of alternately placed anthracite black and white door leaves.

Fig. 8. Edge banding machine HOMAG.

3 Results

Results of the gap time measurements between the entrance of particular door leaves to the technological line in each passage of door leaves for colour sorted set are presented in Table 1, while Table 2 contains the measurements for the mixed set.

After averaging the gap times between the subsequent door leaves, it was revealed that the average gap time between white door leaves is 10,4 s. For anthracite black it is 10,6 s. However, the average gap time between the door leaves of various colours when the change of the edgeband occurred increased to 22,9 s.

Table 1. Gap time between the door leaves in colour sorted set.

No	Colour	Gap time between the entrance of subsequent door leaves [s]		
		Passage 1	Passage 2	Passage 3
1	White			
2	White	00:11,0	00:09,7	00:09,8
3	White	00:09,2	00:09,7	00:10,3
4	White	00:09,4	00:09,9	00:09,8
5	White	00:11,2	00:09,6	00:09,5
6	White	00:09,5	00:09,2	00:09,6
7	Grey	01:52,0	00:19,1	00:17,6
8	Anthracite	00:07,8	00:21,9	00:21,6
9	Anthracite	00:08,9	00:09,8	00:09,7
10	Anthracite	00:09,5	00:09,6	00:10,3
11	Anthracite	00:11,2	00:09,6	00:10,0

Table 2. Gap time between the door leaves in the mixed set.

No	Colour	Gap time between the entrance of subsequent door leaves [s]		
		Passage 1	Passage 2	Passage 3
1	Anthracite			
2	Anthracite	00:11,3	00:09,5	00:10,2
3	White	00:20,5	00:23,9	00:23,8
4	Anthracite	00:20,1	00:23,9	00:23,9
5	White	00:22,1	00:23,9	00:23,8
6	Anthracite	00:21,1	00:23,8	00:23,9
7	Anthracite	00:09,7	00:23,9	00:09,8

4 Conclusion

Conducted short test indicated that the parameter concerning the colour of the door leaf edgeband is a factor that influences the efficiency of the softforming line. With each change of the finishing colour, the line tact doubles in relation to a situation where such a change does not occur. This results from the cyclic heating and cooling of the heater to reach the temperature of the application of edgebands with various colours. The final effect of the machining with the change of edgeband colour for each item can be a worsened efficiency at the same level. The study was limited to only one parameter affecting efficiency. Further research directions will include the study of other more complex parameters of the TechnoPorta line. The results may serve to create digital twins of such production lines in the future.

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Pilot Project of Industrial Costing in a Ceramic Company

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Abstract. This work was carried out in an industrial context though the adoption of action-research. The main objective was two-fold: (i) to implement a pilot project for improving the method for calculating the cost of ceramic products, and (ii) to achieve improvements in the production process by cost reduction though lean principles. Organizational intervention and direct observation were applied to carry out this work. This could deliver an update method for calculating the cost of products, which fulfilled the needs of a company from the ceramic sector. Improvements were achieved both in the costing method and in the organization management. The results included enhancement of a previous outdated costing method (main barrier) that enabled better management and control of a specific type of product ('blank' ceramic). Lean manufacturing applied to the production process contributed to achieving a standardized process with less waste. Future work involves expanding the company pilot project in medium and long term. Work limitations include an intervention in a single unit of analysis and a low scientific contribution.

Keywords: Industrial Costs · Ceramic Industry · Continuous Improvement

1 Introduction

Companies are usually demanded to compete in the market, so they have been looking for organizational improvements concerning products and services, in order to differentiate themselves from their competitors [1]. Thus, organizations continuously strive to innovate, thus they may increase productivity, customer satisfaction, quality, and create a competitive advantage [2]. Achieving excellence is a key factor that keeps companies able to compete in their market, always combined with the ability to quickly adapt to constant changes [3]. Continuous improvement with a focus on eliminating waste has been recognized as one of the most important tasks for organizations. Waste is seen as burden that does not add value to the product or services. Conversely, it adds costs and takes up time [4]. In this context, this paper aims to implement a project pilot for improving an outdated method for calculating the cost of products in a ceramic company. This work also considers improvements that may contribute to the cost reduction of product manufacturing.

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2 Theoretical Background

2.1 Relevance of Industrial Costing

Measuring the company's performance plays a key role in operational development and strategic direction, as Krishnan [5] highlighted that "the cost management system is important to provide timely and quality information, in a timely manner, in order to assist managers in the decision-making process". Reducing costs is one of the main objectives of companies in favor of obtaining and capitalizing profit [6]. To achieve this goal, companies should control their activities, providing the best products at the lowest prices or reducing product costs to be able to be competitive. The definition and use of a costing system helps to understand whether or not the costs are acceptable, to what extent it is possible to reduce and control them rigorously, taking into account the market where the organization operates [6].

Several parameters are necessary to calculate costs, such as raw materials, labor, equipment, energy, work hours, etc. Companies need a costing system to respond to their needs to value the products, to analyze and carry out financial reporting, and to estimate the costs of activities, services, and products [7]. This provides relevant information to managers about the efficiency of the process.

Determining the cost object of a costing system is crucial for classifying costs as direct and indirect. Direct costs are costs precisely related to the selected cost object that can be easily and cost-effectively tracked. In turn, indirect costs require the application of distribution criteria to be allocated to the cost object. Cost reduction is also a fundamental factor for the competitiveness of any company. Through this reduction, it is possible to increase the added value of products. Thus, in order to have full control of the organization's costs, it is necessary to involve all departments, as well as all their stakeholders. In addition, due to the constant change in the business world, knowledge and cost management requires continuous reduction and improvement. Therefore, it is imperative that companies adopt a cost management system that fits the company's so that it is possible to systematically seek reductions in the product costs, to the level that allows them to obtain a satisfactory return [8].

It is also important to combine the development and innovation of a product with costs right at the beginning of creation, so that companies improve their products, reduce launch costs and build a track record [9]. Making a rigorous and in-depth analysis of production costs can save time, resources, and future problems, while ensuring the success of the company.

2.2 Lean Manufacturing Principles

Competitiveness and efficiency are two challenges that today's industrial organizations face in order to gain a foothold in the global market. To overcome this challenge, they try to innovate in their industrial management strategies [10]. One of these management strategies is the Lean Manufacturing, early developed by Toyota Production System.

Rohani & Zahraee [10] add that through a systematic interaction between its production principles and methods, it became possible to reduce waste in all activities that do not generate value for the final customer, thus as one of the best methods used to

increase company competitiveness [11]. Lean Manufacturing emerged as a set of methods and techniques based on a goal of maximizing productivity while minimizing waste and all activities that do not add value to an industrial operation. Based on this, Lean principles and tools are applied, such as [11, 12]: Just in Time, kaizen, kanban, continuous improvement, among others. Thus, Lean contributes to the creation of standard mechanisms that promote more efficient processes.

Lean Manufacturing offers a comprehensive set of advantages, such as: reducing cycle time, waste, costs, increases productivity, improves product quality [13], and triggers a cultural change, being one of the most difficult changes to implement and achieve [14]. It is easy to understand this concept relevance, since its purpose is to increase the value of the product, helping organizations to become more profitable.

2.3 Lean Manufacturing in the Ceramic Industry

The ceramics industry is exposed to several factors that determine its profitability, from competition in internal and external markets, high labor costs, to the lifting of restrictions on imports into European Union countries of low-cost products, generally ceramic products from Asia, especially from China; this has led to the insolvency of small and medium-sized ceramic companies [15]. Companies in this sector should try to minimize as much as possible non-conformities, unnecessary waiting times, excess stock, and others. Thus, the focus must be on increasing its efficiency and productivity through continuous improvement of production processes.

Rodriguez et al. [16] reported improvements by considering the integration of Lean Manufacturing tools and methods in a ceramic company. The authors highlighted the reduction of the company's transport internally, improvement of the work environment, and a reordering of operations, which achieved more machine availability and reduction in production time [16]. Positive results was achieved from using simple to more complex tools and methods, e.g. Kaizen [17], the 8 wastes of Lean [18], etc. Some of those tools and methods were applied in the studied company.

3 Methodological Approach

This section firstly presents the object of study in an action-research approach [19, 20], followed by a description of the phases and activities of the pilot project.

3.1 The Company Object of Study

To preserve confidentiality, the object of study was "Alpha", a medium-size Portuguese ceramic company established for more than three decades. Portugal is a country with a long tradition in ceramics, both in production and consumption, and is ranked as one of the main European manufacturers of ceramic products due to the high quality of the raw materials [21]. Alpha develops and produces porcelain products within the ceramic sector. It was the first company in the ceramics sector to have its quality system certified by ISO 9002 standard in 1995. Later on, it obtained certificates of the Environmental Management System (ISO 14001) and ISO 9001. Alpha has a wide range of products.

There are 55 collections both in-house developed or by customers. In 2021, the company had a sales volume of about 4 million Euros, with 98% of sales internationally and 2% in the domestic market.

Alpha has had a diversified customer portfolio, operating all over the world. Currently, it is present in 50 countries, growing in the number and variety of customers. The growth and variety of customers resulted in an increasingly complex products, which called for a change in current work standards, both at a strategic but mainly at operational levels. It was necessary to rethink company organizational processes to achieve more customer response and profit. The main barrier to go forward was an update of the company costing method, since this resulted in undervalued products, losses, and waste. Thus, a pilot project was built to address these issues, outlined next.

3.2 Pilot Project Phases

The pilot project was related to production monitoring, data analysis, and construction of a new costing calculation method. The first phase was: (i) Updating and improving costing methods for 'blank' products. Due to the growth of product diversification at Alpha, current costing system was restructured. A diagnostic showed that previous costing methods were obsolete. There was also a lack of a basis for recording production times in each stage of production. Another barrier was concerning new products. It was essential to have cost calculation methods compatible with the current manufacturing processes, since the manufacture of new products often requires novel operations, new raw materials, and equipment availability.

The second phase consisted of the (ii) Development and validation of a procedure for calculating the cost of products. After updating the costing methods, it was necessary to establish an assertive work instructions and procedures, so that current and future employees could work with this new organizational system. The system should be as flexible as possible so that it can be applied to new products in the long term. Procedures should then be clear, simple, and ease to understanding for any user.

The third phase was (iii) Implementation of improvements that contribute to the reduction of product costs. A major part of the pilot project was devoted to monitor the production stages in order to fully understand all the expenses involved in the manufacture of a product. Thus, another purpose of the pilot project was to implement practices for continuous improvement to achieve cost reduction, also considering team member characteristics [12]. In this sense, the principles of lean manufacturing were introduced for fulfilling these goals, based on Kleszcz [3].

3.3 Steps and Methods for the Phases of the Pilot Project

The methods and steps adopted in the phases considered direct observation (e.g. in the shop floor), critical analysis of the stages of the production process, and associated costs. These enabled to identify opportunities for improvement that existed. An example of the steps and methods applied in the phase (i) is summarized in Table 1. Contents were also developed for steps (ii) and (iii), not shown in this paper.

As aforementioned, this work adopted action-research, a multidisciplinary approach whose purpose is to take actions and create knowledge about them, in the sense of helping

Table 1. Example of steps and description for "(i) Updating and improving costing methods".

Steps	Brief description
(i.i) Diagnosis and analysis of the general process	In-site shop floor observation in the production process for 3 weeks; experimentation in various process stages. The collaboration with employees allowed data collection and feedback
(i.ii) Follow up of 10 products	Ten products were selected that followed pre-established criteria, e.g. product type, dimension, weight, etc. Products were timed and quantity of raw material (glass etc.) in each one was calculated
(i.iii) Assessment and improvement of the current costing procedures	Document development to record times and characteristics of the products (it was inexistent) to ease the characterization of the products in terms of workmanship, raw materials, and dimensions. Since some costs are fixed and depend on external sources, all these values were provided by the financial department. Creation of a form in MS Excel for the costing calculation including all operating times, fixed costs, etc. to achieve the final cost of the product
(i.iv) Propose a method of scoring parts	A scoring system was developed for comparing production costs among different products. In the ceramic industry of tableware, the production of white products is characterized by point attribution (e.g. a flat plate, without reliefs or cut edges values 1 point/cost). The remaining products have higher or lower scores depending on the sequence of activities and time involved. Based on this score, a method for inputting points by extrapolation was proposed. For the set of specific products under study and based on the collected data, created a procedure for assigning points to new products that do not yet exist
(i.v) Development of the procedure for costing	Based on the methods used and data collected, a procedure was elaborated on how to calculate the cost and which should be taken into account. A section in the MS Excel explains all the calculations, which parameters were taken into account. This help to have a better understanding of the system so in the future they can be replicated without difficulty. Final proposal was validated by the managers

to understand the problems and address them through practical actions [20]. Finally, the pilot project was carried out over 7 months.

4 Results

4.1 Document Development

As mentioned earlier, one of the problems identified in the old costing method was the access of 4 databases. The first step was to monitor 10 pre-selected products ('blank' products), as a pilot. The result was the development of a form that recorded product and production data, as illustrated in Fig. 1.

Reference:		Initial date:	
# part in the batch:		Code:	
Type of past:		Product dimension:	Width [mm] / Length [mm] / Height [mm]
Blank weight [g]:			Volume [m³]

Date	#	Operation	Qty parts OK	Qty parts scrap	Operation time time	Operation time part/h	Operation time time/part	number of operators	Notes
	1								
	2								

Fig. 1. Form (recording sheet) concerning product and production data (partially showed).

A follow up of the production of the pilot products enables to achieve a consistent sample of production times. Then, the development of a method for calculating the costs of manufacturing 'blank' products began. To do so, it was required to identify the costs involved in the production by dividing them into main groups (Table 2).

Table 2. Costs involved in the pilot products ('blank' product).

Type of costs	Description
Production-related cost	Labor, equipment, maintenance, depreciation, electricity
Raw material	Plaster, glass, additives (e.g. extra white)
Natural gas	Average gas consumption of industrial ovens (price/m3 = 0,39 €)
Overhead	Laboratory, offices, etc.
Quality issues	Broken products, scrap

4.2 Costs Incurred

In order to update the old costing method, one of the steps was to calculate direct and indirect costs provided by the finance department. There were costs related to each manufacturing sections, as shown in Table 2. According to the costs of each functional

section, an hourly cost unit was calculated, based on Ref. [22]. To these were then added the standard costs of manufacturing overhead, resulting in a total standard cost for each section. The proposed costing method offered a more effective cost calculation. Figure 2 summarizes the steps for the whole process of development and operation. This costing method brought about benefits to Alpha, since it contributed to calculate the product costs more precisely. These benefits however were not assessed and presented in this paper.

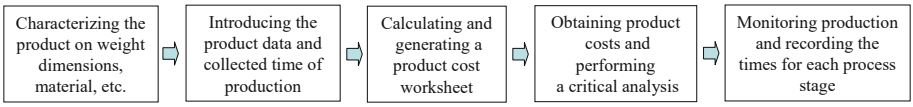

Fig. 2. Short cycle for achieving the costing method.

4.3 Improvements in the Production Process

Firstly, a three-week diagnostic was carried out in the shop floor, and delivered a report on strengths and weaknesses. By on-site observation, several potential opportunities for improvement were raised (related to employees, working place, etc.). Table 3 summarizes some of these issues and how solutions were addressed.

Table 3. Opportunities for improvement and implemented solutions.

Related to	Issues	Approach to address
Employees	Lack of training and supervision	Development of a competency matrix Introduction of daily kaizen Implementation of team assessment
Work environment	Dim lighting and placement	Writing a luminance assessment report Remodeling the lighting system (LED)
Work organization	Uncontrolled inventory	Implementation of a kanban system Introduction of a molding map

5 Concluding Remarks

Currently, organizations aim to sustain and increase their profits by controlling and reducing production costs, as a strategic business factor to gain competitive advantage and obtain waste-free processes. The contribution in the creation of a costing method

involved an update of the method to calculate product costs and development of operational procedures. This achievement was due to an action-research approach by performing daily observation and monitoring of the production process, critical analysis of existing documents and the development of news ones, supported by the relevant literature. The importance of a rigorous and flexible product costing method was imperative to Alpha. Future work involves improving the proposal in medium to long term to achieve better academic contribution.

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Development of a Cost Estimation Model in a Furniture Manufacturer

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Abstract. This work was developed to improve the costing process of new products within the Product Development Department of a furniture manufacturer. It consisted of creating a parametric cost estimation model based on applying simple and multiple linear regressions, considering the existing data of the products produced and their respective costs. The proposed model considers the cost estimation of creating a product that covers the materials and operations costs. The suitability of the different independent variables was studied by applying simple and multiple linear regressions. A set of functions that return an estimate of the cost as a function of these predictor variables was obtained. The model built with the functions obtained provides the materials and operations cost estimation. The results indicated that 75% of the tests performed show an estimation error of less than 2% in the total cost of a product. Incorporating this model in a tool with the purpose of cost estimation brings the ability to predict prices faster, improving the internal process of obtaining costing and enhancing the analytical capacity of the team in the relentless pursuit of cost minimization and value creation.

Keywords: Cost Estimation · Regression analysis · Parametric model

1 Introduction

This research project arose from the necessity of improving the development process of new products by identifying solutions that lead to greater efficiency. Product costing is viewed as a fundamental activity with significant opportunities for improvement. In this sense, and to optimize the costing process, it was proposed to develop a cost estimation model that allows predicting the cost of new products in a less time-consuming and far more efficient way by using the historical data of existing products. The ability to estimate the prices of products or services is a competence that may significantly

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impact any company's competitiveness. The degree of accuracy within the cost estimation directly influences a company's performance and efficiency, giving the organization a strategic and operational view of its business and activities [1]. Cost overestimation can result in the loss of customers and a poorer image of the organization in the market. The underestimation can lead to financial problems related to insufficient earnings for the business. Additionally, making reliable and accurate cost estimates is vital to meet customer needs by delivering a high-quality product at a low price and within the required time frame [1]. Making cost estimation errors in the early stages of the product life cycle can compromise the product's quality and potential. An underestimation can lead to a perspective of a product as being merely economical. An overestimation can undermine the product concept [2], jeopardizing the product development process and affecting the manufacturing issues involved with the cost analysis from an Engineering design perspective [3].

2 Literature Review

In the literature, four main classifications of cost estimation techniques were identified. The methods' differences focus on the type of data used, its potentiality, the estimation accuracy, and the degree of integration between different techniques [2]. Therefore, the classifications could be divided as follows: Qualitative and Quantitative Methods [1, 3]; Analogy-based Techniques [4, 5], Parametric Models and Engineering Approach [6, 7]; Cost Estimation (CE) based on Variants, Generative or Hybrid [8]; Classical and Advanced CE Methods [3]. The most popular categorization is proposed by Niazi et al. [1], in which an extensive hierarchical classification of CE techniques is made, grouping different approaches according to the similarity of characteristics. CE using qualitative methods relies on comparative analysis between a new product and other existing products to identify similarities between what is already produced and the new item. The experience of the person responsible for the CE and data relating to the current product can be the basis for estimating the costs of a new product similar to one already produced [1]. The efficiency of the CE will be improved if there is a history of cost data from existing products. Add that qualitative techniques can be used in the early stages of product development to obtain initial CE of the costs associated with the product under study.

Quantitative techniques are based on a detailed analysis of the product's characteristics and production process (PP). The costs are obtained by applying parametric or analytical functions that describe the cost as a function of specific product parameters or by calculating all the resources consumed while manufacturing the item [1]. These techniques' complexity and calculation details are substantially more significant, allowing for more accurate estimates but requiring a more mature product description, thus appearing at more advanced stages of a product's life cycle. The classification proposed by Niazi et al. [1] is similar to the one defined by Kadir et al. [4] since the different authors subdivide qualitative techniques into "Intuitive" and "Analogical" and quantitative methods into "Parametric" and "Analytical".

The CE using Intuitive techniques is obtained based on the experience and knowledge of other products whose characteristics and parameters are known [1, 10, 11], the

empirical knowledge of the people performing the EC emphasized by [9]. Analogical techniques are based on past knowledge, particularly in data relating to the costs of other known products [1], and the experience and degree of knowledge of the person on the development and process to be estimated are crucial alongside the historical data on products and their costs [9]. Concerning parametric techniques, the models result from applying statistical methods that allow the definition of functions capable of explaining costs as a function of certain product variables, variables often called cost drivers (CDs) [1]. Analytical techniques consist of decomposing the product into units and operations that represent the different resources consumed throughout the production of the product [1, 9]. Another classification is proposed by Cavalieri et al. [7], in which those techniques are divided into three categories: Analogy-based Techniques, Parametric Models, and Engineering Approaches, based on the different degrees of accuracy obtained in each approach. The classification proposed by Wierda [13] divides estimation techniques into Variant-based, Genetic, and Hybrid techniques. The taxonomy proposed by Curran et al. [14] can be considered more straightforward since the techniques are grouped into Classical and Advanced Methods. Altavilla [2] offers a new taxonomy in which CE techniques are classified according to a five-layer system, namely: the nature of the method, the nature of the analysis, the product/process characteristics, the objective, the application phase, and the responsible party, and lastly, the estimation object. The taxonomy proposed by Niazi et al. [1] was considered during the development of this research work.

3 Methodology and Methods

A cost estimation model for new products based on the existing data of the articles already produced in the company was developed to improve the product development process efficiency. Therefore, the following research question was raised: Can simple and multiple linear regressions (SMLR) be applied in developing a parametric cost estimation model? Moreover, the general objective was to create a parametric CE model using SMLR. A relationship between two variables can take on various natures, ranging from simple mathematical functions to highly complex expressions. The most straightforward linear relationship can be represented by a straight line in which a variable X (independent) variation leads to a variation in the variable Y (dependent). Simple Linear Regression can be described according to the following linear model expressed in Eq. (1):

$$y_i = \beta_0 + \beta_1 X_i + \varepsilon_i, \quad i = 1, 2, \ldots, n, \tag{1}$$

where y_i, $x_{i,}$ represent, the estimated value of Y and the value of the variable X of observation i, where ε_i is the approximation error of y_i. When two or more independent variables are considered, it enters the domain of multiple linear regression, as expressed in Eq. (2). Thus, considering a sample of size n, each value of the variable Y can be described as follows: for observation i, y_i corresponds to the value of the response variable, x_i represents the values of the explanatory variables, and ε_i the error associated with the approximation of y_i. Where, β_0, β_1, β_2, ..., β_p are the regression coefficients and ε is the associated random error.

$$y_i = \beta_0 + \beta_1 x_{i1} + \cdots \beta_p x_{ip} + \varepsilon_i, \quad i = 1, 2, \ldots, n \tag{2}$$

The methodological approach used was deductive, with the quantitative method and the mixed research strategy, with documental analysis and case study in the company where the project was developed. The data obtained are secondary and come from the historical data in the different information systems. The time horizon associated with the execution of the project is cross-sectional. This methodology followed witin this investigational context: contribute in a pragmatic way to the improvement and resolution of existing problems in the system under study, create scientific knowledge through the production of results and conclusions drawn from the analysis of the system under investigation, and ultimately to support the development of problem-solving skills and to learn for all stakeholders [15, 16].

4 Results

This research project was conducted within a furniture manufacturing company's Product Development Department (PDD). In development and innovation activities, besides seeking to ensure quality and the satisfaction of customer needs, it is also necessary to consider that the price of the product/service is an aspect that can significantly influence the final purchase decision. Therefore, the PDD performs some tasks regarding product costing since, in any given project, it is required to determine the costs of the products or solutions under development. After the initial pre-study phases of product development, and in case of a decision to implement, a project is formalized, and all activities associated with introducing a new item in production are carried out. During this process, changes are made to products and procedures, and the product and production details begin to be sharpened and defined. At later stages, when the product is less subject to change, it becomes possible to determine costs more analytically and accurately. Therefore, a cost estimation model was proposed to be developed, aligned with the organization's context. Through some analysis of the organization's information systems, it was possible to detect a set of reports in a table format that contained a description of all costs allocated to a product, with a breakdown of the costs of materials, operations, and outsourcing for each product reference. Outsourcing costs are related to reworking and scrapping a product and are defined as a percentage per range of articles. As they are obtained after implementation in production, they are outside the scope of the estimation.To assess the possibility of creating a parametric cost estimation model using regression analysis, two product families were selected, "Products A" and "Products B", in a total of 382 references that represent the company's remaining products. As mentioned before, the total cost of a product is the sum of the Cost of Materials, Cost of Operations, and Outsourcing. However, due to the percentual nature of this final component cost, the study reflects only on the first two. Furthermore, the cost of materials and operations were studied individually since they differ. Therefore, the CDs explaining the materials costs could also be distinct from those associated with operations costs.

The materials costs were first analyzed for both product families, and the operations cost only afterward. Similar steps were followed from data treatment to results analysis for cost analysis, materials, and operations. Several cost drivers were defined in the data processing phase to represent the cost behavior. The CDSs are independent variables in a cost function and can be used to explain the variation of a given cost. In this costing

context, it is intended to obtain an estimate of the costs of materials and operations, which implies that different CDs are studied. Therefore, the CD defined were the following: Length (*mm*); Width (*mm*); Thickness (*mm*); Colour; Perimeter (*m*); Surface Area (m^2); Total Lateral Area (m^2); Total Area (m^2); Volume (m^3); Run Time (min/piece).

The set of defined CDs comprises dimensional characteristics that characterize each article. These parameters were selected within the context of the cost of materials because they are always associated with any product or component. In addition, the cost behavior of PP can be related to product dimensions. For example, the variety of sizes and process limitations may influence the cost of each part at a given work center. It is expected that this study will also enable the identification of the variables that explain cost behavior and thus confirm the assumptions defined above. The cost of Materials is one of two primary components of a product since it represents the cost of raw materials and materials consumed in manufacturing an item. Therefore, the analysis was split into two distinct phases: the study of the "Product A" items and the analysis of the "Product B" items. Given the work done for the various possible CD, the analysis of one of the predictor variables for the "Products A" family will be presented in the following paragraphs. First, however, it exemplifies the analysis done for all the independent variables. After the data processing and preparation of the costs, several scatter plots were made to, in a first analysis, evaluate the type of relationship between the independent variable and the cost of materials. In this case, the predictor variable under study is Volume (m^3), and the dependent variable is the Cost of Materials (€).

Once an apparent linear relationship was found between the independent variable and the cost of materials, statistical analysis was performed to confirm this linearity. For this purpose, IBM SPSS Statistics 25 was used to perform the regression analysis and its statistical validation, considering a confidence level of 95% with a significance level of 5% ($\alpha = 0.05$). From the results of the RA and the Analysis of the Variance test (ANOVA), the hypothesis that the Volume (m^3) influences the Cost of Materials (€) was confirmed. Furthermore, the linearity relationship can be confirmed by regression analysis of the coefficients of the independent variable.

Since each family of products is composed of several different items, various samples were considered in the study developed. Nonetheless, for a sample of all articles of the family considered and taking into account the effect of more than one predictor variable, it can be concluded that the variation explains 99% of the Cost of Materials (€) in Volume and Color of the product with an error of approximately 3%.

Once the various CDs have been analyzed, after looking at both families of products in general and from the perspective of material cost estimation, it can be concluded that Volume is a product parameter that can be used as a cost predictor variable. The simple linear regressions carried out on the different samples of the two families of products considered and in which Volume is the only independent variable indicate that the variation in the Volume of the pieces primarily explains the cost behavior. In turn, a product's color can also improve the fit of the regression line to the points when it appears to complement the Volume in multiple linear regression.

The operations costs analysis was done similarly to the analysis of materials costs. First, the work centers and production lines belonging to the products' families' production flow were identified. Similar to the methodology followed in the analysis of Costs

in Materials and the Costs of Operations, the CDs, with the potential to be variables that predict the cost, was defined for each work center.

A preliminary analysis found a linear relationship between the time a part remains in a work center and its operating cost. As expected, this relationship between time and cost is verified in all centers. So the study developed was based on the search for the parameters/characteristics that influence the production time of a part in a production line. The variables that determine the cycle time will then be the ones that determine the cost of an operation, this being the assumption for the study carried out in the various work centers. This way, for each work center and respective CD defined as possible predictor variables, several simple and multiple regression analyses were performed to understand which ones are more adequate for each production environment. Throughout this process, it was observed that Volume (m^3), Length (m), and Width (m) are the CD with the most significant predictive capacity of the operation costs.

By understanding these variables that best fit each PP, it is possible to define cost functions that allow the estimation of the operation cost in each work center and, consequently, the total operation cost of a product.

Through the statistical analysis, it is possible to define a product cost estimation model based on applying SMLR. Through this statistical technique, functions that describe the behavior of a cost as a function of a given parameter can be obtained, in this case, explaining the costs in materials and operations through certain independent variables related to the product. Furthermore, understanding the variables that influence costs, and characterizing this relationship using functions, allows estimations for new products based on existing products and manufacturing processes by using criteria of similarity between a new product and the products already produced.

As previously mentioned, the value of outsourcing refers to the cost of rework and scrap and is currently defined by the family product. Thus, establishing a certain similarity between a new product and an existing item to estimate the cost of materials and operations indirectly represents the outsourcing percentage associated with the new product. In this way, summing the estimated cost in materials, operations, and value assesses the product's total cost.

To test the estimates returned by the equations obtained throughout the investigation, four test products were selected, two from each family considered, for which the actual costs in materials and operations are known.

When considering the sum of costs in materials and operations, according to the information available in Table 1, it can be seen that the estimation led to a positive result highlighted by errors of less than 2% in three of the articles considered. However, in the article (XXXXX575), the error obtained in estimating the total cost was 8.6%, which may need to be revised in this context.

Table 1. Total Cost estimation test results.

Test Article	Product	Total Cost Avr. Error Error (%)	
XXXXX575	VEDDINGE frnt dshwshr 45 × 80 wh	0.484 €	8.6%
XXXXX574	VEDDINGE frnt dshwshr 45 × 80 grey	–0.018 €	0.4%
XXXXX552	BODBYN frnt dshwshr 45 × 80 wh	0.106 €	1.6%
XXXXX551	BODBYN frnt dshwshr 45 × 80 grey	0.107 €	1.6%

5 Conclusions

According to the results obtained in the analyses conducted on costs of materials and operations, it is possible to conclude that using certain independent variables as explanatory variables of a dependent variable can be an approach to estimating the cost of a product based on similarity criteria. Applying SMLR allows the definition of cost functions whose independent variables are product and process parameters known in advance when estimating a given item or component. Using these functions to obtain a cost estimate led to positive results. Comparing the estimated and actual cost values for the tested items enables the conclusion that in 75% of the tested cases, the total product cost estimation error was less than 2%. The proposed model increases the product development process agility, specifically within the costing and CE processes. It also ensures the ability to evaluate a new product based on costs and other historical data, therefore, contributing to freeing up human resources for new activities where they can effectively add value.

The effectiveness and accuracy of the proposed model are strongly related to understanding the dependent variable's behavior through certain independent variables. In certain future situations, the complexity of the PP may limit the identification of these variables, and the model may not be able to obtain better-quality estimates. Throughout the analysis of costs in materials and operations, other independent variables were identified that could be incorporated into the study and led to improved results, namely to obtain better adjustments and consequent cost predictions. Overall, the objective initially established has been met, and the stated research question can be answered positively. Therefore, the use of SMLR as a basis for a parametric model for estimating the costs of new products can be confirmed.

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Driver Analysis to Solve Dynamic Facility Layout Problems: A Literature Review

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Abstract. The Dynamic Facility Layout Problem (DFLP) is concerned with finding an optimal facility design considering changes in the planning horizon. Since DFLP belongs to the non-polynomial hard class problem, different solutions have been used to find an optimal solution. However, a correct performance evaluation is needed to validate and compare the results with others. This performance evaluation refers to using both statistical and computational tests. When searching the literature on related papers, none consider these tests. The lack of such information and the constant evolution of algorithms motivated this work. The current document reviews the solution methodologies applied to solve DFLP and the manner the performance evaluation is done. In addition, the methods used to mix solution methodologies, called hybrid approaches, are included. This work was carried out using the Barbara Kitchenham methodology, in which studies from 2015 to 2022 were considered. A sample of 59 articles was analyzed, all about DFLP. As a result, this study identified two commonly used categories when solving DFLPs: hybrid and metaheuristic approaches. Furthermore, performance evaluation is done using different statistical methods in some cases, comparisons of some numerical results obtained from the algorithm output, and studies without comparisons. Finally, the results do not find any instances in which a methodology is applied to compose the algorithm when a hybrid approach is used. To the best of our knowledge, this work is the first in which performance evaluation is considered.

Keywords: Dynamic Facility Layout Problem · Optimization · Heuristics · Metaheuristics · Hybrid methods · Literature Review

1 Introduction

In today's industry, customer requirements challenge the manufacturing and production stage to be flexible when facing competitive pressure, increased demand,

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and product complexity [1]. These problems lead to indirect costs, such as the acquisition and operation of material handling equipment (MHE). A good design of the facilities can reduce these costs and maintain a company's competitiveness [2]. In addition, the MHE can represent from 20% to 50% of a company's budget, so an efficient layout of the facilities can substantially reduce production costs [3]. Therefore, the Facility Layout Problem (FLP) deals with the allocation of facilities in the available space and aims to optimize the total material handling cost (MHC) [4]. FLP can be divided into the static facility distribution problem (SFLP) and the dynamic facility distribution problem (DFLP). In SFLP, the layout design is fixed for multiple periods, and there is no reorganization cost (RC) [5]. On the contrary, DFLP consists of a series of static design problems, each with its own material handling cost. Reorganization costs are incurred when facilities change locations in consecutive periods [2]. Therefore, the goal of DFLP is to minimize MHC and RC simultaneously.

In recent years, numerous reviews have been conducted on various topics covered by FLP. T. Zhu, J. Balakrishnan, and C. H. Cheng [6] identified some solution methodologies: exact methods, heuristics, metaheuristics, and hybrid approaches, of which exact methods are adopted in very few studies, and most of the effective algorithms used were heuristic, metaheuristic, and hybrid approaches. P. Perez-Gosende et al. [7] classified FLP as an extensive taxonomy based on the type of problem, approach, stage of planning, and characteristics of production facilities. P. Flores-Siguenza et al. [8] showed that FLP research has grown in the last five years, and the most common methodology used was the metaheuristic approach. J. Vazquez et al. [9] reviewed the literature on FLP research trends on design evolution, workshop characteristics, problem formulation, and solution methodologies. Their results showed that SFLP is the most frequently approached FLP variation when facility design is needed. Furthermore, genetic algorithms and simulated annealing are the most common metaheuristics used to solve FLP.

Due to the industry's dynamic environment, the trend to develop complex DFLP models is growing. However, current DFLP reviews do not consider essential factors such as algorithm performance evaluation or the methodologies used to mix algorithms (commonly called hybrid approaches or hybrid algorithms). The lack of this information motivated this systematic literature review on the different solution methodologies applied to DFLP, the evaluation techniques to evaluate the algorithms, and the process of composing a hybrid solution. This information will help researchers to build a robust methodological approach using the results of this study as a foundation. The current document is organized as follows. Section 2 describes the methodology used to carry out the systematic literature review. Section 3 depicts the findings through content analysis and a brief discussion. Finally, Sect. 4 presents the conclusions generated from the systematic literature review.

2 Methodology

The most common reporting guideline for systematic reviews is the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA), which contains a 27-item checklist for reporting in systematic reviews [10]. However, this methodology was created as a guide that describes in detail the process of preparing and maintaining systematic reviews on the effects of healthcare interventions [11]. As this systematic review was conducted in the engineering field, Barbara Kitchenham's methodology was selected to conduct this review. In fact, the engineering community has widely accepted this methodology as it attempts to tailor medical guidelines to the needs of engineering researchers [12]. This consists of three stages: Planning, Realization, and Reporting of the review. The planning stage is associated with developing a review protocol, the Realization stage is concerned with applying the review protocol from the planning stage, and the Reporting stage is related to the document's publication.

2.1 Planning

The planning stage consists of five steps: 1) research questions, 2) search strategy, 3) primary study selection criteria, 4) primary study selection, and 5) quality assessment.

Research Questions. PICO-based strategy was used to compose the research questions. PICO [13] represents an acronym for Patient, Intervention, Comparison, and Outcome and is used extensively by medical researchers. Still, in software engineering, [12] recommends using PIO strategy: Population, Intervention, and Outcomes. The Population helps to limit the search space, Intervention is associated with the tools or process applied to the population, and Outcomes are related to factors of importance. In this manner, the following research questions were defined following the PICO-based strategy:

1. **RQ1.** What methodologies are used to find an optimal solution to the problem in the DFLP context?
2. **RQ2.** How is the proposed methodology's performance evaluated on the solution methodologies used to solve the DFLP?
3. **RQ3.** When a hybrid algorithm is developed, what is the selection process carried out to choose the set of algorithms that will compose it?

Search Strategy. The search strategy is a sophisticated search string constructed with Boolean AND and OR [12] and is used to identify all relevant studies. The search strategy uses a combination of terms based on the research questions. This paper was carried out in three scientific databases: Scopus, Web of Science, and Scielo. The search strategy defined for this study was:

"facility layout problem" AND ("optimization" OR "algorithm") AND ("Heuristic" OR "Metaheuristic" OR "Hybrid" OR "deterministic" OR "exact").

Selection Criteria for Primary Studies. Selection criteria were defined to answer the research questions. The extraction criteria helps to classify the selected primary studies and obtain the necessary information for this study -see the Fig. 1.

Criteria	Name
RQ1. What methodologies are used to find an optimal solution to the problem in the DFLP context?	
C01	Solution methodologies
C02	Algorithm's name
C03	Year
C04	Country
RQ2. How is the proposed methodology's performance evaluated on the solution methodologies used to solve the DFLP?	
C05	Evaluation methods
C06	Algorithm validation process
C07	Algorithms for comparison
C08	Method for algorithm parameter tuning
RQ3. When a hybrid algorithm is developed, what is the selection process carried out to choose the set of algorithms that will compose it?	
C09	Methodology applied to develop the hybrid algorithm

Fig. 1. Extraction criteria utilized for primary studies

Selection of Primary Studies. The results obtained by applying the search strategy in the scientific databases were subjected to a selection process. This selection consisted of three well-defined steps: 1) evaluation of the inclusion and exclusion criteria, 2) selection of articles by title and abstract, and 3) selection of articles after full reading. Figure 2 shows the number of articles obtained in each step. The search strategy used was limited from 2015 to 2021, and the inclusion and exclusion criteria were:

- Inclusion criteria
  - Articles focused on DFLP
  - Articles in Spanish and English
  - Articles from scientific journals, books section and proceedings
- Exclusion criteria
  - Duplicate articles
  - Theoretical articles

Quality Evaluation. Each article was checked for how many times, on average, it has been cited to avoid bias with articles published before others. Therefore, according to Google Scholar's scholarly citation counter, three categories were created: high, medium, and low, where the number of papers belonging to each category was 25, 13, and 21, respectively.

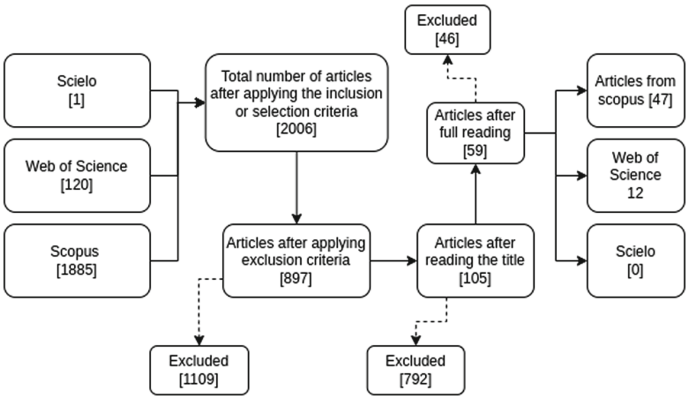

Fig. 2. Flowchart of the applied methodology

3 Results and Discussion

This section shows the results obtained in this work. The Rayyan tool was used to organize and manage the information retrieved from each study, and Python was used to perform the numerical analysis. Therefore, the results were divided into 1) Metadata analysis and 2) Descriptive analysis.

3.1 Metadata Analysis

The demographic information obtained from each article (C04) shows the geographic area of origin of the study. The findings report a total of 15 countries, in which Iran, China, and India remain at the top of the ranking, with 17, 12, and 12 papers, respectively, followed by USA, Turkey, Canada, and Malaysia, with three, three, two, and two papers, respectively. This group of articles represents approximately 69.50% of the selected papers. In C03, the year of publication is considered to know how many articles on DFLP are published using different solution methodologies. Figure 3 shows the trend of the investigations carried out to solve the DFLP, where from 2017 to 2021, a downward slope is shown, which means that interest in this important line has declined.

Finally, information about the document type (journal article or conference article) was obtained. The results give a total of 48 sources, one article was obtained from 38 sources, and two were brought from nine sources. The journal with the most articles published was "Annals of Operations Research", with three papers.

3.2 Content Analysis

To answer RQ1, the reviewed articles show a great inclination towards Metaheuristic solutions, which are applied to 39 articles representing 66.10% of the

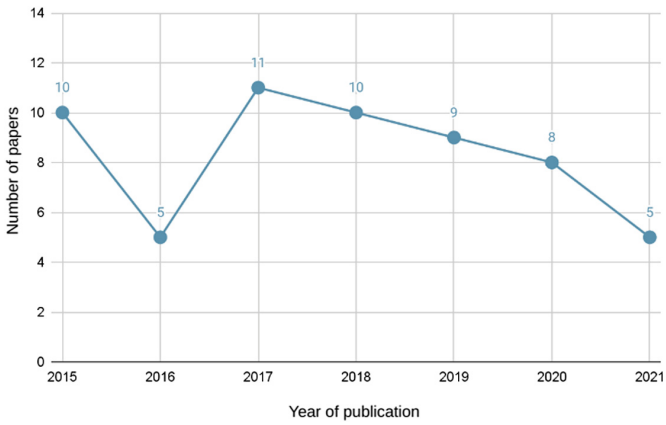

Fig. 3. Number of papers per year

total, followed by hybrid solutions, with 13 articles representing 22.03%. The remaining solution methodologies are Heuristic, Exact, and others. The most used metaheuristic algorithms were: 1) Simulated Annealing (SA), 2) Genetic Algorithm (GA), and 3) Particle Swarm Optimization (PSO) with 18, 8, and 4 occurrences, respectively, in which the ranking takes into account for variations of the algorithms. The most relevant articles are in [14–19]. Through this study, it can be seen that researchers are more interested in applying metaheuristic algorithms and hybridizing them to exploit the strengths of each metaheuristic and, therefore, obtain better-quality solutions in the shortest possible time.

To answer RQ2, the articles were classified into three groups: statistical comparison (SC), quantitative comparison (QC), and no comparison (NC). The results show that 16.94% of the studies apply one or several statistical methods to determine if there is a statistical difference between the article algorithm and the selected base algorithms regarding solution quality and/or computation time -about SC-. Whereas 45.76% of the studies do not show an objective comparison but rather compare their quantitative results and draw a conclusion from these - belonging to QC. 37.3% of the studies do not present any performance evaluation method - belonging to NC. The most common statistical methods used in the SC group were: Student's t-test, ANOVA, Tukey's test, Sign test, Mann-Whitney test, and Wilcoxon signed-rank test. Studies in the QC group obtain the objective function values after running their algorithms and performing a smooth comparison with other algorithms (62.96%) or results from other studies (37.04%). In addition, the Taguchi method was the most used parameter adjustment method, presented in 11.84% of the studies, followed by trial and error (8.47%) and article suggestions (5.08%). Finally, to answer RQ3, the results did not yield studies that explained the process or the methodology applied to form the hybrid algorithms. Sometimes, the studies refer to some advantages of the chosen algorithms [19] [21] but do not make a comparison with other promising algorithms.

4 Conclusions

This work was carried out to know the solution methodologies applied to solve DFLP, its performance evaluation, and the selection process followed to build a hybrid algorithm in case it is used. The results show that researchers are more interested in applying metaheuristic algorithms and hybridizing them to obtain better results, where 66.10% of the studies use metaheuristic approaches to solve DFLP. In metaheuristic approaches, three algorithms are commonly used: SA, GA, and PSO. Furthermore, the studies were labeled into three categories to understand the performance assessment: 1) best statistical comparison, 2) quantitative comparison, and 3) no comparison, where most studies fall into the second category. The first category recorded some statistical methods used to evaluate the developed algorithms: Student's t-test, ANOVA, Tukey's test, Sign test, Mann-Whitney test, and Wilcoxon signed-rank test. In addition, many studies use the Taguchi method to adjust the parameters of their algorithms to obtain the best values that make it work best. Unfortunately, the results of this work did not show studies that explained the process or the methodology applied to compose the hybrid algorithms. This work aimed to report studies where DFLP was solved with different solution methodologies to understand better the flow of the chosen solution methodology and its evaluation. In addition, the methods used when building a hybrid approach were also investigated. The lack of implementation of performance metrics to judge the performance of an algorithm and the poor selection process when using a hybrid system encourage future projects to consider these aspects. In addition, future work may include studies evaluating various facility design issues and the performance effects of the technology used when evaluating the algorithms.

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Understanding Determining Factors: Purchasing Decisions

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Abstract. The paper aims to highlight the lack of usage of knowledge-based expert systems in purchasing decisions in the context of hybrid corporate reality. We use the transdisciplinary approach in our work, which is essential to examine the problem that occurs in the reality. While reviewing publications containing the keywords "Cognitive bias" and "Supplier selection", we focused on the methods used. The examined methods in the pooled papers are mainly based on arithmetic and rank the possibilities without considering the available expert knowledge then and there. Afterwards, we propose a solution beyond analyzing the data measured in the past; in addition, the decision-maker, their mental model, and their knowledge is considered. We assume that the effects of cognitive biases are more readily identifiable when using expert systems in considering the decision-maker's opinions in connection with the actually applied rules in making decisions. In addition to seemingly objective solutions, in our experiment, we propose that by using past cases with known results, complex rules, which are based on the expert's knowledge, can be simplified without changing the results of decisions in purchasing.

Keywords: Purchasing Decision · Cognitive Bias · Expert System

1 Introduction

Based on various keyword combinations, the present paper aims to provide an overview of the research on expert systems in the purchasing domain that also address cognitive biases. The literature review is conducted based on the framework to find the research gap in the qualitative literature review [1]. To understand the real problems the transdisciplinary approach is essential, and the process of reasoning must also be mentioned in relation to decisions. From among the deductive, so-called rule-based reasoning (RBR), the abductive and the inductive reasoning approaches, in this paper the emphasis is on inductive reasoning, and our presented solution looks at case-based reasoning (CBR).

The listed searches (see Table 1) were conducted in Web of Science (WoS) and ScienceDirect (SD) in February 2023. The nine searches were based on different combinations of five keywords.

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Table 1. Summary of the results of "Cognitive bias" and "Purchasing decision"/"Sourcing decision"/"Supplier selection" and "Expert system".

Keywords			Results in WoS	Results in SD
Expert system	Purchasing decision		253	600
Expert system	Sourcing decision		2171	77
Expert system	Supplier selection		459	872
Cognitive bias	Purchasing decision		79	210
Cognitive bias	Sourcing decision		426	17
Cognitive bias	Supplier selection		6	34
Cognitive bias	Purchasing decision	Expert system	0	7
Cognitive bias	Sourcing decision	Expert system	0	0
Cognitive bias	Supplier selection	Expert system	0	3

Because the term "Sourcing decision" is used by researchers for multiple disciplines in the Web of Science database, the number of the publications in ScienceDirect is lower.

Based on the overlay visualization of the "Expert system" and "Purchasing decision" keywords search, the terms do not appear in connection with cognitive biases and the mental models of decision-makers (see Fig. 1).

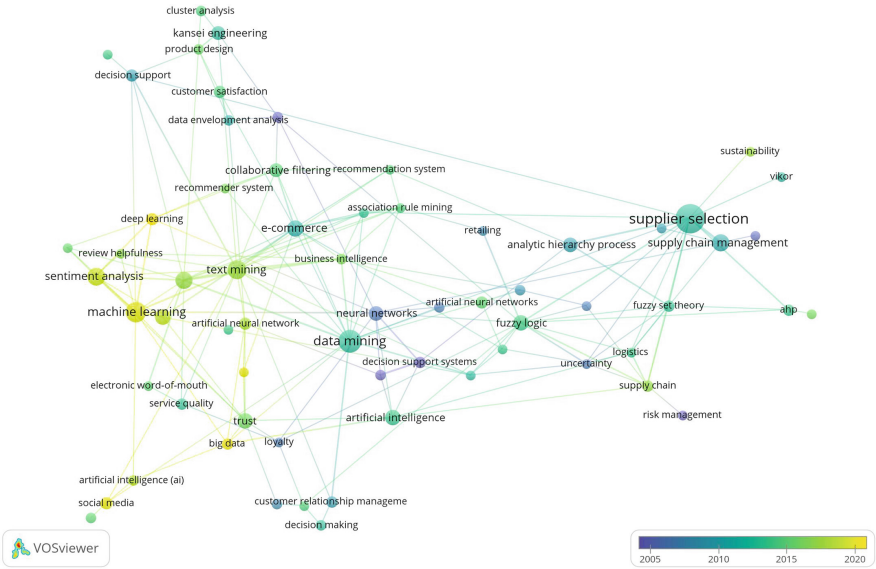

Fig. 1. Overlay visualization of "Expert system" AND "Purchasing decision" keyword combination by VosViewer based on 253 results in Web of Science database.

The "Cognitive bias" and "Supplier selection" and "Expert System" keyword combinations listed two review articles and one research article. The first paper emphasizes the essence of Fuzzy multi-criteria decision-making, possible research proposals, and the open difficulties and limitations based on publications between 2007 and 2017 [2]. Another paper aims to develop a decision support system that detects and addresses biased decision-makers in group decision-making [3].

In our paper, we conduct research in connection with supplier selection; therefore, we will focus on the search for "Supplier Selection" and "Cognitive bias" keyword combinations. In several of the examined publications no explicit methods were used, as can be seen in the topics of increasing innovation with the possibility of data science [4]; research in the cross-border e-commerce (CBEC) domain [5]; and environmental supply chain management and its effects on reputation [6].

The examined literature reviews aim to demonstrate how buyer-supplier maturity disparities increase risk [7], to examine buyer-supplier behavior in a sustainable supply chain management decision-making [8], to examine a new venture's early development, supplier relationships, and consequences [9], and emphasizing advanced manufacturing concepts developed over the past decade [10].

Controlled behavioral experiments, surveys, and empirical research were conducted to explore the role of rational and intuitive decision-making approaches in supplier selection decisions (focusing on supplier's cost and quality/delivery/innovative performance) and to investigate its effects [11], and to provide insight into the supply chain managers' biases [12].

Scenario-based techniques were used to summarize the possibilities offered by scenario technology [13]. Based on a scenario-based role-playing experiment where it was shown that in the context of a supply disruption, the supplier's non-compliance depends on its controller, the effects of emotions during supply management processes were examined [14]. In the examined papers, simulations are said to make accurate forecasts of demand when looking at failures in the final phase in military operations [15], as well as when examining the impact of managers' problems and resistance in the supply chain domain [16].

Among the publications in which several requirements were taken into account during supplier selection, two main directions were observed; one being multi-criteria based methods and the other, group based methods (see Table 2). The table below shows the grouping we have carried out, and our methods used during supplier selection are summarized.

Table 2. Summary of the used methods in examined publications in the supplier selection decision-making domain.

Multi-criteria based methods		Group based methods		
Fuzzy	Other	Group decision based	Multi-criteria group based	
		(Fuzzy)	Fuzzy	Other
[2, 17–19]	[20, 21]	[22, 23]	[24]	[3, 25, 26]

The first result of our literature review is that the pooled papers only partially deal with the cognitive biases, despite the fact that cognitive biases' effects are undeniable. Furthermore, their recognition and measurability with the pure quantitative approach is biased from our viewpoint.

In our paper, we first investigated the applied methods in pooled papers. Cognitive biases are the subject of further research. Second, a possible solution is presented, which is able to reduce the number of attributes which describe the decision, excluding unnecessary expectations. In our illustration of the solution, the effects of cognitive biases worth considering are also presented.

2 Method

A knowledge-based expert system (KBES) is an Artificial Intelligence application designed to simulate human expertise in decision-making, using the expert's knowledge. The system consists of two main components: the knowledge base and the inference mechanism [27]. The advantages of KBES include the ability to make effective use of expertise to support the decision-making, and it also allows knowledge to be shared in the organization.

The Logic Theorist computer program, referred to as the first artificial intelligence program, and the first software designed to reasoning, was created in 1956 [28]. In 1985, the schema of knowledge representation was based on the artificial integration of human cognition, taking into consideration the semantic nets, relationships, nodes, and the process by which people store information [27]. Nowadays, decision support that is based on past measured numbers is gaining ground, omitting the expert's knowledge in the 'then and there'.

In contrast to this trend, the presented KBES highlights the relationships between attribute-value pairs in a multicriteria dimension. The recognized patterns make it possible to simplify complex rules which consider the expert's knowledge beyond the measurements.

In support of the points made in the above section of the article, an experiment has been conducted through which cognitive biases can be filtered. A large international company's purchasing decision-maker was the participant for this project, wherein the participant required anonymity.

We gathered knowledge during the supplier selection process, where the purchasing expert explained in detail the attributes (expectations) that describe the supplier. Seventeen attributes were collected, each expectation was described with 3–5 values. The expectations and values work with the knowledge and vocabulary of the decision-maker, and this was fully preserved during the experiment. In the experiment, thirteen cases were investigated, in which the decision-maker evaluated the different cases. In each case, all expectations were evaluated by the decision-maker. For example in the case of price (attribute), values are high (value 1), low (value 2), appropriate (value 3).

Our paper does not demonstrate all the cases, but we will use one of the supplier choices to illustrate the evaluation process itself. After the cases were identified by the decision-maker, the value that describes the case was selected for each of their attributes. Without going into too much detail, the following is an illustration of the characterization

of suppliers through one case profile (in order: attribute – value): opinion – predictable; payment deadline – average; cooperative willingness – forced; commitment – under protest; contact – sent; repetition – regularly; willingness to provide feedback – upon request; feedback quality – usable; suggestibility – unconcerned; time commitment – weeks; price flexibility – 5–15%; share among the like – 15–30%; reference – versatile; accuracy of pre-planned deliveries – various; willingness to extraordinary delivery – with conditions; compliance with quality parameters – partially appropriate; price – high.

This knowledge was collected and processed in the knowledge based expert system. Our expert system uses artificial intelligence for the implementation of both CBR and RBR. We aimed to reduce the number of attributes in the recorded cases that describe the real decision and exclude those that do not significantly impact the outcome. We have also tried to prove that a complex set of rules can be simplified to a set of 7 ± 2 rules, which is closely related to working memory capacity [29]. Through the use of the module in the application, a set of rules has been created that meets the pre-defined objective.

3 Result

We already mentioned deductive, rule-based, and inductive, case-based reasoning, but now we will also mention the reductive reasoning formed from the combination of these two [30]. During our experiment, based on the knowledge shared by the decision-maker from cases that happened in the past, the results of which are well known, we obtained the knowledge to create a decision tree for the knowledge-based expert system we used.

Using artificial intelligence, the complex rules of the so-called Case Based Graph are turned into single-level rule-based knowledge [30]. The solution we use also gives us the opportunity to consider unmeasurable opinions, which brings us closer to understanding the real problem. In the illustrated case, out of the 17 expectations formulated by the decision-maker, it turned out that only 3 expectations are relevant to the outcome of the decision. This is a consequence of the bandwagon effect [31], since decision-makers set expectations for suppliers as well as their own expectations, which are available to them then and there.

The process described below aims to reveal the complex rules that have emerged based on decision-makers' knowledge. As a starting point of the experiment, the decision-maker formulated the attributes and determined 3–5 values for each of them. For example, the "Willingness for extraordinary delivery" values are "Rejective", "Unconditionally" or "With conditions". Even though during the experiment the decision-maker formulated 17 attributes corresponding to the expectations towards suppliers, it turned out that whether a supplier is the worst (unreliable) or the best (reliable) depends reliably on just 3 attributes reflecting the decision-maker's vocabulary. From this, we can present in detail the first simplified rule as follows: the decision-maker judges the supplier as reliable **if** the "Accuracy of pre-planned deliveries" takes the value "in time", **and** the "Reference" value is "no" **and** the "Commitment" value does not affect the perception of the supplier (is irrelevant). The supplier is rated as "unreliable" based on the following simplified rule: **if** the attribute of "Reference" value is "no", **and** the value of the "Accuracy of pre-planned deliveries" is "various" **and** the "Commitment" attribute is again irrelevant.

4 Conclusion

A transdisciplinary approach to the problems that arise in the hybrid world is essential to understanding phenomena in the context of reality, not just in their simplified form. As can be seen from examining the literature, research using quantitative methods is given more weight in knowing, understanding and supporting a decision. Initiatives to understand cognitive biases provide seemingly objective solutions that are also influenced by the effects of cognitive biases themselves, and in some cases examine problems detached from hybrid corporate reality. In the publications examined, the consideration of multiple criteria is given great role in research, and the decisions are supported by arithmetic rankings. However, the mentioned methods usually use predefined attributes, which lead to questionable objective solutions that are not flexible in considering the expert knowledge that is available in the moment of the decision, then and there.

In this paper, we point out the usability of soft data in KBES-supported supplier selections to get closer to understanding the decisions. Of the 17 expectations formulated by the decision-maker, only 3 expectations actually influenced the outcome of the decision. This is due to, among other biases, the bandwagon effect. This brought us closer to understanding decisions, as the effect of cognitive biases in setting expectations has become more visible.

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Lean

A Lean Framework for Developing Circular Business Models

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Abstract. This paper presents a novel framework for developing Circular Business Models based on a strategic approach adopted from lean production. Building on existing theory in both the circular economy and the lean production research domain, the framework was developed from the findings of a longitudinal single case study based on a mixed research design of case study and action research. The research was carried out over a three-year period as part of a larger research project that explored the connection between lean thinking and circular economy. The aim of the research was to help close the gap on the integration of lean and green and to guide academics and practitioners who seek to accelerate the transition to a circular economy.

Keywords: Lean Strategy · Circular Business Models · Organizational Learning

1 Introduction

There is an ongoing debate in the operations management literature about the lean phenomena. On one side, researchers argue that lean has moved away from its Toyota roots and should be considered as one of many different approaches to achieving efficiency in manufacturing and operational excellence [1]. On the other hand, it is argued that lean is a different business paradigm and therefore should be considered a meta-theory based on learning and people development [2]. As these different viewpoints could be considered different paradigms, there is no reason both cannot be true. It depends on the eye of the beholder. As Lean Production was first introduced as a full business model (how to develop, make and sell a product, and how to run a company) [3], we have found the latter paradigm more fruitful when exploring the impact of lean thinking on sustainability and circular economy. In an ongoing research project this subject has been explored in multiple ways, from operations strategy [4] to product development, human resource management [5] and business model development [6].

In the age of storytelling, lean production still has an eye on performance. Companies that are adapt at lean thinking and practice have shown that utilizing all employees' hands and brains to face the environmental challenge and move towards more circular business models is a path worth exploring [7]. In fact, Toyota Motor Corporation, in which lean production originated, are themselves transitioning towards what they call a

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"Future Society in Harmony with Nature" through their 2050 Environmental challenge [8]. Despite being criticized for not adopting to the rapid move to Electric Vehicles, Toyota have achieved remarkable results in both recycling of vehicles and CO_2 reduction in both vehicles (through electrification) and plants [9]. The first supported by its ongoing LCA strategy [10], and the latter driven by its 6 attitudes for energy reduction (eliminate, repair, stop, reduce, pick up and change) [11].

[12] found that the connection between lean and green is already well documented, especially the effect of waste reduction on environmental impact, and that lean and green can work together based on this synergy of waste reduction. However, the same study suggested more research was needed to better understand the integration of lean and green as a consolidated approach. To respond to this call for research this paper presents a novel strategic approach for the development of circular business models that combines theory from the Circular Economy literature with the lean theory. The research is based on a single longitudinal case study of a Norwegian, multinational original equipment manufacturer (OEM), and in this paper is presented in the following manner: After this introduction we present the theoretical background for the study in the second chapter. In the third chapter the methodology, followed by the Findings and Discussions in the fourth and fifth chapter.

2 Theoretical Background

Typical linear business models are models that describe how companies create value and profit. There are different definitions of a what a business model is, but in essence it describes the value proposition (what it offers), the value creation (how it makes and supplies what it offers) and value capture (how it profits) [13]. In addition, a business model is also a representation of the underlying core logic and strategic choices for creating and capturing value in a value network [14]. These two perspectives are complementary since the first can be used to develop, analyze, and understand a business model, while the latter allows us to study the underlying core logic and strategic choices which led to a business model.

Traditional linear economic models center on the financial, and therefore, economic profit of a company. It often, but not always, creates what economists call external costs. Costs that are not covered by the company that creates the cost but is instead shifted externally to society at large [15]. Throughout history, companies have sought profit by shifting the burden and cost of pollution, workers' rights and so forth, to outside of the company. The Circular Economy seeks to realign the environmental cost of extraction and exploitation with the cost of doing business and emphasizes the need for economic growth without increased consumption of resources.

A suitable and widely used framework are the principles of "reduce, reuse and recycle", that aim at core patterns of production and consumption, as well as habits in all societal aspects [16]. These three basic principles have since been developed into a larger framework of "r-strategies" that can serve as principles for developing Circular Business Models (CBM). A representation of these strategies can be seen in Fig. 1. These strategic principles address different levels of circularity [17].

The principles can be considered hierarchical as they seek different outcomes and will have different implications both for the business and the environment. [18] suggests

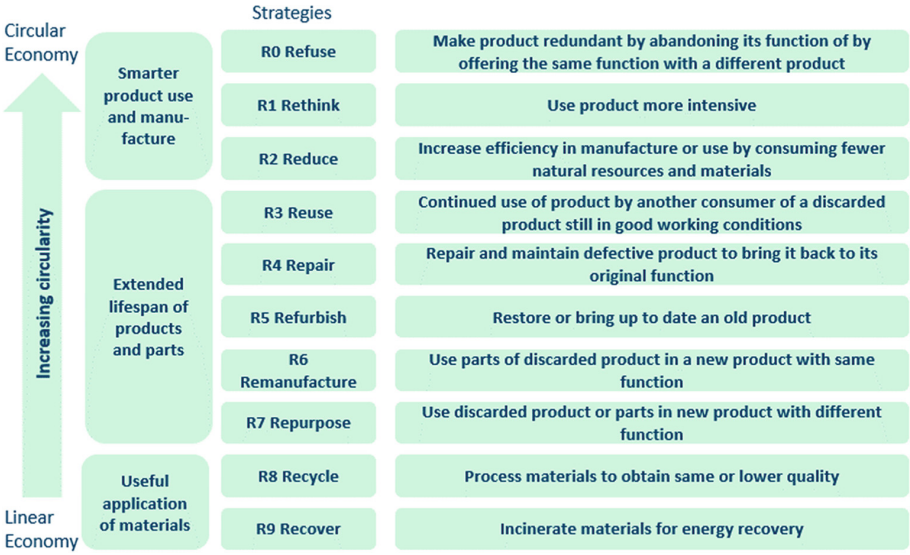

Fig. 1. Principles for Circular Business Model Development adopted from [17]

that these "r-strategies" can be used to tackle different parts of the linear value chain with the lower levels dealing with the loop between disposal and new production (material or energy recycling), the next level dealing with the loop between disposal and distribution (i.e. take-back strategies, re-manufacturing and re-furbishing for secondhand sales or leases), the next level with reuse (second or third hand in good condition) and the highest level with extending and intensifying use, as well as dematerializing (reducing and refusing materials, functions etc.)

Although high-level models like those presented in Fig. 1 act as useful frames for thinking about circular economy and how to move towards a circular economy, defining and developing a truly circular business model from scratch is a difficult challenge. As such, the lean approach to strategic thinking should be an interesting alternative for companies who wish to move towards business models based on a circular economy. [19] presents lean strategy as an alternative strategic framework based on accepting challenges and committing to changes as opposed to the traditional frame of separating strategy from execution. These two strategic frameworks are defined as "4D" (Define, Decide, Drive, Deal) and "4F" (Find, Face, Frame, Form).

According to [20] Toyota have an evolutionary approach to technology and business development. It challenges the organization to strive towards ideal or hard to reach conditions and new technology and business models are formed as responses from those challenges. A recent conversation with a retired senior executive from Toyota shed anecdotal light on this process when he informed us that "*Toyota don't tell their managers what to do, we expect them to figure it out for themselves based on the challenges we set out*." The model presented by [19] argues that this is a strategic approach which starts with finding problems in the real world and accepting the challenges these problems entail. The challenges are then framed (as opposed to defined) to allow the organization to

form new (and sometimes innovative) solutions by sharing initiatives, experiments, and counter measures. Thus, aligning strategy with execution and forming future business models as opposed to defining and implementing new business models. This eventually led us to our research questions: "*How can a lean strategy support the development of circular business models*?", and "*how can the r-strategies act as frames for forming new solutions that support circular business models*?".

3 Research Method

The researchers' original intention was to engage with the company in an action learning research design as described by [21]. As such, interventions were designed to develop new circular business models through interaction between researchers and personnel from the case company. However, during the interventions with the case company it was discovered that it already had many different ongoing initiatives that would provide interesting and useful data for the researchers. Based on this discovery it was decided to combine the action research design with single case study research based on the recommendations of [22]. Because of this, data was collected by combing these two approaches. The case study is also longitudinal (carried out over 3 years), providing an in-depth study of a change process as it happens inside an organization [23]. The empirical data presented in the next chapter was derived from a multitude of different sources including observations, documents, interviews, as well as interventions and participatory workshops. The data was then carefully analyzed guided by the theoretical propositions that informed the research questions. The interviewees and active participants from the case company came from different parts of the organization and included the Vice President of Supply Chain & Manufacture, the Vice President of Hardware Platform Technology, the Sustainability Manager, the technical director and product manager of the main product line, the Director of Strategic Sourcing, a Plant Manager, in addition to different personnel from functions such as manufacturing, product development, materials and purchasing.

4 Case Study

The case company is a Norwegian multinational manufacturer of products and equipment for a professional market. It designs and manufactures its own products on three different continents and has offices across the globe. It started its global sustainability work by mapping its company-wide footprint in 2019 and set a target of 70% carbon emissions reductions by 2030 and to introduce circular solutions across its global value chain. The company has also developed, tested, and implemented its own sustainable design tool. In addition to collaborations with researchers and consultants for data collection, analysis and improvement suggestions, the case also launched a company-wide initiative encouraging its employees to come up with ideas and to bring these ideas to light.

An example of a successful initiative was an idea to first reduce the size of packaging for their main product line (two large suitcases), and then remove (refuse) the packaging all together and replace with cardboard. A small cross-functional team worked on the idea for several months and came up with a new suitcase design that allowed the suitcases

to fit into each other. This new design reduced the shipping footprint with 50% for ingoing logistics. The idea was based on the matryoshka doll and is now implemented. Currently the same team is testing a new cardboard box which will reduce shipping footprint with 75% for outgoing logistics.

Another example of local initiative is the removal of several electrical components and materials such as clothing from the basic configuration. In addition, the same team are experimenting with take-back policies to determine what components are suitable for take-back and refurbishment, which components outlive the normal product life-span and are viable for re-use. One of the product development teams is also switching to recyclable materials continuously.

During one of the visits, a product manager mentioned that the American sales unit had started to experiment with a subscription model without informing him. However, the idea was soon taken onboard and has turned out as a successful experiment with different sales models in a marketplace that is notoriously conservative.

To share these success stories across company sites, the company has also initiated an annual internal conference where employees can nominee themselves or their colleagues' ideas and implementation for a sustainability award.

The researchers also engaged with the company to support them in their move to more sustainable and circular business models. During one of the interventions, it was discovered that the company didn't have the data available to create Life-cycle-assessments (LCA) of their products. There was plenty of data, but not a clear understanding of what data is useful and needed to create a meaningful LCA (such as weight, usage and so forth). Therefore, the effort of the researchers instead focused on supporting the development of the internal design tool so that more informed decisions could be made on future products.

Another ongoing intervention has been to help bring Sustainability in as a key topic in the manufacturing organizations hoshin, to give direction to the plants and departments in reducing CO_2 footprint of plants and supply-chain. This intervention has been described in more detail in [4].

Finally, researchers have also been working together with one of the product developments teams to find ways in which both current products can become more sustainable in terms of reusable parts, manufacturing, and refurbishing strategies and how the next iterations of products can include more recycled materials, new biomaterials, reused parts as well as in finding other ways in reducing the product footprint.

In addition to experimenting with revenue models that are more in line with circular economy ideals, reducing the footprint of current operations and products, and introducing more recycled material into current products, the case company is also looking to the future. It has recently started a new technology development department charged with facing the R&D challenges that they need to solve to close the circular loop for the future. The different technology functions responsible for the development of future sustainable technologies all have resources dedicated to working on circular solutions.

5 Findings and Conclusion

The study found that a lean strategy (Find, Face, Frame, Form) can support a company in developing circular business models. In addition, the R-strategies acted as useful frames when forming new solutions within the company studied. Based on the theoretical background and the findings from the case study a framework for lean circular business model was developed to generalize the findings. The framework point to core challenges from three perspectives and to the knowledge that needs to be development (past, present, future). The framework is based on the core thinking of the 4F framework as described in chapter two. The model should not be considered a step-wise model, but companies should to the best of their ability address the different perspectives in parallel.

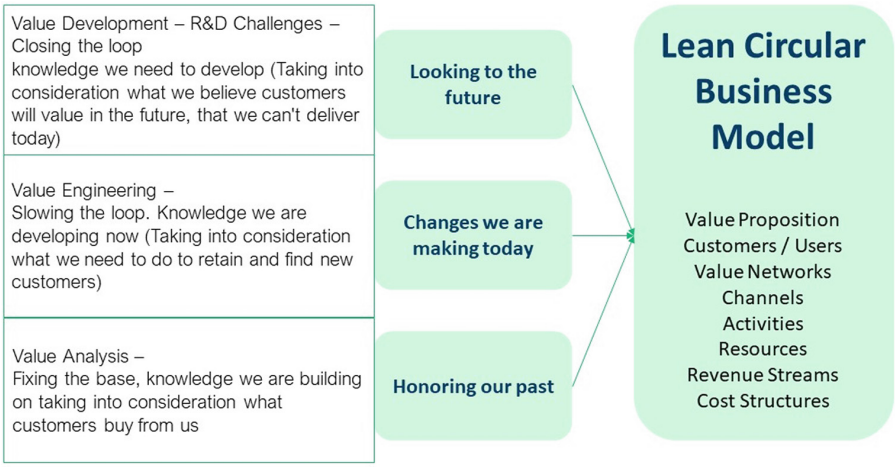

Fig. 2. Lean Circular Business Model Concept

A lean circular business model builds on the foundations of a company's previous success. It also takes into consideration the mistakes made and the implications of strategic choices made in the past. Fixing the base of the business means bringing value back into the products and taking responsibility for the environmental impact of historic production and install base (Fig. 2).

Customers are never satisfied and always ask for more, but what do we need to change, what do we have to change, what do we want to change, and what do we keep as we move towards more circular product and process designs? How can we slow down the waste of resources by intensifying, dematerializing, reducing resource usage, or how can we create new markets through refurbishment or remanufacturing?

As there is no one-size-fits-all for developing CBMs, creating future value concepts in parallel with ordinary development is key for established companies to be able to break free from technological production processes and value propositions that are mainly rigged to support linear economic actives. Working on the solutions of the future can speed up the adoption of new materials and technologies that are circular by design.

Allowing for insights and results of future research and development to trickle down into ongoing projects.

The main limitation of the single case study is the generalizability of the findings. However, the format also allows for in depth understanding of the phenomenon being studied in its context. To address this limitation we suggest that more research should be done in testing the developed framework in other companies, in other industries. To validate and improve on the approach that is recommended here in this paper.

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Implementation of a Standardized Replenishment System and Kanban Application in the Metalworking Industry

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Abstract. This paper presents the improvements in the internal logistical flows of material and information on the welding section of a company, specializing in the production of sterilizers for laboratories and hospitals. Based on the diagnostics phase, associated with the Action Research Methodology applied in this project, the main problems identified were the inadequate quantities of material at workstations, leading to production stoppages, lack of standardized material supply routines, and lack of stock management methods to "trigger" purchase orders. The line-side inventory of the workstations was dimensioned, based on the 2-bin system, resulting in a constant volume of production. The quantities in the containers of the supermarket, and in the containers of the line-side inventory should be the same, allowing the direct replacement of empty containers for full containers. After the implementation, a route was defined to replenish the workstations once a week, reducing considerably the number of travels each worker performed to resupply his workstation and preventing unnecessary production stoppages. A study on the references bought externally was conducted, resulting in 53% of the references will be replenished every three weeks, 22% of the references will be replenished every two weeks, and 25% of references weekly. At the supermarket, a purchase order should be placed with an amount equivalent to the Reorder Point when the material is removed from the last (second) container. To signal this request, the kanban system was introduced in these containers, facilitating the management of the developed system and reducing stockouts.

Keywords: Lean · Replenishment · Standardization · Internal logistics · Kanban

1 Introduction

In the current competitive landscape, it is crucial that organizations have the ability to deal with the volatility of markets and the variability associated not only with their internal processes but also externally at the level of supply chains [1]. Concerning the increasing

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requirements from customers, companies need to be agile in order to provide high-quality products in a short period of time. To achieve this, an increasing emphasis has been put on the improvement of the internal logistical processes, establishing effective supply systems to guarantee a continuous production flow and an efficient use of resources, reducing the time to market [2]. Moreover, the application of Lean tools, such as kanban systems, allows for a smoother flow of materials according to the real demand, which reduces the dependency on forecasts and brings stability to the production and purchasing processes [3]. The goal of this study is improving the in the internal logistical flows of material and information on the welding section of a company, that produces sterilizers for laboratories and hospitals. In this section, the importance of internal logical process is emphasized, Sect. 2 presents a literature review; Sect. 3 the materials and methods; Sect. 4 presents the results of the improvements implemented; Sect. 5 presents the conclusions.

2 Literature Review

Lean is a long-term approach aimed at eliminating waste and inefficiencies in a systematic way, to establish a continuous flow in the processes and add value for the customer [4]. To achieve the goals proposed, several Lean tools were used, such as Kaizen, Visual Management (VM), Standard Work (SW) and Kanban. VM plays an important role in transmitting information on the shop floor, aiming to guide employees, assist in the standardization of tasks and contribute to productivity improvement, through the implementation of intuitive visual systems that promote safety and the elimination of waste in the workplace [2]. SW is one of the fundamental tools of Toyota Production System (TPS), being responsible for establishing standards that represent the best-known methods of performing the work [5]. The line-side inventory referred in this paper consists of a physical location of inventory present at the workstations, essentially comprised of small containers, to allow the supply of material to employees in an accessible way and in a short time. Its use is intrinsically linked to the application of SW, and the presence of materials in the vicinity of workstations minimizes the movement of workers and establishes standard methods of carrying out processes efficiently. Its design involves the definition of the location, quantity and selection of materials that must be present in each station, to ensure the uninterrupted flow of processes responsible for adding value to products. The kanban system consists of a tool that supports the visual control of production, through the use of cards that contain information to regulate the flow of inventory and materials [6, 7] on Lean manufacturing. Usually combined with other Lean tools, as Constant Work in Progress (CONWIP) with significant gains. Hybrid Kanban-CONWIP system was proposed by [9] and its implementation reduced the cycle time and achieved an increase of 38% in inventory turnover. Positive experiences included improved visibility, improved collaboration, and improvements in lead time were reported as a result of applied Kanban system to services [10]. The use of kanban results in a pull system of production, ensuring the supply of the materials in the right time and quantities and avoiding overproduction and cost reduction [7]. Improved control of stock was achieved through the reformulation of kanban (approximately 30%); a reduction in the time required to replenish material in the consumables cabinet was ensured by means of the mizusumashi (expected improvement of 50% [11].

3 Materials and Methods

In this section, the development of the systematic supply system to the line-side inventory locations will be explained, detailing how the adjustment of the quantities present in the containers allowed to satisfy the company's requirements, integrating the supply system with the production in the machining section, to replenish the containers. The implementation of a Kanban system in the supermarket that supplies the line-side inventory will also be explained, as well as the new methods of organization, standardizing the location of references to reduce the time and effort during replenishments. Due to the nature of the company's Make-To-Order production strategy, which provides high customization for the clients, there is a high complexity in the management of orders and materials. During this analysis, several issues were identified that affected, the line-side inventory locations; lack of a systematic supply system for this locations, as well as an inadequate dimensioning of the quantities for each reference, leading to stockouts and workers leaving their station to gather the materials to complete the order in production. Also, it was found that the supermarket (Fig. 1) lacks standardized organization methods, with materials being store on the floor, when there is no capacity to store them. Furthermore, there is no specific storage position for each reference, resulting in an increased effort to ensure the material supply processes.

Fig. 1. Supermarket ("Interface")

Following the diagnosis phase, associated with the second step of the Action Research methodology, an action plan was developed to address the issues identified during the diagnosis phase. A brief study was conducted on the company's sales during the last 3 years to assess and estimate the demand value, which would be used as a reference for the line-side inventory. At the same time, several "Worst Case Scenarios" were developed as the method to establish a basis for a replenishment system capable of avoiding stockouts. To estimate the capacity of the system, the year with most sterilizers sold was used as a reference (2.7 sterilizers per week), which resulted in establishing a capacity of three sterilizers per week, with 11.1% of slack to avoid stockouts and to make it practical to define the quantities per container. For the references produced within the company, the requirements consisted on taking into account the limited capacity of the machining section, to establish a constant volume of production to facilitate planning for this section and to define a reduced number of replenishments per week, as the operator chosen to carry out these tasks will have to stop his work in production to perform them. An important aspect for the dimensioning of the quantities in the line-side inventory and

at the supermarket was that each sterilizer produced by the company could spend one or four units, depending on the reference. Moreover, this aspect will have an impact on the material supply process, which works accordingly to the 2-bin system, in which the logistics operator follows a route through each line-side inventory location and collects empty containers, replacing them for full containers, with material collected from the supermarket. To replenish the supermarket, production orders are sent to the machining section, depending on the number of empty containers at the supermarket, as will be explained next. Several scenarios were developed to study the process of weekly replenishments, adjusting the quantities present in the containers both in the line-side inventory locations and at the supermarket to ensure it was possible to satisfy the requirements presented above. As a result, it was established that the containers of the references that consume one unit per sterilizer should contain 8 units, being able to satisfy the demand of 8 sterilizers. Considering a demand of 2.7 sterilizers per week and a quantity of 8 units per container, these references need to be supplied once every 15 days, fulfilling the requirement to reduce the time the operator spends performing the replenishment tasks. In this case, since there are two containers in the line-side inventory locations and two more at the supermarket, it was defined that when the two containers in the supermarket are empty, a production order would be sent to the machining section, so that the quantities on both empty containers are produced (16 units). For the references that consume 4 units per sterilizer, the quantity presents in each container at the line-side inventory and at the supermarket would be 16 units, which can satisfy the demand of 4 sterilizers. Since each container has materials for 4 sterilizers (16 units), it was decided that only one empty container at the supermarket was needed to "trigger" a production order, guaranteeing that both types of references have a production quantity of 16 units, see Fig. 2.

Fig. 2. Summary of the replenishment scenario for both types of references.

Considering two full containers at the line-side inventory, with material for 4 sterilizers each (8 in total) and a demand of 2.7 sterilizers per week, it is possible to conclude these references need to be supplied 2 times every 3 weeks. The patterns associated with the number of replenishments for both references, can be seen in Fig. 3.

For the references acquired from external suppliers, it was established that the time between replenishments would be based on the references produced internally, varying from 1 to 3 weeks. Following the need to reduce the workers load, it was prioritized that the supply process would be performed once every 3 weeks. However, considering the restrictions in terms of the size of the components/containers and the number of units needed to satisfy the demand for that time, some references needed to be replenished more frequently. Table 1 presents an example explaining the though process to support the results obtained, based on an estimated demand of 2.7 sterilizers per week.

From this process, resulted that 19 references would be supplied every three weeks, 8 references every two weeks and 9 references every week. The first step to address the

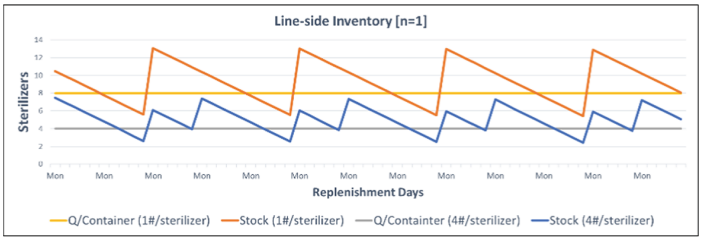

Fig. 3. Replenishment system of line-side inventory locations.

Table 1. Supply process for external references

Units/sterilizer	Q/container units)	Q/container (sterilizers)	Time between replenishments
1	9	9	3 weeks
4	24	6	2 weeks
10	30	3	1week

problems associated with the lack of organization in the supermarket and nonexistent methods for stock management, was to establish a Reorder Point (RP) for the references acquired externally. The calculations are based on the well-known formula from Toyota, as used by several authors [12, 13], to calculate the number of kanban needed in a system, see Eq. (1).

$$RP = \overline{D} * (te + L) * (1 + \alpha) \tag{1}$$

RP – Reorder Point;
$\overline{D}$ – Average Demand (units/day);
te – Waiting Time (time unit);
L – Lead Time (time unit);
α – Safety Factor (percentage).

This way, it would be possible to reduce the occurrence of stockouts, the need to rely on experienced workers to signal when to order and to standardize the ordering process. Next, several scenarios were made to obtain solutions that improved the time and effort needed to organize the supermarket, facilitating the process of collecting and supplying components to the line-side inventory locations and ensure the process is standardized. Each component is now organized according to its reference number and specific position in the supermarket, providing an easy way to identify its location. For each reference, it was decided that there would only be two containers, to facilitate their handling, and that both containers would have the same size, in order promote standardization. One of the containers is going to have the quantity associated to the Reorder Point, as well as a Kanban card, so that when there is a need to take material from this container, the Kanban will be removed and delivered to the Procurement department, so that an order can be made. Along with this changes, elements of visual management were used with

the purpose of avoiding mistakes in the implementation of this new processes, being decided that the containers related to the Reorder Point should be red, while the others remain blue.

4 Results

This section presents the evaluation of the results focusing on the improvements associated with the developed replenishment system, the kanban implementation to reduce the probability of stockouts and the reorganization of the supermarket. Concerning the scenario described in the previous sections, associated with the new replenishment system, there are three main reasons to support its implementation, to meet the requirements of the project. First, the references that consume 1 unit per sterilizer are produced every time that two empty containers are present at the supermarket, while the references that consume 4 units per sterilizer have 16 units and are produced when only one container is empty. This means that all references are produced 16 units at each time, establishing a constant volume of production, as required. The time to produce these 16 units was measured for a big portion of the references within the scope of the study, leading to the conclusion that the production time was low enough to guarantee that the demand was satisfied, while avoiding the possibility of stockouts, meeting the requirement to consider the availability of the machining section. Lastly, with this scenario, the replenishment cycle is equal to one week, reducing the time the operator has to leave the production line to perform this task. Since the quantities present in the line-side inventory locations and at the supermarket are the same, it was possible to implement a Lean supermarket, meaning that empty containers can be substituted directly with full containers, reducing the time and effort associated with this task. As a result of this scenario, it was possible to meet all the company's requirements for the references produced internally. Regarding the supermarket, the new kanban system was implemented to help manage the stock quantity, and new containers were used with different colours (red) to signal the need to make a purchase order. In Fig. 4 is possible to see the state of the supermarket before and after the implementation phase.

Fig. 4. Supermarket before and after the implementation phase

In this case, some of the transformations in the supermarket are evident, like the lack of material scattered on the floor which previously made it difficult to move and carry out

the processes in an efficient manner. This could only be accomplished after performing a study that involved calculating the quantities needed to be stored, acquiring bigger containers to ensure that most references only needed two containers, which simplified the management of the new system, and by estimating the area that would be occupied. This way, the processes can be standardized, ensuring that the developments made are maintained. Adding, new labels were made for the containers and identification of the racks. This was important since, after defining a place for each reference in the supermarket, this information needed to be identified in the labels that were created for the containers, reducing, considerably, the time the operators spend to find each reference. After adjusting the quantities present in the line-side inventory locations and implementing a systematic supply system, a study was performed to assess the improvements that were expected to be obtained. Before the changes, when a component was missing the operator had to stop his task and go to the supermarket, to get the missing materials. Based on the quantities that were present in the containers and the number of times each worker would have to visit the Interface, the total distance travelled per year would be 66.2 km, approximately. With the new system, the replenishment process happens once a week and all the locations are supplied in the same route, resulting in 12.3 km each year, constituting an expected reduction of 81%, approximately.

5 Conclusions

The implementation of a new systematic supply system to the line-side inventory locations, which resulted from the development of "Worst Case Scenarios", was critical to improve the problems identified. With this changes, an operator is now responsible for the logistical processes of supplying materials every week, ensuring that there is always material to satisfy the demand from the production line. Because of this, the probability of stockouts has been reduced considerably and there is an expected reduction of 81% in the total distance travelled to perform these processes. Considering the company's requisites, a system was developed that promotes the standardization of the replenishment processes, reducing the load on the operator to perform each route. For the references produced internally, a constant volume of production of 16 units was established for all the references, as well as a study to the time needed to produce them, to account for the machining section's limited capacity. By establishing the same quantities in the containers at the line-side inventory and the supermarket, empty containers can be directly replaced for full containers, reducing the time and effort of the process.

In the supermarket, the improvements provided a standardized method of organization, so that each component is stored according to its reference number, and its location is now present in the component's labels. Moreover, implementing the Kanban system, as well as using visual management by selecting red containers to store the Reorder Point quantity, the probability of mistakes is reduced during the implementation phase.

In conclusion, several aspects of the Lean Methodology were applied, to allow the development of standardized processes, related to the storage and supply of materials in the shop floor, using VM to ensure a correct implementation. Kaizen, or continuous improvement, was extensively applied during the scenarios' development, both for the supply system to the line-side inventory as for the supermarket with significant gains, near 80% and 40% respectively, in line with the results of other case studies [2, 7–11].

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A Bibliometric Overview of Quantitative Research on Productivity in Construction Projects (1976–2022)

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Abstract. The construction management literature has made significant strides in studying productivity in construction projects. However, it is challenging to examine the general characteristics of the growing body of literature relevant to this topic because of its diversity. The objectives of this paper are (1) to examine the trends and evolution of research on quantitative analysis of construction productivity; and (2) to suggest a roadmap for future research on quantifying productivity in construction projects. To achieve these objectives, this research performed a systematic literature review, resulting in identifying 84 substantively relevant articles. Subsequently, it conducted a bibliometric analysis to explore the general characteristics of the selected articles, such as conceptual and social structures, year of publications, citations, and journal specialty. This research contributes to the literature by providing useful information about research capacity and how the quantitative research on productivity in construction projects has progressed, in turn assisting construction management scholars and practitioners in shaping the future directions on this topic.

Keywords: Bibliometric analysis · Construction projects · Productivity · Quantitative research

1 Introduction

Construction projects serve as a central driver of the economy of any country. It is anticipated that these projects will account for around 15% of the world's gross domestic product (GDP) by 2030 [1]. The literature acknowledges that enhancing productivity is a key contributor to successfully completing these projects and achieving their intended benefits [2]. Thus, the research on productivity in construction projects has attracted considerable attention over the past couple of decades. Accordingly, several studies on construction productivity have emerged.

The research on construction productivity is inherently multidisciplinary, covering a wide variety of topics as diverse as human resource management and supply chain networks [3, 4]. Because of its diversity, it is challenging to examine the general characteristics of the growing body of literature relevant to this topic. Specifically, quantifying productivity is an essential element of research, but little is known about an overview

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of quantitative research on productivity in construction projects. This elevates the need for a better understanding of the current state of quantitative research on construction productivity, recent achievements, and what lies ahead. In this spirit, this paper aims to achieve two specific objectives: (1) to examine the trends and evolution of research on quantitative analysis of construction productivity; and (2) to suggest as roadmap for future research on quantifying productivity in construction projects.

To accomplish these objectives, this paper employs a two-step research design. In the first step, a Systematic Literature Review (SLR) is carried out to evaluate, review, and synthesize the quantitative research on productivity in construction projects from 1976 to 2022. The second step performs a bibliometric analysis to provide the conceptual structure and explore the evolution of the research on this topic [5]. Furthermore, this step visualizes the scientific production in this area of research.

This paper makes two broad contributions to construction management literature. First, it enhances understanding of the development and evolution of the research on productivity in construction projects. This, in turn, provides useful information about research capacity and how the research on productivity has progressed. Second, to the best of the author's knowledge, this research is the first to provide a bibliometric analysis of quantitative research on construction productivity. Such an analysis enables construction management scholars and practitioners to detect patterns, in turn supporting decision making. As a result, the findings of this research assist in shaping the future directions of productivity analysis in research and practice [6].

This paper unfolds as follows. Section 2 describes the methodology used for the SLR. Section 3 presents a bibliometric analysis of the identified articles. The roadmap for future research is discussed in Sect. 4. The paper is concluded in Sect. 5.

2 Step 1 – A Systematic Literature Review

The SLR was performed through three consecutive steps: (1) searching; (2) selection and evaluation; and (3) data extraction and synthesis [7].

Step 1 – Searching: The main keywords used to construct the search strings were "construction projects", "construction industry", "construction management", "productivity", "quantitative methods", "mathematical modeling", "measuring", and "quantifying". These keywords were combined using the Boolean operators including "AND" and "OR". The Scopus database was selected as the database for finding the relevant articles. Scopus widely covers a broad range of peer-reviewed journals across various research areas in the construction management field including productivity [8]. This resulted in identifying 352 peer-reviewed articles published from 1975 to January 2023.

Step 2 – Selection and evaluation: The abstracts of 352 identified articles were carefully read to exclude substantially irrelevant papers. As a result, 76 articles were removed because these articles clearly highlighted their qualitative approaches to construction productivity. The remaining 276 articles were then read in their entirety to select substantially relevant articles. Finally, a total 84 articles were selected that were published from 1976 to 2022.

Step 3 – Data extraction and synthesis: A spreadsheet containing a summary of information, such as the aim of the articles, the theme of the research, and the methods

used, was created. This allowed for synthesizing the findings of each article into different arrangements based on the aforementioned information.

Since space does not permit, and given that the scope of this research is to provide a bibliometric overview, the findings of the SLR will be presented and discussed in the extended version of this paper.

3 Step 2 – A Bibliometric Analysis

In the second step, the *Bibliometrix-R Package* [9] was used to perform a bibliometric analysis of the selected articles in the previous step. This enabled this research to derive the following information: (1) conceptual structure of the identified articles; (2) journal-specific information; (3) social structure of the published articles; and (4) historical trends of publications and citations.

3.1 Conceptual Structure

This paper conducted Multiple Correspondence Analysis (MCA) of the keywords to construct the conceptual structure map of research on quantitative analysis of construction productivity. Subsequently, K-mean clustering was performed to cluster the keywords obtained from MCA. More explicitly, MCA maps the keywords into a matrix by measuring their proximity [10] and K-mean clustering groups these keywords based on their degrees of similarity/dissimilarity [11]. Fig. 1 presents the conceptual structure map based on the keywords in the identified articles.

As shown in Fig. 1, MCA and K-mean clustering analyses generated two clusters. The first cluster occupies a region of the matrix enclosed in the blue polygon (in the online version), whereas the area enclosed in the red polygon (in the online version) represents the second cluster. From a methodological perspective, the first cluster highlights the use of surveys as a common quantitative method for productivity analysis. Further, regression analysis methods, including logistic regression modeling and linear regression analysis, play a crucial role in differentiating this cluster from the second cluster. From a scoping perspective, the articles in this cluster have addressed the association between risk management and productivity analysis of construction projects.

An explicit focus on data analysis is observed in the second cluster. More explicitly, this cluster signifies the use of automation, computer vision, and machine learning for building analytical models for productivity analysis. Further, this cluster positions the Malmquist Productivity Index as a common method used for productivity analysis of construction projects. An interesting observation from this cluster is that the analytical methods, as the key theme of this cluster, have been mainly adopted by authors from China.

3.2 Journal-Specific Information

The identified articles have been published in 40 different journals. Fig. 2 presents the top 10 most contributing journals publishing quantitative methods for productivity analysis of construction projects. As can be observed, *Journal of Construction Engineering and*

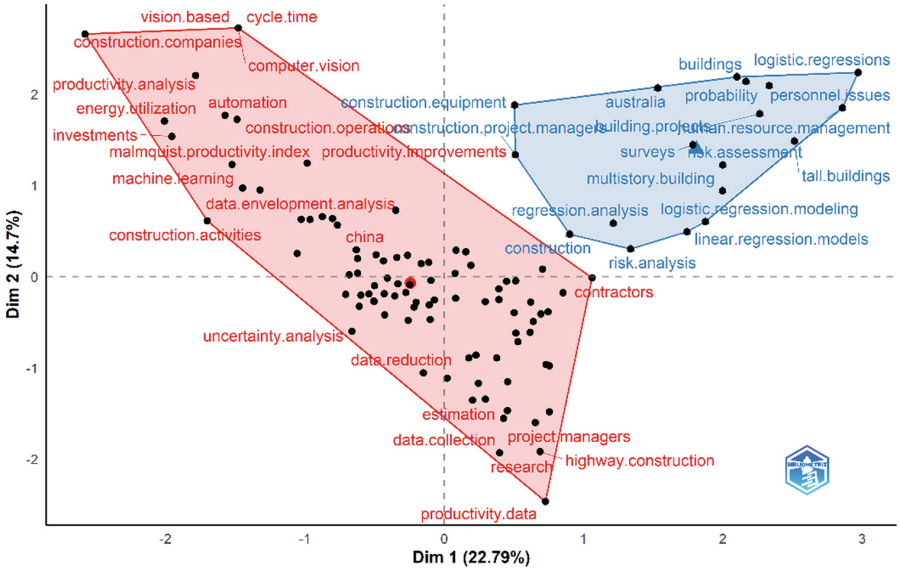

Fig. 1. Conceptual structure map of quantitative research in construction projects

Management is the most contributing journal with 26 articles out of 84 identified articles, followed by *Automation in Construction* (5 articles) and *Construction Management and Economics* (5 articles).

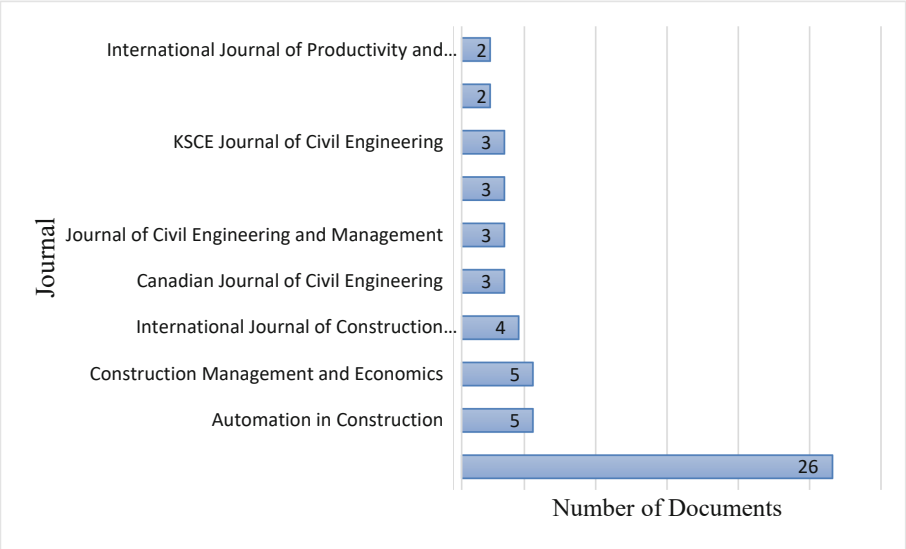

Fig. 2. Most contributing journals

Fig. 3 depicts cumulative annual publications for the top three productive journals. As can be seen from this figure, *Journal of Construction Engineering and Management* demonstrates considerable upward trends in publications of articles over time. Among the top three productive journals, *Journal of Construction Engineering and Management* is the first journal that published articles on the subject, starting from 1986, whereas *Construction Management and Economics* and *Automation in Construction* started publishing articles in 1988 and 2008, respectively.

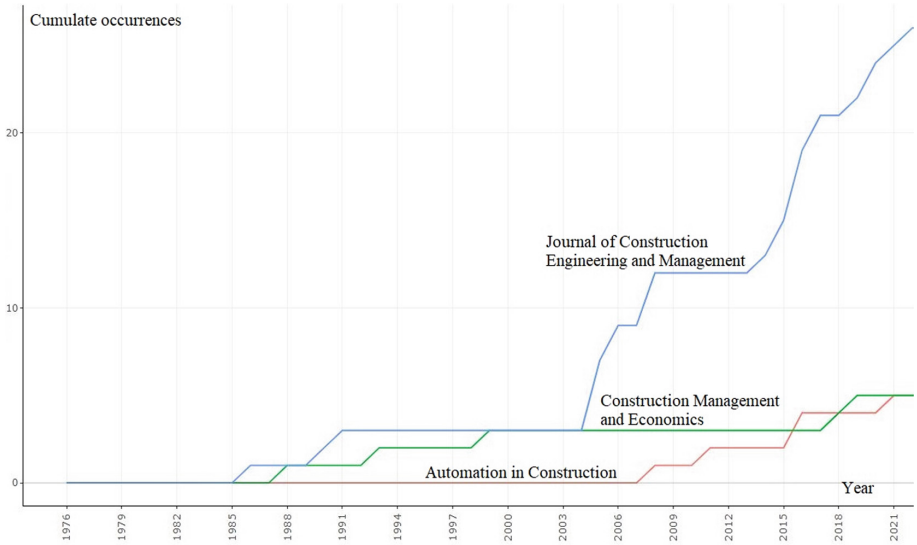

Fig. 3. Cumulative annual publications for the three leading journals

3.3 Social Structures

Fig. 4 presents the world map illustrating the productivity of countries in which dark blue implies high productivity, light blue denotes low productivity, and grey indicates zero publication. As can be observed, the United State with 53 publications is by far the most productive country, followed by South Korea (19 articles), Australia (15 articles), Iran (15 articles), Canada (15 articles), and China (13 articles). Surprisingly, European countries exhibit relatively low productivity, such that the United Kingdom with 2 articles, Lithuania, Sweden, and Turkey each with 1 article are the only European countries that contributed to the field.

Fig. 5 illustrates the frequency distribution of authors' productivity in which the dashed line represents Lotka's law. As can be seen from this figure, the authors' productivity pattern follows Lotka's law. Lotka's law is a widely accepted benchmark for estimating authors' productivity in various scientific fields. According to Lotka's law, the number of authors making n contributions is equal to $\frac{1}{n^2}$ [12]. In the database, 175 out of 202 authors have published only 1 article, whereas only 1 author has published 6 articles.

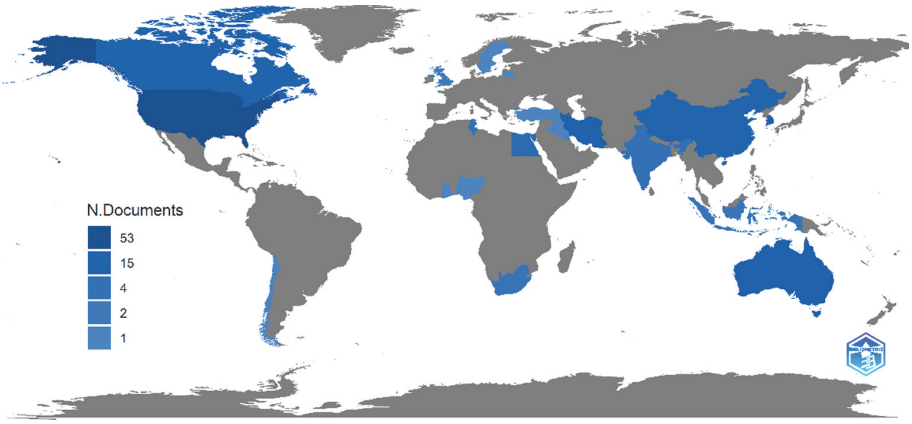

Fig. 4. Country-specific production

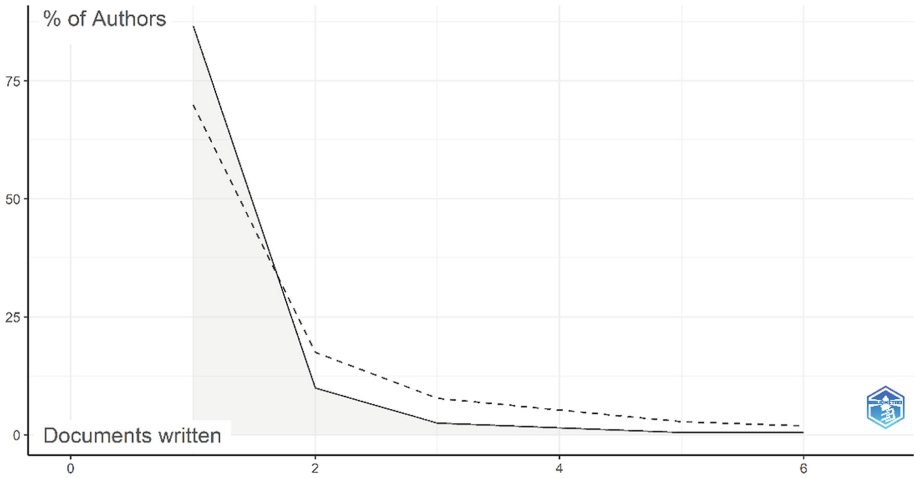

Fig. 5. The frequency distribution of authors' productivity (the solid line indicates the observed trend, whereas the dashed line represents Lotka's law)

3.4 Historical Trends of Publications and Citations

Fig. 6 presents the total number of published articles between 1976 and 2022. Examination of this figure reveals that the year 2016 is the most productive year in which 13% of identified articles (11 out of 84) were published. This figure shows a fall in the number of published articles in 2017. The yearly publications have not significantly fluctuated over the last 6 years. A number of 5 to 7 publications per year is observed in the previous 6 years starting from 2017 to 2022.

This paper employed the Reference Publication Year Spectroscopy (RPYS) method, developed by Marx et al. [13], so as to trace the historical roots of quantitative research on productivity analysis of construction projects. Fig. 7 graphs the RPYS of references

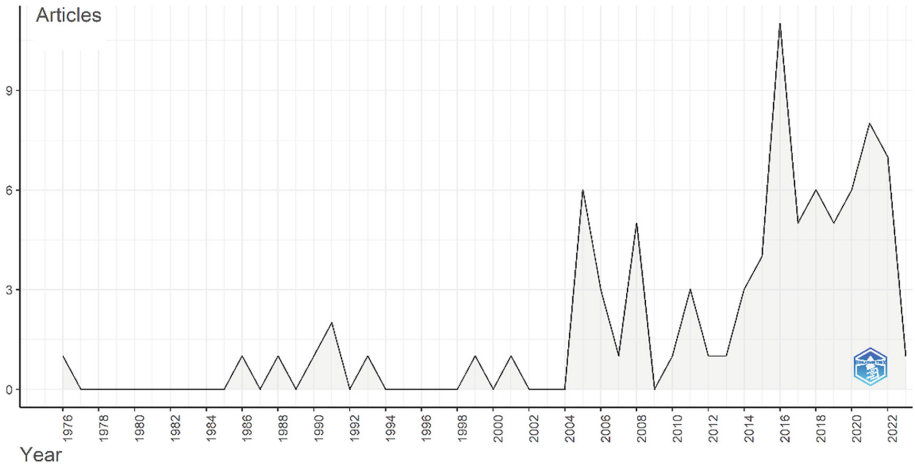

Fig. 6. Distribution of publications from 1976 to 2022

cited by the identified articles. In this figure, the black curve (the outer curve) illustrates the distribution of the number of articles cited from 1904 to 2022, whereas the red curve (the inner curve) indicates the deviation of the number of cited references in each year from the median of the number of cited references in a 5-year period, including the 2 previous, the current, and the 2 following years [13]. This figure shows a larger number of citations for the articles published from 2009 to 2014 than other articles. Clearly, low citations over the time period (2019–2022) is related to the fact that the recent papers have had less time to accumulate citations However, the pattern of lower citations in the time period (2015–2018) compared to the time period (2009–2014) is surprising, which indicates the existence of more seminal/influential articles published from 2009 to 2014.

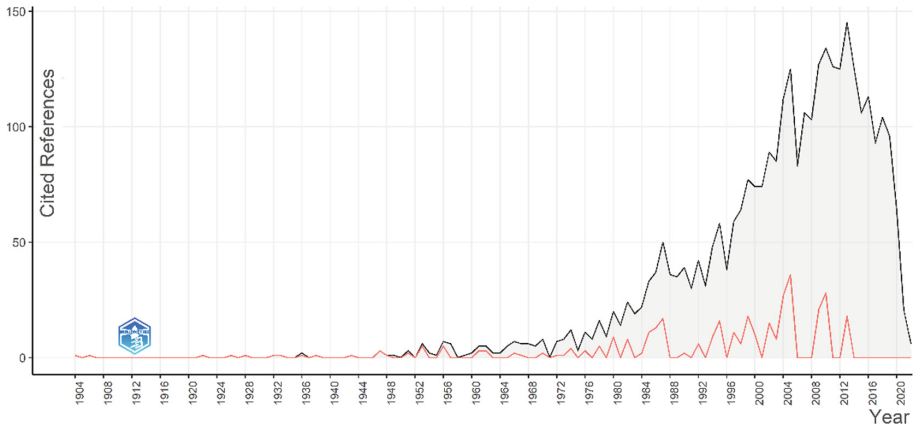

Fig. 7. The RPYS of references cited by the selected articles

4 The Roadmap for Future Research

Building on the emerging trends observed from the bibliometric analysis, this section suggests three directions as a roadmap for future research.

First, survey-based studies have gained more attention in the literature compared to other quantitative methods. While meaningful insights can be attained from survey-based research, the literature has identified several weaknesses of survey research including systematic method error, common method bias, and inability to capture causation from empirical data [14, 15]. These weaknesses question the validity of results obtained from surveys. Given the strengths of analytical methods, the applications of mathematical modeling, such as simulation analysis and optimization, in productivity analysis of construction projects are likely in the near term. Such methods enable eliminating bias and subjectivity associated with survey-based research.

Second, as Section 3.2 revealed, 31% of articles (26 out of 84) have been published in a specific journal: *Journal of Construction Engineering and Management*. Although the fields of construction management and operations research contain a wealth of journals, only one journal has been the main broadcast outlet for quantitative research on construction productivity. The dominance of one journal implies a low diversity of journals that are committed to publishing articles in this topic. One editorial strategy to evade this pitfall is to call for special issues targeted at quantitative research on productivity in construction projects.

Third, a relatively low number of articles published from 1976 to 2022 (84 articles) indicates that quantifying productivity (in particular, mathematical modeling) has not yet gone far enough compared to qualitative research on this topic. This can be attributed to the qualitative nature of courses in construction management education. Consequently, construction management graduates, as future researchers, face difficulty in understanding and applying mathematical modeling. This presents the need for universities, as the leading providers of research, to broaden the scope of their construction management courses to quantitative methods.

5 Concluding Remarks

This paper reviewed the state-of-the-art of quantitative research on productivity in construction projects. Further, by performing a bibliometric analysis, this paper drew attention to trends and the evolution of research on this topic. In this context, this research provided information about (1) conceptual structure of the identified articles; (2) most contributing journals to quantitative analysis of productivity in construction projects ; (3) country-specific productions as well as the frequency distribution of authors' productivity; and (4) historical trends of publications and citations. In addition, this paper suggested a roadmap for future research on quantifying productivity in construction projects.

This research is not exempt from limitations. It attempted to include all relevant journal papers, published from 1976 to 2022. However, this inclusion cannot be exhaustive since some papers might not have been listed in the database available for this research. This paper also excluded Master's theses, doctoral dissertations, textbooks and conference papers.

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The Identical Parallel Machine Scheduling Problem with Setups and Additional Resources

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Abstract. This paper studies a real world dedicated parallel machine scheduling problem with sequence dependent setups, different machine release dates and additional resources (PMSR). To solve this problem, two previously proposed models have been adapted and a novel objective function, the minimisation of the sum of the machine completion times, is proposed to reflect the real conditions of the manufacturing environment that motivates this work. One model follows the strip-packing approach and the other is time-indexed. The solutions obtained show that the new objective function provides a compact production schedule that allows the simultaneous minimisation of machine idle times and setup times. In conclusion, this study provides valuable insights into the effectiveness of different models for solving PMSR problems in real-world contexts and gives directions for future research in this area using complementary approaches such as matheuristics.

Keywords: Parallel machines · Scheduling · Setups · Additional Resources

1 Introduction

The study of Parallel Machine scheduling problems (PM) has mostly relied on machines as the primary resource, neglecting the fact that real manufacturing settings involve other critical resources such as automated guided vehicles, machine operators, tools, pallets, dies, and industrial robots [1–3]. The PM with sequence dependent setup times (PMS) where additional processing and setup resources are required (PMSR) is more complex. It involves sequencing and timing decisions and balancing multiple performance metrics. This study focuses on the injection moulding department of an automotive company that produces plastic injection moulded parts for final assembly plants with a maximum response time of 48 h. To solve this real problem, two existing models are adapted to the PMSR involving identical PM with different machine release dates, and a new objective function that minimises the sum of the completion times for each machine is proposed. This objective function provides a compact production schedule that allows the simultaneous minimisation of machine idle times and setup times for the specific case of dedicated PM with sequence dependent setup times. To the authors' knowledge, no existing research has explored the minimization of the sum of completion times for each machine as an objective function. This study provides valuable insights into the

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effectiveness of different models for solving this type of PMSR problem in real-world contexts.

2 Literature Review

In recent years, several papers have addressed the more general case of PMSP with setups and resources. Akyol Ozer et al. [4] studied the identical PMSP with sequence-dependent setup times, machine eligibility restrictions and multiple copies of shared resources. In this paper, the objective function was the minimization of the total weighted completion time. For small instances (8 jobs, 3 machines and 5 resources), a mixed integer linear programming model (MILP) obtained optimal solutions in almost all tests. For larger problems, a matheuristic consisting of a MILP and a Genetic Algorithm (GA) has been implemented, which provides solutions for up to 100 jobs, 8 machines and 50 resources. Bektur et al. [5] presented a MILP and two metaheuristics, Tabu Search (TS) and Simulated Annealing (SA), for the case of a team as a setup resource and the objective of minimizing the total weighted tardiness. MILP only gives optimal solutions for 2 machines and 10 jobs with a time limit of 7200 s. Regarding the metaheuristics, for up to 10 machines and 100 jobs, TS outperformed SA with an average relative deviation of 5.58%. Pinheiro et al. [6] propose a solution approach to the unrelated PMSP with family setups and resource constraints, to minimize the total tardiness of the jobs. The authors develop a MILP and two metaheuristics, SA and Iterated Greedy (IG). The MILP showed good performance for instances with up to 20 jobs and 6 machines, with a computational time limit of 3600 s. To address larger problems, a constructive heuristic was used to provide an initial solution, which was then improved by the metaheuristics. For instances with up to 50 jobs, the IG algorithm outperformed the SA algorithm, exhibiting lower relative deviation values. In fact, IG and SA algorithms have average relative deviations of 8.84% and 39.87%, respectively. The computational time required for the IG algorithm to provide a solution was also reported to be lower than the MILP model. Fanjul-Peyro [7] addressed the Unrelated PM with Setups and Resources (UPMSR), with three types of resources: specific for processing, specific for setup and shared. The authors presented two MILP models and a three-phase exact algorithm (TPhA) to improve the model's performance. Yepes-Borrero et al. [8] implemented a GRASP algorithm with the objective of minimizing makespan and in [9] have also proposed a multi-objective approach to minimise both the makespan and the number of setup resources, building on the previous work [7, 8]. An adaptation of the Restarted Iterated Pareto Greedy (RIPG) algorithm is proposed that gives solutions for up to 250 jobs and 30 machines. Zhang et al. [10] tackled the unrelated PMSP, with limited worker resources and learning effect. They proposed a Combinatorial Evolutionary Algorithm to minimize makespan and energy consumption. The algorithm can handle up to 400 jobs, 22 machines, and 10 resources. Lopez-Esteve, et al. [11] also developed GRASP algorithms to solve the unrelated PMSP with additional resources during processing and setups which gives solutions with a gap of 1.80% in relation to the Fanjul-Peyro [7]. Yunusoglu, et al. [12] proposed an exact model based on constraint programming (CP) to solve the multi-resource-constrained unrelated PMSP with sequence-dependent setup times. The objective was to minimize the makespan and release dates were incorporated

into the problem as operational constraints to reflect real-world manufacturing environments. The computational results indicate that the proposed CP model outperforms the best solutions of previous works with an average gap of 15.52%. Finally, Afzalirad, et al. [13] inspired on the block erection scheduling problem in a shipyard, studied the unrelated PMSP with resource constrains, sequence-dependent setup times, different release dates, machine eligibility and precedence constraints, to minimize the makespan. The results indicate that in the case of small-scale problems, both methods are efficient and effective, whereas in large-scale problems, the AIS approach statistically outperforms the GA approach.

3 Problem Formulation

3.1 Problem Description

We consider a parallel dedicated machine scheduling problem, where n jobs are processed on m machines, each job belonging to a family and processed on a single machine without preemption. A set of parts which use the same die is a family and a sequence dependent setup must be performed between jobs belonging to different families. Operators are required to process jobs and setup teams are required to perform the machine setups. Operators and setup teams are renewable and dynamic resources. The number of operators for each shift is known in advance, and the system must provide scheduling solutions at the start of each shift. The objective of the Injection Moulding Department is to meet the daily demand for parts within the constraints of capacity, and the availability of operators and setup teams, minimizing the maximum completion time for each machine.

3.2 Model Formulation

In this section we formally introduce the dedicated parallel machine with setups and resources. In this paper we use small letters to refer to parameters and capital letters to refer to variables. The sets of variables and parameters used are the following:

- A set of m machines that can process the jobs, denoted as $M = \{1, \ldots, m\}$, indexed by i.
- A set of $m + n$ jobs to be processed, $N = \{1, \ldots, m + n\}$, indexed by j, where the first m jobs represent the initial jobs on the respective machine number.
- p_j denotes the time required to process job j.
- s_{jk} denotes the time required to do the setup between jobs j and k.
- r^P_{max} are the maximum amount of processing resources. These are required specifically for processing jobs and cannot be used for setups. We denote these resources as P-resources.
- r^S_{max} are the maximum amount of machine setup resources. These are required specifically for machine setup and cannot be used for job processing. We denote these resources as S-resources.
- r^P_j are the resources of P-resources required to do processing of job j.
- r^S_j are the resources of S-resources required to do setup of job j.

- M is a sufficiently large constant.

As the machines are dedicated, the set of N jobs is divided into m subsets $(N_1, \ldots, N_m)$ so that the jobs in set N_i are only processed on machine i. Each machine has a dummy job (0) representing its start and end. Therefore, N_{i0}=$N_i \cup \{0\}$ represents the set of jobs which are to be processed on machine i plus the dummy job. Moreover, processing and setup times (p_j and s_{jk}), as well as the resources required for each operation (r_j^P and r_j^S) are deterministic. In this paper the UPMSR models based on strip-packing and indexed to time introduced by [7] are adapted to a real problem where the parallel machines are dedicated and have different release dates (the production system has an initial state), and a new objective function is proposed to minimize the sum of the machines completion times. The decision variables used are the following:

- $X_{ijk} = 1$ if job k is processed immediately after job j on machine i, zero otherwise.
- $Cmax_i$ is the completion time (minutes) of machine i.
- C_j is the completion time of job j (coordinate where processing of job j finishes in the time dimension) (minutes).
- B_j is the completion time of the setup before the processing of job j on the corresponding machine (coordinate where setup of job j finishes in the time dimension).
- $R_j^P \in [0, r_{max}^P]$ is the coordinate of processing of job j in the P-resources dimension (the specific resources employed in the processing of job j).
- $R_j^S \in [0, r_{max}^S]$ is the coordinate of setup of job j in the S-resources dimension (the specific resources employed in the setup before processing of job j).
- $D_{jk}^P, E_{jk}^P, F_{jk}^S\ G_{jk}^S$ are binary auxiliary variables with value = 1 when the variable value studied in constraints (time or resources) of job k is higher than the variable value studied (time or resources) of job j. The letters in superscript are used to indicate the dimension where they are used.

The MILP strip-packing model is:

$$Min\ Z = \sum_{i \in M} C\,max_i \tag{1}$$

$$X_{i0i} = 1, i \in M \tag{2}$$

$$\sum_{j \in N_i, j \neq k} X_{ijk} = 1, i \in M, k \in N_i \backslash \{i\} \tag{3}$$

$$\sum_{j \in N_{i0} \backslash \{i\}, j \neq k} X_{ikj} = 1, i \in M, k \in N_i \tag{4}$$

$$C_k - C_j + M\left(1 - X_{ijk}\right) \geq s_{jk} + p_k, i \in M, j \in N_i, k \in N_i \backslash \{i\}, j \neq k \tag{5}$$

$$C_k \geq \sum_{j \in N_{i0}, j \neq k, s_{jk} > 0} X_{ijk} s_{jk} + p_k, k \in N_i \backslash \{i\}, i \in M \tag{6}$$

$$C_i \geq p_i, i \in M \tag{7}$$

$$Cmax_i \geq C_k, i \in M, k \in N_i \tag{8}$$

$$B_k - C_j + M\left(1 - X_{ijk}\right) \geq s_{jk}, i \in M, j \in N_i, k \in N_i \backslash \{i\}, j \neq k, s_{jk} > 0 \tag{9}$$

$$B_k \leq C_k - p_k, k \in N \tag{10}$$

$$r^P_{max} \geq R^P_k, k \in N \tag{11}$$

$$R^P_k \geq r^p_k, k \in N \tag{12}$$

$$r^S_{max} \geq R^S_k, k \in N \tag{13}$$

$$R^S_k \geq r^S_k, k \in N \tag{14}$$

$$C_k - C_j + M\left(1 - D^P_{jk}\right) \geq p_k, i, q \in M, q \neq i, j \in N_i, k \in N_q \tag{15}$$

$$R^P_k - R^P_j + M\left(1 - E^P_{jk}\right) \geq r^P_k, i, q \in M, q \neq i, j \in N_i, k \in N_q \tag{16}$$

$$D^P_{jk} + D^P_{kj} + E^P_{jk} + E^P_{kj} \geq 1, i, q \in M, q \neq i, j \in N_i, k \in N_q, j \neq k \tag{17}$$

$$B_k - B_j + M\left(1 - F^S_{jk}\right) \geq \sum_{l \in N_{q0}, l \neq k, s_{lk} \geq 0} X_{qlk} s_{lk}, i, q \in M, q \neq i, j \in N_i, k \in N_q \tag{18}$$

$$R^S_k - R^S_j + M\left(1 - G^S_{jk}\right) \geq r^S_k, i, q \in M, q \neq i, j \in N_i, k \in N_q \tag{19}$$

$$F^S_{jk} + F^S_{kj} + G^S_{jk} + G^S_{kj} \geq 1, i, q \in M, q \neq i, j \in N_i, k \in N_q \tag{20}$$

$$X_{ijk} \in \{0, 1\}, Y \geq 0, C_k \geq 0, B_k \geq 0j, k \in N_i, i \in M \tag{21}$$

The objective function (1) minimizes the sum of maximum completion time for each machine. Constraints (2) ensure that the initial jobs are the first to be processed immediately after the dummy jobs on each machine. The constraints (3) and (4) make sure that only one job is processed immediately before and only one job is processed immediately after each job. Constraints (5) break subtours and give the right scheduling order, because if k is processed after j on machine i, it forces finishing the processing of job k not earlier than s_{jk} $+p_k$. . Constraints (6) set the lower limit of completion time of job k (C_k) to be greater or equal than the sum of its setup plus its processing time while constraints (7) do the same for the initial jobs. Constraints (8) establish the relationship between $Cmax_i$ of machine i and the completion times of jobs on that machine. Constraints (9) force that, if job j is the previous job done before job k on machine i, the finishing time of setup k must be later than the finishing time of processing

of job j plus setup time of job k. Constraints (10) ensure that setup finishing time of job k is earlier than processing starting time of job k. Constraints (11)–(14) set the coordinate limits of specific resources used in processing (R_k^P) and used specifically in setups (R_k^S). Constraints (15) show that, if C_k is later than C_j, the difference between these completion times is greater than or equal to the processing time of job k. In (16) if R_k^P is greater than R_j^P, the difference between coordinates of these resource points is greater than or equal to the resources used in the job k processing. Constraints (17) force at least one of the binary variables to have the value of 1. Constraints (18) show that, if B_k is later than B_j, the difference between these setup finishing times is greater than or equal to the setup time of job k. In (19) if R_k^S is greater than R_j^S, the difference between coordinates of these resource points is greater than or equal to the resources used in the job k setup. Constraints (20) force at least one of the binary variables to have the value of 1. Finally, constraints (21) set the limits of the variables. In this model, in addition to several simplifications of the original model, the objective function (1) and the constraints (2) are new to reflect the specific conditions of the real problem. The MILP model indexed to time is:

- $E_{ikt} = 1$ if k is being processed on machine i in time t, zero otherwise.
- $F_{ijkt} = 1$ if k is in setup after job j on machine i in time t, zero otherwise.
- t_{max} is the planning horizon.

E_{ikt} and F_{ijkt} are decision variables and t_{max} is a parameter. For this MILP we use Eqs. (1)–(10) and (21). The other constraints are:

$$\sum_{t \le t_{max}} E_{ikt} \ge p_k, i \in M, k \in N_i \tag{22}$$

$$C_k \ge tE_{ikt}, i \in M, k \in N_i, t \le t_{max} \tag{23}$$

$$C_k + 1 - p_k \le tE_{ikt} + M(1 - E_{ikt}), i \in M, k \in N_i, t \le t_{max} \tag{24}$$

$$\sum_{t \le t_{max}} F_{ijkt} \ge s_{jk} X_{ijk}, i \in M, j \in N_i, k \in N_i, j \ne k, s_{jk} > 0, k \ge m \tag{25}$$

$$B_k \ge \sum_{j \in N_i, j \ne k} tF_{ijkt}, i \in M, k \in N_i, t \le t_{max}, s_{jk} > 0, k \ge m \tag{26}$$

$$\begin{aligned} B_k + 1 - \sum_{j \in N_i, j \ne k, s_{jk} > 0} s_{jk} X_{ijk} \le \sum_{j \in N_i, j \ne k, s_{jk} > 0} tF_{ijkt} + \\ M\left(1 - \sum_{j \in N_i, j \ne k, s_{jk} > 0} F_{ijkt}\right), \ i \in M, \ k \in N_i, \ t \le t_{\max} \end{aligned} \tag{27}$$

$$R_{max}^P \ge \sum_{i \in M, k \in N_i} r_k^P E_{ikt}, t \le t_{max} \tag{28}$$

$$R_{max}^S \ge \sum_{i \in M, j, k \in N_i, j \ne k, s_{jk} > 0} r_k^S F_{ijkt}, t \le t_{max} \tag{29}$$

Constraints (21) and (22) work together to ensure that the E_{ikt} variable is only 1 for the exact duration of time that job k is being processed on machine i. This prevents

unnecessary idle time on the machine and ensures that each job is processed for the minimum amount of time necessary to complete it. Constraints (23) complements these constraints by requiring that when E_{ikt} is equal to 1, the current time t must be greater than or equal to the completion time of job k minus its processing time plus 1. Constraints (24)–(26) represent the same for setups, where the time considered is the setup time. Constraints (27) ensures that the sum of all resources used in processing at each instant t is less than or equal to the maximum number of resources available for processing. Constraints (28) ensures the same for setups.

4 Computational Experiments

To generate the instances, the number of jobs, number of machines, processing and setup times, number of setup teams, number of operators available, and their use by jobs were defined based on the real data from the company, and the time is in minutes. The sets of problems, small, medium, and large, are presented in Table 1. For each of the sets, 10 instances were randomly generated using processing and setup times generated from distributions of $U(20,240)$, and $U(30,50)$, respectively, and the number of operators to support the processing of jobs on the machines generated from the distribution of $U(1,4)$. Setup times must satisfy the triangular inequality. The setups require a setup team. For the time indexed model, t_{max} was set to 480 min (one shift).

Table 1. Sets of test instances

Instance	Machines	Jobs	Operators	Setup Teams
Small	4	12	8	1
Medium	8	24	16	2
Large	16	40	30	2

The CPLEX 22.1.1.0 solver was used, with programming done in Python using the Pulp library on Microsoft Visual Studio Code 2023 IDE. The computational tests were executed on an Intel Core i7-85654 CPU1.80 GHz, with 8.00 GB of RAM. To ensure reasonable runtimes, a time limit of 1800 s was set. Throughout the computational study, the indicators analysed were the gap to the optimum solution, the percentage of optimal solutions obtained, and the computation time. The performance of two models, strip-packing and time-indexed, was analysed and the average results for each set of instances are presented in Table 2. For medium and large cases, only the results for the strip-packing model are presented, as the time-index model could not find a solution within the time limit. The strip-packing model gives good results for the small and medium instances, and for the large instances it could always find a feasible solution with and average gap of 14.09%. In contrast, the time-indexed model can only solve small problems.

Table 2. Comparison between strip-packing and time-indexed models

	Strip-packing			Time-indexed		
Instance	%Gap	%Opt	Time (s)	%Gap	%Opt	Time (s)
Small	0.00	100	0.91	5.6	60	1800
Medium	2.15	40	984.05	–	–	–
Large	14.09	0	1800	–	–	–

5 Conclusions and Future Research

This paper studies the special case of PMSR. To solve this problem, two previously proposed models have been adapted and a novel objective function, the minimisation of the sum of the machine completion times, is proposed to reflect the real conditions of the manufacturing environment that motivates this work. Overall, the strip-packing model outperforms the time-indexed model in solving this type of PMSR problem and shows a good potential for solving real-world problems and for future research in this area. The solutions obtained show that the new objective function provides a compact production schedule that allows the simultaneous minimisation of machine idle times and setup times for the PMSR with identical parallel machines with different release dates. To further enhance the performance of the strip-packing model, complementary approaches such as matheuristics can be explored. Matheuristics combine the strengths of mathematical programming and metaheuristics to provide a hybrid optimization approach that can efficiently solve complex problems.

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Enhancing Efficiency in the Maritime Industry Through Lean Practices: A Critical Literature Review of Benefits and Barriers

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Abstract. The maritime industry is an important sector of the world economy, facing many challenges. Lean tools can have a significant impact on reducing waste, time and costs, and increasing efficiency. This paper aims to identify and categorise the different lean practices implemented in the maritime industry and the main barriers and benefits of their implementation through a systematic literature review. This categorisation is intended to improve the understanding of lean practices and their benefits and to contribute to the decision making of stakeholders for their implementation. The analysis of the selected articles suggests that the implementation of these practices is effective in the context of the maritime industry, having as main benefits the increase of efficiency, and cost reduction. It was also possible to see that the vast majority of studies do not specify the lean tools used. The lack of knowledge, know-how, training of workers, and the lack of management involvement were identified as the main barriers to the implementation of these initiatives. However, further research is needed in this industry, namely in quantifying the impacts and identifying best practices for the implementation of these initiatives.

Keywords: Lean manufacturing · Maritime Industry · Supply Chain · Ports

1 Introduction

The urgent need to fully decarbonize international maritime transport by 2050 to meet the 1.5 °C target established in the Paris Agreement requires immediate action [1]. Targets of zero greenhouse gas (GHG) emissions by 2050 are being adopted by countries worldwide. The global maritime transport industry is also evaluating the feasibility of increasing its current target of 50% reduction by 2050, agreed upon by the International Maritime Organization, to 100% [2]. Several large international maritime companies

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have already pledged to achieve carbon neutrality by 2050 or earlier. Several technologies, tools and methods are used to achieve this goal. Lean manufacturing is one of them [3].

Lean manufacturing is a systematic approach aimed at eliminating waste in manufacturing processes. This approach has not only challenged mass production practices in the automotive industry but also sparked a reassessment of various manufacturing and service operations [4]. Lean principles have been extensively studied and implemented in academia and various sectors. The first book to examine these principles was authored by Womack et al. in 1990, and has become one of the most frequently cited references in operations management [5]. A fundamental principle of Lean is just-in-time (JIT) production, which aims to achieve optimal production flow by eliminating inventory and simplifying product design to focus on customer-valued features [6].

Lean manufacturing is a philosophy that seeks to minimize lead times in production processes. The lead time encompasses not only the production process itself but also waiting times between individual processes and during storage. It is generally recognized that lead time and productivity are closely related; reducing lead time leads to increased productivity. High product quality, low costs, and increased flexibility are other key benefits of Lean manufacturing [7].

Although there is a myriad of studies about the application of lean and the consequent advantages for companies of its application [e.g. 8, 9], the characteristics of the maritime industry justify its differentiated study. One of the obstacles to the effective implementation of lean tools is the inexistence of a systematic identification and characterisation of the different lean practices and the advantages that come from its implementation [10]. Although there are studies that already answer some of this need [11–13], either by limitation to a methodology (Lean Six Sigma) [11], or by restriction to only one implementation unit (supply chain) [12], they do not give a complete answer. Thus, this study aims to identify and categorize the different lean practices implemented in the maritime industry, i.e., ports, supply chain, logistics, shipping industry and maritime/shipping operations, through a systematic literature review. Furthermore, it is intended to provide an overview about the implementation of these practices, namely the reasons that lead to their implementation, the existing barriers, and the various benefits that this practice provides. The aim of this categorisation is to improve the understanding of lean practices and their benefits and to contribute to the stakeholders' decision making for their implementation. The study also aims to provide a basis for the identification of research gaps, and to indicate future paths, not only in terms of implementation units, but also in tools to be used. This study is organised as follows: Sect. 2 outlines the review methodology used; in Sect. 3 the results obtained through the systematic literature review are presented and discussed; and finally in Sect. 4 the main conclusions are presented, and future research opportunities are pointed out.

2 Methodology

The present review was conducted by researching articles relevant to the area of the application of Lean practices in the maritime industry. For this, the Scopus academic database was used. A structured search string with several keywords was used to cover

as many studies as possible. Thus, the complete search string used was: (Maritime OR Marine OR Naval OR Port OR Vessel) AND Lean Manufacturing. The searches produced 2599 documents. To broaden the search, several combinations of "Maritime keywords" with some Lean tools, such as, DMAIC, Kaizen, 5S, VSM, among others, were also used. The publications considered for the study were journal articles, conference papers, and book chapters. No time limit was imposed and articles that were not written in English were excluded. The articles were then screened. Thus, titles, keywords and abstracts were read to assess the relevance of the article for the purposes of the study. The inclusion and exclusion criteria were as follows: i) focus on the shipping industry (e.g., supply chain, logistics, ports) and not shipbuilding; and ii) application of lean tools in the maritime industry and not just as an example or different contexts (the word lean has different meanings and many of the studies found were not related to this practice). If any doubts remained as to the inclusion of the publications, a more detailed analysis of the article was carried out. Thus, the list was reduced to 16 publications, on which a more detailed review was focused.

3 Results and Discussion

3.1 General Research Trends

The results reported in this section assess the existing literature based on the annual evolution, the type of publication, and its distribution across the journals, publishers and implementation units considered. Figure 1 illustrates the annual distribution of the 16 selected publications according to the unit of implementation of lean practices: Maritime/Shipping Operations, Shipping Industry, Logistics, Supply Chain, and Port. The consideration of different units is directly related to the scope of application of the lean tools considered in the different studies. Although all are related to shipping, the scope of activities involved in the application of lean tools is different. Hence the need to group the studies into different units.

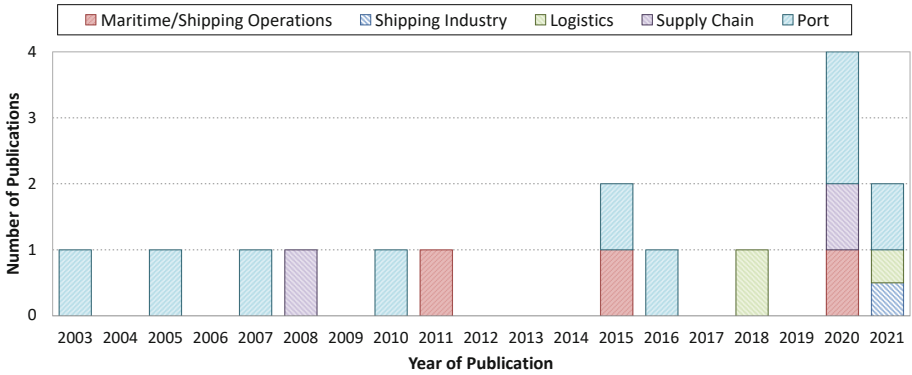

Fig. 1. Temporal distribution of the number of publications by implementation unit.

According to Fig. 1 it is possible to verify that although the time span is high, the number of articles over the years has been reduced. The highest number of publications

was recorded in 2020, representing 25% of the total. Although in 2021, the number of publications is still significant, compared to the distribution of the other years, in 2022 there was no article published. However, this does not mean that the topic does not have attention from academia. Considering articles of application of lean tools in shipbuilding, the scenario is different, verifying an increasing number of publications, mainly after 2020.

In terms of the distribution of publications by implementation unit, ports are those with the most studies (9), representing approximately 53% of the total. This is followed by Maritime/Shipping Operations with 18%, Logistics and Supply chain, both with 12% and finally Shipping Industry with only one publication, 6%. In terms of article type, case studies represent the majority (12 publications), approximately 75% of the total, followed by studies of a theoretical nature (theoretical and conceptual articles, as well as those using models from mathematical functions, i.e., modelling and simulations) with 19% and only one review article. Concerning the type of publication, 75% are research papers, 19% are conference papers and only 1 is a review article, 6%.

Regarding editorial sources, 12 publishers, 13 scientific journals and two conference proceedings books were identified. Emerald is the main publisher, which published 4 of the 16 studies considered. It is followed by Elsevier with 2, and the others with only one publication each. Regarding journals, the International Journal of Lean Six Sigma, is the main one, with 2 publications. It is relevant to note that 12 of the 13 journals published only one article.

3.2 Studies on the Application of Lean in the Maritime Industry

Table 1 provides an overview about the implementation of lean in the maritime industry, namely the location of the implementation unit, the lean tools used, the reasons that led to its implementation, the existing barriers, and the various benefits that this practice provided. Analysis of the data in Table 1 reveals that the majority of studies (10 out of 17) refer to the application of lean or six sigma, without specifying the tool used, as illustrated in Fig. 2. The most common tools identified in the review were DMAIC and VSM, reported in 5 and 4 studies, respectively. These are followed by SIPOC and Ishikawa Diagram, reported in 2 studies each. All others are only referenced in a single study. In terms of diversity of tools used, ports clearly stand out from the other implementation units. However, this is mainly due to two studies [14, 15] where the number of tools applied was clearly diversified.

As mentioned above, studies of lean implementation in ports are the predominant ones, representing about 53% of the total publications. This fact may be related to the importance that ports have for economic development, in that approximately 80% of the volume of international trade in goods is transported by sea [28]. In addition, they also promote economic globalisation by linking distant production clusters and consumer markets [29]. As for the location of the implementation units, the majority are located in Asia, representing 50% of the total number of studies, followed by Europe with 30% and South and North America with 10% each.

The most frequently mentioned reasons for implementing lean practices are related to increasing efficiency, reducing costs, and increasing productivity. The reduction of waste is also frequently mentioned, mainly related to non-productive time. However,

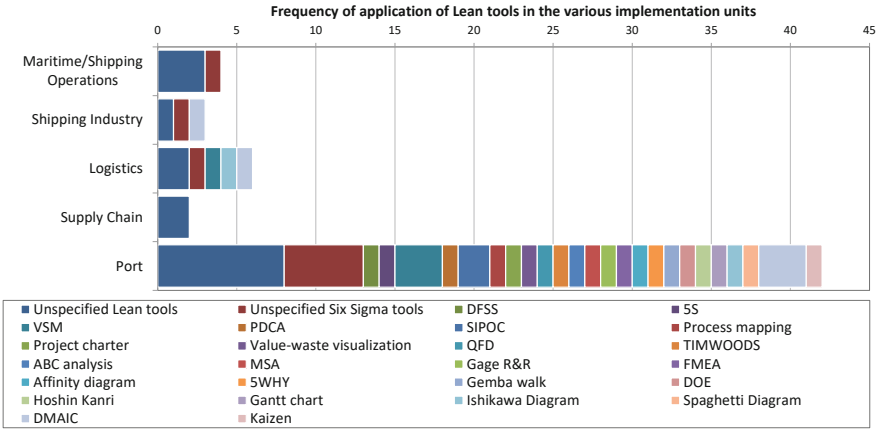

Fig. 2. Frequency of application of Lean tools several units identified in the literature.

some studies mention the lack of knowledge, know-how and training of workers and the lack of management involvement as the main barriers. Also, the characteristics of the process, namely the existence of long cycles and high complexity are pointed out as barriers to the implementation of lean practices.

Twenty-two different benefits were reported from the studies conducted. Those related to increased efficiency, cost reduction, and time are predominant in the studies, representing 23%, 18% and 14% respectively. It should be noted that the main benefits are related to the main motivations that lead the maritime industry to implement lean tools. It should also be noted that most of the studies (82%) presented in Table 1 only refer to the benefits of the application of lean tools in the maritime industry, without quantifying the impacts of the application of these measures. To encourage and disseminate these practices, it is essential that companies feel motivated to do so and knowing the real impacts of the implementation of lean can be a highly persuasive factor.

Regarding cost reduction and optimisation of the system, which are the great advantages of the application of lean, it should be noted that in the case of maritime transport, it is essential to ensure that this reduction does not put at risk the transport of certain goods or expose the capacity of the system to vulnerabilities. One of the examples studied that refers to this compromise between cost reduction and system vulnerability was that carried out by Berle et al. [30] on the transport of natural gas.

Table 1. Studies regarding the implementation of lean practices in the maritime industry.

Unit of Implementation	Location	Lean Tools	Reasons for Implementation	Barriers to Lean Implementation	Impact on Performance	Refs.
Maritime operations	Singapore	Unspecified Lean Tools	Reducing costs and improve the level of manufacturing quality, and increase operational efficiency	Lack of knowledge, skills, and the know-how to implement lean manufacturing; lack of understanding of the key benefits of lean manufacturing; lack of management involvement; lack of empowerment of employees; and inability to engage and support the workforce in achieving and maintaining a lean improvement culture	N/A	[16]
Shipping operations	Møre, North-Western Norway	Unspecified Lean Tools	Increase the competitiveness, output and productivity	Long and complex production cycles, modifications or rewriting of specifications due to premature sales and frequent changes of supplies, little regard by sales and marketing departments for production capacity	N/A	[17]

(*continued*)

Table 1. (*continued*)

Unit of Implementation	Location	Lean Tools	Reasons for Implementation	Barriers to Lean Implementation	Impact on Performance	Refs.
Maritime operations	N/A	Unspecified Lean and Six Sigma Tools	Operational efficiency, reduction of environmental waste, reduction of energy consumption, dwindling international fares, and raised environmental awareness	N/A	N/A	[18]
Shipping industry	Indonesia	Unspecified Lean and Six Sigma Tools; and Define, Measure, Analyse, Improve, Control (DMAIC)	Delayed loading and unloading of cargo, unnecessary transportation or movement, lack of standardization in the working procedure and in the departments, lack of customer focus/miscommunication, and underutilized of existing resources	N/A	N/A	[11]
Logistics	Indonesia	Unspecified Lean and Six Sigma Tools, and DMAIC	Overproduction, delivery delays, unnecessary transport or travel, lack of standardisation, lack of customer's focus, miscommunication, and under-utilised resources	N/A	N/A	[11]

(*continued*)

Table 1. (*continued*)

Unit of Implementation	Location	Lean Tools	Reasons for Implementation	Barriers to Lean Implementation	Impact on Performance	Refs.
Logistics	N/A	Unspecified Lean Tools, Cause and Effect Diagram/Ishikawa diagram, and Value Stream Mapping (VSM)	Reduce logistics between subsequent production facilities, and minimise production costs per product	N/A	Reduction of production costs	[19]
Supply chain	N/A	Unspecified Lean Tools	N/A	N/A	Benefits in the engineer-to-order environment, improved supply chain management, and contribution to supply chain sustainability	[12]
Supply chain	United Kingdom	Unspecified Lean Tools	Product cost and supplier delivery performance	N/A	N/A	[20]
Port	India	Unspecified Lean and Six sigma Tools, and VSM	High dwell time at container terminals (waiting), high overall container handling time, and container congestion linked to smooth process flow	N/A	Increased efficiency of the process cycle	[21]

(*continued*)

Table 1. (*continued*)

Unit of Implementation	Location	Lean Tools	Reasons for Implementation	Barriers to Lean Implementation	Impact on Performance	Refs.
Port	Santos, Brazil	Unspecified Lean and Six Sigma Tools, DMAIC, and Kaizen	Reduction of process time, and minimisation of costs in logistics	N/A	Cost reduction	[22]
Port	Houston, United States of America	Unspecified Lean and Six Sigma Tools; DMAIC; Plan, Do, Check, Act (PDCA); VSM; Suppliers, Inputs, Process, Outputs and Customer (SIPOC); Process mapping; Quality Function Deployment (QFD); Value-waste visualization; TIMWOODS; ABC analysis; Measurement System Analysis (MSA); Gage R&R; Failure Modes and Effects Analysis (FMEA); Design For Six Sigma (DFSS); 5Why; 5S; Gemba walk; Affinity diagram; Design of Experiments (DOE); Hoshin Kanri; and Gantt chart	High waiting times, and improve the efficiency of the port	High process complexity, loose planning and scheduling, lack of a common measurement system, and lack of a central authority that coordinates all stakeholder activities	N/A	[14]

(*continued*)

Table 1. (*continued*)

Unit of Implementation	Location	Lean Tools	Reasons for Implementation	Barriers to Lean Implementation	Impact on Performance	Refs.
Port	Sultanate, Oman	Unspecified Lean and Six Sigma Tools; DMAIC; Project charter; SIPOC; VSM; Ishikawa diagram; and Spaghetti diagram	Reduction of the ship loading commercial time, improve ship loading operations, increase customer satisfaction, and avoid demurrage charges for exceeding agreed loading times	N/A	Improved ship loading process capacity, improved loading commercial time, operational savings, and increased loading productivity	[15]
Port	Saint-Nazaire, Nantes, France	Unspecified Lean Tools	Existence of waste in the use of port information systems, lack of flexibility in information systems design, duplication of data and need to re-enter information, high cost of using information systems, the training time to master the information systems, lack of suitability of several information systems bulk carrier sector, and loss of productivity	N/A	Flexibility of port information systems	[23]
Port	Marmara, Turkey	Unspecified Lean Tools	Insufficient capacity in terms of infrastructure, superstructure, equipment, etc., for transit cargoes	N/A	N/A	[24]

(*continued*)

Table 1. (*continued*)

Unit of Implementation	Location	Lean Tools	Reasons for Implementation	Barriers to Lean Implementation	Impact on Performance	Refs.
Port		Unspecified Six Sigma Tools	Improving or maintaining the efficiency of port operations	N/A	Improving the quality of port security measures, increasing customer satisfaction, and increasing the efficiency of port operations	[25]
Port		Unspecified Lean Tools	Improve overall efficiency, need to optimise resources, and increase productivity	N/A	N/A	[26]
Port		Unspecified Lean Tools	Overcoming ports' poor timeliness and reliability	N/A	Easy identification of any form of waste, defect or bottleneck; increased effectiveness and efficiency of operations; reductions in lead-times, cycle-times, capital requirements, and inventory; reduction of operations and maintenance costs; and increased quality	[27]

4 Conclusions and Future Research Perspectives

This paper proposes a literature review to identify and categorise the different lean practices implemented in the maritime industry and provide an overview about the implementation of these practices. It is expected that with this categorisation, to improve the understanding of lean practices and their benefits and to contribute to stakeholders' decision making for their implementation. From the analysis of the articles, it was possible to conclude that: (1) most studies concern ports (53% of the total); (2) 59% do not specify the lean tool used in the study; (3) 24 lean tools were used; (4) the most common tools implemented were DMAIC and VSM; (5) the most frequently evoked reasons for implementing lean practices are related to increased efficiency, cost reduction, and increased productivity; (6) the main barriers to its implementation are the lack of knowledge, know-how, workers' training, and lack of management involvement; (7) the main benefits are the increase in efficiency, cost and time reduction; and (8) 82% of the studies do not quantify the benefits.

Although there are some specific publications on the application of lean practices in the maritime industry, more studies are needed, not only on best practices for the implementation of lean, but also on how to overcome the barriers that affect this implementation, given the specificities of the sector. Besides this, further research on the quantification of impacts and the extension of the study to other dimensions, such as environmental, would be important for the extension of the application of lean.

In addition, in-depth studies of new theories and practices could be conducted to address the growing demand for increased competitiveness and efficiency in the maritime industry. One of the ways that has been studied with clear advantages in these matters is lean, agile, resilient, and green practices [e.g. 31, 32]. However, given the specificity of the sector, concrete studies of the application of these practices to the maritime industry are needed, namely their integration, the drivers and the challenges involved in their application. Furthermore, it would also be interesting in future work to address the impact that digitalisation has on the development of lean in the maritime industry, as studies have proven its importance as an enabler for lean and lean-green [9].

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Lean Agile's Contributions to Automotive Industry

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Abstract. The automotive industry deals with complex processes. Becoming aware of the importance of agile management they are contributing to a creative fusion known as "*leagile*". However, this concept needs further study and investigation. This work presents a systematic literature review on Lean Agile implementation in the automotive industry. Thirty-three publications were reviewed and characterized according to the year of publication, country of origin, industrial sector, used tools and their contributions to the automotive sector. The results show that 50% of the articles were published after 2018. The countries with the most publications are India, Portugal, and United Kingdom. The most cited tools are Value Stream Mapping (VSM), Just in Time (JIT) and 5S (23%). This study confirms the growing use of "*leagile*" in the automotive industry and the growing potential for research development in the area.

Keywords: Lean Agile · Automotive Industry · Continuous Improvement

1 Introduction

The automotive industry is an important sector of the world economy. Its mass production has a great contribution to technological advances and equally brings complex challenges [1]. Thus, the great pressure to generate better products has made it increasingly important to obtain competitive advantages within the volatile, uncertain, complex, and ambiguous market that exists today [1, 2]. To this end, lean manufacturing was used in the automotive industry with the goal of ensuring lean processes. Nevertheless, it revealed to have a lack of tools to direct it towards greater agility [3]. Agile process management act precisely on this gap.

Given how complex automotive manufacturing can be, lean management emerged in the industry to make production systems more efficient, while agile methodology emerged to speed up this process [4]. By implementing agility, it is possible to plan

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and develop prototypes, which are first tested before investing in the final product [3]. Thus, the Lean Agile philosophy emerged, enabling a new contribution to continuous improvement and achievements of organizational goals through a variety of lean tools together with Agile [3, 5].

It is possible to find extensive literature on the application of agile methodologies in the information technology (IT) area. However, few scientific literature regarding lean agile methodology in the manufacturing sector, and in particular regarding the application of lean agile in the automotive industry exits. Thus, this was the main motivation and novelty of this work. This study focused on this literature gap, seeking to define and characterize the contribution of lean agile in the automotive industry by collecting data from existing scientific works.

The implementation of lean and agile practices in the automotive industry benefits companies, customers, and the economy, while reducing negative impacts [4]. There are, however, many implementation challenges. As an example, the authors noticed that although conceptual and empirical studies on lean and agile proliferate, most of the studies show that industries almost implement lean or agile approaches separately, and not simultaneously [6–9]. Lean and Agile approaches have distinct but efficient advantages. The association of both principles – *leagile* – highlights all non-value activities to minimize costs, while agile gives celerity to the process, allowing to absorb market opportunities in a timely manner [9]. Thus, Lean Agile is a combination of the Lean philosophy with the Agile methodology that combines elements of both and consequently the value added of the product increases [10]. The first applications of combining both methodologies were implemented in IT companies [4, 5] and demonstrated an enormous potential for implementation within other scenarios, such as in the automotive industry.

Given the relevance of this topic, and to better characterize the studies and map the state of the art on the application of lean and agile in the automotive industry, the purpose of this work is to present a systematic literature review that covers the application of Lean and Agile in the automotive industry. In particular, this paper aims to answer the following research questions: Should automotive industries implement lean agile? What is the chronological history of lean agile implementation in the automotive industry since 2001? Which countries have more industries with lean agile implemented? Which are the most used tools and industries with lean agile implemented? What are the main contributions to the automotive industry?

This paper is organized as follows: Sect. 2 specifies the methodological procedures for selecting the articles and the aspects of classification and the analysis of the studies. Section 3 presents the discussion and the results of the synthesized relevant literature. In Sect. 4, some opportunities for further studies are identified, and finally, Sect. 5 presents the conclusion and the main contributions of this study.

2 Methodological Procedures

A systematic literature review aims, by defining keywords, to map and assess the state of the art to identify mainly potential research gaps. The limits of knowledge should be described after searching the literature and completing the review [10]. It is a replicable, scientific, and transparent six-step process used for data collection and field evaluation

with the goal of identifying the most influential studies, providing insights for current research interests, and directions for future research in the field [11, 12].

In this work, the selection of the studies was based on the guidelines for conducting systematic reviews proposed by [10, 11]. A first search was performed using the string "(lean OR toyota production system OR lean manufacturing) AND (agile OR agile methodologies) AND (automotive industry OR car manufacturer)". As result 1575 publications were collected from Science Direct, 1083 from Emerald Insight, 6 from IEEEXplore®, and 1 from Scopus. After, based on [12], the literature search followed the following steps. First, the research string was considered in each database; second, only studies published since 2001 were selected, since it was when the Agile Manifesto was published and Agile began [13]. Third, only studies published in scientific journals, books, book chapters and conference proceedings were selected. The articles were selected by relevance based on the criteria contained in each database. In fourth, the first 300 listed results were selected. Fifth, title, abstract, keywords and, sometimes, articles' content were analysed to eliminate those that are not part of the Lean Agile application in the automotive industry. Sixth, the final selection of the most relevant works was made excluding repeated studies, which were listed and selected in more than one database. Table 1, illustrate the results of the performed six steps. At the end thirty-three studies were selected and analysed.

Table 1. Results of the search and selection of the studies in the databases.

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Science Direct	1575	1485	1309	300	27	20
Emerald Insight	1083	1056	945	300	13	13
IEEEXplore®	6	5	0	0	0	0
Scopus	1	1	1	1	0	0
						33

The IEEEXplore®, and Scopus databases presented few results with the defined string. This demonstrates the scarce number of works published on this subject. However, databases such as Science Direct and Emerald Insight presented a satisfactory number of publications allowing the continuity of this study.

3 Discussion and Results

This section presents the discussion and the results of the selected relevant literature. Figure 1 shows the number of published papers from 2001 to 2022. Approximately 50% of the articles were published since 2018. Moreover, 2018 was the year with more publications. It is also noticed a reduction of publications between 2020 and 2021, probably caused by COVID-19 pandemic. The countries with more publications are India, Portugal, and the United Kingdom (see Fig. 2).

In this work the most common tools in distinct study areas were also mapped. Table 2 shows the most common tools identified in the analysed publications. It is important to highlight that, among the analysed publications, VSM, JIT and 5S were the most frequently used tools (23%) in the field of Lean Manufacturing. Table 2 also reveals the similarity of tools used between two or more publications.

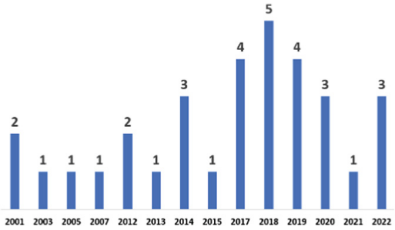

Fig. 1. Publications by publication year.

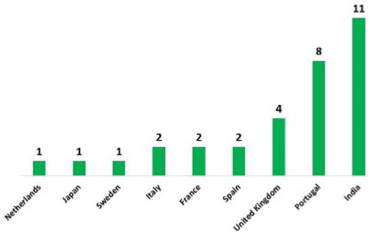

Fig. 2. Publications by countries.

Among the analysed publications the identified tools are Fuzzy Analytic Hierarchy Process (FAHP) [14], Performance Value Analysis (PVA) [14], Design of Experiment (DoE) [36], Matriced' Impacts Croise's Multiplication Appliquée a UN Classement (MICMAC) [34], Structural Equation Model (SEM) [38], Printed Circuit Boards (PCB) [30], Electronic Data Interchange (EDI) [30], Interpretive Structural Modeling (ISM) [39], Cloud Computing [15], Jidoka [16], Visual Management [25], Autonomous, preventive and predictive maintenance [20], Define, Measure, Analyse, Design and Verify (DMADV) [40], and Total Quality System (TQS) [22] (see Table 2).

These tools represent a total of 26% of the tools mapped. Nevertheless, a total of 14 tools were identified in one single article, without reference to the same tools in other publications. For this reason, they were not mentioned in Table 2. Figure 3 illustrates, the implementation areas of the used tools. Most of the cited tools in the articles come from the Lean Manufacturing philosophy (28%) and Industry 4.0 (21%). The word cloud presented in Fig. 4 illustrates the most cited tools in the analysed documents.

According to [32] "Agile Manufacturing" is a unique form of industrial competition for US companies where changes may occur in customers, suppliers, and competitors to gain advantage in the market opportunities to satisfy customer requirements. Thus, Agile Manufacturing can be implemented in distinct study fields and can work together with other methodologies being Lean Manufacturing one of the main ones.

Table 2. Common tools identified in the publications.

Area	Tools	Papers	%
Lean Manufacturing	Value Stream Mapping (VSM)	[14–20]	23
Lean Manufacturing	Just in Time (JIT) flow	[16, 19, 21–24]	23
Lean Manufacturing	5S	[16, 17, 19, 20, 24–26]	23
Lean Manufacturing	Kaizen	[16, 17, 23, 24, 26]	16
Industry 4.0	Intelligent Manufacturing Systems (IMS)	[15, 16, 27–29]	16
Industry 4.0	Multicriteria decision making (MCDM)	[27, 28, 30, 31]	13
Business Environment	Framework	[16, 24, 32, 33]	13
Lean Green Agile Manufacturing System (LGAMS)	Total Interpretive Structural Modeling (TISM)	[26, 28, 34]	10
Supply Chain/Manufacturing	Advanced MRP/ERP	[21, 29, 35]	10
Agile	Design Thinking	[15, 19, 26]	10
Reliability	Remaining useful life (RUL)	[16, 19, 23]	10
Lean Manufacturing	Lean Line Balancing	[16, 18, 25]	10
Supply Chain (SC)	Taguchi Loss Functions (TLFs)	[19, 36]	6
Industry 4.0	Additive Manufacturing	[25, 30]	6
Hybrid lean–agile manufacturing system (HLAMS)	FDD – Feature Driven Development	[35, 36]	6
Lean Manufacturing	Standard Work	[16, 25]	6
Lean Manufacturing	SMED	[20, 37]	6

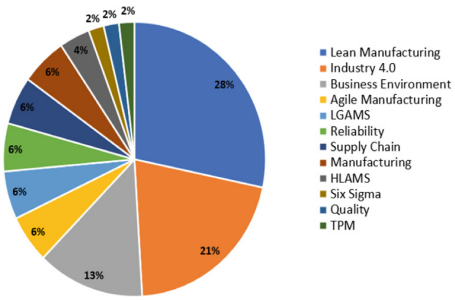

Fig. 3. Agile manufacturing application areas.

Fig. 4. Tools word cloud.

Throughout this research, it was found that Supply Chain is one of the areas where Agile is constantly being implemented [30, 33, 38, 39]. This is an area of constant changes requiring high adaptability. Also, in [31] a case study was presented to select the best warehouse location for an automotive manufacturing company using a fuzzy-based decision-making approach. Leagile techniques were also present in the Environmental area [14, 21, 32, 35, 37]. In example, according to [28] lean tools, applied in an agile way, can contribute to the management of environmental risks.

This work highlighted the combination of Industry 4.0 tools with Lean Agile practices to achieve leaner production systems. However, the relationship between leagile and Industry 4.0 still needs to be further investigated. Despite this work confirms the growing use of leagile in the automotive industry, the studies that have combined lean and agile techniques are mainly in supply chain, manufacturing, and environmental management areas. Another particularity is that all the studies are based in real case. This highlights that Lean Agile can contribute to increase the adaptability of the automotive industry according to the market's requirements. The industry will have the ability to change strategy quickly, without losing product quality or information.

Leagile pillars have been presented in the studies as drivers to succeed competitors and enhance innovative capacity. Yet, its full implementation is not always possible since it depends on decisions aiming to obtain the maximum flexibility at the lowest possible cost. Unfortunately, the tendency to value cost reduction, can often mean economic losses. These aspects bring to discussion a vast number of studies that can be used and learned by organizations seeking integrated solutions that can be proposed to obtain improvements and developments in the sector.

4 Research Opportunities

Some research opportunities were identified in this study. It is possible to say that there is still a shortage of literature regarding the implementation of leagile in the automotive industry because it is still a relatively new field of study. The debate about Industry 4.0 in the automotive industry is also growing. Nevertheless, there is still a lack of specific and detailed studies focusing on the tools used and their contributions, being also a field opportunity for future research.

This work also highlighted strategies in the Environmental area of the automotive industry. However, few studies have associated the use of Industry 4.0 technologies. The integration of the Industry 4.0 with the leagile was more present in the areas of Supply Chain and Automotive Manufacturing, in general. Thus, it also lacks comparative studies between the several techniques of leagile and their advantages and disadvantages of use.

5 Conclusion

This study analysed thirty-three articles on the implementation of Lean Agile in the automotive industry. The publications were characterized according to year of publication, country of origin, application sector, tools used, and their contributions to the automotive sector. It was possible to outline a current state of the art on this topic, contribute to address some limitations highlighted in the literature, and identify future research opportunities.

The analysed studies allowed to provide a set of interesting results about the implementation of leagile in the automotive industry. It was possible to draw conclusions about the importance of leagile in the automotive industry, the chronological history of implementation, the countries with the highest implementation rates, the most cited tools and industrial sectors of implementation, as well as the main contributions to the automotive industry. It is important to note that the chosen topic was conceived in the context of the automotive industry and that the authors' experience focuses mainly on a lean and agile oriented industry.

This research gathers and highlights the best contributions of leagile so that it can help to managers, practitioners and researchers for future reference and an invitation for traditional manufacturing systems to consider the advantage of combining Agile and Lean principles. It also strives to promote the importance of agile transformation in the automotive industry that, combined with Industry 4.0, can transform and impact processes in key sectors such as supply chain, operations, and environmental.

Finally, this research reinforces the key elements for creating a more economically viable, potentially more agile, technological, and sustainable automotive industry.

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Challenges to Lean 4.0 in the Pharma Supply Chain Sustainability

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Abstract. The Pharma sector is increasingly under pressure to improve the sustainability of supply chains, as consumers and regulators require greater transparency, efficiency, and accountability. Although Lean 4.0 has created a lot of buzz in the organization, the pharmaceutical sector faces challenges in implementing it. The main goal of this literature review is to identify the challenges of Lean 4.0 for the sustainability of the pharma supply chains (PSCs). A series of papers extracted from the most relevant scientific databases, including the Web of Science, Scopus, Google Scholar, and ProQuest was analyzed and synthesized from 2007 to 2022. 31 articles were used in the study. The findings of the study indicate that challenges include financial, staff experience and specialization, ongoing maintenance, resources for generating new skills and experiences, employees, and partners' resistance to changes in regulations, and cyber-hacking of key information. The results will facilitate future work by practitioners and researchers and make an important contribution to existing knowledge.

Keywords: Industry 4.0 · Lean 4.0 · pharma supply chain · sustainability

1 Introduction

One of the primary goals of the pharma sector is to provide medicines and to be consistent with the goals of the health system. Its supply chain should provide medicines to patients in sufficient quantities with acceptable quality at the appropriate location and time with the lowest possible costs [1]. To achieve this pharma manufacturers should choose the best raw materials and suppliers, as well as production facilities that are environmentally and socially responsible [2]. Therefore, supply chains are embracing a digital transformation known as Industry 4.0 (I4.0), which refers to the application of a set of digital transition technologies that extend beyond organisational boundaries [3]. "Industry 4.0" refers to the combination of the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and advanced technologies to drastically transform the production environment as well as the supply chain [4].

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It is consistently gaining attention in sustainability by contributing to long-term economic, environmental, and social development [5]. According to Marodin et al. [6], Lean Supply Chain Management is defined as a group of actors which are directly linked by upstream and downstream flows of products, services, information, and funds that collaborate to reduce cost and waste by efficiently pulling what is needed to meet the needs of individual customers and at the same time benefit the company's stakeholders.

The pharma sector is expected to respond to concerns over the hazardous waste that may harm the environment and human health. At the same time the PSCs need to be cost-efficient, transparent, and accountable in the manufacturing and distribution of pharmaceuticals [1]. However, today, Lean 4.0 which combines Lean management and I4.0 enablers have been identified to achieve positive synergies, with the potential for significant improvement in supply chain sustainability that is also applicable to the Pharma sector [7]. Despite these advances in the pharma sector with regards to development and manufacturing, significant challenges in the sector can jeopardise the long-term viability [8]. This has prompted the research question: "What are the challenges for Lean 4.0 in PSC sustainability?". This research objective highlights the challenges of Lean 4.0 to bridge the knowledge gap, allowing practitioners and researchers to better understand these challenges and contribute significantly to the existing knowledge and facilitating future work in the field.

2 Literature Review

2.1 Lean Management and Industry 4.0

Industry 4.0 techniques have recently been used in the Pharma sector and have been strictly regulated by several stakeholders to ensure the safety and overall well-being of the society [4]. By employing intelligent sensors and other I4.0 technologies it has enabled the monitoring and optimization of energy consumption in areas such as water, electricity, and gas. Pharma companies in developing countries have started to implement the basic resource management practices that focuses on individual machines. It has paved the way for upgrading of production lines or factory sites through the use of big data, resources and cost analysis, resulting in precise forecasting and adhering to regulation [9, 10].

Lean manufacturing eliminates non-value-added activities from manufacturing processes to maintain effectiveness, flexibility, and profitability, in the health sector [11]. Vinodh et al. [12] have identified 5S, Kanban, Kaizen, Total Productive Maintenance, Total Quality Management, Failure Mode and Effect Analysis, Quality Function Deployment, Value Stream Mapping, Cellular Manufacturing and other lean manufacturing techniques which are currently being implemented in the manufacturing sector. According to Taj [13], Lean principles are aimed not only at waste reductions but also at improving production systems efficiency by increasing value-adding activities in product flow and reducing costs [14].

2.2 Lean 4.0 Enablers

Due to its direct impact on environment, human health and safety, the sustainability of PSCs is far more complex and challenging compared to that of other industries.

As a result, the Pharma sector has received increased attention for the impact of its activities on long-term sustainability [15]. The Pharma sector is increasingly sourcing productions and related services to emerging countries with suitable suppliers that are environmentally and socially responsible [2]. According to Schneider et al. [16], the increasing energy prices, the potential impacts of climate change, and the strict regulations have resulted in the Pharma sector focusing more on energy usage and emission reduction throughout the entire life cycle of pharma products. Sustainability is influenced by environmental, societal, and economic factors. Hence exploiting Lean 4.0 technologies facilitates sustainable value creation, which will lead to efficient sustainable PSC designs and management, assisting pharma companies to gain long-term competitive advantages [17].

3 Methodology

In order to identify the challenges in implementing Lean 4.0 in PSC sustainability, a Systematic Literature Review Analysis was used to select and analyse articles. Given this, the web of science, Google Scholar, ProQuest, and Scopus were used between (2006 to 2022).

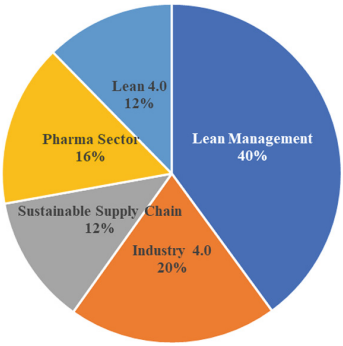

Fig. 1. Article distribution based on keywords

Figure 1 shows the percentage of articles viewed in order to achieve the outcome of this paper. Five hundred and three (503) articles were reviewed, two hundred (201) were on lean management, hundred (100) were Pharma 4.0, sixty-two (62) were sustainable supply chain, seventy-eight (78) were pharma sector and sixty –two (62) were Lean 4.0.

The search string was (Lean AND pharma), (pharma AND industry 4.0) (pharma Lean AND Challenges), (Pharma challenges AND pharma barriers) OR (pharma difficulties AND pharma barriers), (pharma SCS challenges AND pharma SCS barriers) (pharma procurement). Irrelevant title, abstracts and full text, was used to reduce the number of articles to a manageable number, the selection process yielded thirty-one articles, which were subjected to an appropriately comprehensive review.

A structure essential to carrying out a secondary inquiry, such as a systematic literature review (SLR), is shown in Fig. 2 to reduce study bias. The flowchart encapsulates

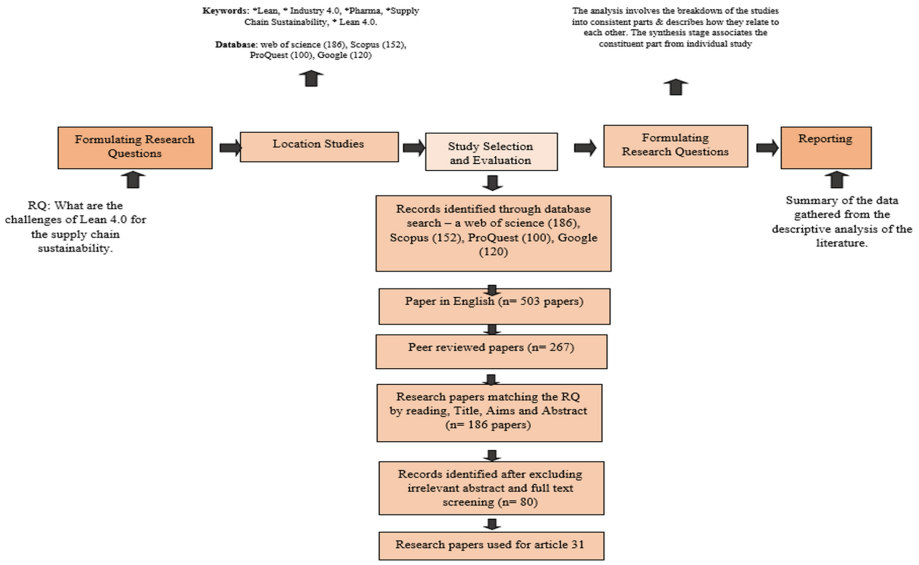

Fig. 2. Systematic Literature Review

the review's thorough plan, including the steps to be taken to produce results and facts that will serve as findings.

4 Results and Discussion

Lean 4.0 manufacturing practices emphasise customer-centricity, which keeps traditional processes focused on efficiency through digitalised systems and processes that cause synergies and help sustainability within the supply chain. However, the pharmaceutical sector seeking to upgrade its supply chains and operations faces several challenges, as shown in Table 1. Management requirement for necessary resources, such as a cross-functional team of experts and necessary investments, is one of the barriers to implementing Lean 4.0 in the Pharma sector [18].

Supply Chain Management has its roots in sustainability and focusing on digitalisation is therefore a step towards the adoption of sustainability. According to Linton et al. [19], sustainability must include challenges that extend beyond the core of supply chain management, such as product design, production, distribution, end-of-life products, and recovery processes. In addition, building new experiences and competencies would be expensive and time consuming as employees and supply chain partners learn over time that they may need to familiarize themselves with the Lean concept and the digital interface [20]. As a result, challenges to its successful implementation include the complexity of the adoption process, evidence of innovation sharing and change embedding, high process variability, a lack of understanding of Lean 4.0, and issues with defining waste [21]. Also, employees' negative perception of Lean 4.0 makes it difficult [21]. Furthermore, a lack of commitment from top management to allow flexibility [22], in changing processes to create fully integrated end-to-end supply chain solutions necessitates close

collaboration with partners [23]. Finally, regulatory aspects add another layer of complexity because they include new business requirements and a changing environment [22, 24].

Table 1. Challenges to Lean 4.0 in the PSCs

Challenges	Concept	Author
Management: *Financial *Inexperience staff *Lack of infrastructure *Low management support and dedication *Poor existing data quality	Financial constraints in developing capabilities in terms of advanced equipment and machine, facilities and sustainable process innovations in Lean 4.0. Lack of employee understanding of the concept makes it difficult to implement it effectively. Also, management support and willingness to accept changes are critical for the development and effective Lean 4.0 concept Several interconnected machines, sensors, manufacturing systems and facilities generate huge structured/unstructured data	[18, 21, 22, 25]
Employees 'and business partners' resistance	Unaware of the potential benefits, most industries are hesitant to adopt Lean 4.0 based technology since employees believe that the use of technology would eliminate their job	
Security issues	Cyber hackers have access to vital information	
Regulations	Lean 4.0 is about a cyber-physical network that connects various machines, sensors, facilities, and humans to the internet. This cyber-physical network may raise several complex legal issues with regards to personal and sensitive data	[19, 23, 26]
The problem of coordination and collaboration	Technology integration is critical for effective communication and increases productivity. Industries are struggling to create a flexible interface to integrate various heterogeneous components	[24]
Legal issues	Lean 4.0 tends to emerge with lean concepts and several complex legal issues	[28]

One of the reasons pharma companies have been hesitant to implement Lean 4.0 is a significant capital investment and a need for skilled labour [18, 21]. Building new experiences and competencies would be expensive and time-consuming because employees would need to be trained due to their unfamiliarity with the Lean 4.0 concept and the digital interface. The complexity of the adoption process due to poor existing data quality [22, 29], evidence of innovation sharing, embedding change, and issues with defining waste need understanding with structural flexibility while adopting new changes [7]. Sustainable manufacturing in the pharma sector involves regulatory compliance with aspects such as the 3Rs (reduce, reuse, and recycle). It extends product life cycles through remanufacturing, recycling, and the use of clean technologies that reduce pollution, reflecting the changing environment in which pharma regulators operate [30]. Also, in terms of regulatory barriers, as well as legal issues [25] operating within existing regulatory frameworks can pose a challenge to technological innovation [30].

Employees are reluctant to accept change because they believe digitalisation will eliminate their jobs, which they find uncomfortable as well as due to fear of the unknown and failure [23]. Also, the absence of commitment from top management to permit flexibility in changing processes creates a deficiency of end-to-end supply chain solutions that necessitate close collaboration with partners [18, 21, 31]. Security issues concerning cyber hackers and data-sharing protocols are on the rise. According to Muller et al. [31], there is a need for a shared ground for a relevant architecture in place before implementation begins, this is because the manufacturing of drugs has a direct impact on human life, and therefore, an environmentally friendly culture must be established from early stages of production.

5 Conclusion

The present study conducted an SLR analysis and identified ten challenges of Lean 4.0 for supply chain sustainability in the pharma sector. I4.0 technologies are evolving and the use of Lean 4.0 has the potential to significantly improve agility, efficiency, productivity, and sustainability throughout the entire supply chain. However, the Pharma sector struggles to adopt Lean 4.0 because it is heavily regulated to ensure patient safety, product quality, and data integrity. It also expects smart technology to be fully integrated into the pharma sector as well as incorporate social, economic, and environmental protection and control within its supply chain. This future is attainable if the challenges are managed effectively.

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Lean 4.0 Deployment Case Studies in UK Industrial Companies: Lessons Learned

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Abstract. The current paper aims to fill this gap through case-based research, understanding from empirical data the application of Lean 4.0 in four UK companies. The findings showed that Lean 4.0 represents an excellent strategy to improve the manufacturing systems' performance, mainly productivity, flexibility, real-time data accessibility, and quality control. Also, it was possible to confirm that financial resources, adversity to change, and process complexity are the main barriers to Lean 4.0.

Keywords: Lean 4.0 · Lean Manufacturing · Industry 4.0

1 Introduction

The integration of Lean and I4.0 (Lean 4.0) has been considered as a great strategy to remain competitive in complex and dynamic markets [1–4]. Lean Manufacturing has already consolidated as one of the most appropriate management philosophies for increasing productivity and quality in production [5, 6]. Besides, Industry 4.0 (I4.0) technologies emerged as an essential role to get the competitiveness of manufacturing systems [2, 7].

The I4.0 covers a range of technologies, such as Cyber-Physical Systems (CPS), the Internet of Things (IoT), Cloud Computing, Big Data, etc. [8]. The literature highlights that implementing these technologies creates industrial value focused on sustainable development [9]. Xu et al. [10] point out that there has been a growing demand for research related to I4.0 to provide insights into issues and solutions related to design implementation and management. As example a great support to Lean tools implementation [4, 11]. Furthermore, it is missing studies that empirically validate the synergies between Lean and I4.0 and examine the effects of Lean 4.0 on operational performance [12–14].

This research aims to analyze the application of Lean 4.0 through case studies from UK companies. Specifically, it expands and cover the Lean 4.0 literature gap with empirical results showing the practical application of Lean 4.0, presenting the main tools,

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requirements, benefits and barriers that the literature has not yet pointed out, such as the risk aversion.

The paper is organized as follows. We present a brief theoretical background about Industry 4.0, Lean and Lean 4.0 in Sect. 2. Next, Sect. 3 we describe the materials and method used. Design. Subsequently, Sect. 4 presents the results and discussion. Lastly, Sect. 5 highlights the main conclusions.

2 Background

2.1 Industry 4.0 (I4.0)

The term "Industry 4.0", "intelligent manufacturing" (smart manufacturing), or "smart factory" [15, 16] is a complex concept to be defined [17]. This term was first used to describe a high-tech strategy proposed by the German government [15], and in recent studies, several different definitions of I4.0 have been found [17].

For the study of [18], I4.0 is operationalized using smart products and smart processes, which enables autonomous data collection and analysis, as well as the interaction between products, processes, suppliers, and customers via the internet.

Schumacher et al. [19] complement that I4.0 refers to recent technological advances in which the internet and supporting technologies (e.g., embedded systems) serve as a backbone for the integration of physical objects, human actors, intelligent machines, product lines, and processes, across organizational boundaries. It forms a new type of networked, intelligent, and agile value chain. I4.0, which involves increasingly affordable hardware and software solutions, accelerates the transition to the smart, interconnected factory envisaged by this revolution [20, 21].

2.2 Lean Manufacturing (LM)

Lean Manufacturing (LM) is considered an approach that goes beyond a production management strategy; it is a way of thinking about the management of organizations that seeks the reduction of debris in the production chain. Also, LM is considered a set of principles and practices to eliminate all forms of waste within an organization [22].

Several researchers in various industries have reported the good results promoted by the implementation of Lean, for example, in the automotive sector [23], electro-electronics [24], aerospace, textile [25], and construction [26]. This indicates that the LM can be implemented in a wide variety of industries [27].

Furthermore, LM has significantly changed what was considered a trade-off between productivity and quality, resulting in a new way of thinking about operations. That is, LM has become a more viable way of organizing production to simultaneously obtain high levels of productivity, quality, and product complexity [28, 29].

2.3 Lean 4.0

First, this study adopted the concept of Lean 4.0 as can be defined as a Lean philosophy that can integrate cutting-edge digital technologies into its core tools to enhance

waste detection and reduction in both virtual and physical processes [14]. Lean is also associated with fixed production sequence and slow responsivity. These constraints significantly impact the possibility of attending to the constant changes and adaptability required by productive systems in the digital era. On the other hand, I4.0 involves product modularity and flexibility. Given this paradox, investigating how to integrate both paradigms effectively are an urgent need. There is no consensus about how both paradigms influence each other [30].

Bittencourt et al. [31] concluded that high investments are required to digitalize the productive process. Given this context, Deuse et al. [32] observed that small and medium-sized enterprises still face challenges in the selection and implementation of suitable Lean 4.0 solutions. Also, the Lean concepts of standardization, organization, and transparency are the pillars for implementing I4.0.

Based on a literature review, Gallo et al. [2] investigated what tools of the I4.0 are used by companies to promote Lean. Also, the authors investigated the reasons that push companies towards integrating digital tools with Lean practices and the advantages of using these tools. They concluded that the IoT and Big Data are the most important I4.0 tools because they enable flexibility and increase productivity. Finally, in accordance with previous literature, the authors concluded that the human factor is one of the most relevant pillars in the I4.0 process.

Also, based on another literature review, Pangliosa et al. [12] identified and categorized nine I4.0 technologies and LM practices. Twenty-four pairs of Lean 4.0 practices were identified as highly synergic, e.g., the relationship between CPS and Value Stream Mapping (VSM). They concluded that there is a positive interaction between Lean and I4.0 toward the achievement of higher operational performance.

Research [1] investigated how the I4.0 tools can improve the Lean implementation and results from this study reveals that some I4.0 technologies support Lean practices such as Just-in-time and Jidoka, but little or no support for human resources and waste reduction. Another case [33] shows I4.0 supporting Lean presents the integration of I4.0 into TPM results in benefits as the improve the decision-making process. The impact of Lean 4.0 was investigated [1] in the improvement of operational performance. The authors executed a survey with 108 manufacturers in Europe and evaluated the data through multivariate analysis. Findings indicate that a higher maturity level of I4.0 may enable Lean 4.0. In opposition, when processes are not robustly designed and continuous improvement practices are not established, companies may not be focused on adopting novel technologies either.

3 Materials and Method

Building theory from case study research is most appropriate in the early stages of research [34], as this topic still have many research gaps [3]. In addition, the case study is a suitable methodology when research questions focus on contemporary events and when it is unnecessary to control behavior events or variables [35]. Moreover, this method sheds light on why a decision or set of decisions were made, how they were implemented, and what results were achieved [35]. This research aimed to analyze the application of Lean 4.0. This study is about four UK companies from different industrial sectors that

have already implemented Lean 4.0 tools. Companies' information from an interview with a Lean 4.0 specialist from the consultancy company that implemented the Lean 4.0 on them, the interviewed give the information from implementations reports, that is not allowed to present in this document.

The first stage of this research consisted of elaborating a theoretical background about the main concepts of LM, I4.0, and Lean 4.0. The next step was data collecting, structuring the interview, adjusting the protocol, analyzing companies' reports companies' websites and conducting the case study. The first part of the data collection consisted of a structured questionnaire that aims to understand how the LM and I4.0 integration empirically happens and identify the main practices adopted, advantages, barriers, benefits, and guidelines to Lean 4.0. The interviewed Lean expert has participated in the implementations of Lean 4.0 in the four companies. The interview was recorded, and Appendix A presents the questions of the semi-structured interview. The questions were elaborated on based on the background and the proposed goal.

4 Results and Discussions

Table 1 summarizes the results from the four companies.

The interviewee states Lean 4.0 can be understood as a methodology that combines LM principles with I4.0 technologies by complementing and reinforcing each other mutually. Also, Lean 4.0 takes advantage of the analytics algorithms of I4.0. With analytics, companies can examine the data and discover the inefficiencies in processes, so there is minimum wastage in production by avoiding non-value-adding procedures.

Based on the company's information it was verified the guidelines to implement Lean 4.0. First, it was argued that it is necessary that having a Lean organizational structure proves effective in the implementation of I4.0. Also, the digitalization of an organization needs transformational thinking throughout the organization, which Lean methodologies can provide. Another important issue that was identified is that I4.0 tools enable Lean. The following tools were observed: **5S** – A digitized version of 5S can include computerized checklists, making it easy to communicate, analyze, and make decisions based on evaluations; **JDI Automation** – JDI provides organizations with transparency of work, holistic knowledge of the whole process, and help in future maintenance planning. It can help schedule the tasks in advance to keep track of the overall productivity and efficiency of the machinery and stock management; **Kanban** – Tools implementing the digital T-card software accurately map the process in the organization to integrate them with the digital environment; **Lean Daily Management System (LDMS)** – LDMS forms the foundation of the long-term success of excellence of the organization. It measures whether the organization is moving on the right track to meet the goals, corrective actions are taken, and improvements are sustained. LDMS includes all the operational control activities, integrates Lean tools, and brings considerable organizational changes in productivity and quality improvements; and **TPM** – TPM can link with the I4.0 technologies to monitor the machines and equipment more accurately in a manufacturing facility by identifying problem areas, addressing them, and preventing re-occurrence.

On the side of I4.0 tools, such as the IoT, CPS, and Industrial Big Data, their integrations can create a powerful impact on the implementation of LM in the organization.

Table 1. Summary of the investigated companies.

Case industry	Lean tools	I4.0 tools	Main barriers	Main benefits
W Healthcare company	5S, A3, Hoshin Kanri, Standard Work, Kaizen, Kamishibai Tcard, Lean Daily Management System, VSM, Transition Plan, TPM	Computerized Maintenance Management Information System (CMMIS)	Risk aversion, Lack of subject knowledge	Safer working conditions, Increased Knowledge Sharing and Collaborative Working
X Rubber manufacturer	5S, A3, Hoshin Kanri, Standard Work, Kaizen, Lean Daily Management System, VSM, TPM	Automated Shop Floor, Data Capture System, CMMIS, Digital T-Card Software: Workflow Management, Datapoint, Balanced Scorecard Software, 5S application	Data Ownership apprehensions and concerns about cyber security, Organizational challenges	Proper tracking of the entire process, Ease overall production process
Y Pharmaceutical	5S, A3, Hoshin Kanri, Standard Work, Kaizen, Kamishibai Tcard, Lean Daily Management System, VSM, Transition Plan, TPM	Datapoint, Balanced Scorecard Software	Difficulty in commencing the digitalization plan, Adversity to change	Flexible operations and efficient changeovers, Real-time data accessibility
Z Plastic and paper packing	Kamishibai Tcard	Digital T-Card Software: Workflow Management	Technology glitches in the implementation, Internal roadblocks, Lack of combined leadership	Data-driven quality control, Increased productivity, and efficiency

Regarding the benefits of Lean 4.0, it was pointed out: Flexible operations and efficient changeovers; Increased productivity because the predictive algorithms can improve

autonomous maintenance systems; Real-time data accessibility; by applying predictive algorithms, manufacturers can overcome the challenges of managing production in real time; Identification the error's root cause and conduct detailed tracking, based on data-driven investigations; and Safer working conditions.

In respect of the main barriers, it was pointed out that the investment costs and other factors. It includes **Lack of subject knowledge** (proper understanding should be given as to how to start, where to aim, and what to be aware of); **Adversity to change** (thought of having prescribed operations giving predefined outcomes and the tendency not to deviate); **Risk aversion** (tendency to avoid the ingress of the technology as the risk factor of going wrong is high); and **Complexity of the process** (the training should be given if the intended results are to be produced).

5 Conclusions

This study provided empirical insights about the application of Lean and 4.0, demonstrating a good performance result for companies as demonstrated in literature [2, 12]. The cases also demonstrated improvements in quality, productivity, safety, and information sharing. It was important to emphasize the innovativeness of the study, as it was possible to add Risk aversion (tendency to avoid the ingress of the technology) as a barrier. The complementarity of Lean and I4.0 was also demonstrated, as Lean is the enabler of I40 as well as I40 can support the Lean implantation. For future works, it is important to explore these relationships in a great sample, in other industrial sectors, and in different company sizes.

Appendix A

Semi-structured questionnaire for the interview

(1) Based on Lean 4.0 implementation cases, please point out the main Lean and I4.0 tools implemented; (2) How is it possible to define Lean 4.0? (3) Is a Lean structure necessary before implementing I4.0? Why? (4) Is Lean an enabler in implementing I4.0? Which tools? How? (5) Is I4.0 an enabler in implementing Lean? Which tools? How? (6) What are the main benefits of Lean 4.0? (7) What are the main barriers to Lean 4.0? (8) What are there some essential steps in implementing Lean 4.0? (9) What are the most relevant implementations cases in big companies? Please point out: Industrial Sector, implemented Lean Tools, implemented I4.0 tools, Main Barriers, and Main benefits.

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Lean Manufacturing vs Coaching Alliance in Engagement Promotion: An Employee Suggestion System Prototype

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Abstract. Industry 4.0 is being pushed by Industry 5.0 to put the human factor at the centre of technological innovation by fostering engagement practices, namely through participatory design and communication and knowledge sharing. Kaizen Teian, or suggestion systems, are tools that empower employees with voice behaviour, giving them the possibility to foster innovation in the organisation by fostering in them this feeling of involvement and/or belonging. This paper brings a prototype of a suggestion system, co-created with employees from three multi-sector companies that integrates the PDCA cycle with the Disney strategy, a Neuro-linguistic Programming technique used in Coaching. The Disney strategy aims at supporting innovation through a process for the realisation of ideas, giving them a mature character. This system fosters two of the predictors of work engagement, which are participative design and knowledge sharing, and brings transparency to suggestions, enabling the employee to monitor them. The promotion of sustainable innovation through the Disney strategy, the improvement of labour engagement and the sharing of knowledge, are all enhancing factors of organisational competitive advantage, not only by retaining the workforce, but also by preserving organisational knowledge. This is a digital tool adapted to the current challenging technological context, where Lean must be preserved and coaching tools applied.

Keywords: Workforce Engagement · Industry 4.0 · Lean Manufacturing

1 Introduction

The fourth industrial revolution and now the fifth industrial paradigm are affecting how a company ought to emphasis on training and human capital development [1]. Industry 5.0 appears so that Industry 4.0 does not rely only on technologies and starts, then, to put the human factor at the center of innovation, so that it can more easily adapt to changes in processes, while adding skills [2].

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Work engagement is one of the most popular management tools and enables the achievement of high levels of organizational performance, while promoting innovative work and keeping employees within the organization [3]. It is, therefore, fundamental that dynamics that reinforce this factor within companies be created, while these dynamics are aligned with digital strategies. The literature already contemplates a dynamic based on participatory design, which refers to the contribution, by the employees, of improvements to their workstation, consequently fostering communication and knowledge sharing [4].

Wasted human potential is considered the eighth significant waste defined by the lean approach and occurs when employee involvement in process improvement is devalued. However, it is known that due to employees' familiarity with day-to-day operations, they are at an advantage in suggesting improvements to work activities for organizational advancement [5]. Kaizen Teian is seen as a system for submitting suggestions, which appears to give employees a voice to contribute to process improvements which is the participatory design basis. These systems foster organizational innovation, contributing to high levels of performance [6].

Thus, this paper, intends to present a prototype of a solution for a suggestion submission system, which gives employees a voice, while helping them in the creativity process, through the integration of a Neuro-linguistic Programming strategy, called Disney Strategy. The PDCA (Plan-Do-Check-Act) tool widely applied in Lean Manufacturing was also integrated to facilitate the visualization of the status of suggestions. This prototype was developed from the reality of three multi-sector companies (chemical, metalworking, and furniture and lighting retail), in which the employees contributed through the co-creation process using interviews.

The remainder of this work is structured in the following way. Section 2 presents a theoretical background for the concepts related to engagement in industry 4.0 and kaizen ideas or improvement suggestions. In Sect. 3, the prototype is presented as well as the context goals and methods used, and the last section reveals the main results and summarizes the most important conclusions and some future work.

2 Theoretical Background

2.1 Employee Engagement in Industry 4.0

Industry 4.0 is a paradigm that is profoundly affecting organizational processes, especially the way a company should look at human capital training and development [1]. Industry 5.0 centers the whole digital revolution on man/human standing considered as the answer to the question of a renewed industrial paradigm centered on man/human, starting from the reorganization (structural, organizational, managerial, knowledge-based, philosophical and cultural) of the industry's production processes [7]. For this change to happen, skills in adapting to change, teamwork and social interaction, communication, critical thinking and cognitive abilities are vital as future workforce 4.0 competencies [8]. Hence, the paradigm is shifting to adjust systems to the human operator, and job satisfaction is a major concern [3], because accomplishing higher levels of performance deeply depends on how the employees are handled and engaged in the daily activities [9]. Engagement is a psychological state, seen as an "illusory force", that enables high levels of performance for employees and organizations beyond innovative

work behavior [10]. Within the digital paradigm it is necessary to focus on improving work engagement. To this end, one of the factors to be promoted is participatory design, in which employees are called upon to provide suggestions for improving products and workplaces. These benefits come from knowledge sharing and mutual learning, contributing to the reduction of tacit knowledge within the organization, which is the basis for the preservation of organizational knowledge (explicit knowledge) [3]. Both communication and knowledge sharing enhance team performance, and so it is crucial that organizations must ensure that knowledge is shared and applied. Increasingly in organizations, gamification solutions and knowledge sharing tools can be integrated into pre-existing information systems [4, 11]. To ensure sustainable levels of engagement, it is necessary to have a constructive organizational learning culture. This type of organizational culture helps generate resources that are deemed adequate and sufficient to handle the demands of the job. It should be noted that this results in the idea that workers' needs are met, which intrinsically motivates them to exert discretionary effort at work [12].

2.2 Kaizen Ideas or Improvement Suggestions

In a context of rapidly evolving markets, studies have shown that companies that focus more on innovation are more successful and ultimately more profitable [13]. The greatest wealth that makes up an organization, a region or even a country is its people and their knowledge. We know that almost two-thirds of the value of a large company comes from its intangible assets, that is, what people know, the ideas and relationships people have, patents and copyrights, databases and brands, the training or human capital to realize ideas [14]. Employees are often closer to the products and processes and are therefore more likely to create new ideas and knowledge to improve them. For this reason, in the new world of work where the role of the individual is central, bottom-up initiatives for idea generation seem to be very promising and more democratic in nature, leading to more ideas. Having more ideas is crucial, because growing in ideas also means growing in accepted proposals, which contributes to more innovation, giving companies a competitive advantage [13].

According to the Lean Manufacturing philosophy, the eighth waste centers on the unused potential of people, which can, according to what was seen earlier, seriously result in a decrease in a company's efficiency. Kaizen Teian is originated in Japanese business school and is mentioned in the works of the Japan Human Relations Association [15]. This concept presents itself as an employee suggestion system (ESS), where small to medium improvements are proposed and implemented directly by employees in their workplaces, processes and work areas [15]. In individual suggestion systems, workers recommend their suggestions in a suggestion box that can be physical or digital. After this, the employees are removed from the process and a committee is assigned the responsibility of selecting the winning ideas, for subsequent awarding and decides the people or groups responsible for the implementation of the approved ideas [6]. A suggestion system improves organizational performance as it focuses on continuous employee improvement through teamwork, cost savings, improved quality, improved communication and knowledge sharing, reduced employee resistance to change, and implementation

of best practices throughout the organization. It should also be noted that this type of system is correlated with improved morale and cooperation among employees [5].

3 Practical Case

3.1 Context Goals and Methods

The main objective of this paper is to present a concept and respective prototype of an employee suggestion system, with a proposal to meet the needs of involvement promotion, considering the reality of three multi-sector organizations (chemical, metalworking and furniture and lighting commerce). This development started as an analysis of the suggestion systems that these companies already had, through informal interviews with employees, mostly office staff. The major difficulties were found, and a first version of the prototype was developed in Adobe XD. Afterwards, formal interviews were carried out to understand the acceptance of the system created, at the same time as a co-creation process with the employees. In this scope, it was possible to approach the integration of the Disney strategy in the system and understand its suitability to the organizational processes. Furthermore, since the PDCA tool (originating from lean) was widely used in the three companies, it was adapted to the visualization system, thus facilitating the monitoring of the status of the suggestions submitted. In the end a new version of the prototype emerged, which is the one demonstrated in the following chapter.

3.2 The Kaizen Ideas System: A Prototype

Based on the first analysis of informal interviews with the companies, with a view to identifying the problems in the current suggestion systems, the main difficulties that emerged were: 1) The employee can only view their suggestions (with those of others being left out) - according to employees this makes it difficult when someone wants to give a new suggestion, but does not know what others have submitted, and there may be redundancy; 2) Employees are not able to view the status of their suggestions and cannot follow up on them; 3) There is submission of suggestions that do not add value (because there are monetary rewards); and 4) Two of the organizations had physical suggestion systems where a lot of information was constantly lost.

The prototype built aimed to solve the problems encountered by creating a more visual platform where employees can see everyone's suggestions and monitor their status. This visualization and monitoring were based on the adoption of the PDCA tool, currently used in the Daily Kaizen boards [16], where it is possible to visualize the follow-up of corrective and/or improvement measures. The dashboard represented in Fig. 1 shows the view regarding the employee's own suggestions. Note that the PDCA frame has been changed to "Submitted", "Under Evaluation", "In Implementation" and "Implemented" (in the employee's view there is one more which is the "To answer").

This tool, besides submitting suggestions, has embedded a creativity process recognized by Neuro-linguistic Programming called the Disney Strategy [17]. This strategy intends to phase the creativity process into three distinct moments (see Fig. 2). The first moment is the **Dreamer phase**, in which the person has the idea and must specify (always

Fig. 1. Interface that communicates the status of employee improvement suggestions

positively) the parameters of that idea, while determining what results/improvements it would generate. The second moment is the **Realist phase**, in which the person must think about steps to take in the realization of the idea, establishing milestones for the entire process. And finally, the third moment is the **Critic phase** where the person takes a long look at what the two previous phases had as output and thinks about what could go wrong, thus realizing if the whole process is ecological.

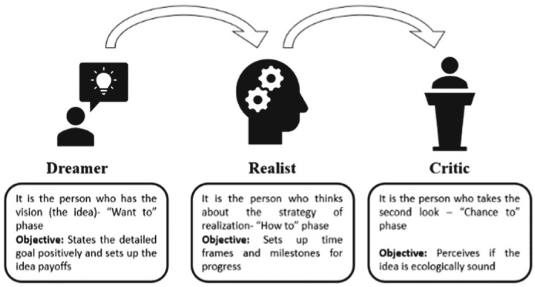

Fig. 2. Diagram representing the phases of the Disney Strategy

This strategy was then adopted by the platform (see Fig. 3) in an adjusted way, in which the person who has the idea starts the process with a set of questions oriented to the goal of the first phase (Dreamer) and then, randomly, people from the same area are selected to constitute the Realist and Critic places. These people receive the Dreamer's idea in the "To answer" box (see Fig. 1) and must proceed to answer the questions that guide to the second and third phases. In the original method only one person performs the process consisting of the three phases, but the change to three people is intended to make the ideas more mature when they move to the evaluation moment.

It should also be noted that after submission, it is possible to add comments or "like" any suggestion, so that there is always the opportunity to improve it or even establish the need for its implementation through positive reinforcement.

After final submission by the Dreamer, an evaluation committee receives the suggestion and proceeds to evaluate it. It should be noted that the status of the suggestion will always be monitored, both by the participants in the suggestion and the other employees of the company (using the adapted PDCA cycle).

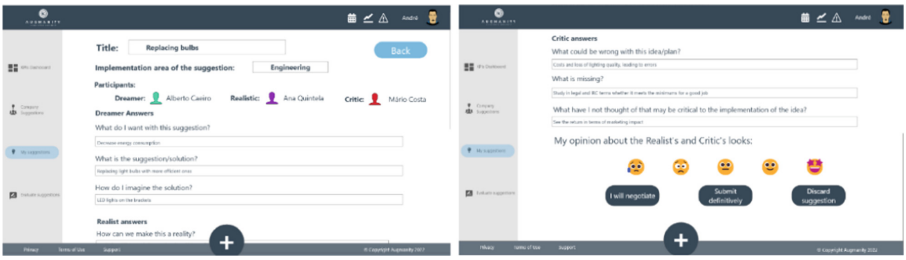

Fig. 3. Interface where questions from the Dreamer, Realist and Critic phases have already been answered (Here the Dreamer checks to see if he is happy with the answers or if he still wants to negotiate them with the people in the Realist and Critic roles).

4 Discussion and Final Remarks

The presented tool aims to provide solutions to the problems encountered - (listed from 1 to 4 in Sect. 3.2) in the suggestion submission systems of the three companies addressed. Through the implementation of the PDCA tool in a dashboard format it is possible to follow the status of suggestions (from the employee and the company) and visualize which suggestions are being submitted (to avoid redundancy of ideas), thus solving problems 1 and 2. The Disney strategy, which comes from Neuro-linguistic Programming and is strongly applied in Coaching practices, is integrated here in order to promote the maturity of submitted suggestions, so that there is no waste of time and resources in the evaluation, which solves problem 3. Since this is a digital tool, problem 4 highlighted is also solved.

This tool seeks to act at the level of employee engagement, since it enables, in a very transparent way, a participatory design, directed not only to the employee's workplace, but to the entire organization. At the same time, it promotes a learning culture, where tacit knowledge is shared, because suggestions are accessible to anyone and, in addition, it is possible to comment with new add-ons or even positive reinforcement of the suggestions submitted. Knowing from the literature that engagement fosters innovative work, the Disney Strategy comes to structure this creativity in the submission of suggestions for improvement. On one hand, it allows the creation of more mature suggestions, in which three people have already thought about them, providing some filter before evaluation. On the other hand, it determines such a step-by-step process that reduces the occurrence of the employee putting obstacles right at the birth of the idea, an action that is inherent to the human constitution. Thus, this is a technological tool that can strengthen two of the pillars of work engagement, being participatory design and knowledge sharing. In this way, and consequently, it is likely to create a culture of labor retention where the employee gains voice behavior and, furthermore, a supporting structure is created to start to build a Learning Organization, preserving the organizational knowledge, which can be threatened with the departure of employees.

The tool described here unites two major areas, Lean Manufacturing (through the PDCA tool and the Kaizen Teian) and Coaching (through the Disney Strategy). The truth is that these areas were already born together, however companies undervalued the application of Coaching when applying Lean, which was essential for companies to

truly succeed in lean transformations [16]. With such market volatility, it's time to invest time to truly develop people, and the same leadership that encourages Lean may have to encourage coaching.

As limitations, this is a tool that still needs further validation, where other activity sectors can be included, as a way of extending it to the industrial sector. As future work, the development of the tool is already underway and, after that, it will be tested in a real context, starting in the three organizations described.

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How Industry 4.0 and Lean Management Are Interrelated with Green Paradigm

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Abstract. Recently, sustainability has been tackled several times due to the impending climate change the earth is facing. Numerous techniques have been applied to reverse the direction companies were going into. In this paper, it is explained the importance that Lean Manufacturing tools and Industry 4.0 technologies can have on the sustainable side of a company. The aim of this work is to fill the scientific gap related to studies deepening the combination of these different paradigms, Industry 4.0-Lean-Green, which have been scarcely investigated together. Thus, a Systematic Literature Review has been performed to detect which were the key variables of these three fields and then, it was studied what their interaction was. This study is giving the opportunity to understand the main variables of Industry 4.0 and Lean manufacturing on which companies have to act in order to have an impact on green variables and their overall sustainability.

Keywords: Green · Industry 4.0 · Lean Manufacturing

1 Introduction

Nowadays, customers' requests and environment's claims push industries to be even more precise, correct, fast and respectful. Customers wants products to be still more customized, flexible, durable with the least possible cost and the highest possible quality which can respect their private and social needs. On the other side, the environment asks for the reduction of resources' usage and the release of the minimum possible pollution, tackling the climate change and working to preserve the eco-system. As a result, industries, as part of our society, are pushed by an urgent call for action. To answer to these combining needs, companies select and team up different approaches. In this paper we will discuss in particular about the Industry 4.0 technologies, Lean practices and the Green paradigms. Lean manufacturing is one of the most applied methodologies and according to Womack and Jones [1], it is about the implementation of a continuous improvement which allows companies to reduce costs, improve processes and eliminate wastes in order to increase customers satisfaction. The fourth industrial revolution, recognized as the Industry 4.0 (I4.0), involves a hyper-connected system of smart materials, factories, suppliers, distribution channels, and even customers. It

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can provide higher levels of productivity and customizations [2] by delivering a value-add to end users. The Green paradigm (GP) was born as a philosophy to reduce the negative ecological influence of an organization. It aims to reduce environmental risks and impacts while improving ecological efficiency and eliminating environmental waste in organizations [3]. Despite the strong interest on the Industry 4.0-Lean Manufacturing implementation from a sustainable perspective, the literature lacks of real knowledge to adequately address all these topics within companies. In order to address this lack, this paper will identify the relevant variables, coming from the GP, the I4.0 and Lean Manufacturing (LM) paradigms, and their relationship.

2 Research Question

The aim of this paper is to combine three different paradigms, Industry 4.0-Lean-Green, which have been scarcely investigated together. The detection of variables in each domain is of paramount importance as also the existing associations between them. Given these premises, the developed research question (RQ) is: "What are the key variables and their relationship that the manufacturing organizations have to take care of in implementing the Industry 4.0 together with the Lean paradigm towards the Green one?". This question has found an answer in the paper through the conduction of a Systematic Literature Review (SLR) and a subsequent table showing the linkages among the identified variables.

3 Methodology

3.1 Systematic Literature Review

The Systematic Literature Review (SLR) represents the starting point and it is beneficial to answer to the focal question of this work. Firstly, to guarantee valid results, each of the three paradigms was defined. Secondly, to study all the three topics, it has been decided to focus the attention on three investigations made by the combination of the three paradigms. A structured methodology was applied for each of the investigations and relied on a five-steps process showed in the following Fig. 1.

The database selection was fundamental to base the research on a reliable source. Papers have been selected from Scopus containing renowned publications like Emerald, Taylor and Francis, Springer, IEEE, and Elsevier. The keywords have been chosen with the aim of reaching more inherent articles possible. The filtering performed after the research was based both on inclusion criteria as document type (review), subject area (Business, Management and Accounting; Engineering; Energy; Environmental Science; Social Sciences; Decision Sciences; Computer Science; Economics, Econometrics and Finance) and language (English) and on additional screening techniques looking at the Journal Quality type (Q1), title, keywords and abstract. Finally, the reference analysis was done checking the inherent topic, the Journal Quality type (Q1), title, keywords and abstract of the cited documents.

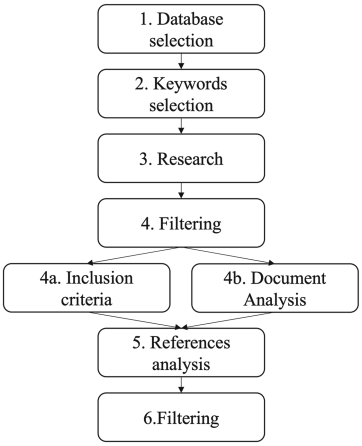

Fig. 1. Structured Methodology of five-steps adopted for conducting the literature research.

3.2 Interrelationship Table

To continue answering the research question, it is necessary to understand the relationships between the variables found thanks to SLR. Thus, the relations identified in the literature have been collected in the Table 1. The first column represents the "impacting variable" that influences the "impacted variable", put in the second column. In the latter column, for the affected variable, there are indicated also the references to the considered articles which talk about that specific relationship.

4 Results

4.1 Systematic Literature Review

As a result of single researches about the three topics, the I4.0 and the LM represent analyzed and well-defined topics in the literature, while the boundaries around the Green paradigm result still more blurred, because addressed in recent years. Then, the involved combinations have been the following: the understanding of how Industry 4.0 technologies and Lean practices link each other, how Digital technologies (DTs) can influence the GP and how Lean practices impact on the GP. To each of them the 5-steps process has been applied.

Industry 4.0 & Lean Manufacturing. The analysis related to the combination of Industry 4.0 and LM concepts saw the selection of "Lean AND Industry 4.0 AND Literature review" as keywords to conduct the research. The initial quantity of found documents was 110. After filtering them and taking into account references, 30 articles have been considered. Industry 4.0 and lean tools are presented as complementarities to support system design and improvement [4]. Although LM practices can be carried out without the help of IT tools, manufacturing digitization is crucial to the LM implementation and its continuous improvement to achieve benefits in term of productivity improvement [5].

The literature evidences that is unclear, on a quantitative basis, which practices could be combined, which ones are complementarities, and which contradict each other, concluding with the lack of a framework quantifying all the possible links between Industry 4.0 and LM [6].

Industry 4.0 & Green Paradigm. In order to analyze the Industry 4.0 and Green context, the keywords have been "Green AND Industry 4.0 AND Literature review". The research has given 201 documents as a result. After the filtering phase, 9 papers remained, and the next phase of the reference analysis added 31 more. Through sustainability practices (sustainable production, sustainable purchasing, sustainable performance measurement and management, sustainable governance, sustainable marketing, sustainable design and circular economy), Industry 4.0 contributes to sustainability performances (environmental, social and economic ones). Such practices offer advantages such as manufacturing productivity, resource efficiency and waste reduction [7] and control of energy consumption. Overall, DTs will have a positive impact on the environmental performance, even if fully automated production could lead to a higher energy consumption or an increased demand for scarce raw materials. Only those companies able to integrate a sustainable use of Industry 4.0 standards in their systems will be competitive in the long run.

Lean Manufacturing & Green Paradigm. For the analysis between the LM and the GP, "Lean AND Green AND Literature review" as keywords have been chosen. This time the research led to 38 documents of which just 5 were selected according to the inclusion criteria. The final number obtained from that investigation resulted to be 44, because other papers were added after the reference analysis phase. Researchers conclude that LM and GP are overlapping in terms of obvious similarity: the LM considers as the main objective the reduction of time and waste, as well as the GP consider the reduction of the environmental footprint, but the definition of waste represents a conflicting point. LM focuses on workforce and space reduction to increase flexibility, while GP aims at reducing, recycling and reusing (3Rs). Additionally, LM aims at reducing non-value adding activities which could be translated as the reduction of energy and natural resource consumption. Considering the lean practices, the Value Stream Map (VSM) is one of most used tool because it is adaptable to the context with just a change in the meaning of the type of non-value added activity. 5S allow to achieve less defects, cutting the environmental waste; the Human Resource Management (HRM) has a positive effect considering the training and commitment of the people. Total Productive Maintenance (TPM) also has a positive effect through the proactive and preventive maintenance, reducing emissions, resources and scraps; JIT is one of the most conflictual, in both positive and negative way [8–10]. Tools, principles, resources, practices and strategies, proper of each of the three cited paradigms, can be promoted as variables to achieve the common goal: the exploitation of the I4.0 and LM paradigms to impact the Green one. Thus, the SLR allowed to answer to the first part of RQ with the identification of twenty-seven variables distributed in the following three clusters showed in the Fig. 2:

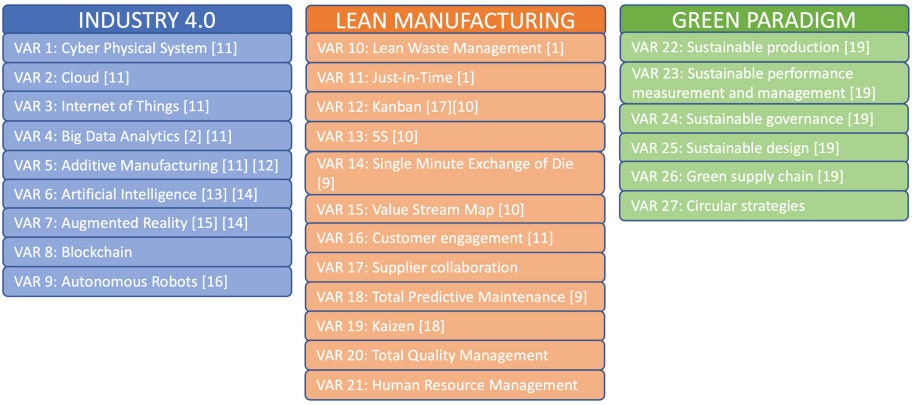

Fig. 2. Three clusters of key variables.

4.2 Interrelationship Table

This passage is very important, because a variable can be affected not only by increasing and dedicating to it more resources but also influencing other variables on which it depends. In this paper the relations under analysis were the ones identified in the Systematic Literature Review between the variables of three domains: the I4.0 and the GP, the LM and the GP and the I4.0 with the LM. The influence of "variable 1" to "variable 2" for each of these three combinations is meant to be unidirectional. As a result, the following table (Table 1) is showing all the of the 21 variables (I4.0 and LM ones), according to the directed and chosen combinations.

Table 1. Interrelationship table

Impacting variable	Impacted variable [references]
1	12, 15, 18 [16], 21, 22, 25, 27
2	11 [20, 21], 12 [7], 14, 16 [21], 17 [21], 23 [19], 24, 25, 26 [19], 27 [22]
3	12 [21], 15 [6], 22, 23, 25 [20], 26, 27
4	11 [10], 12 [7], 13 [7], 14 [5], 16 [16], 17 [16], 18 [16], 20 [21], 21, 22 [19], 23, 24 [23], 25 [20], 26 [19], 27 [24]
5	11, 12, 14, 18 [10], 22 [25], 25, 27 [25]
6	11 [13], 12 [13], 15 [13], 18 [13], 19 [13], 20 [16], 22 [26], 23, 24 [23, 27, 28], 26, 27
7	11, 12 [29], 13 [16], 15 [4], 21, 23, 27
8	16 [30], 17 [30], 23, 26

(*continued*)

Table 1. (*continued*)

Impacting variable	Impacted variable [references]
9	11 [21], 12 [5], 13 [21], 21, 22, 23
10	1, 3, 4 [6], 9 [13], 22, 23, 26, 27
11	2 [16], 22, 23, 26
12	5 [12, 13], 22, 23, 26
13	7 [13], 9 [13], 22, 23, 26, 27 [8]
14	22, 23
15	2 [16], 4 [16], 22 [9], 23, 25, 27 [9]
16	23, 25, 26, 27
17	23, 26 [18], 27
18	22, 23, 27
19	2 [16], 4 [6], 9 [6], 22 [9], 23 [18], 25, 26, 27
20	22, 23, 26, 27
21	22, 23 [8], 26, 27 [17]

5 Discussion

From the interrelationship matrix, the most impacting I4.0 variable for the green ones is VAR 4, as Lopes de Sousa Jabbour declared, the collected data foster sustainable operations management decisions, contributing to the connection between the principles of circular economy and I4.0 [11]. It affects all the GP variables identified, thus it is convenient to manage it cleverly. The most impacted green variables from I4.0 and LM ones were VAR 22, VAR 27 and VAR 23 an example is provided by Tan in the case of green logistics implemented by blockchain [31]. While the less affected variable from the Green paradigm was VAR 24, where sustainability should be considered at a business long-term decision level, thus more complicated to reach.

6 Conclusions

An answer to the formulated research question has been given in two steps. Firstly, the Systematic Literature review referred to the three combinations of the domains and produced an outcome of 27 key variables. Secondly, the relationships between these variables were analyzed. As a result, the most impacted green variables from Industry 4.0 and Lean manufacturing variables were identified. Indeed, in manufacturing contexts, where DTs and lean tools can be recognized, they can be used as levers from the company to reach, through their performances, yearly company's sustainable goals.

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Improvement of an Air-Conditioning Pipes Production Line for the Automotive Industry Using Lean and CONWIP Methodologies

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Abstract. The presented work is focused on applying continuous improvement tools to reduce waste and process variability throughout an air-conditioned pipe production line (PL), to determine the line's capacity and improve efficiency so that the desired productivity levels can be achieved. The line's processes were analyzed, together with the integrated application of continuous improvement and Lean tools to determine and improve its production capacity. Thus, a variability study was carried out, focused on balancing the PL, to reduce the main bottlenecks. After balancing, several improvements were performed in the line layout, improving the line efficiency, and reducing unnecessary employees' movements. Simultaneously, the Constant Work-In-Progress (CONWIP) methodology was implemented facilitating the management of the component's production before their entry into the PL. Other modifications were also implemented, both mechanically and in terms of documentation, to support production and contribute to the line's increase in efficiency, quality, and safety. The results obtained are relevant, with an increase in the capacity of the line and its productivity and efficiency, from 28.81% to 47.21%, and an increase of 18% in the Overall Equipment Effectiveness (OEE).

Keywords: Lean · Balancing · Improvement · CONWIP · Efficiency · OEE

1 Introduction

In a constantly evolving business context, organizations operate in increasingly complex environments, as is the automotive industry, with the need to develop different and better-quality products, ensuring even more demanding temporal commitments [1]. The competitiveness and the demands of this industry increasingly require improvements and the elimination of waste [2]. Factors as increased availability of equipment are essential to allow an efficient response from the company to the customer. Thus, companies present in this market, with production areas organized mainly in the form of assembly lines, will consider the reduction of losses and waste levels in their processes.

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The study described in this article was performed at a company focused on the production of air-conditioning pipes for the automotive industry. The main objectives were to determine the production's line capacity, to analyze the main bottlenecks within the process and apply Lean and Continuous Improvement Tools (CIT) to optimize it, ultimately identifying and acting over the main sources of waste detected during this analysis, and compare the Overall Equipment Effectiveness (OEE) results before and after this work. To achieve these objectives the research question is "How to improve the air conditioning pipes' Production Line (PL) OEE?". Throughout this work, several CIT and Lean tools will be applied to solve the problem in scope. Namely, concepts like Just-In-Time (JIT), the *Kanban* method, *Heijunka* and Standardized Processes [3]. This article is organized in five sections. Beyond the current section, Sect. 2 presents a literature review, with a brief explanation of Lean philosophy, Kaizen, CONWIP, and OEE. Section 3 presents the used methodology. Section 4 exposes the main problems founded. Section 5 presents the results were and in Sect. 6 the conclusions and contributions of this study to the automotive industry are revealed.

2 Literature Review

Lean Production represents a better way to manage business relationships, as well as the supply chain, product development and production operations. In the same line, CIT also known as *kaizen*, defines a company's approach, contributing to the creation of a culture of continuous learning and an environment that promotes change [4]. Known as Lean philosophy, whose focus is to eliminate *Muda* (waste), associated with activities that consumed resources but did not create value for the organization [5]. Besides Kanban, another stock control system the Constant Work-In-Progress (CONWIP) can be used [8]. Characterized by its flexibility and superior efficiency and easily adapted to scenarios with greater variability and differences between products, its purpose is to control or manage the total amount of work (WIP) in a productive environment, keeping it constant, at the end of the line releases the respective card, then it becomes available for a new order [9]. Other relevant tool is 5S + S (an evolved version of the 5S methodology [9, 10]. The OEE is one of main metrics considered in mass production environments. This indicator is represented by three different indexes: availability, efficiency and quality, respectively accounted to consider breakdowns and setup pauses, short- or long-term breakdowns and scrap or rework related breakdowns [10]. Several cases describe whose objective is to increase the efficiency and capacity of PL in the automobile business with the implementation of Lean philosophy and tools [11, 12]. A project associated with the installation of 7 final PL and 7 pre-assembly lines was analyzed to assess how waste reduction could be achieved in the production scenario. It was concluded that eliminating unnecessary activities, along with the optimization of work, resulted in large savings, namely around 10.9% of the investment initial cost considered for the project, €2,159,000 [13]. Antoniolli et al. [11] applied Standard Work methodology, supported by Lean and Kaizen philosophy, in a PL of a company in the automotive sector and it was possible to define the line's capacity and the efficiency values also raised, as the OEE, that increased on average from 70% to 86% [11].

3 Methodology

Action Research (AR) [14] and methods from Lean (Heijunka, Standardized Work, 5S) and CONWIP [8, 9] were the applied methodologies that consists of three main parts: 1) Deep observation of the manufacturing environment, escorted by the mapping of the processes and material flows of the PL, to better understand it and how it operates; 2) Initiation of the variability study regarding this work's target, by analyzing the PL and determining the main problems and respective opportunities for improvement; 3) Method application, starting by measuring times, forming product families, and determining the processes' bottlenecks. The found opportunities were explored to balance and improve the efficiency of the line and its capacity, so production objectives could be achieved and the waste levels, reduced.

4 Study Development

This study's target PL had little and outdated information regarding its capacity and its production objectives. Hence, the line worked with an undefined number of workers and shifts, according to the client's needs and place orders. On the initial stage of this work, the only data that was provided was that the global production objective defined for the line was of 28 parts/h, defined according to the bottleneck of the line. The PL was supported by several preparation areas, where the components are submitted to several operation until they are ready to enter the line. These components are assembled and submitted to a different set of operations in the PL, until a completed part or reference is obtained. In the preparation phase, the process starts with two distinct operations: the hose is provided directly to the line; the aluminum tubes are supplied to the line through a *Kanban* system, being submitted to several preparation operations until they are put into shop stock. Usually, two references are produced at the same time (Line A and B), depending on the occupation of the workstations. As the preparation stages are finished, the aluminum pipes in Shop Stock are used by the PL. The references of Line A will first be pressed, being the hoses united with the aluminum pipes for each subset. These subsets will then be submitted to an obstruction test (to assure that no occlusions exist internally within the tube), followed by a leak test (to verify that the tubes are leak free). Some references will then go through a *Stud* screwing operation, along with a labeling, bracket and clip assembly process. Both subsets will then be screwed together. In the end, all the finished products geometry will be verified in a final control gauge and packed as indicated. In Line B, the parts are less complex, two parts of one subset, and are submitted to lesser operations, being the pressing, stud screwing, leak testing, and verification and packaging stations process equivalent to the process in Line A. Final, the products are transported to the finished products warehouse and shipped to the final consumer according to the orders. The line's complexity reveals the need for a deeper analysis to better understand the production process and to uncover the best way to increase the manufacturing line's OEE. An up-close monitoring of the PL was made, complemented with interviews conducted with the workers and the production's supervisor to better know the real problems that the line was currently facing. It was possible to summarize the main problems identified in Table 1.

Table 1. Description of problems identified

Problems	Description
Unbalanced line	Workstations were not balanced due to the large variability of the conceived products and the different production times between them (PL monitoring showed in several workers' meetings)
Low efficiency	Low efficiency, since the efficiency of the line is very low when compared to the remaining assembly lines in the company (meeting with the production's supervisor)
Unattainable demand	Failure to match the established objective with customer demand for some references (meeting with the production's supervisor)
Displacements	Long and unnecessary distances covered between workstations (PLMonitoring)
Negligence before non-cyclical operations	Non-cyclical activities such as the material supply to the line workstations and displacements between stations were not considered when defining the initial production objective (PLMonitoring)
Difficult component's preparation stage management	Hard supervision of the component's preparation stage before they entry the assembly line, leading to an increased difficulty to manage the assembly line (concluded through the meetings with the line's workers)
Long bottleneck workstations	Excessively long bottleneck times in some workstations to produce several references (observed during the PLMonitoring)

After determining the main issues, one proceeded with the description of the main opportunities for improvement. Regarding the customer orders, it was possible to conclude that the production objective was around the 862 parts per day. Following, it would be possible to apply several improvements to eliminate all the wasteful activities and improve the line's condition. After the Initial analysis stage, the improvement implementation is divided between 2 additional stages: Iteration 1(I1) (first improvement stage) and Iteration 2 (I2) (second improvement stage). Considering the previously stated opportunities for improvement, the improvement process began by the execution of a variability study to evaluate the true capacity of the line when compared to the initial situation it was in. The process started with the following steps: the formation of reference families, the determination of the production proportion per family, the measurement of Cycle Times (CT) (according to the procedure) and the line's balancing for the minimum number of operators $N, N-1$ and $N+1$ operators. In I 1, the cycle times were analyzed for the work

defined for two shifts, respectively associated to 77, 5 h of weekly work. From these data, a Takt Time (TT) of 186.3 s was obtained, i.e., a production rate corresponding to the manufacture of two parts every 129.5 s. Considering that the bottleneck for a large number of family combinations exceeded the value of the TT, then it was possible to consider that the customer's needs could not be satisfied in this situation. In this sense, it was necessary to intervene in the process. Several improvements made were made at a mechanical level, among which: the modification of the leak test appliances (that promoted the reduction of scrap parts by reducing the damage tubes due to this tool feature), the reduction of the screwing machine gaps (that led to the minimization of the equipment failure frequency) and the improvement of a bracket closing machine. This machine had a wait time of 8.3 s because the operator had to wait for the machine to automatically close the "clips" and brackets to be able to start the manual operation of placing the tube label on the next part. In changing the label dispenser to the exterior of the machine, the wait time was eliminated, and the workstation CT was reduced from 249.4 s to 232.8 s. Several improvements regarding the existing documentation were also conducted to simplify and improve the processes for the operators and other stakeholders involved in the production, such as: the actualization of the preparation instruction document to include the drills identification (so that the workers can easily replace them when they are lost or damaged) or the creation of an Roadmap Problem Solving (RPS) to guide people to readjust the already altered screwing machine, amid others. After the implemented improvements, the line was rebalanced in I 2, and the line's operation was also tested for three shifts, with 111.5 h of work per month, thus resulting in a TT of 186.3 s. It was found that the bottleneck was lower to the TT for at least one of the balances carried out for each combination of families, thus indicating that the line would have to work three shifts to fulfill customer orders. After performing the balancing, it was a need to determine the actual capacity of the line, because TT is calculated based on the available working time and according to the number of daily parts needed to be reached. As each combination of families is subjected to a different set of processes, with production times that also vary greatly among themselves, the comparison between CTs with a general production rhythm may prove unfounded. Thus, it was decided to analyze the capacity of the line, considering the cycle times and the production of parts required by combination of families, in detriment of the response against a fixed number of 862 parts/day. In this sense, a comparison of the capacity of the PL between I1 and I2 was made, considering the operation of the line at an efficiency of 90%. Considering the family combinations, we used the respective monthly requests per reference and the CT of each family combination to determine the Total Production Time (TPT) for $N - 1$, N, and $N + 1$ workers. To obtain the total time consumed in production at a 90% efficiency (I 1), it was necessary to know the N for each family combination. For Combination A, N is equal to 2, meaning a balancing for 1, 2 and 3 workers. For Combinations from B to J, N is equal to 3, meaning a balancing for 2, 3 and 4 workers. Summing the production times of each combination for N, $N + 1$, and $N - 1$ workers, it was possible to calculate the TPT(1 part per cycle) was of 477.9 h for N − 1 workers, 343.9 h for N workers and 286.7 for N + 1 workers. To obtain the total time consumed in production at a 90% efficiency (I 2), it was once again required to know the N for each family combination. For Combination A, N remains equal to 2, meaning a balancing for 1, 2, and 3 workers. For

Combination F, the N value changes and becomes equal to 4, meaning a balancing for 3, 4, and 5 workers. For the remaining Combinations from B to J, N is equal to 3, meaning a balancing for 2, 3, and 4 workers. Summing the production times of each combination for N, $N + 1$ and $N - 1$ workers, it was possible to calculate the TPT (1 part per cycle) was of 470,0 h for $N - 1$ workers, 336 h for N workers, and 272.1 for $N + 1$ workers. It is understood that the operators would work an average of 21 days a month and that, per day, after removing all breaks (time for breakfast, lunch and cleaning the station), they would actually work for 14.9 h when working three shifts and 22.9 h when working three shifts. This way, one was able to determine that the effective monthly working time corresponded to 312.9 h per month, working two shifts, and 480.9 h, working three shifts. Considering the results for I1 and I2, it was concluded that with a two-shift work, $N + 1$ operators are still needed to fulfill customer requests, as usual. It also becomes possible to work in three shifts with $N - 1$ operators to satisfy demand.

5 Results

As previously stated, the only data initially provided was the line's bottleneck - about 28 parts per hour, considering the production of one part per cycle. Through the results present in above, and considering a monthly production of 18102 parts, it was possible to compare the results between the current situation, I1 and I2 (with the production of 1 one part per cycle). The results are presented in Fig. 1.

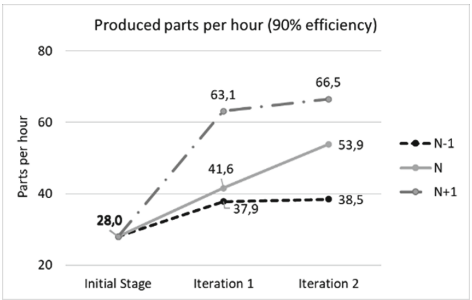

Fig. 1. Produced parts per hour at a 90% efficiency

Through the graph of Fig. 1, it is possible to state that the best results can be obtained choosing I2. Based on the exposed times, and with the line working three shifts with $N - 1$ operators or two shifts with $N + 1$ operators, it is now possible to confirm that the targeted production time is 38.5 parts/h or 66.5 parts/h, respectively. The OEE has been calculated, see Table 2. PL's OEE includes the availability, efficiency and quality indexes provided and measured by the company's internal management system, considering that the line's efficiency is obtained through the ratio between the time determined at the time of delivery of the project, taking into account the estimated time consumed with the production of one part, in comparison to the actual total time required to produce one part. The results demonstrate that, by February, the OEE was approximately 28%.

However, in June, prior to the industrialization actions on the PL (which contributed to additional stoppages, damaging the line's OEE), this indicator reached the value of 46%. With an approximate increase of 18%, it is possible to conclude that the actions implemented were beneficial and contributed to the line improvement. Also, regarding Table 2, it is possible to observe that OEE is mainly affected by the Efficiency factor, which can be explained by the problems previously identified.

Table 2. PL's OEE

Months	Availability (%)	Efficiency (%)	Quality (%)	OEE (%)
February	98,5	28,8	99,5	28,2
March	99,6	38,8	99,8	38,6
April	99,2	44,2	99,9	43,8
May	98,8	44,5	99,5	43,8
June	98,0	47,2	99,8	46,2

6 Conclusions

The work carried out consisted of applying CI tools to reduce waste and process variability along the production line, with the objective of determining the line's capacity and achieving the desired productivity levels, namely, the OEE improvement. To this end, an analysis of the production line processes of the company that manufactures flexible tubes for air conditioning systems and the integrated application of continuous and Lean improvement tools was carried out, through the use of AR methodology, to determine and improve its production capacity. To this end, the work started by carrying out the line variability study, starting with the development of line balances. Considering the previously mentioned balances, the best results were obtained after I2. At the production/hour level, there was proportionally an overall increase in the objectives of the line from 28 parts/h to 63.1 parts/h, 41.6 parts/h and 37.9 parts/h (for $N + 1$, N, and $N - 1$ operators), for I1 of the balancing, and later, for 66.5, 53.9 and 38.5 parts/h (for $N + 1$, N, and $N - 1$ operators), after balancing and applying improvements in I2. It was concluded that for the operation of the line in three shifts with $N - 1$ operators or two shifts with $N + 1$ operators, the production objective would be 38.5 parts/h or 66.5 parts/h, respectively. After carrying out the balance, multiple interventions were carried out, namely in terms of layout and the ease of organizing the components before going online. For the layout, several changes were made to increase efficiency and safety. Likewise, the implementation of the CONWIP methodology on the line made it easier to manage the production stages for the components before coming online. In addition, many other improvements were also made, ranging from mechanical modifications to the equipment, to the updating and implementation of technical documentation to support operators, namely through visual aids and RPS. To do that, 5S + S tool has been

used. These contributed beneficially to the increase in production, quality and safety of the processes. Globally, the positive effects result from the implemented improvements were notorious. The efficiency of the line increased from 28.81% to 47.21% in a five-month span. This increase was also reflected in the OEE, which rose from 28% to 46% in the same period. It is possible to conclude that the initially established objectives were fulfilled, since it was possible to determine and increase the production line capacity, through the application of several CI techniques. At once, there was a gradual increase in the line's efficiency, as well as in the OEE, which indicates that the improvements had a positive effect.

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Application of Lean Office Concepts in the Management of Labor Grievances and Commercial Matters: A Case Study in a Retailers' Network

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Abstract. Although Lean was developed for manufacturing, it was quickly expanded to other areas, thus resulting in Lean Office (LO), which can be defined as a system of standardized service operations. It consists of activities to generate value for the customer and am to meet their expectations of quality and price while focusing on intangibles. This study evaluated the applicability of LO concepts in the management of labor grievances and commercial matters in the legal department of a network of retailers. The data was collected through unstructured interviews, observations, and database analysis. The study was divided into diagnosis, application of Lean tools, and the implementation of indicators. As a result, the internal mapping was developed, and new flows were established, eliminating waste and activities that had not added value. Following the Lean philosophy, a new management system was defined and implemented, which increased processes efficiency and reduced the expenses in lawsuits.

Keywords: Lean Office · Lean Service Management · Labor Grievances and Commercial matters

1 Introduction

Given the current context in which we live, the search to reduce waste, adapt the environment to high productivity, and improve the quality of services has become increasingly crucial for a company to maintain its position in the economic scenario. Therefore, Lean becomes a powerful tool for achieving these objectives, even if the differences inherent in the service sector concerning the manufacturing sector could result in difficulties in evaluating and controlling internal processes.

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This case study reflects the analysis of a project developed and implemented by a consultant in the legal department of a large retail company operating in Brazil. The main objective was to evaluate the applicability of Lean Office (LO) concepts in managing labor grievances and commercial matters (management of non-strategic lawsuits) of a retail company to reduce the provision of lawsuits against the company so that there is a positive impact on the company's results. The company maintains a multi-business and multi-channel operation, with over 500 physical stores distributed in several Brazilian states and e-commerce operations.

Although there is no empirical evidence to support the hypothesis that poverty, economic crisis, and unemployment are directly related to the increase in the number of conflicts, the complexity of Brazilian society and its economic inequality were factors related to the stimulation of the high potential for litigation [1]. The company's legal department deals with advisory, compliance matters, labor, civil, regulatory, tax, corporate, and real estate lawsuits. However, the case backlog is predominantly made up of civil and labor lawsuits, which have a stock of active cases of approximately 110 thousand cases, a filing rate of approximately 7.5 thousand cases per month, and a closing rate of approximately 4,300 lawsuits per month. To manage the portfolio of lawsuits, the department had approximately 140 employees and 25 outsourced law firms that assisted in the management and defense of lawsuits.

This paper was based on a project developed by a consulting company in a large Brazilian retailer. The project consisted of implementing LO concepts in the company's legal department and was developed throughout the first half of 2017. The project was developed only for managing labor grievances and commercial matters, i.e., only non-strategic lawsuits concerning labor and civil law. Also, there is a lack of studies extending the Lean philosophy to apply the Lean Office in the legal sector and management of labor grievances."

To achieve the main objective, this paper aimed at identifying the value flows of the legal department processes, carrying out the internal mapping, creating flows eliminating waste and activities that do not add value and defining new system management supported by the control and improvement of internal processes following the precepts of the Lean philosophy.

It was possible to increase the efficiency of internal controls, processes, and document management, increasing the wrongful dismissal rate of the company's opposing notices, improving synergy with the accredited offices and their results, besides structuring preventive actions so that there is no impact on the company's cash flow, by implementing a continuous improvement and LO project in the company's legal department, since ongoing legal lawsuits are passive contingencies needed to be recorded in the balance sheet. The practices recorded here could be implemented in several other companies and service contexts.

Regarding the structure of the paper, Sect. 2 presents the Literature Review of LO. Section 3 describes the Research Method in seven processes (prior to Lean transformation, implementation of the LO, value streams, mapping, design of future flows, definition of the future operating model, and process control and improvement). Section 4 presents the results and discussions, and Sect. 5 presents the final remarks.

2 Lean Office (LO)

As of the good results in the manufacturing processes, Lean started to be used in the administrative areas, having as approach the "Lean Office" (LO). The study of [2] defines this approach as the improvement in the information flow and in administrative areas. The study shows that LO assists in the reconfiguration of the information flow and the continuous improvement of organizations.

[3] present the application of value stream management and define eight steps for the implementation of LO: commit to lean; choose the value stream to learn about Lean; map the current state; identify lean metrics; map the future state; create Kaizen plans and implement them. They also consider that in administrative areas, the waste is more severe than in the manufacturing environment.

[4] considers that LO can be characterized from two perspectives: improvements focused on the standardization of tasks and rearrangement of the physical space, and the other and more recent focused on learning and problem solving focusing on reducing lead and task times. In summary, the LO concept focuses on eliminating the seven types of lean waste: (1) overproducing; (2) waiting; (3) overprocessing; (4) inventory; (5) motion; (6) defects or correction; and (7) transport. The new office design should be architecturally designed to eliminate these wastes.

They exemplify that the waste of inventory refers to waste in the office process caused by the storage of work material. A standardized workstation design and equipment be limited at both workstations and the office; work material can be limited by digital storage instead of physical storage of working material; and applying the 5S system, a system that aims to bring order and limit space at the workstation. Besides, the waste of motion within the workspace can be reduced with the limitation of a place of standard office equipment such as typewriters stations.

[5] show in a case study the application of Lean principles in the company's office floor in handling the administration of customer order acceptance. The Value stream mapping was used to identify the wastes in the current state and to design the future state to achieve the company's target by eliminating the occurring wastes, focusing on reducing the customer response's Lead time.

Another application is presented by a case study in a university office in Portugal [6], where Lean tools such as electronic standardization were applied to six educational projects of the department, the organization of computer desktop to improve the information flow, implementation of Key Performance Indicators (KPIs) and 5S. They got a reduction of 84% in the time to search for the files, 69% for search information, and improved the visual analysis and monitoring of KPIs.

3 Research Method

The data was collected through interviews, participant observation, and extraction of management reports referring to the period from January 2016 to April 2017, whose data illustrate the old model. The data from the management reports extracted between the period from August 2017 to October 2017 reflect the model implemented and its results obtained. The data was collected from the legal department's strategic planning team,

which is responsible for generating reports extracted from the legal lawsuits management system. The data were treated and compiled into spreadsheets.

3.1 Process Prior to Lean Transformation

The internal process flow consists of seven steps, plus inputs and outputs, as follows:

Inputs: court summons of the defendant. (1): Screening and centralized receipt of lawsuits against the company, with their proper filing and digitization. (2): Registration of all information needed for the internal control of the legal department. (3): Survey of the documents required for preparing the company's defense against the claims presented by the claimant, documents which are called subsidies. The elaboration of the defense thesis, based on the subsidies presented, is usually done through third-party offices specialized in the subjects addressed. (4): Calculation of provisions for possible losses. (5): Making payments of the agreement or judgment during the execution phase of the lawsuit in the judicial system via the shared service center. (6): After the payment of the agreement or sentence, the lawsuit is closed in the company's internal system. (7): Between the moment the defendant was summoned and the conclusion of the lawsuit in the judicial system, the company has several obligations with the justice that must be carried out in parallel, such as: appearing at hearings, making judicial deposits, paying fees and taxes related to the lawsuit, reimburse offices when they pay fees; hire experts when applicable among other legal obligations. **Outputs:** Unfounded lawsuits, convictions with burdens, and convictions without burdens.

3.2 Implementation of the Lean Office (LO)

The implementation project was carried out following the Project Management Body of Knowledge (PMBOK) recommendations, understood through processes of initiation, planning, execution, monitoring and control, and closing, which can be organized in five stages according to a flow of an implementation of the Lean concept: Identification of value streams, process mapping, flow creation, the definition of the new system, and process control and improvement.

3.3 Identification of Value Streams

The labor and civil or regulatory aspects were considered. The other areas were out of scope. In addition, the service offered by the sector and the important processes for the value stream were identified. The main methods used to identify value were unstructured interviews with area coordinators and those responsible for macro activities, observation, and data collection.

3.4 Process Mapping

Mapping the processes of the company's legal department enabled an understanding of how the activities occurred and were related to each other. Later the gaps were diagnosed, and the opportunities for improvement were evaluated. Then the leverage of benefits,

that is, the relationship between the proposed improvement and its financial impact was studied. The process mapping stage was made through interviews with those responsible for the activities, flowchart designs, and database analysis.

3.5 Design of Future Flows

The design of the future operational model was developed using the Business Process Model and Notation (BPMN) software, as the company had the know-how to correlate the designed flows and the legal department's management system.

3.6 Definition of the Future Operating Model

People are the main instruments for carrying out service provision and the main cause of variation, i.e. it is important to train and qualify people. During implementation of the new operating system, specific training was provided to people who had their functions redefined and transmit knowledge about the new model.

3.7 Process Control and Improvement

Due to the difficulty in creating ways of measuring and creating control points for the service segment, when compared to manufacturing processes, a specific cell called "Analytical" was created to raise the quantitative aspects of the new operating model. Its responsibility is to build KPIs, manage and create the budget operating costs, detect patterns and behaviors, implement analytical tools, and carry out the relationship and governance of continuous improvement.

The KPIs created were: (1) Evaluation of Offices, (2) Backlog of registration, (3) Judicial deposits versus Closed lawsuits, (4) Reason for the Request, (5) Level of qualification of employees (6) Percentage of agreements, (7) Lawsuits entry rate, (8) Lawsuits closure rate, (9) Wrongful dismissal rate, (10) Time to close the lawsuits, (11) Average ticket per conviction, (12) Product defect versus Manufacturer.

4 Results

4.1 Diagnostic of Wastes

Seven wastes in a production system according to [7]: defective service, unnecessary processes, intermediate inventory, inventory of finished products, unnecessary movement, unnecessary transport, and waiting time. Thus, from the processes mapping and the unstructured interviews with those involved, it was possible to relate Ohno's wastes to the legal department of the retailer company as follows: (1) Defective service: e.g., loss of lawsuit deadline due to the late submission of documents. (2) Unnecessary processes: e.g., registration of lawsuits already registered when the receipt is from another source (3) Intermediate Inventory: e.g., inventory of lawsuits with potential for an agreement. (4) Inventory of finished products: e.g., cases closed in court but active in the internal system. (5) Unnecessary movement: e.g., non-standard movement of employees to look for documents in other areas; t. (6) Unnecessary transport: e.g., lawsuits are sent to other units before reaching the legal department. (7) Waiting time: e.g., time spent to correct registration errors.

4.2 Application of Lean Tools

Based on Lean tools proposed by [8], we sought to understand how LO could be applied in the legal department of the retail company. The main evolution of the operational model, when compared to the old model, was the modification of the profiles of professionals who managed the matters and strategic lawsuits. The new operational model requires a certain professional profile properly trained to develop each task. The pre-processing tool implemented is a mechanism to reduce the execution time of activities, because the lawsuits are directed to their correct flow, and labor and civil lawsuits are properly filed, digitized, and sent to their respective track. So, a unique multipurpose and skilled operator makes an accurate registration according to the request and reason for labor grievances and commercial matters against the company.

In addition, there is a specific cell to lawsuits that cause a great financial impact on the company, e.g., strategic lawsuits that are initiated by former high-ranking employees or processes opened by public agencies. The analytical cell was created for information management and control interface with client areas such as the back office. It is responsible for informing KPIs, providing status reports and management reports to client areas, identifying behaviors and trends that will support new defenses, and building more robust theses against lawsuits. Also, a financial management cell was created, whose purpose is to guarantee and control the values involved in the lawsuits and possible judicial recoveries. In addition to the cellular organization, there was an improvement in synergy between areas and a decrease in dependence on specific resources for the development of tasks.

There is also an industrialization of the treatment of commercial matters, i.e. lawsuits that are not impacting as strategic ones but have a large volume. And a segregation of responsibilities regarding the Information Technology (IT) system. It has a new area to operate and maintain the system to best attend legal needs.

The exploitation of poka-yokes helps operators avoid failures and the loss of deadlines. They automated some activities, thus reducing the risk that there would be no task due to the lack of notification of the previous activity. For example, before the application, operators and lawyers notified those responsible for the following tasks via e-mail. However, now when making the final input of the information in the system, it automatically notifies the person responsible for the next task.

Despite the nature of this project highly requiring the participation of the human workforce, some activities have managed to be automated, thus reducing time and the risk of failure. In this case, there was a modeling of the system so that there was the prioritization of automatic collection of lawsuit information during registration, so operators would act only in a lawsuit that the automatic system did not detect in the online judicial system. In addition, the alert and notification poka-yokes made the flow of information no longer dependent on emails.

The standardization resulted in the improvement of the meeting of the deadlines determined for the presentation of the defenses against lawsuits, payments, sending documents, and the quality of the services performed, allied to the mechanisms of self-control that help in monitoring the performance of the entire internal process.

4.3 Performance Indicators

Before this project, there was no system of continuous improvement. A balanced Scorecard system was implemented combining financial and non-financial KPIs for the legal department. The classification of criteria used to construct the KPIs was as follows. Financial Perspective: Evaluation of offices, Judicial deposits versus Closed lawsuits, Average Ticket per conviction and Vice, and product defect versus Manufacturer. Internal Perspective: Registration backlog, Reason for application, Time for closure of process, Percentage of agreements, Process entry rate, Closing rate of lawsuits, and wrongful dismissal rate. Qualification: Level of qualification of employees.

Through the KPIs, it was possible to act more incisively in the improvement of the department, allocating resources in a coherent way where improvements were desired. The Balanced Scorecard became a system of internal communication, information, and learning. The KPIs enabled the use of corrective actions to prevent the recurrence of causes of non-conformities, identification of preventive actions regarding the request for cause, and provide more assertive follow-up on the control of the lawsuit portfolio and productivity of outsourced offices.

Immediately after the implementation and analysis of the indicators "Lawsuits entry rate", "Lawsuits closure rate" and "Time to close the lawsuits", many lawsuits with incorrect status were identified. That is, judicially, they were already closed, but in the internal system were still assets. Once the measures were taken, there was an 11% decrease in the number of active lawsuits in the system.

Evaluating "Backlog of registration", i.e., registered lawsuits that had not yet been passed on to an outsourced office, it was observed that before the restructuring plan of the registration cell, a backlog of approximately 3,000 lawsuits was maintained. After the implementation of changes, there was a reduction of 73%. With "Product defect versus Manufacturer", it was possible to evaluate that on average 2.26 million Brazilian Real (BRL) currency was spent monthly on lawsuits related to product defect. Through this analysis, the legal department, jointly with the legal departments of suppliers are working to have these types of lawsuits notified in advance to the suppliers.

Based on "Evaluation of Offices", it was clearly noticed the inefficiency of some outsourced offices, so these were no longer hired by the retail company. As for the policy of payment of fees, it was observed it was completely in favor of the outsourced office, so new policies were defined to tie the payment to the efficiency of the office. According to [9], outsourcing services through the value chain is related to the solid construction of partnerships and without abdication of responsibilities, making the company take advantage of benefits brought by offices' specialized knowledge.

"Reason for the Request" shows what the main causes of the requests for lawsuits are. With it, the company was able to act actively in preventive measures, especially for labor grievances, which caused a greater financial impact. In addition, jointly with the "Reason for the Request" indicator, measures were taken during the restructuring of internal processes so that requests linked to rescission funds, meal vouchers, wage and commission matching, and integration could be defended more efficiently. Finally, with "Judicial deposits versus Closed lawsuits", there was a qualitative gain in the process as there is now greater control over deposits in court accounts.

5 Final Remarks

In summary, the project achieved its main objectives. Based on LO, value flows of the legal department's processes were identified, internal mapping was elaborated, and new flows were created, eliminating waste. Thus, a new management system for improvement of internal processes enabled increasing the efficiency of controls and processes, with a consequent reduction in expenditure with lawsuits.

Like what was observed in the context of a university office in Portugal [6], here, the results could also be measured by direct improvement in KPIs and monetary savings. For example, 11% of the lawsuits were adequately tracked and closed in the system, also, 73% of the backlog was reduced. Also, the implementation of KPI enabled the company to understand where to focus its preventive and corrective policies for preventing future Labor Grievances and Commercial matters. This results in an expected cost avoidance of 35 million BRL.

Due to the short time, this project was limited to the study of only one case. However, further studies are recommended to investigate which other Lean tools can be applied to different office departments within retail companies, as well as expanding these investigations to the office departments from other industries. Future works are recommended to investigate the application of the LO to avoid judicialization. Finally, it is essential to highlight that judicialization should be prevented and avoided when possible, mediation and conciliation can be alternative ways.

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Case Studies About the Impact of Lean Tools on Worker Safety

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Abstract. The market is increasingly competitive and innovative. In this way, it is necessary for companies to find tools that help them to innovate and manage to reduce costs. It should also be noted that companies need to have good strategic management with a focus on continuous improvement of processes. Companies can only remain in the market when they differentiate themselves from their peers, for which it is necessary to invest in the improvement of production processes. Safety and health at work is also a very important factor in the success of companies. This theme has been gaining more and more importance, because in their work activities, employees are exposed to various risks that affect their safety and health. Regarding accidents at work and occupational diseases, in addition to the damage to employees, they also generate high costs for companies and society. Lean is an innovative and revolutionary methodology with positive impacts in many areas. Currently, it is implemented by several companies, leading them to reinvent themselves to be more competitive and secure.

Keywords: Lean · Lean-Safety · 5S · 6S · Safety · Visual Management

1 Introduction

Currently the market is increasingly competitive, innovative and with more demanding consumers. In this way, the existence of a strategic management focused on the continuous improvement of production processes is essential for the survival of organizations [1]. Organizations can only remain in the market when they differentiate themselves from their peers, for which it is necessary to invest in the improvement of production processes. In this sense, Lean methodologies have proven benefits in the widest areas of industry in terms of process improvement. There are significant benefits for companies through the reduction in the number of defects and elimination of waste, thus leading to continuous improvement [2, 3]. The key point of successful organizations relates to greater production, at the lowest cost, with quality and safety, creating value for all interested parties. Since this point also represents constant challenges for organizations [4, 5]. Lean production, nowadays, is implemented by various organizations, leading them to reinvent themselves in order to be more competitive [6]. Over the years, the subject of Occupational Health and Safety has gained greater relevance for the management teams

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of organizations, as employees are exposed to various risks to their safety and health in their work activities. With regard to accidents at work and occupational diseases, in addition to the damage to employees, they also generate high costs for organizations and society.

2 Literature Revision

The lean philosophy originated in Japan around 1940 at the Toyota company. It emerged from the work of Taichii Ohno and Shigeo Shingo who developed the TPS (Toyota Production System), with the aim of making production in continuous flow independent of large-scale production, making it efficient. Thus, it began to be recognized that only part of the total production time adds value to the customer's final [8]. Currently Taichii Ohno continues to be related to the principles of the Lean methodology - Lean Thinking started in 1988 [9].

The lean concept is considered a "thin" thinking, without waste and without excesses, however, associated with a well-planned methodology and applied in a certain organization, it is possible to obtain the elimination of all and which waste.

Over the years, several authors have defined Lean in different ways, some mention a more practical definition, others argue that lean can be seen as a philosophy and thus encompassing a practical vision [10].

The lean methodology has 3 main ideas: delivering value from the consumer's point of view, eliminating waste (they do not add value to the final product) and continuous improvement. Lean thinking is considered by several authors as a philosophy that aims not only at creating value but also at eliminating waste [11]. It is a management and leadership model aimed at continuous improvement, encouraging employees to participate in problem solving [12, 13]. Some authors argue that the successful implementation of any tool Lean, depends on the involvement of all people from all organizational levels [14].

Problems in safety and health at work affect the environmental quality of companies and can lead to accidents. There are several authors who refer that with the use of lean tools it is possible to improve workplaces. For example, they claim that the 5S methodology is implemented to make the process efficient and therefore safer [15, 16].

The pairing between lean and safety was a topic of study by Prakash [17], where he related lean tools and safety in the construction sector. Although the present work is developed in the furniture sector, the study also brings added value to the evaluation of the tools, which will bring improvements to the results. Based on this study, we can conclude that lean entails several benefits for safety, presenting a new methodology called lean Safety. Lean Safety is the creation of a safe and healthy environment in the workplace, which requires motivation from top management and all employees [18]. The presentation of Lean Safety led to the use of 6S - an extension of 5S: Seiri (organization), Seiton (storage), Seiso (cleaning), Seiketsu (stabdartization), Shitsuke (self-discipline) + Safety. The first three "S" have the function of taking the company to higher levels of organization and the last two guarantee its maintenance.

All different levels of the organization need to direct all their daily efforts and work as a team to achieve better performance and reduce waste [19]. The lean environment can

help make workplace safety a little more evident and visual. For example, using visual management, visual instructions and/or diagrams of safety rules can be created. Visual management helps employees quickly visualize and can facilitate the identification of a possible unsafe action, helping to correct it before it becomes an injury/accident [20]. Implementing lean tools leads to many benefits in occupational health and safety [21].

In the last 20 years, many studies have shown a deterioration in working conditions, an intensification of work, an increase in work-related stress and an increase in musculoskeletal disorders in workers. In all companies, health and safety problems at work affect their environmental quality, creating risky situations and causing accidents that are often fatal. Lean about the OSH theme has provided a series of opportunities for improvement that generate several positive impacts and thus combining the two concepts we have arrived at the methodology called Lean Safety.

Some authors such as, defines Lean Safety as the creation of a safety and health environment in the workplace, however it is only possible when there is motivation and good management on the part of the workers [18].

For this methodology to have the best results, all different levels of the company need to make every effort daily and work together to achieve better performance and reduce [22]. Argues that lean can help make safety more apparent and visual and thus make the work environment safer [20].

However, the current intensification of work leads to greater productivity, but also entails major adverse ergonomics and adverse effects on workers' health. [23].

According to the existing literature, some companies, when implementing lean tools in their production processes, identified some positive impacts such a financial benefits, increased quality, and productivity, however, others have negative impacts with regard to difficult working conditions, highlighting the various effects of work intensification, the social climate taking into account tensions, conflicts and stress.

3 Research Methodology

The current investigation intends to evaluate the impact of lean tools in the industry and how these methodologies contribute to a higher level of productivity and health and safety at work. The final investigation will focus on the furniture industry; however, lean tools are transversal and can later be applied to other areas of the industry. The investigation will begin with bibliographical research through the selection and analysis of several articles on the Mendeley, b-on and web-of-knowledge platforms, to carry out the literary state of the art with all the necessary information.

Several case studies carried out in other industries will also be analysed to create a guideline for the implementation of some lean tools in the company in question. Before any implementation, it will be necessary to survey the state of the company where the selected tools will be applied. This survey will be carried out by direct observation, according to [7] the same occurs when the researcher performs the collection of information directly; they also state that it is more frequent that the observer also participates, that is, when there is direct, frequent, and prolonged contact between the investigator and the real context under study. In the end, a questionnaire with 13 questions was prepared and distributed to all company employees to analyse the implementation carried out.

4 Study Cases

The application of 5S and visual management brings many benefits to companies. Between 2018 and 2021, after applying the tools, some authors achieved the following improvements:

2018: [15, 26, 27]

- Allowed solving problems in a simple way, without large investments;
- Waste reduction;
- Increase from 31% to 91.7% in the quality of the work environment;
- Reduction in the occurrence of accident risks;
- Improved stock management;
- Positive effects on workers' mental health;
- Stress reduction during working days.

2019: [24, 29]

- Greater safety for workers;
- Improved stock management;
- Early identification of activities that can effectively be carried out weekly;
- Easy recording of reasons for not carrying out scheduled activities;
- Easy presentation of production performance indicators;
- Reduction in the risk of accidents.

2020: [12, 25, 28]

- Reduction of activities without added value;
- Decreased time spent looking for tools;
- Decrease in the percentage of defects by 66%;
- Cycle time reduced by 43%;
- Reduction of WIP;
- In addition, the positive impact on safety in the work environment;
- Better organization on the factory floor;
- 83.4% of workers say that the work environment has been improved, thus reduce the risk of accidents.

2021: [21]

- Cleaner and more organized place;
- Reduction of stress at the end of the day;
- Decreased physical effort;
- Reduction in the distance travelled by 85.9%;
- Reduction in travel time 83.3%;
- Improved shop floor organization;
- Improvements in communication;
- Improvements in working methods.

5 Results and Discussion

The project was implemented to improve jobs in terms of safety, also creating a culture of continuous improvement. For this, the project started with an initial assessment of the state of the company, through which it was possible to remove the points that needed improvement.

Based on the initial work, the need arose to intervene in the section of the edges, the sheet and the joinery. The collection of data from all sections was carried out based on constant observation of the same, always seeking the involvement of all workers.

5.1 Sheet Section

In the sheet section, a new storage layout was applied, as well as the application of 5S. Through the implementation of the new layout and the 5S tool, improvements were achieved in terms of organization, cleanliness, and search time for raw materials; obtaining a reduction of the preparation time to start a new part in 75. The 75% reduction in time was possible thanks to the cleaning and organization of the sheet section. The section was organized by grouping the sheets on pallets and separating them according to type. In this way, the process time was reduced from 4:12 min to 1:06 min.

5.2 Section of Edges

The same type of productivity improvement is observed on the Stream A and B1 edging machines, where gains of 48% are observed; and 54% respectively in the decrease of time spent and 21%; and 74%, respectively, to the decrease in meters travelled. These results are due to the implementation of measures to create offices and organize raw materials. The cabinet created for the storage of raw materials.

Helped reduce the time on the Stream A edger from 4:12 min to 1:06 min, this cabinet has a layout where workers can easily find what they are looking for. The same was applied near the machine, thus reducing the meters covered by workers from 14.20 m to 11.20 m. The same was applied to Orladora Stream B1, thus achieving a time improvement from 9:20 min to 4:25 min and from 37.80 m to 9.80 m.

5.3 Assessment of the Impact of Lean Tools on Safety Through a Questionnaire

Bearing in mind that this project's main purpose is to study the impact that the improvements made have on the company in terms of health and safety at work, a small questionnaire was prepared for the entire company community.

The questionnaire consists of 13 closed-answer questions, and its completion is optional and anonymous. Of the 67 workers, 61 answered the questionnaire, of those who did not answer, 2 were on sick leave and 4 did not want to answer. A Likert scale of 1 to 5 was chosen, with 1 being the most critical and 5 being the most favourable. In Table 1 it is possible to verify the results contemplating the sum of results 4 and 5 in each answer.

In short, with this survey regarding the perception, by the workers, of the measures implemented, it can be concluded that the application of cleaning, organization, marking

Table 1. Results of workers' perception of their work environment

Question	%
1. Is the workplace cleaner?	88%
2. Is the workplace more organized?	85%
3. Did the demarcation of work areas contribute to the reduction of accidents at work?	84%
4. Increased autonomy in the workplace?	60%
5. Improved communication and information sharing?	77%
6. Did the identification of spaces make it easier to understand where materials are stored?	78%
7. Did the identification of spaces make it possible to reduce the time spent looking for materials?	75%
8. Did the Layout Creation make it easier to arrange/find materials?	75%
9. Did the storage of materials closer to the workplace reduce physical effort?	79%
10. Did it allow you to increase productivity and/or efficiency?	71%
11. Does the identification of raw materials and machines facilitate their recognition?	77%
12. Is there a greater motivation to work in a safe environment?	67%
13. Increased willingness to improve working methods?	76%

of work areas, identification of MP storage spaces, proximity of materials of jobs, resulted in improvements in productivity, reduced risk of accidents or occupational diseases, greater motivation, and ultimately greater productivity.

In addition, workers claim that there is a greater openness, on the part of the hierarchies, for continuous improvement in the workplace, namely improvement of working methods and conditions.

6 Conclusions

The implementation of this project was essentially centred on the implementation of two lean tools: 5S and Visual Management in the manufacturing area. The winning organizations, in the last decades, bet on leadership based on lean tools, as they all want the fastest possible production, with lower costs and high quality. Despite this, not all organizations can or even should implement the same set of practices.

Over the years, the subject of Occupational Health and Safety has gained greater relevance for the management teams of organizations, as employees are exposed to various risks to their safety and health in their work activities. Regarding accidents at work and occupational diseases, in addition to the damage to employees, they also generate high costs for organizations and society.

Evaluating the results obtained at the end of the project, it is possible to state that the application of lean tools translates into an improvement not only in the improvement of production processes, productivity gains and cost reduction, but also in the quality and

safety of the work environment. These improvements have made workers more satisfied and motivated to work in safe and clean environments.

The main results obtained, in terms of safety, were the reduction of physical effort on the part of workers, where 79% stated that there was a decrease; a 74% reduction in the distance covered in the Stream B1 edging section; and a 79% decrease in the time spent looking for materials in the sheet section. The main results obtained, in terms of safety, were also proven through the answers to questions 3, 9 and 12, where the results exceeded 76%.

It is possible to conclude that the work environment is also a very important factor for employee satisfaction and consequently increases the company's productivity.

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The Role of Lean Practices in Successful Warehouse Management System Implementation

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Abstract. Industry 4.0 opens new business opportunities and allows companies to gain a competitive advantage by introducing digital technologies in their processes. However, the digitalization process can be critical and, if poorly executed, could lead to worse performance than at the beginning. It requires a great deal of analysis, but most importantly, it must be seen by all stakeholders to be successful and valuable to the firms. The following study explains how Lean Management practices can facilitate the success of Digitalization projects. Overall, Lean practices have been recognized as a fundamental driver for driving the process of digitalization. In particular, hard Lean practices facilitate the removal of waste from the process before the digitalization and a fair selection of the investments. On the other hand, soft practices such as the operators' involvement are critical for overcoming the barriers to digital transformation and achieving the overarching company's goal.

Keywords: Lean practices · Digitalization · Lean Digital Transformation · Operators involvement

1 Introduction

The world of work is constantly evolving, and digitalization has been identified as one of the key trends influencing these changes. Companies must find ways to manage change, innovate, and improve to compete simultaneously. The fourth wave of technological revolutions in manufacturing, known as Industry 4.0, is setting new standards and premises for working life in industry. Many companies see digitalization as an enabler for greater competitiveness [1].

New technology trends continue emerging, and companies adopt them differently to improve working methods and gain a competitive advantage over rivals. While the digital revolution can lead to new business opportunities, it must be implemented efficiently to reduce costs and avoid simply "digitalizing current waste". From an organizational perspective, digital technologies involve a series of transitions that emphasize cultural, organizational, process, and relational changes [2, 3].

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Companies must ensure their employees have sufficient skills and competencies to maintain productivity. Many firms have adopted Lean Management, for example, to improve customer satisfaction and reduce costs in the manufacturing [4] and service [5] industries. Some studies also showed the high process orientation of Lean manufacturing could facilitate the transition to Industry 4.0 [4, 6]. While there is a correlation between the presence of both digitalization and Lean practices [6, 7], it is rare to find empirical evidence of how hard and soft Lean practices facilitate digital transformation [8].

The literature shows a recognized relationship between digitalization and Lean practices, but correlation alone does not prove that one facilitates the other. Although some evidence suggests that digitalization can ease the introduction of Lean practices [9, 10], there is a lack of empirical demonstration of how hard and soft Lean practices enable digital transformation. This study addresses this gap through a case study on a project where a digital tool was implemented by using Lean practices. The study was conducted at an engine manufacturing company following the A3 Problem Solving template, with interviews conducted to validate the findings. This paper examines how Lean practices can be used to drive and promote digital transformation in manufacturing companies. It will be structured as follows: after the literature review, the methodology will be presented and then the results from the case study. Afterwards, these results will be discussed together with the conclusions and limitations.

2 Literature Review

2.1 Digitalization

From an organizational perspective, digital technologies involve a series of transitions that emphasize cultural, organizational, process, and relational changes. Companies are therefore called upon to adapt their processes without compromising their competitiveness [3].

Digitalization is about rethinking current operations from new perspectives enabled by digital technology. How to manage digitalization while remaining competitive, however, is complex. Companies must ensure that their workers find digitalization valuable and relevant to exploit the potential for increased value. Sufficient and appropriate skills and competencies are critical to maintaining high productivity in the future [8] and supporting the use of digital tools in the long term.

2.2 Lean Manufacturing

Lean manufacturing is a customer-focused process that aims to reduce waste and improve standardized work by identifying unnecessary activities, streamlining processes, and creating standardized practices [11]. Some authors [12] pointed out that Lean practices belong to “hard” and “soft.” “Hard” practices include technical and analytical tools such as Value Stream Mapping (VSM), JIT, Heijunka, Total Productive Maintenance (TPM), Visual Management, Kanban, Single Minute Exchange of Die (SMED), and Poka-Yoke [13]. “Soft” practices, on the other hand, include small group problem solving, employee training, top management leadership for quality, supplier partnerships, customer engagement, and continuous improvement [14].

While Lean practices can eliminate waste, reduce start-up and delivery times, reduce inventory, and improve performance, they can also improve employee morale and satisfaction, communication, and decision-making attitudes. Lean can be applied to all processes that aim to increase competitive advantage, operations, and profits in regional or global markets, regardless of the type of organization, company size, or economic sector. Implementing both "hard" and "soft" practices is crucial for successful Lean implementation and achieving desired results [2, 13].

2.3 Lean and Digitalization Relationship

Industry 4.0 and Lean manufacturing use decentralized control to increase productivity and flexibility [13]. Therefore, it is critical to investigate how these concepts are introduced in companies and whether they can coexist within the same company.

Rossini M. et al. [7], through a survey among different European manufacturing companies, show that the highest levels of adoption of new technologies from Industry 4.0 are present in those companies for which there has been concurrently an implementation of Lean production practices for process improvement. Several studies consider Lean practices a prerequisite for Industry 4.0 and a tool to overcome the limitations of Industry 4.0 and increase its practices [2, 4].

Digitalization processes facilitate the implementation of certain concepts from Lean manufacturing, such as implementing JIT, visual management, autonomation, and Poka-Yoke [15]. Accurate inventory data are essential in Lean supply chains because large buffers and safety stock are eliminated. A digitized supply chain supports this by providing timely and accurate inventory level and location data. Implementing cyber-physical systems (CPS) in production gives intelligence to machines, thus facilitating autonomy. Autonomy is about giving machines the intelligence to distinguish between normal and abnormal operations autonomously. Therefore, the machines will stop in case of problems, avoiding producing defective products. Machines can report deviations more quickly, analyze their causes and automatically initiate measures. Automating data collection reduces the time spent on data collection and the probability of error [13].

On the other hand, it is much rarer to find empirical demonstrations of how hard and soft Lean practices facilitate digital transformation [15]. Knowledge of how companies should integrate new Industry 4.0 technologies into Lean production systems still needs to be improved. It is unclear which practices can be combined, which complement each other, and which contradict each other [13]. Wang [16] argues that a manufacturing process that has already implemented Lean manufacturing is more likely to be modelled and controlled. Therefore, he contends that this environment is an easier foundation for building a smart manufacturing platform.

Some Lean production techniques can enable the introduction of Industry 4.0 in general [4]. VSM can be adopted to identify crucial areas within the value stream to invest with Industry 4.0 to boost performance. Kaizen events engage people and facilitate their acceptance of Industry 4.0 implementation by creating shared opportunities to bring in new ideas. Kaizen events feature multifunctional teams that can adopt different problem-solving and waste-elimination techniques to solve an inefficiency or improve an area. Also, there is a need to map processes, not necessarily in a value stream view, but at least

in a process flow view, to identify the flow of materials, WIP, and information, which are essential for the Manufacturing Execution System (MES) design [2].

However, these effects have been studied; only a few empirical studies have been conducted on this topic. A more in-depth analysis of the relationship between Lean practices and digitalization is performed individually, answering the following research question: "How do the Lean practices influence Digitalization?".

3 Methodology

The study adopted a single case study methodology, utilizing data collection techniques such as observation, interviews, and document analysis. The study presents a case study in which a new Warehouse Management System (WMS) has been introduced using the A3 problem-solving. The A3, belonging to the wide set of Lean Management tools, was used for driving the digitalization process and as the main problem-solving tool. This paper will describe how the company used this tool and how this was helpful for the achievement of a successful digitalization project.

The case study under analysis is based on the Italian subsidiary of a multinational enterprise producing various types of engines for several applications. There are offices, warehouses, and a production site where more than 120 people work, generating a turnover of about 100 million (1.6 per cent contribution to the group total). Considering the specific context in which the company operates and its strategic directions, in order to increase competitiveness and profitability in an increasingly demanding market with increasingly stringent regulations, it operates intending to achieve and maintain a position of preeminence regarding the quality of its products and services to ensure the satisfaction of its customers with a view to continuous improvement.

Interviews, Gemba walks, and analysis of company data were used to depict how the company used Lean tools to drive the implementation of the new software. Additional face-to-face semi-structured interviews were conducted with four individuals from the same company to gather data on digitalization and Lean tools, to identify the possible relationship among them and thus answer the research questions. The interviews were recorded and transcribed verbatim and then analyzed.

4 Case Study

4.1 Problem Background, Breakdown and Targets

The company faced challenges with its shipment planning and scheduling process, resulting in various issues, such as shipment delays, inventory obsolescence, difficulties tracking orders, and operator frustration. To address these issues, the company has decided to better quantify the problem in terms of man-time or monetary terms to understand the impact on operations and financial performance. Additionally, the company has adopted a Lean Management approach to streamline its operations due to white-collar workers' dissatisfaction with the shipment planning process.

The Lean approach involves gathering information through targeted interviews and shadowing operators to identify inefficiencies and areas for improvement. The company

formalized nine workflows based on customer and product categories and described seven processes involving different teams. The shipping plan, an Excel tool used to coordinate shipments, was analyzed using activity quantification to identify the effort required to complete tasks and the number of times each task is repeated. The analysis revealed that the logistics department was the most involved, with the delivery dispatch note generation and billing activity taking up more than 60% of the required time. To address these inefficiencies, the company applied the concept of waste and used the Yamazumi approach to identify opportunities for improvement. A continuous improvement team was established to involve operators in the improvement process and reduce resistance to change. The planning and logistics departments were identified as having the most potential for improvement.

Then the project's targets were defined, focusing on reducing the number of non-value-added activities and customer dissatisfaction. The must-have targets aim to reduce the number of full-time employees required by 26% and the number of customer complaints from 10 to 2 per week. This saved time will be precious for the firms since it can be used for value-added or other future improvement activities.

4.2 Root Cause Analysis

Identifying and addressing the root causes of inefficiencies was crucial to ensure the project's success. The process involved all the project stakeholders belonging to different departments and using the five whys method to analyze cause-and-effect links for different departments and work cycles. The logistics department's root causes of inefficiency included the absence of fields containing useful data in the WMS interface, data not being transferred from one system to another, and changes in the Enterprise Resource Planning (ERP) software not being reported in the WMS. The sales department's inefficiencies included extracting and sending the Excel string to the planner, a necessary but non-value-added activity.

The logistics department's root cause analysis also identified the wastage in maintaining the Shipping Plan as the leading cause of inefficiency. Pareto analysis (Fig. 1) helped prioritize the root causes according to their impact on hours spent. Thus, 7 Class A root causes, with RC.6, RC.15, RC.16, and RC.17 being the highest priority to eliminate. RC.9 and RC.10 receive the most criticism from operators but are considered class C and low priority, but were accounted as the ones requiring monitoring for increased frequency.

4.3 Countermeasure Development

The previous lines discussed the importance of identifying and addressing the root causes of inefficiencies in a project. After identifying these issues, specific countermeasures were implemented to eliminate their presence and generate savings. The process involved generating a multitude of countermeasures, evaluating them, and prioritizing their implementation using an amended version of the Quality Function Deployment (QFD) methodology. Technical features of the software were identified as countermeasures to address root causes. In contrast, the root causes replaced customer needs.

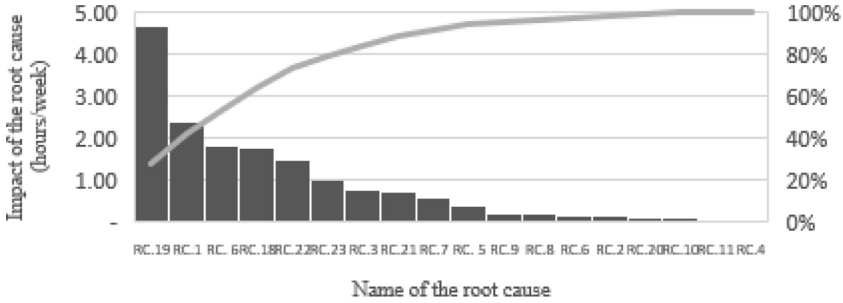

Fig. 1. Pareto analysis of root causes impact

The relationship between root causes and countermeasures was determined based on benefit and effort, with effort quantified through cost and strategic criticality. Countermeasure correlation was also assessed to identify those that should be implemented together versus those with opposite effects. Thus, the best countermeasure to implement was the technical software features with the best cost benefits tradeoff. In that way, the company could implement only the most effective countermeasures, thus avoiding waste in terms of time and money. Consequently, only 12 of the 26 identified software features were selected as beneficial for the company and thus implemented. For instance, one of the main features was "WMS Customized Mask", which could address multiple root causes and create an error-proof data entry process.

4.4 Implementation, Monitoring and Standardization

The implementation plan for the project involved identifying countermeasures to eliminate root causes, designing a Gantt chart with a specific go-live date, and prioritizing activities such as requirements analysis, functional analysis, and feasibility analysis. The implementation involves three phases: implementing process countermeasures, installing digital changes, and implementing new procedures. An extensive training phase was set after this phase to train all the employees involved and minimize errors during the first days of software use. The simulation of the new procedures showed a reduction of 13.73 h per week, meeting the company target with the possibility of further improvement. The implementation is expected to reduce errors and suffering, thus improving working conditions.

Afterwards, a monitoring system was designed to control the implementation phase and set the basis for a standardized and controlled to-be process. Several KPIs were identified at both the strategic and operational levels, including ordered line shipped on time in full (OTIF), lead time for promotion-billing and invoicing-billing, quantity shipped, order status, precision to picking, ordered line picked up on available, and Pareto causal delays. An interactive Excel dashboard was built to display these KPIs and provide clarity and ease of reading to all the users. The dashboard was designed to be aligned with the Lean visual management approach, presenting all processes and information useful to the flow of work and thus keeping the new process standardized and controlled.

5 Discussion and Conclusion

Implementing digital solutions helped optimize non-value-added activities, reduce working time, and eliminate data recycling. This case showed that soft and hard practices were fundamental for implementing the digital tool correctly. This study showed that a clearer understanding of the current condition and the issues of digitalization was obtained thanks to hard Lean practices. After doing this, the company saw digitalization as a way to reach process improvement and not as the final target. The A3 was the main tool used to drive the process, and it highlighted how the main issues were several inefficiencies to be tackled before digitalization. Then, other tools, such as the Yamazumi chart and visual management, helped the company select the right features to implement, thus optimizing the firm's investments.

On the other hand, soft practices such as training, group problem-solving, and listening to the voice of operators were fundamental to guaranteeing digital transformation success. Involving operators in the project was crucial for identifying and addressing problems and generating interest, thus removing the main barriers to the change. In that way, all the future users were engaged and participated in developing the requirement for the digital tool, thus leading to an improved WMS.

In conclusion, this study demonstrated the fundamental role played by Lean practices in digitalization. How they can aid in overcoming hurdles to digitalization and improve the likelihood of success in digital implementation was shown. In particular, Lean sets the basis for improvements in quantification and monitoring; furthermore, it drives improvement through improved process analysis. This leads to a better understanding of the current issues and helps reduce the digitalization of waste. This standardization facilitates process control, monitoring, and the reduction of post-go-live interventions. The operators' involvement and training facilitate even more this thing and minimize the learning time.

Even though the research highlights the importance of Lean manufacturing practices in facilitating digital implementations, it only presents one successful case study in this direction. Thus, further research is needed to deepen and extend the outcomes of this study. Future research can use a similar approach by studying several companies using Lean practices to introduce digital technologies.

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Toyota Kata as a Scaffolding for Human-Centric Manufacturing: Applying Lean Thinking for a Digital and Sustainable Factory of the Future

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Abstract. Industry has a key role in leading the digital and green transitions for the economic and societal transformations that we are experiencing. The approach towards a sustainable, human-centric, and resilient European industry, so-called Industry 5.0, complements the existing "Industry 4.0" approach by focusing on a circular, human-oriented, and durable industry. Thus, industrial systems need to have a focus shift from technology to human so that technology will serve human and not vice versa. In this way, human play a central role between technology and organizations. This paper seeks the challenge of this focus shift and how lean thinking and practicing soft lean tools such as Toyota Kata may contribute to the development of a human-centric approach in the industry. A literature review was conducted to answer these questions, and a conceptual modified Toyota Kata methodology, the so-called Human-centric Kata, was suggested to assist industry in reaching its goals towards a human-centric green-digital era.

Keywords: Lean · Toyota Kata · Human-Centric · Industry 4.0 · Industry 5.0

1 Introduction

The status quo obligates industry to transform to be greener and more robust by using human-oriented approaches. Industry 4.0, known as the cyber-physical transformation, results in a comprehensive transformation of the entire world's industrial production by combining digital technology and the internet with traditional industry [1]. The term *Industry 4.0* originated from a government initiative in Germany, called Industrie 4.0. The promises of Industry 4.0 are mainly focused on the digitalization of the industry and the improvement of the processes' efficiencies. Furthermore, the decentralization design principle and technologies like blockchain encourage consumers and businesses to make environmentally friendly decisions [2, 3]. However, according to Nahavandi [4], when Industry 4.0 reaches its full effect, it may face resistance from labor unions and politicians as soon as it is realized that the benefits of Industry 4.0 are neutralized by an increased workforce. In addition, Industry 4.0's purposes do not align with the climate crisis, planetary emergency, and social tensions [5]. Thus, an updated and/or

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revised version of Industry 4.0, so-called Industry 5.0, may contribute to tackling these obstacles. Industry 5.0 is aimed at utilizing the creativity and craftsmanship properties of human beings; and the speed, consistency, and productivity of robots to better appreciate the cooperation between them by combining their diverging strengths [6]. Østergaard [7] refers to Industry 5.0 as the "human-touch revolution", and it represents a shift from mass production to mass customization. This approach focuses on human needs, interests, and what technology can do for human, not vice-versa [8]. Such evolution/revolution may combine learnings from the pandemic with the design need for the industry to be resilient and green [5].

Lean, a term coined first in 1988 [9], was originally derived from industry in Japan, and its philosophy covers the idea of creating needed value for the customers with fewer resources/less waste and pursing this idea continuously [10]. However, only leading people to implement lean tools and methodologies is not sufficient to be competitive and continuously improving [11]. It is rather crucial to teach people to grasp the situation, react accordingly, and practice these behavioral routines on a daily basis [12]. Originating in the martial arts, Kata provides such structured routines consisting of patterns. The model is not a substitute for lean tools, but rather a support that strengthens their effectiveness [13]. According to Rother [14], there are two types of kata: improvement kata and coaching kata. Soltero and Boutier [15] combined Toyota Kata with training within industry (TWI) modules and concluded with seven kata; improvement kata, coaching kata, nested job instruction kata, problem solving kata, job relations kata, job safety kata, and job methods kata. This set of katas may boost an organization's lean transformation [15].

This study investigates the challenge of the industrial shift from Industry 4.0 to Industry 5.0 and how applying soft lean tools such as Toyota kata mentioned above and lean thinking in general may work as a scaffolding for the human-centric approach that is needed for the digital and sustainable factory of the future. A systematic literature review method was followed, as explained in the method section. Conceptual research is exploited as a framework. The rest of the paper is structured as follows: The next section explains the research method used in this paper. Section 3 summarizes the findings from the literature review. Discussions, conclusions, and suggestions for future work are given in Sect. 4 and Sect. 5.

2 Method

In this paper, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method is used [16]. A systematic approach was key. The primary objectives of this review were to determine the major transition challenge of the industry towards Industry 5.0, the interrelationship of lean thinking/soft lean tools, and a human-centric approach, and how Toyota Kata methodology can contribute to this transition towards a digital and sustainable factory of the future. Thus, this review aimed to answer the following Research Questions (RQ):

– (RQ1): What is the challenge of transition from Industry 4.0 to Industry 5.0 from the aspect of human-centric focus?

– (RQ2): Can/How Toyota Kata methodology be used as a basis to create a new methodology for the human-centric digital and sustainable factory of the future?

For this systematic review, electronic searches were conducted for eligible studies, including conference papers, within Google Scholar and Scopus between 2011 and 2023, until December 5th, 2022. Scopus is modern and has a greater emphasis on the humanities. The goal, in conjunction with Google Scholar results, is to find the most related results within the subject. In addition, all eligible studies' reference lists were searched, and forward citation tracking was used. The search was limited to English records. The following string was searched on each database:

- lean AND human AND kata (digital* OR sustain*) -karate -finance

From the 1019 records identified, 38 were eligible (see Fig. 1) Inclusion criteria are human-centric, kata as a coaching method, soft lean, and industry 4.0/5.0, while exclusion criteria are finance, economy, karate, and martial arts.

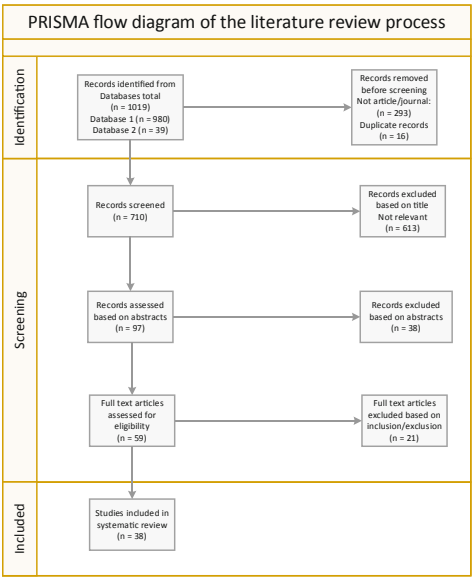

Fig. 1. PRISMA literature review process

3 Findings

In this section, findings from the literature review and our forward-looking analysis are given in three groups. These findings are used as the basis for the discussion.

3.1 Soft Lean, Digitalization, and Sustainability

Lean communities had a focus on tools until around the mid-1990s. In the twenty-first century, there has been a shift in emphasis toward culture and human-aspects of lean

[17]. Powell and Coughlan [18] stated that lean is more of an education system than a production system, while Liker [19] defined it as a socio-technical system. Furthermore, lean is described as a psychological theory with Kaizen, which supports the human focus on lean [20]. The learning roadmap for Digital Lean Manufacturing (DLM) suggests a five stage maturity model, and the last stage, namely "advanced innovation," is based on human and system integration [21]. Human-centric decisions about process improvements are possible by adopting lean [22].

It is crucial that workers are involved in every step of the digital transition to ensure a human-centric approach in the industrial context [8]. Lean thinking principles were suggested as a driving motor for digitalization initiatives in the industry to avoid focusing on the technologies, rather than using them as enablers [23]. Digital continuous improvement (CI) must have "go to gemba" principles so that it will not replace employees or their creativity, but rather support them [24].

The expected results of lean; scheduled production activities, decreased non-value adding activities, and waste, are positive impacts for environmental sustainability [25]. However, the literature also reveals several aspects regarding the synergy between lean and green, which argue against the negative impacts of lean on sustainability [26].

3.2 Industrial Revolutions and a Human-Centric Approach

It is still debatable whether Industry 5.0 is an evolution or revolution, and obviously the very same question was asked before for Industry 4.0 as well [23]. In recent years, new concept discussions have moved from Cyber-Physical Systems and the Internet of Things (IoT) to human-centered production with competent workers [22]. According to Nahavandi [4], utilizing human brain power and creativity will increase process efficiencies, which will be possible by bringing back human workers to the factory floor, namely with the fifth industrial revolution. Finally, for manufacturers that would like to be successful in adopting I4.0 technologies, complementarity with lean, defined as cognitive and behavioral transformation, can be enabled by action learning [27].

3.3 Toyota Kata

The Kata concept, which originated from ancient Japan's martial arts, consists of basic, repetitive forms. The concept is also derived as a standard, a predefined or choreographic sequence, a training method, and a structured practice routine [14, 28]. Organizationally, Improvement Kata and Coaching Kata create muscle memory for continuous improvement [29]. Toyota Kata is expected to decentralize decision-making, allowing employees to propose improvements on their own [22]. The three main benefits of using Toyota Kata are collaboration, learning, and continuous improvement [30]. Finally, developing an appropriate kata competency necessitates interaction and experience [12].

4 Discussion

4.1 The Challenge of Transitioning from Industry 4.0 to Industry 5.0

The literature review revealed that concept discussions are moving from Cyber-Physical Systems to human-centered production [4, 22]. Industry 4.0, which aims to connect human and organization to technology by placing technology as an interaction center between human and organization, does not fulfill the requirements of this industrial trend. On the other hand, Industry 5.0 puts the human aspect at the center to make it the main interaction hub between technology and organization. This implies that a shift in interaction center will be required for human, technological, and organizational aspects. Activities and strategies should be designed in such a way that human is the interaction center between organization and technologies. As a conclusion, this focus change may be one of the major challenges. Industry 4.0 already focuses on the interaction between technology and human. Thus, especially the soft part of lean may contribute well to this transition since it focuses mainly on the other bridging element, namely interaction between human and organization [31].

To illustrate the transition challenges from Industry 4.0 to Industry 5.0, the Human-Technology-Organization (HTO) concept, suggested to analyze interactions between these three aspects in regards to Industry 4.0 and lean [31, 32], may be used as a basis (see Fig. 2 Interaction center shift from I4.0 to I5.0).

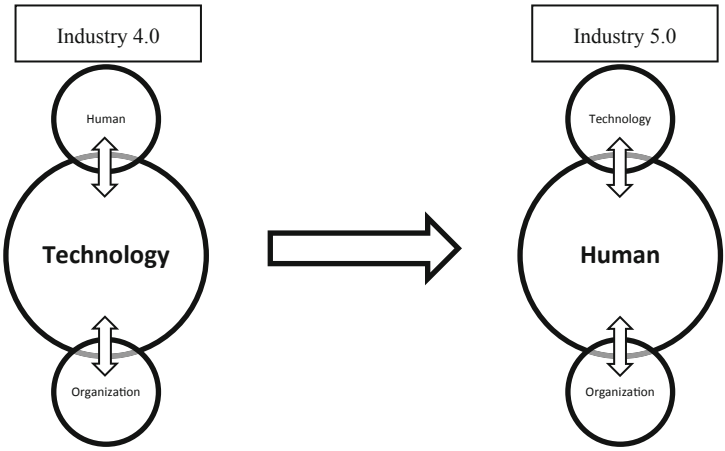

Fig. 2. Interaction center shift from I4.0 to I5.0

4.2 Applying Lean Thinking and Toyota Kata for a Human-Centric Approach

Both lean thinking and industry have a tendency to have a common focal point in recent years, namely the human aspect [17]. Likewise, several studies indicate that Toyota Kata may serve as a structured standard routine that synchronizes the industry towards a

human focused approach by creating a humane muscle memory [14, 28, 29]. Its strength in centralizing decisions on employees, its advantages of collaboration, learning, and continuous improvement, may provide a good foundation for the industrial transition [22, 30]. Thus, applying lean thinking by practicing a standard routine such as Toyota Kata may assist this transition. In the next section, a modified version of Toyota Kata, the so-called "Human-centric Kata," is introduced for this purpose.

4.3 Human-Centric Kata

Human-centric Kata is a conceptual modified Toyota Kata that aims to assist industry in having a habitual human-centric approach towards Industry 5.0. Toyota Kata is made up of four-steps and routines: vision, current condition, next target condition, and experiments/obstacles towards the next target [14]. 4-steps for Human-centric Kata are given below.

Human-centric vision. This is the first step in understanding our sense of direction. For Human-Centric Kata, the vision is to have a focus on human and to involve human in every action we take.

Current condition. At this step, we examine our current situation clearly. From the perspective of human-centric kata, this is a verification of whether the process we work on has human factors in it or not. If so, whether the human involvement is sufficient should also be evaluated at this step. It will help us identify our next target condition.

Next target condition. At this step, we determine a good next step goal for the challenge. When determining the next step for human-centric kata, it is important to define the step towards a goal that will serve human so that the next step makes the process more humane.

Experiments/obstacles. At this final step, we conduct an experiment scientifically, to achieve the next target condition.

5 Conclusion

Findings of the literature review reveal that the major challenge in transitioning from Industry 4.0 to Industry 5.0 from a human-centric perspective is the required interaction center shift from technology to human and that applying lean thinking by practicing Toyota Kata has a positive impact on human focus. In line with this information, this paper suggests a conceptual modified version of the Toyota Kata, the so-called "Human-centric Kata," that may be used to accomplish industry's transition towards the human-centric digital and sustainable factories of the future.

This study was limited to the human-centric approach of Industry 5.0. Thus, all other challenges related to the industrial transition were not investigated. As future work and research, it is suggested to empirically validate the "Human-centric Kata" concept in real-world use cases.

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Using *Kamishibai* Tool to Restructure the Audit Process System of an Aeronautical Company

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Abstract. This paper presents the effectiveness of *Kamishibai* audits use in restructuring the audit system on a daily basis in the aeronautical sector. This lean tool has a strong visual component allowing to verify if the numerous processes and activities are in accordance with the company's standards, triggering improvement opportunities in all audited areas. The paper objective is to present how this tool was developed and implemented, being described the audit framework, requirements to be audited, the many cards guiding the auditor, the operating method and how useful this tool can be even in large productive process audits. In order to demonstrate this tool effectiveness, an application example to four pilot areas in the company is presented, taking into account some pre-established restrictions. There is a practical motivation due to the existence of numerous non-conformities registered in previous audits. With this tool, company gains were: less audits, audit reduced cost of 5.000 €/year, more non-conformities corrected, reduced time performing the audits. These audits can be successfully used to assess industry standards and increase internal control.

Keywords: aeronautic · audit · Kamishibai · lean · standards

1 Introduction

In last few years, society and all those playing the role of customers have shown concerns regarding performance of the goods/services acquired. These concerns have led organizations to rethink their strategies, assigning greater relevance to quality standards. For [1], quality consists on product characteristics that meet the customers' needs and absence of faults. However, to meet customer needs is essential to identify what value is for the customer, which, according to [2], is everything that he/she is willing to pay for, namely, activities that add value to the product. Thus, with this concept in mind, the Toyota Production System (TPS) was designed, later dubbed Lean Production System by [3], and made popular by [4] which has as its great premise, produce with the minimum resources, using only what is necessary so that no waste of any kind is produced.

Lean Production was first applied in the automotive industry but given its success it has been applied in other industries [5], namely, the aerospace industry. This industry is a world leader in the advancement of science and technology [6] and its need for

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compliance with strict standards and requirements is paramount. According to [7], the company duly authorized to manufacture a part is responsible for its quality. Audits are a process that can simultaneously monitor product and process quality control and identify activities that do not add value, triggering actions to eliminate them. According to [8], auditing is a systematic, independent and documented process for obtaining audit evidence and evaluating it objectively to determine the extent to which the audit criteria are met.

Attending to auditing system importance, companies spend much time in this process, having many steps and documents to fill to assure that nothing fails. Nevertheless, the value added of such steps was doubtful, document traceability and update time was too high and fails continue taking place. This happened in the studied company described in this paper. Therefore, the study's objective was to develop and implement an auditing system, easy to track back and update that daily audits process without being a "heavy" system. This paper describes how a researcher in the context of action-research project achieved this purpose.

This paper is divided in six main sections. After this first introduction, it is presented the tool concept used in the project mentioned. Then, is explained the existent and proposal auditing system in section three. Some main results and discussion are reported in section four. Section five discusses the results. Finally, section six draws some final conclusions.

2 *Kamishibai* Concept

The *Kamishibai* concept comes from Japanese culture, being translated as "paper theatre", used in children's education, with fictional stories creation through drawings on colored paper. At Toyota, creator of the new TPS production paradigm, an internal audit tool was first called *Kamishibai*, in which administrative staff and department directors were encouraged to go to the *Gemba* to check if everything was as defined.

Generally, a *Kamishibai* board is organized through several identical double-sided cards, with distinct colors - green and red, as presented in Fig. 1. The cards represent different sectors and contain requirements relating to area/process, which must be strictly fulfilled. If requirements present in *Kamishibai* are fully complied with, the card is placed on the board with the green face visible. Otherwise, the red-face side is displayed.

With the *Kamishibai* board use it is possible for any person to make an audit in an intuitive and simple way and understand the situation of a process/procedure/company. This visual tool allows to obtain an immediate *status quo* through the color code used. Its main objective is to train people understanding problems and develop mechanisms to solve them, without blaming anyone.

This tool started to be used in TPS, as an instrument for internal audits, increasing contact between managers and production line teams, since the evaluation takes place in the *Gemba* [10]. [11] stated that *Kamishibai* works in any type of *Gemba*, productive or administrative, constituting a strategy to support, create and sustain processes, with visual signals allowing to easily observe situations incoherent with the defined standard, culminating in a replacement action, eliminating waste.

[12] analyzed the possibility of using *Kamishibai* audits in a quality inspection area, concluding that this tool has advantages such as:

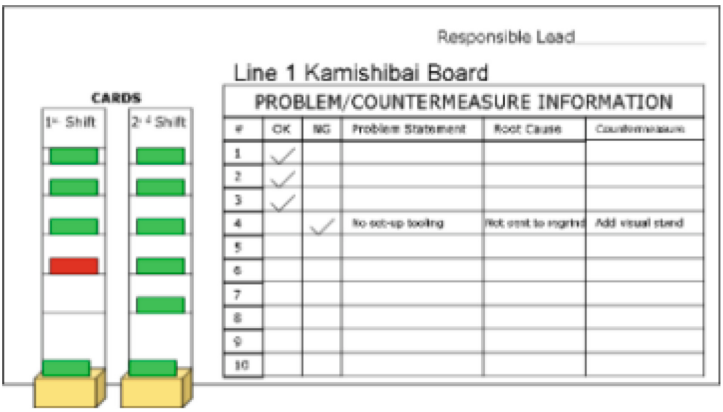

Fig. 1. Electronic *Kamishibai* [9].

- Low time needed to perform an audit, so there is no great effort on the auditor's part;
- Audit is unannounced, which makes it possible to verify the real condition within a given area (there is no preparation for the audit);
- Audit enables identification and elimination of deviations from standards in the area/process analyzed, as well as the standards' improvement.

Usually, these frameworks represent a tool to help clean and organize, and their advantages at this level have been proven in several case studies. The benefits of applying this tool have also been demonstrated in industries such as plastic packaging industry [13], in helping to carry out internal audits and in metallurgical sector [14] as a visual management tool. However, this tool usefulness in large auditing systems in rigorously monitored industries is still to be proven, being this paper aim to demonstrate the possibility of implementing this tool in aeronautical industry. The main disadvantages are related with lack of achievement consistency, acceptance, or lack of involvement.

3 Existent and Proposal Auditing System

This section describes the existing auditing system and failures had. Then, it is presented the proposal auditing system. The monitoring and company's processes verification is carried out through audits. The Deployment Diagram, presented in Fig. 2, illustrates audits process functioning in company and respective responsible.

Given external audits importance, internal audits represent a reliable means of preparation. These internal audits help monitor the processes implemented and verify compliance with certain standards.

Table 1 summarizes internal audit process aspects using the 5W2H tool. The main problems identified in the audit method used by the company were the: 1) low frequency of audits (only one to two months before an external audit) and 2) preparation time-consuming task. Related with the first problem: the low frequency did not allow for continuous monitoring of compliance with standards over time. Related with second, the audit preparation stage was wasteful considering the time it took to be carried out

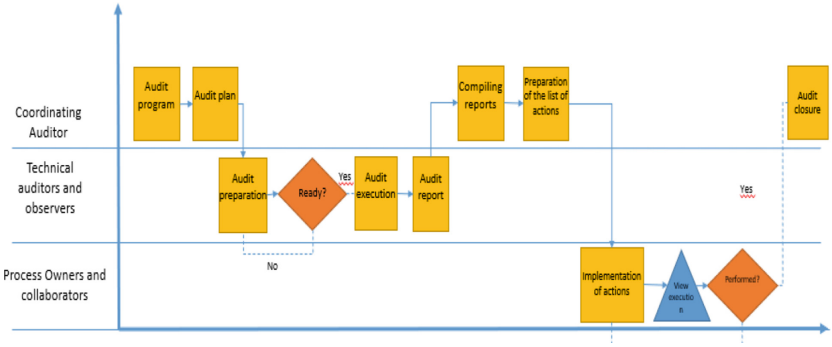

Fig. 2. Deployment Diagram of activities of Internal Audit process.

and not the most effective method, being a time-consuming and intensive phase. These problems had as a consequence the detection of high non-conformities in external audits.

Table 1. 5W2H for internal audit process.

	QUESTION	DESCRIPTION
5W	What?	Internal audit of processes/procedures
	Why?	For preparation and preparation of information documents for external audits.
	When?	1 to 2 months before an external audit
	Where?	In all processes of the company
	Who?	Coordinating auditors and technical auditors
2H	How?	Follow-up of the standard audit steps
	How much?	Salary corresponding to about 1 to 4 weeks

4 *Kamishibai* Development and Implementation

This section presents the steps given to develop the *Kamishibai* tool. These were: 1) Board design; 2) Card design; 3) Questions database creation; 4) Working method definition, which is the most important part of a *Kamishibai* system well implemented. The company had some restrictions about this tool implementation, such as:

- Each *Kamishibai* audit cannot exceed 15 min;
- Tool should be implemented in a pilot area composed of four critical process areas;
- Tool must be versatile and flexible so that, in future, it can be implemented in all factory, involving all workers' types.

4.1 Board Design

The framework design is the first phase of this tool development. Thus, for its construction, design is independent, i.e., without adaptations from other companies. The board characteristics are result of the company's needs and characteristics and this tool type normal operation.

Therefore, a table was built with a space to place cards with the respective audit results according to the department to which questions referred and factory section where audit was carried out. The second space consists of another table with the actions to be carried out according to non-conformities detected. This table shows fields such as the card number to which the non-conformity (NC) refers, requirement in breach, factory area, standard to be reset, person responsible for action, maximum conclusion date, and status of its execution. This monitoring is extremely important to guarantee that NCs detected are corrected, ensuring that they do not persist over time as has been the case in the company. Also, this framework has a storage area for all cards. The implemented physical proposal result is presented in Fig. 3, containing all mentioned elements.

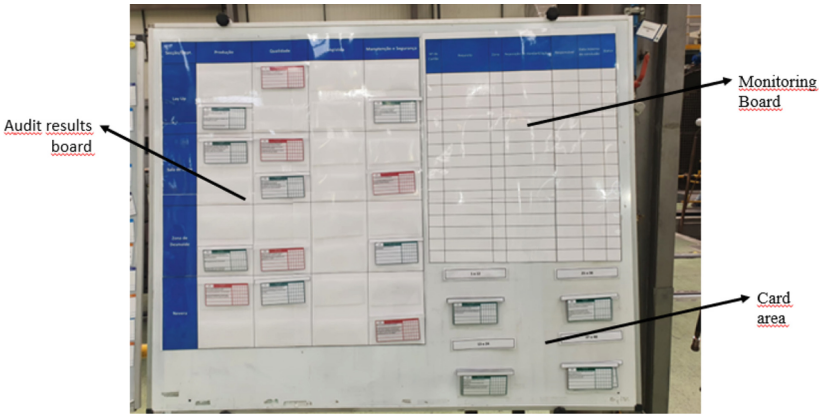

Fig. 3. *Kamishibai* Board.

4.2 Card Design

For the *Kamishibai* implementation, the card mechanism used was adapted from the audit system used by a partner company, with minor changes. This card, shown in Fig. 4, has two sides, green and red, both containing the same requirements to be audited.

To monitor the requirement evolution throughout the audits, the card contains a monitoring grid to mark the status (compliant or non-compliant) during a certain period. Considering the defined pilot area and departments involved, the card header also presents fields for these data insertion. For better card traceability and to facilitate requirement identification in the monitoring table, all cards are numbered sequentially. This numbering is also important in terms of scheduling, as it allows cards from different areas to be allocated uniformly.

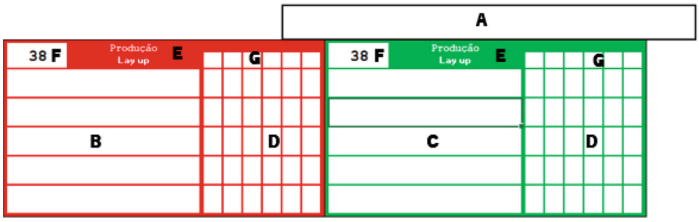

Fig. 4. Graphic format of the *Kamishibai* card (A - Support zone; B - Red zone of requirements/questions; C - Green zone of requirements/questions; D - Audit result; E - Section and department to be audited; F - Card number; G - Time period (weeks)).

4.3 Database of Questions and Questions Distribution

After deciding on the framework format to be implemented in *Gemba* and K*amishibai* cards design, it was necessary to survey the questions to be included on cards that would translate the requirements to be audited. To this end, a survey of more than 100 requirements was carried out based on the following criteria:

- Non-conformities, observations or opportunities for improvement detected in audits carried out in 2020 and 2021;
- *Gemba* Walk audit requirements implemented in the company;
- Common requirements of the aeronautical company and investment partner company with defined auditing system;
- Requirements of heads of aviation programmes and heads of section.

More than 100 questions are distributed among the cards. A maximum of three requirements per card to be audited was defined, bearing in mind that certain requirements could take longer to audit and should therefore be unique on the card or be audited together with simpler requirements. The distribution criteria consists on the estimated audit time and the workload of auditing a particular issue. In addition, given the card design, each one has issues related to the same department and same factory area, reducing unnecessary travel. Figure 5 shows an example of a card to be audited, in digital format.

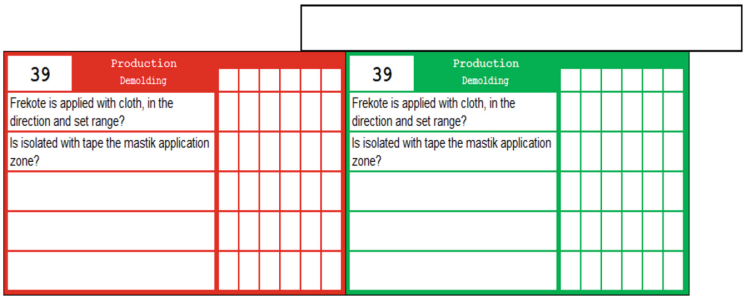

Fig. 5. Graphic format of a filled *Kamishibai* card.

4.4 Working Method

The process defined for conducting the daily audits is explained next. At the end of each working week an audit schedule is drawn up for the following week, containing the auditors' names and the *Kamishibai* card number they have to audit. This information arrives via email to the auditors concerned. This email consists of a 'With-Appointment' appointment type that allows scheduling in Microsoft Teams calendar. For this process, some assumptions are considered:

- A card with a negative result in the previous week is carried over to the following week so that a new audit can be carried out;
- An auditor does not verify the same questions in consecutive weeks;
- No more than two cards per week from the same section and department are audited.

During the week, the auditor chooses the most convenient day for auditing the requirements contained in the card. During this process, the auditor collects, in the board card area in the *Gemba*, the card allocated to him/her, and then performs the audit. At the end, if all the requirements conform to the standard, the green face remains visible on board. Otherwise, that is, at least one non-compliant requirement is detected, the card is placed with the red face visible. This requirement must, mandatorily, originate a standard reset in the second monitoring table, filling table all fields. Additionally, this standard reset also originates, in parallel, an orange post-it with action that must be placed in the Kaizen Daily chart of related department. Once action is executed, post-it returns to the person in board charge, who deletes action from the monitoring board.

At the end of the week, the person in charge, collects the cards from the auditing board, recording which red card numbers should be audited again in the following week. She/he then places them in the board card area. The process is flexible and adaptable, so questions can be added to any card, according to its department and area, or new cards can be created.

5 Results Analysis and Discussion

The internal audit methodology implemented in company presented a series of phases, being a time-consuming and intensive process. These internal audit phases highlighted the preparation, which required a joint effort of two auditors, who met for an estimated time of about one hour (value determined empirically) discussing aspects related to the audit to be carried out. With *Kamishibai* methodology, it was possible to eliminate this phase, as demonstrated in the Deployment Diagram in Fig. 6.

Given that, a collection and treatment of requirements to be audited and included in cards were carried out, because it was not necessary to prepare the *Kamishibai* audit, as requirements to be assessed are predetermined through escalation. Thus, since preparation phase did not added value, it was possible through the new methodology to reduce this process overprocessing. Additionally, since one of this project restrictions was related to the maximum daily audit duration of 15 min for this methodology, it would become impossible to continue with this phase.

During this project, results were monitored for about six weeks, in which it was possible to audit almost 100 requirements of the aeronautical sector. In this period,

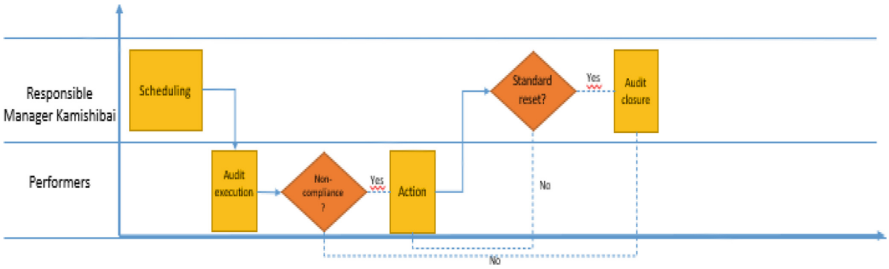

Fig. 6. Deployment diagram of activities with the *Kamishibai* methodology.

about 42 audits were carried out, each with two or three requirements, and several non-conformities were found, which triggered about 30 corrective actions. The results presented allowed to draw some lessons regarding this methodology. First, compared to the internal audit, usually performed one month before external audits, the *Kamishibai* methodology, due to its frequency, allowed the early detection of non-conformities, minimizing some work underlying the internal audits carried out close to external audits.

This methodology implementation had as a secondary objective the workers' involvement, not only from higher-level hierarchies, but also from production labor. During this proposal implementation, it was possible to include in this activity nine engineers, five production heads and two to three dozen operators who were daily being audited and involved in the standards knowledge. Regardless of being a daily activity, it was not considered painful, as its application is practical, fast and intuitive.

Over the weeks, G*emba* operators have been taking notice of this new methodology, always collaborating with high pro-activity. Simultaneously, the fact that they did not know when they could be audited generated a growing awareness to the need to comply with requirements, which was a relevant aspect in the working patterns and methods consolidation.

Additionally, this methodology proved beneficial also among teams of engineers and process heads, increasing the number of opportunities for improvement and observations identified when visiting certain processes. Furthermore, it allowed an information high exchange between departments, based on corrective actions triggered by occurrence of non-conformities.

Finally, in the long term, and considering the daily implementation, this methodology resulted in higher internal control of process critical points, such as compliance with work instructions or updating of skill matrix. An overview of gains is presented in Table 2.

Table 2. Global vision of *Kamishibai* methodology gains.

PROBLEM	BEFORE	AFTER	GAINS
Time between audits	12 months	24 months	12 months (100%)
Audit cost	5.000 €/year	5.000 €/2 years	5.000 €/year
Non-conformities (results of 6 weeks)	Around 30 non-conformities detected	Around 30 non-conformities detected	100%
Overprocessing in audit preparation time	About 1 h per audit	0	100%

6 Conclusion

This paper presented the *Kamishibai* audits implemented to increase internal control in an aeronautical company. This tool was designed and successively implemented in *Gemba*, as well as a database of requirements to be audited and subsequent cards creation. Although it required an initial effort related to requirements collection to be audited, or in construction of all tool aspects, the application advantages exceed the effort when compared to the existing audit system used.

Thus, it was verified that immediate corrective actions were triggered, allowing the establishment of preventive measures, in order to prevent non-conformities to occur again. When compared to the previous system, this tool allowed to detect and correct non-conformities earlier. At the procedural level, this audit process restructuring on a daily basis eliminated wasted and activities that did not add value. An example of this was the preparation step that add up to about one hour per audit. Additionally, the fact that it takes about 15 min to be performed removes the intensive characteristic of the previous system. After that, *Kamishibai* audits allows to increase internal control of the company's shop floor. However, this tool depends on the proactivity of those responsible for the actions, since the correction of non-conformities detected is only possible through the implementation of the actions proposed to restore the standard.

After the consolidation of the tool implementation, it was suggested the digitalization through tools such as Google Forms or Power BI to automate the audits and monitor more effectively the standards. This allowed to conclude that this tool could be used effectively in larges audit systems of a production process.

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Ranking Critical Tools in the Implementation of Lean Six Sigma as an Integrated Management System (LSS) in Portugal

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Abstract. Lean Six Sigma (LSS) is a comprehensive and powerful strategy for processes improvement and products. There is a cornucopia of tools for its implementation and 37 among them were selected to carry out an evaluation based on three factors, namely: Frequency of use of the tool; Difficulty in implementing; Importance and impact of the tool in the implementation of LSS. An online survey was conducted with Portuguese consultants and it included questions on the profile, and the companies they worked, as well as the degree of impact of the tools used. Consultants were asked to choose ten tools, ranking them in order of importance. The frequencies with which each tool had been cited were counted. A procedure was then developed to identify the know-how of consultants to establish a ranking of LSS tools. It was created an ordering list of tools, which emphasized in: Honshin Kanri, VOC, VSM. The results presented are particularly relevant when is considered the importance of understanding the requirements for a successful implementation of Lean Six Sigma management system in the organizations.

Keywords: Lean Manufacturing · Six Sigma · Continuous Improvement · Manufacturing Industry · Management system

1 Introduction

Currently, manufacturing industries increasingly seek to achieve excellence in their operations and production activities to become competitive in the actual global business environment. With this aim, companies are challenged to implement systems or models, which comprises the right set of methods and tools, that helps them to achieve operation excellence. Lean Manufacturing objective was focused on identifying and eliminating waste and increasing the speed of product delivery [1]. Six Sigma gain its expression to reduce variation and defects, deliver products and services to customers that meet their expectations [2]. It is a comprehensive and flexible system for achieving, supporting, and maximizing

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business success: through understanding customer needs and statistical analysis to manage, and reinvent business processes. The integration of Lean Manufacturing and Six Sigma is called Lean Six Sigma (LSS) and constitutes a comprehensive, powerful, and effective strategy for process improvement and creation of high-quality products [3]. Much has been said about the comparison between Lean and Six Sigma [4,5], however, another aspect of great impact is the synergism of LSS with Industry 4.0 [6,7]. This paper intends to evaluate Lean Six Sigma management tools, in terms of frequency of use, degree of implementation difficulty and impact through a Decision Matrix. In the end, by extracting the opinions of experts, a ranking of use of the tools to support the LSS is presented.

2 Online Survey

Research was conducted to verify the number of agents or consultants that are dealing with LSS management system in Portugal, and a number of 21 consulting firms and 50 consultants were compiled. With regard to methodology, there remains indeed the question of the (relatively) small size and representativeness of the sample. This stems from time constraints and the number of consultants (restricted to those who kindly agreed to voluntarily participate in the survey) and the low technical-scientific production in the region of Portugal. As for the differences in the Likert scale, the difficulties are somehow inherent in the process of attributing scores in this area. Between them, there are a variety of academic degree and experience [8]. This questionnaire consisted of 22 questions and was divided into the following topics: Consultant profile; Profile of the industries operated, Tools used in Lean Six Sigma (Frequency of use, Level of difficulty, Degree of impact). The survey was sent to the 50 professionals found via LinkedIn and/or e-mail, and a total of 19 responses were obtained. However, four of them were rather incomplete and were discarded. Regarding the profile of the 15 consultants who responded to the survey, it was identified that almost80% of their academic training is in production or industrial engineering, with chemical engineering in third place with 12.5%. Regarding the time of experience in the market working as LSS analysts, the results obtained from the survey showed almost 70% with a period of less than 10 years of experience, while the most experienced totaled 31.2%. To act as an LSS consultant [9], a Black Belt (or higher) certification was expected. It was noted that more than half (54%) have such a certification. Regarding the geographic location and coverage of consultant's activities in Portuguese manufacturing industries, it was observed in the sample that the majority worked in the district of Porto (75%), followed by Aveiro (67%) and Lisbon (58%). This result is in agreement with the information found at [10], which indicates a greater concentration of industries in the north of the country [11]. Regarding the main sectors of the manufacturing industry that consultants provide or have provided services in Portugal, the automotive industry can be highlighted with 60% [12]. More than half (53%) also worked in the food, base metallurgy and metallurgy sectors.

3 Ranking of LSS-tools in Portugal

In the survey, consultants were asked to evaluate 37 Lean Six Sigma tools, considering three factors for analysis: (1)Frequency of tool use; (2)Difficulty and/or resistance in implementing the tool; (3) Importance and impact of the tool in the implementation of LSS. All the data can be found on [13] The following subsections address these different aspects of the LSS tools, according to the perspective or experience of the analysts who joined the survey.

3.1 Usability Ranking of LSS Tools

For the frequency of the tools, a Likert 1–5 scale was used [14]. The arithmetic mean was calculated for the degree of frequency of each tool and ordered from the most used to the least used (see Fig. 1). Among the tools, the one that can be considered "always" applied (average score > 4) is the PDCA Cycle, Gemba Walk, Kaizen, 5S, in blue, covering about 15% of the investigated tools. It followed by others "almost always" applied, such as the Ishikawa, A3 Report, among others (in green color, totaling 30% of all tools). In contrast, the class of very least used tools (in orange) are, in order of least use: TOC, Harada Method, BSC, QRQC, Benchmarking and FTA (representing about 15% of the pool of tools). Here, just one aspect is concerned: the frequency of use reported in the literature, without considering the difficulty in implementing the tool nor its impact on the implementation of the LSS. The next ranking was built by the same token, but now taking only in account the consultants' perception. Kaizen, PDCA and VSM are the highlight in use this round. Gemba Walk, 5 Whys, 5S, Hoshin Karin and Spaghetti Diagram follow. The top 10 in each case roughly overlap. A mention only for VSM (Value stream mapping) who played a prominent role just in the latter case.

3.2 Resistance Ranking in the Application of LSS-tools

In the case of difficulty and/or resistance in the application of each tool, a Likert scale that ranged from 1 to 3 was applied (see Fig. 2). High were: FMEA, TPM and 5S. Now, the FMEA [15] is applied in about 12 stages that include diagnosis, evaluation, definition of strategies and monitoring for the prevention/correction of failures by the teams; it serves to create a culture for the search for "0 defects", or rather, with 99.99966% quality. TPM is supported by 8 pillars [16], with a general approach to preventive maintenance to achieve sustainability and "perfect production". Finally, 5S (one of Lean Six Sigma's finest tools), which is an approach that encompasses 5 steps, requires systematic planning that involves several factors such as: optimizing productivity, reducing expenses, promoting well-being and safety. About the tools with a lower degree of resistance or implementation difficulty, the following can be highlighted (in increasing order of difficulty): Ishikawa Diagram, Spaghetti Diagram, CTQ and 5 Whys. What these tools have in common is that they are faster, simpler and straightforward to apply for short-term spot investigations.

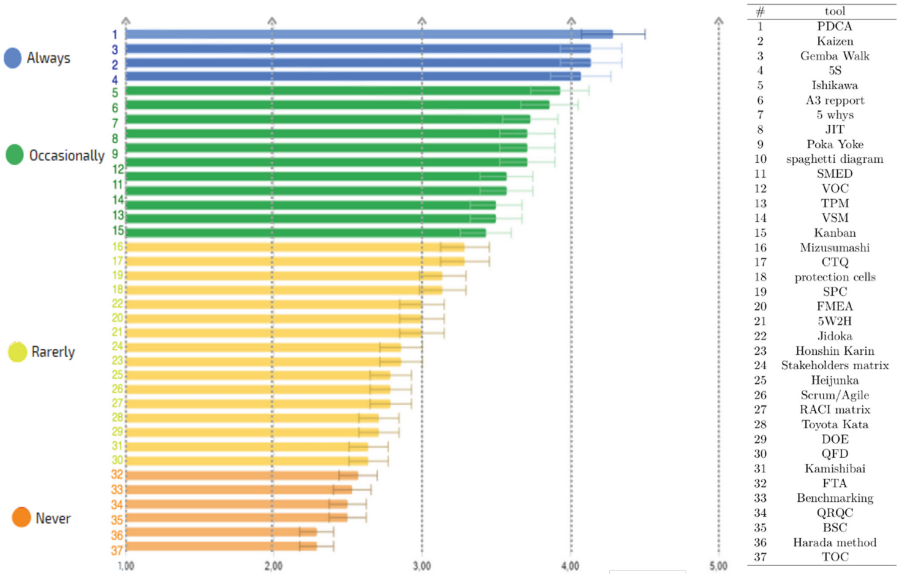


Fig. 1. Frequency of use of tools according to survey.

3.3 Ranking of Tool's Impact on LSS Implementation

The last question of the survey asked consultants to choose 10 tools with the greatest impact on LSS implementation according to their experience and professional practices, ranking them in ascending order of importance. It is necessary to consider the weight of the position of each tool in the responses obtained, and for that, a central measure of the opinions of different analysts about each tool is needed. In Statistics, there are several ways to measure central tendency. The mean is often adopted for symmetrical distributions with a low number of outliers. The median is generally preferred to return to central tendency in the case of skewed distributions with high variability. In the case of consultants' perception, consistency and unanimity is not to be expected, so the average does not seem to be the best choice in the evaluation of the "average opinion". It is relatively frequent some conflicting opinions, due to different views and experiences, increasing the dispersion and asymmetry (see Tab. 1). By selecting the most voted and calculating their respective medians, it was possible to rank recommended tools, with emphasis on: (1st) Honshin Kanri, (2nd) VOC, (3rd) VSM, (4th) 5S, Spaghetti Diagram and Kanban (5th). Although Hoshin-Kanri was not identified as a high-frequency tool in previous assessments, it appeared in the ranking in first place, given its strong impact on the definition and deployment of strategic goals at all levels of the organization that guide improvement projects

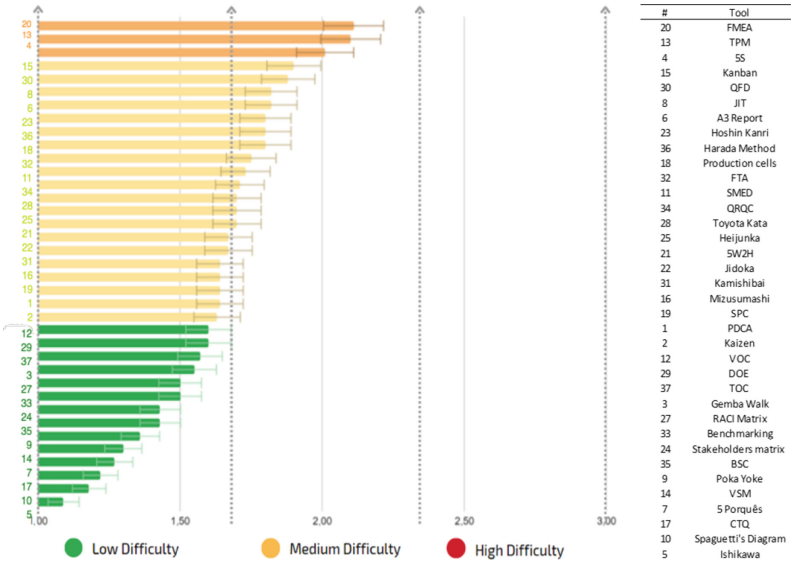


Fig. 2. Perception of difficulty in applying the tool according to Portuguese consultants.

4 Decision Matrix for LSS Tools

To facilitate the analysis of how these tools were evaluated, an adapted Decision Matrix was developed. A Cartesian plane was considered, where the tool application frequency was represented in the Y-coordinate and the Tool application difficulty in the X-coordinate. The 2D-points were plotted, and a characterization was proposed as follows:

1. "Quick Wins" tools: they have a high frequency of use and low implementation difficulty, they can be applied quickly with low resistance;
2. "Big Projects" tools: they have high frequency and high difficulty, they are tools that need a longer period to apply;
3. "Plan B" tools: they have a low frequency of use and low difficulty and can be considered secondary tools, since even with little resistance or degree of complexity, they have a lower rate of use, applicability or impact;
4. "Low use" tools: have low frequency of use and high difficulty in implementation; tools that are not normally used.

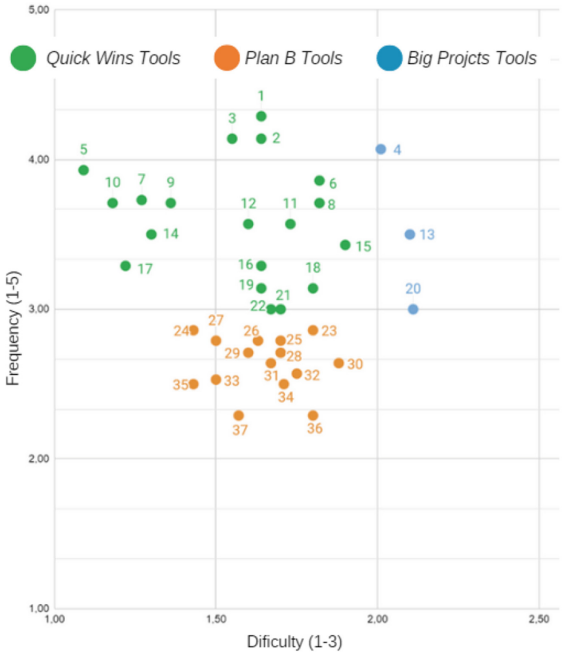
In the Decision Matrix, when considering the tools as the most suitable for application would be in the "Quick Wins" quadrant; while the less indicated tools in "Low Use". So, as to map the tools in the decision matrix, the values obtained from the averages of frequencies and the degree of difficulty were tabulated and used as coordinates to plot on Fig. 3 (color code: blue=1st quadrant, green=2nd quadrant, orange=3rd quadrant). What is observed is, according to the consultants' perspective, that the highest concentration of tools (92% in

Table 1. Ranking of Tool's Impact according to survey.

Tool	F	F%	Positions	Mean	Median	Final
Honshin Kanri	5	0,45	1º, 1º, 1º, 9º, 4º	3,2	1	1º
VOC	4	0,36	1º, 1º, 8º, 4º	3,5	3	2º
VSM	8	0,73	5º, 2º, 4º, 4º, 5º, 3º, 3º, 3º	3,6	3,5	3º
5S	5	0,45	2º, 6º, 7º, 4º, 2º	4,2	4	
Esparguete	5	0,45	4º, 4º, 5º, 6º, 2º	4,2	4	4º
Kanban	4	0,36	1º, 7º, 7º, 1º	4	4	
PDCA	8	0,73	6º, 3º, 3º, 8º, 3º, 2º, 8º, 9º	5,3	4,5	5º
5 Porquês	6	0,54	9º, 3º, 5º, 6º, 3º, 6º	5,3	5,5	6º
Gemba Walk	6	0,54	10º, 5º, 6º, 2º, 6º, 7º	6	6	7º
Ishikawa	4	0,36	7º, 4º, 7º, 10º	7	7	8º
Kaizen	9	0,82	4º, 5º, 2º, 8º, 9º, 8º, 8º, 1º, 8º	5,9	8	10º

total) are classified in the first and third quadrants, Quick Wins (51% of the total) and Plan B (41% of the total), respectively. Regarding those considered as Quick Wins, the use of PDCA, Kaizen, Gemba Walk, Ishikawa Diagram, A3 Report stands out. Once again is observed, now more clearly that most of the Lean tools were considered quick wins; while most Six Sigma tools were classified as "Plan B". Only three of the tools were classified as "Big Projects", namely: 5S, TPM and FMEA. It is also noteworthy that this result reflects the perception and experience of the analysts in the sample and that, its choice and use depend on the needs of the company and the project. When verifying the result, Hoshin Kanri (Akao, 2004) stands out in first place, with an average degree of use. It is a strategic tool for the deployment of goals related to the vision and organizational objectives at all levels and departments (horizontal and vertical). In this way, consultants are concerned about the importance of a strategic vision to guide and guarantee the successful implementation of LSS. In second place appears the VOC, despite low reliability, demonstrating the importance of the "Voice of the Customer" (whether internal or external) in the survey of needs and parameters for improvement opportunities, as well as in the translation of CTQs (critical factors) and in the establishment of key ind-icators to guide projects. The choice of VSM and 5S tools have good reliability and were ranked, respectively, in 3rd and 4th place.

While the VSM maps the value stream chain, which allows identifying waste and maximizing value for the customer, the 5S (Seiri, Seiton, Seiso, Seiketsu, Shitsuke) is a more complete system for handling workplace organization. On the other hand, despite the Kaizen tool being the most voted (highest occurrence), its placement appears in the last position in the *top-10 ranking*, which indicates a great agreement between the consultants.



#	tool	
1	PDCA	6Sigma
2	Kaizen	Lean
3	Gemba Walk	Lean
4	5S	Lean
5	Ishikawa	Lean
6	Relatório A3	Lean
7	5 Porquês	Lean
8	JIT	Lean
9	Poka Yoke	Lean
10	Diagrama de Esparquete	6Sigma
11	SMED	Lean
12	VOC	6Sigma
13	TPM	Lean
14	VSM	Lean
15	Kanban	Lean
16	Mizusumashi	Lean
17	CTQ	6Sigma
18	Células de Produção	Lean
19	SPC	6Sigma
20	FMEA	6Sigma
21	5W2H	6Sigma
22	Jidoka	Lean
23	Honshin Karin	Lean
24	Matriz de Stakeholders	6Sigma
25	Heijunka	Lean
26	Scrum / Agile	6Sigma
27	Matriz RACI	6Sigma
28	Toyota Kata	Lean
29	DOE	6Sigma
30	QFD	6Sigma
31	Kamishibai	Lean
32	FTA	6Sigma
33	Benchmarking	6Sigma
34	QRQC	6Sigma
35	BSC	6Sigma
36	Método Harada	Lean
37	TOC	6Sigma

Fig. 3. Scatterplot of LSS-tools in the decision matrix in consultants' perspective.

5 Concluding Remarks

In this paper, we sought to rank the tools used in the implementation of the LSS, using the perception of specialized consultants. To evaluate these tools, a Decision Matrix was built that took into account the frequency of application of the tool and its degree of difficulty/resistance in the application. Most Lean tools were considered quick wins, while most Six Sigma tools were classified as Plan B. A procedure was developed to establish a ranking of tools according to the Portuguese consultants who responded to the survey, considering their perceptions and practical experiences. The objective was to raise the critical tools in the LSS implementation. By selecting the most voted and calculating their respective medians, it was possible to rank recommended tools, with emphasis on: **(1st) Honshin Kanri, (2nd) VOC,($3^{r}d$) VSM.** It is worth notice that the top 3 tools reflect the 3 pillars of a company, respectively: (1) Mission; (2) Client; (3)Value added. With this characterization of tools, being used in the implementation of Lean Six Sigma, it was given an up-to-date overview of the main issues related to the implementation of continuous improvement in the Portuguese industry. This study it will be particularly valuable when combined with the knowledge about the barriers for Lean Six Sigma implementation. Mainly, it will help to establish the requirements or to define a roadmap for a successful integrated management system accomplishment.

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Integration of Life Cycle Assessment and Value Stream Mapping to Ensure Sustainable Development: A Literature Review

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Abstract. Traditional lean tools such as value stream mapping (VSM) do not account for environmental benefits. Simultaneously, life cycle assessment (LCA) does not account for improving manufacturing performance. Given the advent of the concept of sustainable development as an approach to fulfill the needs of the world's population without destroying the planet, integration of environmental benefits and manufacturing performance presents the next frontier of the industrial improvement. LCA can be integrated with VSM to ensure a sustainable development of the manufacturing industry. This paper presents a review of literature on integration of the tools-LCA and VSM. The reviews show that the main motivation factor is to enhance sustainable development. Further, a key finding is the benefit as a guide for decision making, fostering of a systematically improvement focus and increased engagement expanding the focus to include the sustainable aspect in addition to traditional lean measures. This is enabled through a systematically approach with assessing and visualization of the production process performance from a sustainable viewpoint.

Keywords: Sustainable manufacturing · Lean · Value stream mapping · Life cycle assessment · Literature review

1 Introduction

The concept of Lean has been known as a crucial strategical weapon to remain competitive in a global market for the manufacturing sector. The aim of Lean is to create customer value while eliminating any kind of waste in the organization. Thus, it is important to have efficient, streamlined, and precise production processes and normally use lean measures such as efficiency, quality, and costs to achieve this.

Although the importance of improving production performance, the manufacturing industry can no longer ignore environmental concerns. Despite of its great role in economic growth, its environmental impacts are not satisfactory. SMEs are greatly accountable for carbon emissions, and responsible for 70% of industrial pollution, and are a major source of CO_2 emissions [1]. Thus, there is a need for a fundamental shift from unsustainable growth and development patterns towards sustainable development within the earth's limits.

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Lean and sustainability are two major concepts within the manufacturing industry-each strategy has the potential to maximize the output. Lean to enhance process flow and lead time by minimizing waste from the production process and sustainability to enhance a process and mechanism to attain sustainable development [2].

One of the tools within Lean is the VSM with the purpose of improving production performance by identifying material and waste flows, and specifying the activities' cycle time, downtimes, and delays. From the viewpoint of the customer, it could be understood as everything that comprises value-adding and non-value-adding steps [3]. This approach is based on analysis of a production process by splitting it up into individual value-and non-value-adding steps in the viewpoint of the customer. The next is to improve the process by removing the non-value-adding steps.

The number of tools and methods for environmental assessment on the shop is rather low [4]. One of the most complete tools for environmental assessment is LCA with the purpose to provide in-depth data on environmental life cycle impacts related to all the stages of a product's life [3]. This includes raw material extraction, materials processing, production, transportation, use, maintenance, repair, and disposal or recycling.

In the contemporary scenario, jointly applying LCA and VSA towards environmentally sustainable manufacturing is bringing new perspective into companies. Integrating LCA with VSM offers a path for this restructuring through a model for decision-makers in terms of assessing trade-off between traditional lean measures and environmental aspects in organizations [3]. Based on this, our research aims at answering the following research questions (RQ)s:

- RQ1: What are the motivations for integrating LCA with VSM?
- RQ2: How does LCA integrate with VSM?
- RQ3: What are the benefits of integrating LCA with VSM?

This gives us valuable knowledge about how to successfully integrate LCA into the VSM as a part of a management system, to incorporate environmental aspects along with production performance.

2 Research Method–Systematic Literature Review

To answer our RQs we have chosen a systematic literature review (SLR) as research method. The SLR was conducted based on the approach proposed by Bulto' et al. [5] which highlight SLR as a method reliable to provide collective insight through theoretical synthesis into fields and can be argued as a process that increases the methodological rigor. Our SLR used following criteria:

- The academic databases Web of Science and Scopus for articles were chosen.
- Search string "value stream mapping" AND "life cycle analysis/assessment".
- Publication dates from 2010 to 2022.
- Relevant journal articles and conference paper whose main content focus on the link between LCA and VSM were selected. Papers applying a peer review process and English as language.

After conducting the search 32 papers were found, and the following criteria were used for a final selection:

- Title screening, abstract screening, and paper screening based on inclusion and exclusion criteria.

This resulted in 13 papers that met all criteria.

3 Results and Discussion

3.1 Pattern in Research Literature

Extent literature shows few articles using LCA and VSM simultaneously to reduce environmental impacts and improve production performance. In a period of 12 years the total number of articles assessed was 13 as listed in Table 1. The distribution in journals and conferences showed a broad dissemination, where Procedia CIRP had the largest number but with only 2 articles. Figure 1 illustrates the growth over time in the literature based on publication year, and the pattern on research literature shows that almost 90% were published after 2015. The motivation factors, description of the integration and the benefits are summarized in Table 2. More in-depth descriptions can be found in each of the articles.

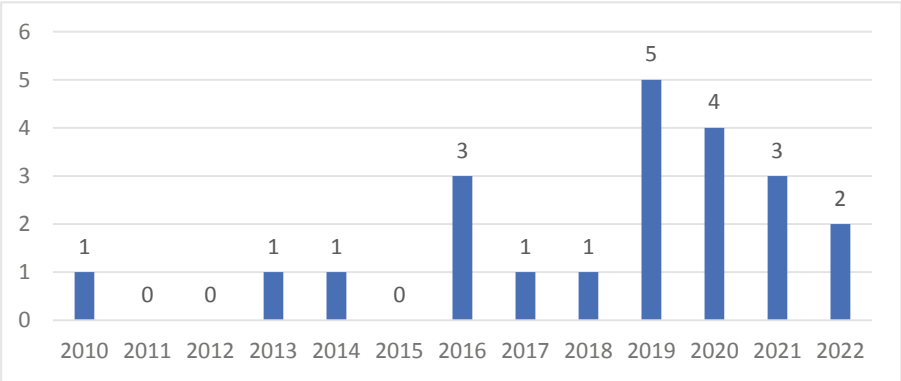

Fig. 1. Distribution of the reviewed literature, 2010–2022.

3.2 Motivations for Integrating LCA with VSM

The first research question was to examine the motivation factors to integrate LCA and VSM for manufacturers. First of all, the LRS shows none were motivated by prioritizing economic growth and traditional lean measures such as efficiency, quality and costs. It was noticed that all of the 13 articles were motivated by sustainability development due to manufacturing industries are greatly accountable for industrial pollution and contribute remarkably to environmental deterioration. In the light of the upcoming crisis of solving UNs sustainable goals and the excessive consumption of natural resources, the LRS shows that lean is more important than ever to reap the benefits from emerging sustainability and integrate with lean for improved sustainability operational performance.

It is seen as important to continuing to improve traditional lean such as productivity, but it is time for a remarkable change. Thus, there is a need for an increased incorporation of environmental consideration into production and management systems.

Table 1. Final selection of articles from the SLR review.

No	Author/year	Title	Journal/conference
1	(Yadav and Gahlot, 2022) [6]	Green Lean Six Sigma sustainability-oriented framework for small and medium enterprises	International Journal of Quality and Reliability Management
2	(de Oliveira Rezende et al. 2022) [7]	A Lean and Green approach for the eco-efficiency assessment on construction sites: description and case study	Clean Technologies and Environmental Policy
3	(Salvador et al. 2021) [3]	Towards a green and fast production system: Integrating LCA assessment and VSM for decision making	Environmental Impact Assessment Review
4	(Mudgal et al. 2021) [8]	LCA of Cast Stone Manufacturing: A Case Study	Procedia CIRP
5	(Heravi et al. 2020) [9]	Energy consumption and carbon emissions assessment of integrated production and erection of buildings' prefabricated steel frames using lean techniques	Journal of Cleaner Production
6	(Samant and Prakash 2020) [10]	Achieving lean and Improving Sustainability through VSM for Complex Manufacturing	IOP Conference: Materials Science and Engineering
7	(Estrada-González et al. 2020) [11]	Decreasing the environmental impact in an egg-producing farm through the application of LCA and lean tools	Applied Sciences (Switzerland)

(*continued*)

Table 1. (*continued*)

No	Author/year	Title	Journal/conference
8	(Shahbazi et al. 2019) [4]	Comparison of four environmental assessment tools in Swedish manufacturing: A case study	Sustainability (Switzerland)
9	(Karunarathna et al. 2016) [12]	Decision support framework for the sustainability of traditional brass industry-a Sri Lankan case study	Proceedings: International Conference on Industrial Engineering and Operations Management
10	(Thiede et al. 2016) [13]	Integrated Analysis of Energy, Material and Time Flows in Manufacturing Systems	Procedia CIRP
11	(Vinodh et al. 2016) [14]	LCA integrated value stream mapping framework to ensure sustainable manufacturing: A case study	Clean Technologies and Environmental Policy
12	(Banawi and Bilec 2014) [15]	A framework to improve construction processes: Integrating lean, green and six sigma	International Journal of Construction Management
13	(Paju et al. 2010) [16]	Framework and indicators for a sustainable manufacturing mapping methodology	Proceedings-Winter Simulation Conference

3.3 Insights from the Description of LCA Integrated with VSM

The second research question was to identify how LCA integrates with VSM. Findings from this showed that the overweight of the articles had done the analysis separately and concluded actions based on the analysis one by one. These articles mostly argue that this gave better overview when prioritizing and deciding actions for improving production performance and reducing the environmental impact. A few of the articles presented a new method, where the principles from VSM and findings from LCA were combined in one model. These articles described a guideline with the steps and a model where the results from VSM and LCA both were illustrated (Table 2).

Table 2. Research work pertains to integration of LCA and VSM.

No	Motivation	Description	Benefits
1	SMEs are greatly accountable for industrial pollution and contribute remarkably to environment deterioration	An eight-facet green lean six sigma framework, which encompasses systematic application of different tools	The incorporated LCA and VSM assist in the analysis of various Green and Lean aspects that provides cause for further improvements
2	A need for a new production mindset–considering the environmental impacts of a building's entire life cycle	A lean and green approach in three steps: 1) VSM, 2) LCA, 3) eco-efficiency assessment	Guide decision-makers on selecting more lean and sustainable construction technologies, materials and/or production strategies
3	Integrating environmental commitment to manufacturing concerns seems unavoidable towards a more sustainable conduct	An approach to a practical integration of LCA and VSM to improve environmental and manufacturing aspects	Decision making improving the environmental performance; environmental preference, economic feasibility, and ease of implementation
4	Reducing the sources of carbon emission due to human activity will help to reduce the Green House Gases	Proposing a method for performing a "cradle-to-gate" CO_2 emissions, by mapping the collected data using LCA and VSM	Greener options, based on quantification of the CO_2 emission of a product from extraction of its raw material to the final product
5	Importance of reducing CO_2 emissions and the energy consumption in construction	To assess the impact of lean techniques (VSM, JIT, continuous flow, TPM), the LCA is used	Reduce environmental impact through waste elimination compared to not using lean techniques
6	VSM suffers from including environmental impact associated with the value stream	Integration of LCA with VSM with a system for score regards to impact of lean and green	Coming up with improvements ideas towards achieving lean orientation and reducing environmental impact
7	The environmental impact of egg production in Mexico is scarcely reported	Design an eco-efficient approach based on LCA and VSM	Helps to facilitate sustainable productivity and leverages benefits that meet lean and environmental needs
8	Few tools and methods exist that specifically target environmental initiatives on the shop floor	Combination of tool to include different types of data collection and analysis	Combining tools lead to better prioritizing, decision-making and increased engagement

(*continued*)

Table 2. (*continued*)

No	Motivation	Description	Benefits
9	Industrialists struggle in decision making process of costing and environmental impact	A decision-making framework for costing and environmental management aspects	Approach for decision making for new designs and products to promote better environmental practices
10	Environmental objectives become increasingly relevant for manufacturing companies in additional to economic objectives	Development of a methodology to analyze energy, material, and time flows of manufacturing systems in an integrated manner	Foster systematic improvement focus on most relevant aspects and also avoids environmental improvements at the expense of economic drawbacks
11	Modern manufacturing systems are expected to be lean and sustainable	A practical framework for VSM integrated with LCA to ensure sustainable performance	Identify specific improvement opportunities for reducing the environmental impacts along with lean
12	The construction industry generates significant waste and produces a host of emissions	A framework integrating lean, green and Six Sigma. VSM and LCA to determine wastes-quantify the environmental impacts	Identify and quantifying wastes and then gives the possibility to embark on improve it afterwards
13	Controlling the environmental impacts is becoming more important for manufactures	A framework with LCA and VSM connecting the production parameters to sustainability indicators	Takes chosen sustainability indicators into consideration

A success criteria when implementing lean as a tool or method is to follow-up actions after the implementation. This study shows that only two of the articles discussed how actions from the analysis should be followed-up. Which is alarming if the intention is creating a sustainable culture for working with the environmental impact.

3.4 Benefits for the Organization

The third research question was to examine the benefit of integrating LCA and VSM in manufacturing companies. This LRS shows that benefits can be categorized within three main areas: assessment of sustainability and production performance, guiding decision making, and fostering continuous improvement extended with sustainability.

First main area regards to assessment of sustainability and production performance aims to provide a structured approach to a practical integration with the aim to apply more sustainable principles in additional to production performance in an organization. By conducting VSM for the current state and future state along with LCA this will give the organization an overview of potential gains. Further, a comparison with the current state and future state for both lean metrics and environmental impacts gives the organization a potential gain from the proposed change.

How to impact environmental reduction without disregarding production performance is something a manufacturer should think carefully on [3]. Therefore, the second main area-guiding decision making based on assessment of environmental impacts in combination with lean metrics-is of high value supporting cleaner industrial practice along with economic concern. The LCA-VSM model by Salvador et al. [3] has developed a decision-making model based on multi criteria assigning score regards to environmental preference, economic feasibility, and ease of implementation. This gives you a benefit based on prioritizing action measures regards to level of contribution along with implementation potential. By comparing current and future state, this can give the organization a valuable overview hindering action that might have conflict results. Some action might not fully contemplate both dimension–environmental and lean measures. Other action that might improve on and worsen the others, as well as some might improve or worsen both. Thus, the benefit will be to guide decision makers to either approve or withhold action promoting greener and more economical initiatives.

The last main area is about the benefit-fostering an **e**xtended systematic continuous culture to include sustainability in a traditional lean concept. When performing an analysis where the two methods are combined, it results in the development of a culture for continuous improvement where environmental impacts and economic activities are evaluated in a symbiotic collaboration. Thiede et al. [13] highlights that such approach will benefit by fostering a systematic improvement culture. They argue that focusing and progress by systematically working on most relevant aspects and also avoiding environmental improvement at the expense of production performance is a key to making sure that this will contribute to fostering continuous improvement.

4 Conclusion

The aim of this paper was to provide a review of literature on integration of LCA and VSM in manufacturing regarding motivational factors, how to integrate them and the benefits for the manufacturers.

Firstly, the main motivational factor identified is the potential to extend existing lean tools to include tools based on sustainability, as an approach towards ensuring sustainable benefits. All papers show that the main motivational factor for LCA and VSM integration is always the want of environmental improvement, dealing with the climate crisis and the possibility to incorporate this view with Lean. The LRS shows that it is time for a radical change from a business where decisions tend to be made by prioritizing profits, to including reduction of negative environmental impacts of the economic activities. Undoubtedly, integration of LCA with VSM is seen as a valuable solution providing a possible path for sustainable productivity. Combining LCA with VSM can reduce the environmental impacts while caring for economic aspects. Supporting an approach of integrating the two methods should be done to apply more sustainable principles in an organization.

Secondly, there are two main ways in which LCA is integrated with VSM. The first way to do it is conducting separate analyses and thereafter looking at them separately to investigate the improvement potential within production and environmental impact. The second way of doing it shows the making of a model where both methods are integrated,

so that VSM and LCA are used as a combination to select and prioritize areas in the value chain to do environmental impact reductions and improve production performance. Here, a few studies also use this for specific follow-up activities in the companies afterwards.

Lastly, the LRS identified three main benefits of integrating LCA with VSM. (1) Assessment of sustainability and production performance: By integrating the two methods, one achieves a structured, cohesive overview, presenting a thorough assessment of environmental impacts and production performance. (2) Guiding decision making: By combining the two, it can be used as a decision support tool that makes sure a company takes take of its environmental impacts while not sabotaging the economic activity. (3) Fostering continuous improvement extended with sustainability: When performing an analysis where the two methods are combined, it results in the development of a culture for continuous improvement where environmental impacts and economic activities are evaluated in a symbiotic collaboration.

A limitation of this study is the lack of research within this field with only 13 articles in a period of 12 years. Future research opportunities should include more empirical research on manufacturing industry implementing LCA with VSA. This to identify opportunities to embark on and barriers to solve.

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Continuous Improvement of the Screen Printing Process of Magnetic Sheets for Electric Machines by Statistical Design of Experiment

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Abstract. Electric machines are an essential element to the electrification of industry and mobility for achieving a sustainable economy. Particularly important are the resource-efficient production of stator and rotor sheet packages and the reduction of iron losses during operation. The screen printing technology enables the production of very thin magnetic sheet laminations in near net shape geometry and thereby minimization of material waste in production. Simultaneously the efficiency of electric motors in use will be increased by reduced eddy current and hysteresis losses due to decreasing sheet thickness and avoided mechanical stress in the manufacturing process. In addition, screen printing enables multi-material components and variable alloy compositions. This paper presents the requirements of the screen printing process for magnetic sheets and identifies the relevant influencing factors and printing parameters to achieve the product specifications in multiple iterations and using universal statistical design of experiments methods. The target parameters investigated are cycle-time, green part weight, roundness, and layer thickness.

Keywords: Additive Manufacturing · Electric Motor · Magnetic Sheets · New Materials · Resource-efficient Production

1 Introduction

Climate change makes the transformation of industry to sustainable value creation politically and economically necessary. Electrification allows avoiding emissions in diverse areas as industry, mobility, and buildings [1]. Electric motors are a key component, as they consume most of the electricity used in industry. The efficiency of motors should be improved, to limit the amount of electricity required [2, 3]. The highest losses occur in the sheet package. These are to be reduced by applying an innovative printing technology that enables the reduction of the eddy current and hysteresis losses. The quality of the entire process of manufacturing printed sheets is strongly related to the green part quality, so continuous improvement using statistical methods is crucial and has a strong impact on the final product quality [4].

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The potential and principle of the technology and the methodology for continuous process improvement are presented. The significant process parameters are then identified, classified, and analyzed by using DoE and performed with the software Minitab.

2 Potential and Principal of the New Technology

Iron losses occurring in stator and rotor laminations are dominant at higher frequencies. Therefore, the laminated core is sufficient for improving the efficiency of electrical machines. [4] Iron losses can be reduced with various solution approaches. Section 2.1 shows three approaches. The screen printing process enables the implementation of these optimization potentials and is described in Sect. 2.2.

2.1 Requirements for Magnetic Sheets and Stator Cores in Electric Machines

Electrification requires further improvements in the efficiency and performance of electrical machines. Three approaches are promising for stator cores:

1. Reduction of sheet thickness: According to Bertotti's loss model, the sheet thickness has a quadratic effect on the eddy current losses. Eddy current losses increase with sheet thickness, hence thinner sheets result in lower losses. It should be noted that due to the iron fill factor, i.e. the magnetic sheet thickness to insulation thickness ratio, the iron content in the sheet package decreases. Therefore, the sheet thickness cannot be reduced arbitrarily for use in electric motors [5, 6].
2. Multi-material combinations for stator and rotor: While soft magnetic properties as high magnetic saturation and low iron losses are important in the stator, a compromise must be found in the rotor between mechanical properties such as yield strength and elongation at break due to high speeds and the associated high centrifugal forces, and electromagnetic properties. The use of specific materials for rotor and stator thus increases the performance of the electric machine [7].
3. Design optimization: The magnetic flux can be better controlled, or flux barriers can be established by the targeted introduction of cavities or bridges [8]. These approaches can only be implemented to a limited extent with the conventional production approach of stamped electrical sheets. The reduction in sheet thickness significantly increases the pre-processing costs due to several additional hot rolling and cold rolling process steps. In addition, tool wear is increased. The use of different materials for the stator and rotor further increases the already high proportion of punching waste and is neither economically nor ecologically sensible. The production of complex sheet metal designs increases the effort and cost of tooling. [9] The above challenges do not apply to screen-printed magnetic sheets. The layer thickness can be variably adjusted, and thin sheets can be produced without additional effort. The use of multi-material components causes no additional material waste. The freedom of design in the printing process creates new options in machine construction.

2.2 Process Chain and Operating Principle of Screen Printed Magnetic Sheets

The process chain shown in Fig. 1 describes the steps that have an influence on the quality of printed sheets. The process starts with powder processing and paste production, followed by screen printing and drying of the green parts. This is followed by debinding and sintering of the green parts. The sintered magnetic sheets are electrically insulated and stacked into a stack of sheets.

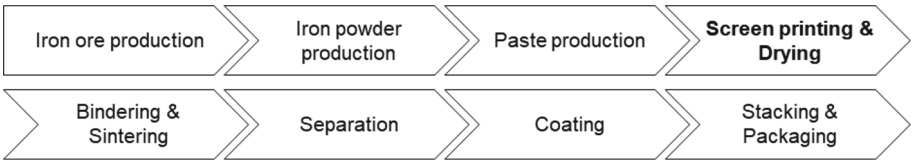


Fig. 1. Entire manufacturing process of printed magnetic sheets [10]

Screen printing is classified as off-contact printing, where the screen openings correspond to the negative to the printed green part [11]. The process proceeds with six steps. The substrate is positioned, then paste is applied to the screen. The screen meshes are filled with the flood squeegee and then the paste is applied to the substrate using the print squeegee. The screen pops off the substrate and then it can be removed. Figure 2 shows the estimated most influencing process variables.

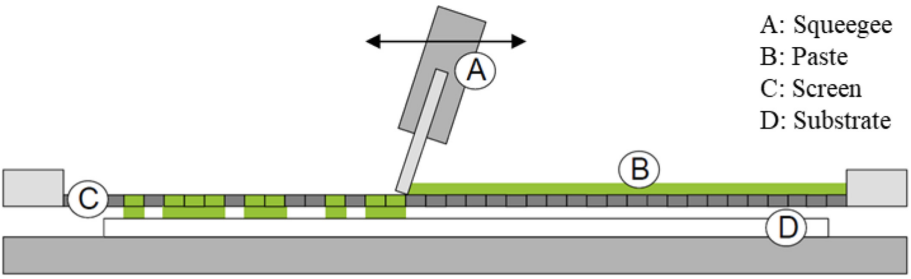


Fig. 2. Screen printing process illustration

The properties of the green part during printing are influenced by squeegee angle, hardness, speed, and force, as well as take-off and down-stop. The screen influences the layer thickness of the green part through the theoretically transferable ink volume. This depends on material, mesh size, thread diameter and mesh thickness [11].

Screen printing of iron pastes has specific challenges compared to established metallic screen printing processes such as wafer production for solar cells with silver or aluminum pastes. Iron is abrasive and therefore affects the lifetime, which has to be taken into account in paste development, screen selection and printing parameters.

3 Experimental Setup and Parameter Definition

For the design of experiment, system boundaries are defined. Then process parameters are identified, classified, and assigned according to the system boundaries. The black-box model is used as the system, in which the process parameters are classified into changeable input variables, into non-changeable or unknown disturbance variables and output or measured variables. Four groups of input variables are distinguished: on the one hand, the variable screen printing parameters and, on the other hand, the properties of the screen, the squeegee and the paste used. Environmental influences and the drying process are considered as disturbance variables that affect the quality but cannot be controlled during the printing process. The output variables are roundness, layer thickness, weight, print quality and cycle time. Figure 3 shows an overview of the identified influencing parameters and target variables on the screen printing process.

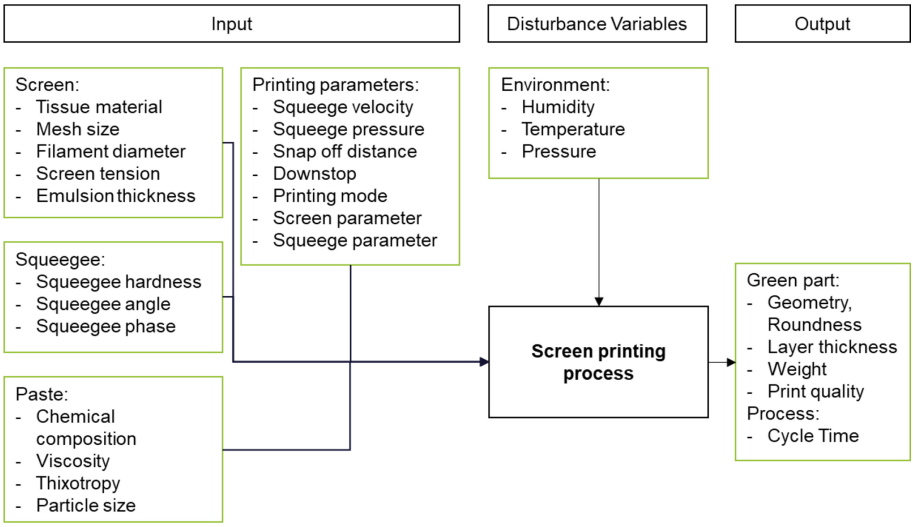


Fig. 3. Input, Disturbance and Output-/measured variables in the screen printing process

Values for the target parameters are to be defined before systematic statistical experiments are carried out. Table 1 shows target parameters for the green parts.

The target cycle time of 6 s can be achieved by maximizing the squeegee velocity. The target layer thickness is 100 µm. It is influenced by several parameters. In the DoE, the influence of squeegee velocity, take-off, print mode and screen is identified and weighted. Roundness is predominantly influenced by take-off and measured by the distortion, which is aimed to be less than 0.5%. Image quality is qualitatively evaluated using several parameters.

Table 1. Target values for green parts investigated in DoE

Parameter	Optimum	Target value	Variables
Cycle time	↓	6 s	Squeegee velocity
Layer thickness	→	100 µm	Squeegee velocity, take-off, Print-Mode, Roller mill
Roundness	↑	99,5%	Distortion, screen
Image quality	↑	Qualitative	Pinholes, defects, surface roughness, Edge sharpness

4 Evaluation and Analysis of the Statistical Test Series

Two DoEs are evaluated and analyzed. First, variable screen printing parameters that can be easily changed, then the influence of different screen structures are investigated. The correlation between input and output parameters is investigated. Squeegee velocity, take-off and roller mill are varied according to Table 2.

Table 2. Factor Information

Factor	Levels	Values
Squeegee velocity [mm/s]	4	60; 120; 180; 240
Take-off [mm]	2	2; 3
Roller mill	2	Yes, No

To determine the significance of the input variables on the output variables, a Pareto diagram of the standardized effects is generated in Fig. 4. It shows that Term B and C for greenpart weight and Term A, B and C for layer thickness have significant influence.

The three factors have significant influence, therefore the main effects on the target sheet thickness of 100 µm are analyzed in Fig. 5. This shows a steady increase of the print weight with increasing squeegee velocity as well as high weight increase of 33% by changing take-off and 25% by omitting the roller mill. The effect in the increase of take-off and roller mill on sheet thickness is comparable to the increase in green part weight, while the effect on sheet thickness differs with increasing squeegee velocity.

To achieve the target layer thickness of 100 µm, the following target values are defined. The squeegee speed is set at 240 mm/s. In this way, the lowest cycle time and the highest sheet thickness are achieved at the same time. If the squeegee speed is further increased, effects on the lifetime of the screen and the surface quality of the green part must be considered. The take-off is set at 3 mm since further tests at higher take-offs have resulted in damage to the screen. The use of the roller chair reduces the viscosity of the paste, which is why the print weight is reduced. However, the use of the roller mill is necessary, because if it is omitted, the paste becomes inhomogeneous and tends to form blisters and agglomerates.

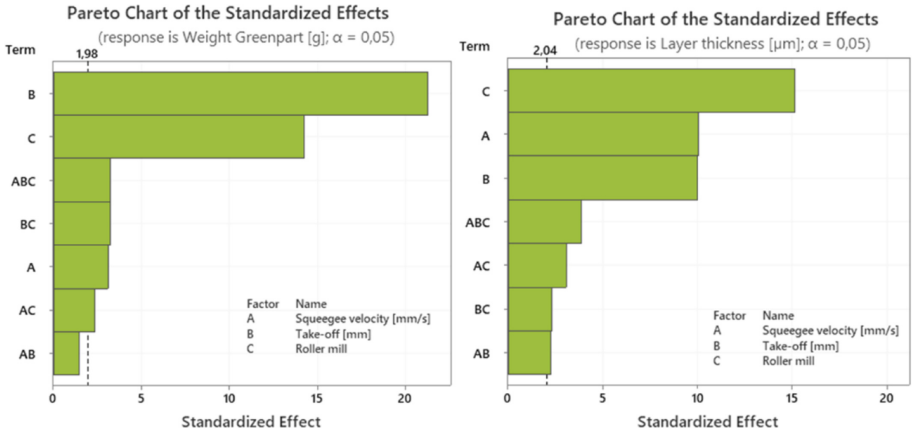


Fig. 4. Pareto Chart of Standardized Effects

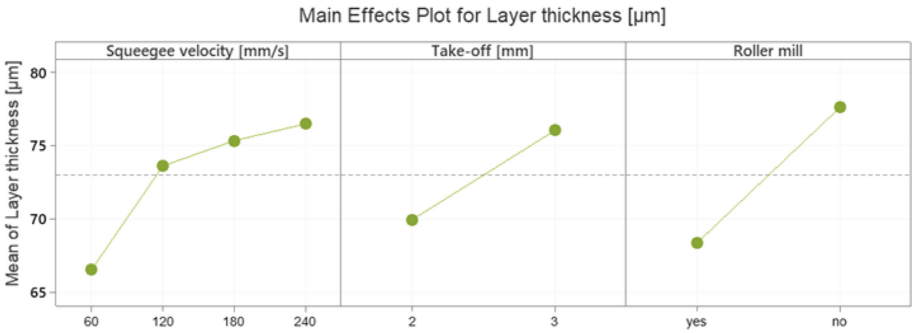
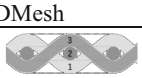


Fig. 5. Main Effects on Layer thickness

The properties of the screen influence the maximum amount of paste that can be transferred per print and thus layer thickness and weight. In this experimental design, the influence of three screen variations on layer thickness, print weight and quality is investigated. Table 3 summarizes the properties of the screens.

Table 3. Screen parameters [12]

Bezeichnung	2DMesh	3DMesh	3DMesh hardened
Screen type			
Mesh size [µm]	245	238	238
Filament size [µm]	65	80	80
Fabric size [µm]	140	225	225

For the first DoE the screen with 2D mesh has been used. For the second DoE the printing parameters are set to even higher squeegee speed (300 mm/s), large take-off (3 mm) and use of roller mill. To ensure statistical evaluation, 100 green parts are printed with each screen and 10 of each session are randomly selected for analysis (Fig. 6).

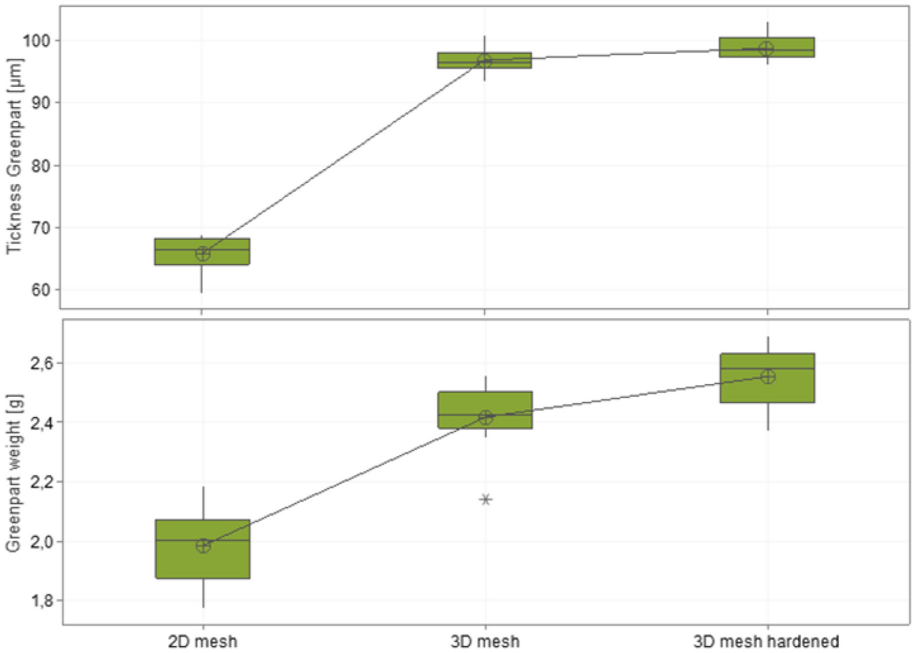


Fig. 6. Green part thickness and weight vs. Screen

Based on the coefficient of determination R^2 of 83.11% for the weight of the green part and 97.60% for the layer thickness, the measurement results can be explained by the screen variation. Layer thickness and green part weight of the 3D screens are higher, which can be attributed to the interaction of the larger mesh size and thicker thread diameter as well as the fabric type. No statistically significant increase in weight or layer thickness can be detected due to the hardening of the screen emulsion. The scatter of the measured values is smaller with the 3D screen, which indicates a higher process stability. The distribution of green part weights is higher than the distribution of layer thickness, which indicates variations in the drying process.

The quality of the printed image is measured by examining the number of pinholes and the square diameter of the pinholes by optical inspection. Figure 7 shows that the number of pinholes can be significantly reduced by using 3D screens. The hardening of the 3D screen has no influence on the number of pinholes. The average diameter of the pinholes is not influenced by the screen.

It can be assumed that the filament size on the 3D mesh has a positive effect on the transfer of the paste from the screen to the substrate. Another logical assumption is that the 3D screen is less vulnerable to clogged meshes due to the higher fabric

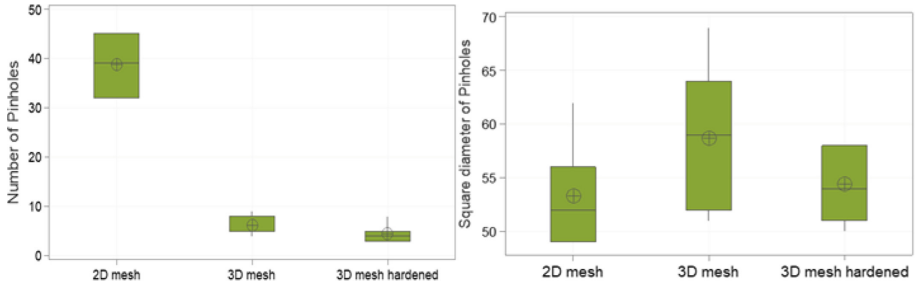


Fig. 7. Number and diameter of pinholes vs. screen

size. However, this assumption could not be confirmed by examine the screens after the printing sessions.

5 Conclusion and Outlook

Both the variable printing parameters and the screen selection have a significant influence on the process time, layer thickness and the quality of the green parts. The investigations show that an increase in printing speed and a coarser screen design do not deteriorate the quality of the green part as expected. The results are even better. In addition, a strong correlation between green part thickness and weight is observed, which needs to be further specified regarding to green part density as well as paste and printing process variation.

The investigation is limited to factors that can be easily changed. In further investigations, the influence of the paste, in particular viscosity, thixotropy, and agglomeration, as well as the influence of the other identified influencing variables are to be determined. In addition, interactions with the preceding paste production process and the subsequent stacking and sintering processes are to be investigated.

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Prediction Model of Product Quality in Production Company: Based on PCA and Logistic Regression

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Abstract. The paper presents the possibility of implementation the Principle Component Analysis (PCA) and logistic regression to develop the decision tool supporting quality of oil inserts for candles production process. The research methodology was divided into three stages: collecting data from the production process, using the PCA method to reduce the dimensionality of the production process parameters, and using logistic regression to develop a predictive model for assessing the quality of products. The results of the research showed that it was enough to have five main components to keep about 84% of the information on variability. In the third stage the logistic regression to develop the predictive model of product quality in production company was used. The developed model explain the impact of the production parameters on product quality. In addition, this decision tool will help the managers in the company identification the improvement actions.

Keywords: Principle component analysis · PCA · Logistic regression · Product quality control

1 Introduction

Analysis of the causes of non-conforming products, and as a result reducing the number of non-conforming products, is one of the most important goals of a manufacturing company [1]. An important challenge in this area is the identification of factors influencing the quality of the product. This task is not easy due to the amount and quality of data from the process [2], as well as the proper analysis and interpretation of the results [3]. Therefore, one of the main goals of the research in this area is to develop models that would allow the identification of input parameters responsible for product quality in production processes [4]. The models developed so far took into account, inter alia, model based on probability test [5], cost model taking into account variance [6], statistical process control [7], Pareto analysis [8] or numerical methods [9].

Recently, models with the use of machine learning methods have been developed in scientific works to improve processes. Despite the fact that these methods are successfully

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used in various research areas [10–13], their use of predicting the quality of production processes is still very limited [14–16]. For example, in the work [17] Authors proposed to use a classification model based on time series analysis using supervised learning methods. Moreover, in the work [18] Authors presented the comprehensive evaluation of several machine learning algorithms and the results of their performances in quality prediction.

In this study the Principle Component Analysis (PCA) and the logistic regression was used to develop the decision tool that can support monitoring of production process and, in consequence, reduce the number of nonconforming products in the production company. The developed decision tool will help the managers of the case company to identify the process parameters that mostly affect the quality of the products and, in consequence, to identify and to implement improvement actions. The research part of the paper consist of three parts. In the first part (Sects. 2 and 3) the research goal, methodology and methods used are described. Then, the results of using PCA method and logistic regression are presented (Sect. 4). The third part summarizes and concludes the work (Sect. 5).

2 Research Goal and Methodology

The main goal of the research was to develop the decision tool that can support monitoring the production process of oil inserts for candles. The research was carried out in a manufacturing company. The process of producing oil candles was analyzed, in which the problem of non-compliance of the product weight with the nominal weight was identified. Currently, the product non-compliance level for this process is 5%. The company tried to reduce non-compliance by using modern methods of process improvement, such as: quality management methods and tools, lean manufacturing or six sigma. However, not all of them achieved the assumed goal.

In this study, Principle Component Analysis (PCA) and the logistic regression were used to develop a model allowing for the identification the most important process parameters affecting the quality of the oil inserts in the company, as well as the relationships between them.

The research methodology is divided in three phases. The main goal of the first phase is to collect the data from production process. After that, the analysis of dimensionality reduction of the production process parameters with PCA method based on the information obtained from the case study company was conducted. Finally the logistic regression to developed the predictive model is used.

All needed analysis has been performed with using the R programming language.

3 Methods

3.1 Principal Component Analysis

In statistical analyzes, it often occurs that the studied area is influenced by many factors. In such situation, the relationships between individual variables are not obvious and often difficult or even impossible to identify, and attempts to fit the model bring results difficult to interpret. In such situation, factor analysis may be helpful. One method that can be used for such analyzes is Principal Component Analysis (PCA).

Principal Component Analysis (PCA) is used to reduce the number of variables describing phenomena, or to discover regularities between variables. It consists in determining the components which are a linear combination of the analyzed variables. Detailed analysis of principal components makes it possible to identify those initial variables that have a large impact on the appearance of individual principal components, i.e. those that make up a homogeneous group. The principal component (in which the variance is maximized) is then a representative of this group. The number of components is less than or equal to the number of input fields. The main component variance is equal to the matrix's eigenvalue in terms of magnitude Coordinate variances in the new space are calculated by the formula: $\lambda_i = \frac{d_i^2}{n-1}$, where d_i, $0 \leq i \leq k$ are singular values of the diagonal matrix. The proportion of variance explained by i–th principal component is equal to $\frac{\lambda_i}{\sum_{j=1}^{m} \lambda_j}$, while the proportion of variance explained by k principal components is equal to $\frac{\sum_{j=1}^{m} \lambda_i}{\sum_{j=1}^{m} \lambda_j}$ for $1 \leq k \leq m$. Each principal component explains some part of the variability of the input variables. Principal components are a synthetic measure of information. Often, PCA is used for classification. In addition, PCA allows to identify difficult-to-find relationships between output variables.

3.2 Logistic Regression

Logistic regression is a mathematical model that allows to determine the influence of several variables $x_1, x_2, x_3,.., x_k$ on a dichotomous variable Y. The logistic regression model is based on a logistic function in the following form:

$$f(z) = \frac{e^z}{1 + e^z} = \frac{1}{1 + e^{-z}} \tag{1}$$

This function takes values from 0 (as x goes to - ∞) to 1 (as x goes to + ∞). Let's define the dichotomous variable Y, as the values [0 and 1], so the logistic regression model defines the equation:

$$P(Y = 1|x_1, x_2, \ldots, x_k) = P(X) = \frac{e^{a_0 + \sum_{i=1}^{k} a_i x_i}}{1 + e^{a_0 + \sum_{i=1}^{k} a_i x_i}} \tag{2}$$

where: a_i, $i = 0,\ldots k$, are the regression coefficients; $x_1, x_2, x_3,.., x_k$ are independent variables. The left side of the equation is the conditional probability that the variable Y will take a value equal to 1 for independent values $x_1, x_2, x_3,.., x_k$. In this regression model (1), the regression coefficients should be estimated in order to fit the best model based on the values of a certain group of data. A condition for applying regression the logistic sample is sufficiently large, which in this case means that the sample size is $n > 10(k + 1)$where k is the number of parameters. To find in logistic regression coefficients $a_0, a_1, a_2,.., a_k$ the MLM (Maximum Likelihood Method) is used. MLM maximizes the likelihood function or its square, assuming that all observations are independent of each other, the likelihood (probability) is the product of the probabilities of the occurrence of individual observations from the sample with the given model parameters. In logistic

regression, apart from the regression coefficients and their statistical significance, there are also additional parameter: odds ratio given by the formula:

$$S(A) = \frac{P(A)}{1 - P(A)} \tag{3}$$

4 Research Results

4.1 Principal Component Analysis (PCA) in Production Parameters Reduction

The main goal of using the PCA method was to reduce the number of variables describing the analyzed production process and to discover relationship between the variables. The analysis consisted in determining the components being a linear combination of the analyzed variables: x_1 – oil mass temperature in the tank [°C], x_2 - worm temperature [°C], x_3 - baths temperature [°C], x_4 - filling machines temperature [°C], x_5 - nozzle temperature [°C] x_6 - priming time [s], x_7 - temperature in the tunnel [°C], x_8 - cooling time [s], x_9 - day of the week, x_{10} - shift, x_{11} – operator.

A detail analysis of the principal components made it possible to identify those initial variables that have a large impact on the appearance of individual principal components, i.e. those that make up a homogeneous group. The principal component (in which the variance is maximized) is then a representative of this group. Subsequent components: they are mutually uncorrelated, they are defined so as to maximize the variability that was not explained by the previous component. The PCA analysis was based on determining the axis retaining the highest value of the variance of the data set. The components were determined as a linear combination of the examined variables. The idea of creating subsequent components is that: subsequent components are not correlated with each other, they are intended to maximize volatility that was not explained by the previous component. In order to search for the principal components of a set, a matrix factorization technique called singular value decomposition (SVD) was used. This technique decomposes a data matrix into a dot product. Before the PCA analysis:

- the dataset was standardized (mean = 0, variance 1) because it is important that the variables in the dataset are of the same scale.
- outliers from the sample were removed, because they may have changed the results.
- missing data were handled because the algorithm does not accept them.

Table 1 shows the obtained principle components (nine principle components) and their relationship with the analyzed variables.

When analyzing the results (Table 1), it can be noticed, inter alia, that the variable x2 has the greatest contribution to the creation of the first principle component (PC1). On the other hand, the greatest contribution to the creation of the second principle component (PC2) is the variable x_{10} and x_{11}. Based on the these results, the dependencies between principle components and analyzed variables for PC1 and PC2 can be written as follows:

$PC1 = -0.17x_9 - 0.29x_{10} - 0.29x_{11} + 0.46x_1 + 0.49x_2 - 0.08x_3 - 0.36x_4 + 0.26x_6 + 0.39x_7$.

$PC2 = 0.09x_9 - 0.60x_{10} - 0.60x_{11} - 0.31x_1 - 0.13x_2 + 0.28x_3 + 0.15x4 + 0.06*x_6 - 0.17x_7$.

Table 1. Principle Components (PC) - matrix of eigenvectors.

```
Rotation (n x k) = (9 x 9):
           PC1         PC2          PC3          PC4         PC5         PC6         PC7
x9  -0.16569659  0.08561233 -0.003483659  0.864684334 -0.22345208  0.40425436  0.04939678
x10 -0.28812685 -0.60770052 -0.213430252  0.021650070  0.02242012 -0.02192145 -0.02604499
x11 -0.28812685 -0.60770052 -0.213430252  0.021650070  0.02242012 -0.02192145 -0.02604499
x1   0.45554832 -0.31393371  0.181281691 -0.132754172 -0.40231752  0.23417870  0.13377095
x2   0.49359642 -0.12922161 -0.277025022 -0.007779607 -0.25865484  0.21917646 -0.58005018
x3  -0.07673981  0.28515458 -0.660832880 -0.041720608  0.24034563  0.10649212 -0.31717309
x4  -0.36310706  0.15220275 -0.115101093 -0.470596073 -0.25326228  0.67511622  0.23500491
x6   0.25786658  0.06158832 -0.590519624  0.077756799 -0.26714593 -0.28623363  0.62814526
x7   0.38873882 -0.17477461 -0.024803650  0.066723057  0.72596651  0.42858739  0.30241999
              PC8          PC9
x9   0.0416121255 -4.860061e-17
x10 -0.0004992689  7.071068e-01
x11 -0.0004992689 -7.071068e-01
x1   0.6394066925 -1.110223e-16
x2  -0.4598500789  5.551115e-17
x3   0.5519527150 -1.387779e-17
x4  -0.1874237688  9.020562e-17
x6  -0.1645875158 -4.163336e-17
x7  -0.1053394504 -1.110223e-16
```

Similarly, other principal components can be written in the same way. Table 2 and Fig. 1 show the percentage of explained variance by each of the principle components.

Table 2. Percentage of explained variance by each PCs.

```
Importance of components:
                          PC1    PC2    PC3    PC4     PC5     PC6    PC7     PC8
Standard deviation     1.5048 1.4180 1.2208 1.0126 0.88525 0.84126 0.7048 0.47001
Proportion of Variance 0.2516 0.2234 0.1656 0.1139 0.08707 0.07863 0.0552 0.02455
Cumulative Proportion  0.2516 0.4750 0.6406 0.7545 0.84162 0.92025 0.9755 1.00000
                           PC9
Standard deviation     2.149e-16
Proportion of Variance 0.000e+00
Cumulative Proportion  1.000e+00
```

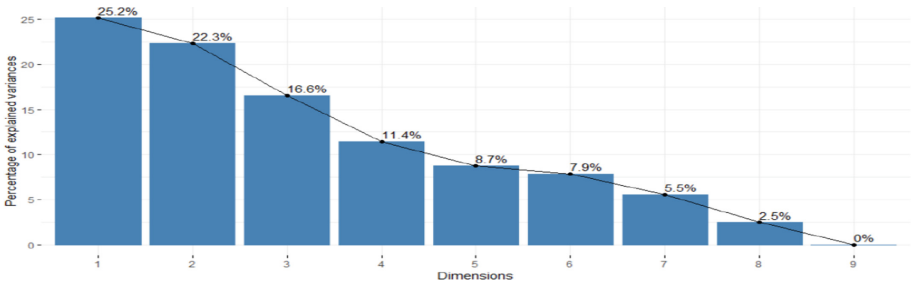

Fig. 1. Percentage of explained variance by each PCs.

Based on the percentage criterion of the explained variance, 5 components are sufficient and explain more than 84% of the original variance (Table 2). Based on the Keiser criterion, the first four components should be selected because their eigenvalue exceeds 1.

Figure 2 shows the initial variables and their correlation to the first two principle components. The arrows with the names of the variables show in which directions and how much they affect the particular main components. In addition, from their mutual position, it's possible to read the mutual correlation between the variables: if the vectors are perpendicular, the variables are not correlated, a small angle between vectors means a high correlation, close to a half angle indicates a negative correlation.

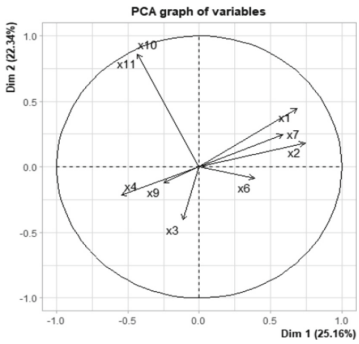

Fig. 2. PCA graph of variables

The results presented in Fig. 2 that the primary variable x_3 and x_1 are the most correlated with PC1. However, for PC2 it is the variable x_6 and x_4.

4.2 Logistic Regression in the Analysis of Factors Influencing Product Quality

The main purpose of using logistic regression was to identify factors of the manufacturing process that affect the quality of the manufactured product. Principle components P1, P2, P3 P4 and P5 were used for the analysis. The quality (Q) of the products was assessed as: OK = 1, NOK = 0. 940 observations were collected from the process and then analyzed. The data set for analysis was divided into two sets: the training set (80%) and the test set (20%).

Figure 3 shows the coefficients for the developed regression model.

```
Coefficients:
(Intercept)          PC1          PC2          PC3          PC4          PC5
     2.0417       0.6415      -0.1062      -0.2053       0.3950      -0.1135
```

Fig. 3. Coefficients in regression model

Taking into account the above factors, the regression model equation can be written as:

*LOGISTIC (Q) = 2.042 + 0.64*PC1 – 0.11*PC2 – 0.20*PC3 + 0.39*PC4 – 0.11*PC5.*

Figure 4 shows the coefficients and the results of the significance analysis for individual principle components. The regression results show that components PC1 and PC4

are the significant predictors in product quality (p-value < 0.001). Additionally, they are positively correlated with the obtained product quality. In order to assess the prediction quality of the developed model the confusion matrix (CM) has been developed. Based on the CM Accurancy of the model for the training data was 0.91 and for test data was 0.89. Moreover, the AUC (Area Under the ROC Curve) (Fig. 5) is 0.85.

```
Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.8360   0.2251   0.4564   0.5875   1.5074

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  2.04172    0.13513  15.109  < 2e-16 ***
PC1          0.64146    0.09053   7.086 1.38e-12 ***
PC2         -0.10625    0.07685  -1.383 0.166793
PC3         -0.20528    0.13785  -1.489 0.136442
PC4          0.39499    0.11409   3.462 0.000536 ***
PC5         -0.11351    0.14693  -0.773 0.439784
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Fig. 4. Coefficients and the results of the significance analysis

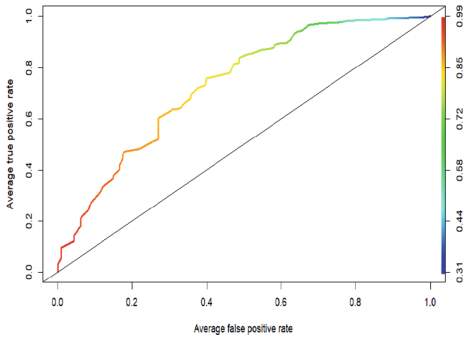

Fig. 5. ROC curve

The values of Accuracy and AUC proves the good prediction ability of developed model.

5 Conclusions

The main goal of the study was to develop the decision tool that can support monitoring the production process of oil inserts for candles. The use of PCA to analyze the parameters of the production process made it possible - at the cost of a slight loss of information - to reduce the number of variables needed to describe the process. The analysis showed that it was enough to have five (percent of explained variance) or four (based on the Keizer criterion) main components (instead of the original 9) to keep about 84% of the information on variability. In the next stage of research, the most important principle components (P1 to P5) and logistic regression were used to develop a model that allows determining the impact of individual parameters on the quality of the product. The analysis of the significance of the model showed that out of five components included, only two: P1 and P4 are significantly important. The qualitative assessment of the model showed a great quality of the prediction model (ACC = 0.89 for the test data and AUC = 0.85). The developed model explain the impact of the production parameters on product quality. In addition, this decision tool will help the managers in the company identification the improvement actions.

Although the research results are satisfactory, it should be noted that they have some limitations. Firstly, research was conducted in a selected company from a specific industry. Secondly, because the research was carried out in one company, the relationship between the input parameters to the process and the quality of the product presented in the developed model can be mainly used for the analyzed company. Nevertheless, the

research methodology presented in the article can be used to develop a prediction model in other companies.

Further research in this area should apply to the use of other machine learning methods to develop a product quality prediction models and compare their predictive abilities.

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Robotization of Training Enrolment Process in a Continuous Improvement Department of a Retail Company

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Abstract. Robotic Process Automation (RPA) emerged as a technology that promises revolutionary gains through the automation of transactional processes, based on specific rules. Through the application of RPA, organizations aim to increase their operational efficiency. The objective of the project described in this article was to develop a automatized procedure to allow the implementation of RPA, in the enrolment process in existing training courses in the "Improve Our Work (IOW)" department of Sonae Academy. After analyzing the current process through the value stream design tool, waste was identified in this process, namely, too much time in the function of data processing inherent to the training enrolment registrations. Then, improvement proposals were suggested and, subsequently, implemented, which allowed the reduction of time spent by the coworker allocated to this function, in approximately 95%. This value revealed the impact that the implementation of RPA has on the digital processes of organizations.

Keywords: Continuous Improvement · Digital Processes · Robotic Process Automation · Waste

1 Introduction

With technological globalization, the market has become increasingly competitive, imposing the need to adopt agile technological solutions, that increase the processes efficiency. During the last decade, several applications have been developed to fulfill these needs. In this sense, robotization emerged tofacilitate monotonous tasks in organizations, proving to be a safe bet, albeit expensive. Robotization emerged in England in the mid-eighteenth century, driven by the industrial revolution [1]. Currently, there are several processes consisting in manual, repetitive and digital tasks, that could be improved, automated and facilitatedby robotic automation [2]. RPA can perform activities such as entering a system, moving folders and files, managing data or even creating reports [3]. To do so, it is necessary to identify which activities do not add value (i.e., waste) to the process, such as waiting, transport, stock, or, even, knowledge waste [4].

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To identify and reduce this waste, there are several tools for this purpose, such as value stream design (VSD), and visual management through dashboards, among others [5]. VSD is a widely used approach to reorganizing the value stream by providing structured guidelines that help the intended path [6]. This helps to define an ideal state and it is one of the most used methods to represent flows [7]. Dashboards show important indicators to achieve objectives and goals outlined in a visual format. Dashboards are expected to improve decision-making, expanding cognition and capitalizing on human perception capabilities [8]. Also according to the same author, interest in dashboards has increased recently, which is also evident by the proliferation of dashboard solution providers in the market.

The project presented in this article aimed to improve the enrolment process of applicants in the "Improve Our Work" (IOW) training courses of Sonae Academy, through the development of a Process Design Document (PDD) for the implementation of a Robotic Process Automation (RPA). This project was developed in Continuous Improvement department of Sonae company between September 2022 and January 2023, by a team of multidisciplinary students of Engineering and Operations Management (EOM), in the context of Project-Based Learning (PBL) active learning methodology. This methodology was used in the curricular unit entitled Integrated Project of the Engineering and Operations Management master (IPEOM). IPEOM was supported by five curricular units: Advanced Lean Tools; Ergonomics, Occupational Hygiene, and Safety; Team and Communication Management; Lean Enterprise and New Product Development.

2 Research Methodology

The project was developed by a students team during the normal classes period (Thursday afternoon, Fridays and Saturday morning). It is important to refer that most of the students in this team were workers in other companies (have the student-worker status). Thus, this project demanded a good project management and organization to accomplish milestones included to assess the project (presentations including project model (PM) canvas, a blog for the report progress, two articles), and to accommodate the visits to the company.

Five visits to the company were scheduled according company supervisor and students team free schedule as well as six meetings (included online meetings). After a first face-to-face meeting with company representatives, details of the process to be analyzed were presented and the following six meetings were scheduled. All five presential visits included direct observation and informal stakeholder interviews. For team communication and document sharing between supervisors and students, various tools and platforms were used, including videoconference calls, due to the location of the company, which was about 50 km away from the university. This platform made it possible to reduce the number of face-to-face visits during the development of the PDD. This had a beneficial impact for both parties, since it was possible to reduce travel times, as the team was made up mostly of members with worker status. To follow a research approach, the team used the five phases of the Action-Research methodology: 1. Diagnosis and identification of the problem; 2. Action planning; 3. Implementation of actions; 4. Evaluation of results and 5. Specifying learning [9].

In the first phase, a diagnosis was made of the AS-IS situation of the applicant enrollment process in IOW training courses, using the VSD tool. This tool was used

with the involvement of all process stakeholders. The second phase, an improvement plan was drawn up to overcome the wastes identified in the previous phase. To achieve this, informal conversations were held with the employee allocated to the process and to understand how this process could be improved. Then, through brainstorming, was carried to design a future state VSD (TO-BE situation) during the third phase (implementation of the plan). Other tools such as kanban, checklists, excel, and the platforms Trello, Sharepoint, zoom, and teams were also used. During the fourth phase, results analysis and discussion were undertaken with company coworkers and supervisor as well with teachers of the different curricular units. This was also important for the assessment to the IPEOM. Finally, the fifth phase of learning specification included this article writing to describe the lessons learned with this project.

3 Description and Critical Analysis of the Current Situation

3.1 Current Situation Description

The challenge was to improve the process of enrolling applicants for training at the IOW competence center, at Sonae Academy. This process was carried out mainly through Excel documents, which were subsequently sent by the different businesses of the Sonae group, to the IOW competence center at Sonae. A full-time coworker was allocated to this process that performed all functions inherent to enrolment training. Training courses enrolled trainees of different levels: postgraduate, master, and continuous training. Sonae Academy trained an average of around 2000 trainees per year. In the future, the company intends to reach around 5000 trainees per year, and therefore, it becomes essential to robotize the process, to reduce resources and increase the processes efficiency.

3.2 Value Stream Design of Current Process and Critical Analysis

The VSD was the tool used to map the current information flow (AS-IS situation) and to design the targeted flow (TO-BE). The VSD was carried out jointly with the support of the company supervisor and coworker responsible for this process to identify the process stages, the tasks performed, the transport (electronic), and the stock (accumulation of documents) throughout the entire information flow. Identified waste and potential opportunities for process improvement were also identified.

In the existent process, whenever an applicant enrolled in training, he/she received all the training content even without attending the training. For this reason, there was a need to change this process. To better understand this process, the AS-IS process was divided into three stages, as seen in Fig. 1.

In the first stage, the calendar was created every six months or whenever a new training appears. Afterwards, invites were created for Teams and made available through links. These links were later added to the calendar and sent to the different business areas (MC, Arauco, Sierra, NOS, etc.). The second stage was the most critical, as approximately 118 min, i.e., almost two hours, were spent per week (71%) in the activities described, namely, the preparation of, the Net Promoter Score (NPS) evaluation files, and the creation of a new survey to collect the evaluations in the future. Subsequently,

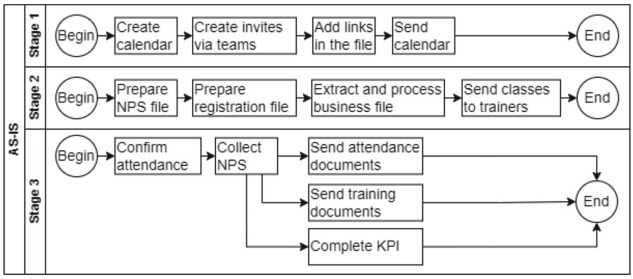

Fig. 1. VSD of AS-IS situation

the registration file was prepared to add the new training courses, date, duration, and trainer, among others. After receiving applicants, they were allocated to training courses, taking into account the limit of available vacancies. This activity was the most critical since it encompassed all training courses and applicants, and the employee added data on subscribers such as name, typewriter number, email, functional area, seniority, and functional group, among other data. After that, the classeswere sent to each trainer. In the third stage, after the end of the training, the NPS was collected. This score evaluated the trainer and the trainees through a survey carried out on a platform external to the company, called "Socrative". Still in this segment, the trainer filled up the attendance document in google forms and later submited it to the IOW.

The AS-IS process mapping through VSD resulted in a total of 13 activities, divided by three stages, as identified in Table 1, four of which were already automatized (activity 7, 8, 11 and 12). The process took about 167 min, i.e. almost three hours, weekly. Eight activities were identified as waste: transport and stock.

Table 1. Process activities (AS-IS situation)

Stage	#	Activities	Transport	Stock	Time (min)	Stage Time (min)
1	1	Create calendar			5	8
	2	Create invites via teams			1	
	3	Add links in the file			1	
	4	Send calendar	X		1	
2	5	Prepare NPS file		x	25	118
	6	Prepare registration file		x	25	
	7	Extract and process business files		x	33	
	8	Send classes to trainers	X		35	
3	9	Confirm attendance			1	41
	10	Send attendance documents	X		1	
	11	Send training documents	X		10	
	12	Collect NPS		x	20	
	13	Complete KPI			9	

4 Improvement Proposals and Results

4.1 Process Design Document Creation

The PDD was the key document to implement RPA. The PDD is a document that details each step on how to implement an RPA, and is divided into six sections: 1. Introduction; 2. Process Flow; 3. Operating System and Software; 4. Process inputs and outputs; 5. Keystroke Level and 6. Dependencies and Accesses. In the Introduction section, the objectives of the chosen process, the idealized changes, as well as data from all parties involved are described. In the Process Flow section, it was defined the AS-IS situation (that was represented in Fig. 1 above) and the TO-BE situation, represented through process diagrams, showing the entire sequence of operations carried out in the process. The process already contained four RPA, and during this project, it was proposed the implementation of seven new RPA. An existing RPA (Send training documents) was improved. The TO-BE process was transformed into just a single step, as can be seen in Fig. 2. It was not possible to automatize three activities (about 23%): create and send the calendar, and confirm attendance. It still require a person due to the need of human interaction.

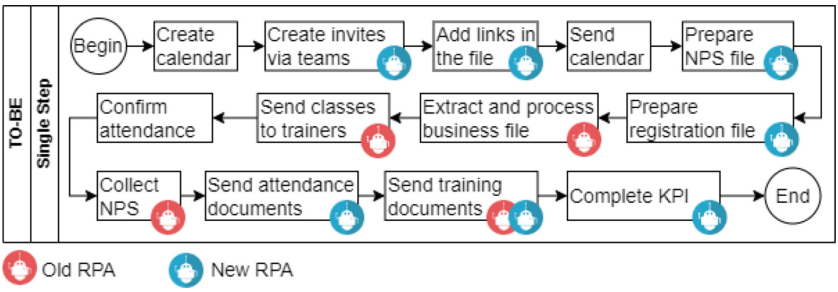

Fig. 2. VSD of TO-BE situation

The Sect. 3 of PDD indicates all the operating systems and software needed on the different devices, to enable the RPA implementation depending on applications with different compatibility. This section, at the request of the company, was left blank and later filled in by the RPA company team.The Sect. 4 lists the inputs and outputs of the AS-IS and TO-BE processes, where the documents used throughout the process were characterized. The inputs were six files in Excel format and the outputs were two in Excel format and one the Outlook type. In the TO-BE process, just three files were considered as input, all in Excel format, namely: "[área]InscriçõesWebinarsIOW"; "Calendário_Formadores_2023" and "Confirmação_Presenças_1". The Fig. 3 shows the PDD part of Sect. 4. After the RPA confirms the presence of those enrolled, if they have effectively attended, the documents of the taught programmatic content are sent.

As for the outputs of this process, they continue identical to AS-IS, however, the Excel file with the indicators created for the training was added. The fifth section, the Key Stroke Level, with greater importance in supporting the process robotization, encompassed and detailed the activities to be carried out in the TO-BE process. To this end, screenshots of

4.1 *Inputs* of AS-IS process

Name	Type	Description
Calendário_formadores_2023	MS Excel	Excel file with training dates and access links
[área]InscriçõesWebinaresIOW	MS Excel	Excel file that contains data on those enrolled in the trainings
Inscrições_Presenças_2022	MS Excel	Excel file pre-filled with classes, trainers and businesses
Cronograma_&_NPS	MS Excel	Excel file pre-filled with training, classes and assessments
Confirmação_de_presenças_1	MS Excel	Excel file resulting from the attendance confirmation foram
Relatório Socrative	MS Excel	Excel file that contains the evaluation of the training given by the participants

4.2 *Outputs* of AS-IS process

Nome	Tipo	Descrição funcional
E-mail enviado aos formadores	Outlook	Email sent to trainers with information about training and respective class
Inscrições_Presenças_2022	MS Excel	Excel file filled with classes, trainers and businesses
Cronograma_&_NPS	MS Excel	Excel file resulting from socrative

Fig. 3. Inputs and Outputs AS-IS

each activity were used, to facilitate the user in its implementation. As an example, in the first activity (Fig. 3 above), the functional description inherent in the preparation of the calendar indicates that: 1) the employee must open the enrollment file and then: 2) must add 20 lines between the different training courses, to register new enrollments for available vacancies. There were also access links to these documents, which, for reasons of confidentiality, could not be exposed.

The sixth section presents the Dependencies and Accesses, intrinsic to the process. The access systems used were defined, containing access to documents mentioned in Sect. 4 of the PDD. To access these documents, credentials or dependencies on platforms external to the company, may be needed.

This RPA implementation resulted in seven activities automatized, corresponded to a reduction of 160 min, i.e., more than 2, 5 h, in repetitive tasks performed manually by a coworker. This was, approximately, 96% of the time previously spent. This achievement allowed the reduction of knowledge waste as this coworker was promoted for a function where she can harness her creativity. The project results were presented recently to the Director of Expertise Center in Continuous Improvement that highlighted the importance of these results and implementation of RPA ongoing.

4.2 Dashboard Design

In the Table 1 above (Sect. 3.2), the last activity (activity 13. Complete KPI) implied that the co-worker responsible for the enrolment process manually inserted the data of the different trainings in different sheets of Excel tables, like to one presented in Fig. 4a). The disparity of information in the same file difficulted the data visualization. This caused many errors and incomplete information. It is expected that later the RPA take over this function, with the activity being automatized and the indicators introduced by the RPA itself. Meanwhile, to solve this problem, it was created a dashboard (Fig. 4b), that was suggested to be implemented, which combined the main and most relevant key performance indicators (KPI) of training according to the IOW department, namely: 1) Total trainees per month; 2) Global assessment of trainees per month; 3) Number of classes per month; 4) Number of trainees with an “indifferent” assessment; 5) Number of trainees rated as “detractors” and 6) The number of trainers with an “autonomous” level. Since there were several trainings, the indicators taken into account were the general indicators, as already used by the company. Using these, will also facilitate the RPA implementation in this activity.

In the header of the dashboard (Fig. 4b), it was inserted important aspects such as the company logo, the title of the indicator, the business area that was using the indicators, the current date, and some concrete data such as the total number of trainees in the year, a month with more trainees, global NPS assessment and the average number of graduates per month.

a

6	7	8	9	10	11	12
Jun	Jul	Ago	Set	Out	Nov	Dez
6	8	0	8	8	8	0
6	13	0	17	**7**	**0**	**0**
1	1	0	1	1	1	0
1	2	0	2	**0**	**0**	**0**
80	80	80	80	80	80	80
83	82	82	73			
16%	16%	16%	16%	16%	16%	16%
0	18%	18%	15%			
3%	3%	3%	3%	3%	3%	3%
0	0	0	6%			
10%	10%	0%	10%	10%	10%	10%
0%	23%	0%	24%	0%	0%	0%
1	1	1	2	3	3	3
1	1	1	1			

b

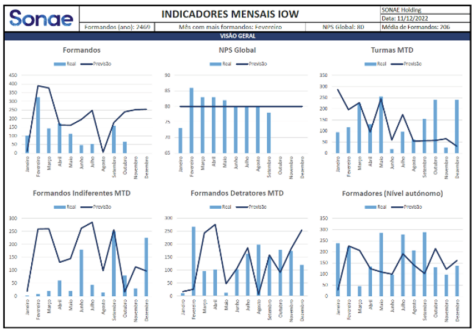

Fig. 4. a) Excel of indicators used for each training; b) dashboard developed for the same Excel with IOW Monthly Indicators (*in Portuguese*)

In this way, KPI will be presented in a more visual, iterative, and dynamic way to support managers' decision-making in a faster and more efficient mode. With this dashboard, it is expected to reduce the disparity and incomplete information and errors (this was not possible to measured yet). At the same time, the coworker responsible for this activity was already released for more creativity tasks, accomplishing one of most important objectives of Lean: reduce the underutilized human potential or knowledge waste.

5 Conclusions

This project was developed in a company by a students team under an Integrated Project in EOM. The project allowed to consolidate the syllabus of the curricular units, and, at the same time, to help the company in solving a problem they had. Given the situation of the students team, since it was made up mostly of student workers, one of the biggest challenges faced was time management and flexible schedules, however these restritions were surpassed with the engagement of all.

This project had as its main focus the automation of the training enrolment process through the development of a PDD, which allowed the implementation of RPA. This implementation resulted in a reduction of more than 2, 5 h, in repetitive tasks performed manually by an coworker, which corresponded to approximately 96% of the time previously spent. In addition to the implementation of this process, a dashboard was developed to increase visibility of the training enrolment main indicators. Future work will be to extend this RPA implementation to other processes of the company, even using different artificial intelligence algorithms.

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Quality

Assessment of Alternative Quality Control Plans in Dynamic Contexts: A Simulation Approach

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Abstract. Process quality planning should establish a Quality Control Plan (QCP) to achieve the desired quality level with minimum Cost of Quality (CoQ). This plan establishes the critical quality variables, control stations in the process, and control method at each control station. The purpose of this study is to, through a simulation approach, determine a QCP for a manufacturing process, which minimizes the CoQ. The inputs to the simulation model are inspection and repair/replace costs, proportion of defectives at process output, type I and Type II inspection errors, alternative control methods (no control or 100% inspection), and the cost of delivering defective units to the customer. The proposed model was developed in Simulation Modelling Based on Intelligent Objects (SIMIO) software to estimate the total CoQ and number of compliant units delivered. This model allows to determine the CoQ of the alternative scenarios and to define a QCP that minimizes the total CoQ. An illustrative example based on a manufacturing process demonstrates the applicability of this model, and the results indicate that the best QCP, amongst defined alternatives, may vary when the model parameters are updated. As future research directions, the simulation models could be relevant when defining digital twins of manufacturing processes and models' results can support process improvements.

Keywords: 100% Inspection · Cost of Quality · Quality Control · Simulation

1 Introduction

Generally, manufacturing systems are composed of several workstations (WS) or stages, in which parts/components undergo various operations and are transformed into finished products. This type of system is called a multi-station manufacturing system (MMS) [1]. In a MMS, each WS produces a proportion of defective items, that can be contribute to the failure costs, one of the categories of the total CoQ [2, 3].

Process quality planning should establish a QCP for the MMS to achieve the desired quality level for the final product at the lowest cost. This plan establishes the critical quality variables to be controlled, and for each quality control station (QCS), its location and control method (e.g., 100% inspection or no inspection), and focuses on operations where there is a higher probability of occurrence of failures and when the inspection is technically and economically viable.

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To identify the optimal QCP (under different scenarios), many authors have suggested different approaches (e.g. analytical models [1, 4] or simulation models [5, 6]) as well as other ways of modelling the system under analysis and different variables/parameters [7, 8]. However, the practical application of theoretical models is poor [9]. The literature presents many barriers [9–11] for this application, such as: high complexity of models, lack of knowledge/information on how to measure the high number of parameters/variables of the models, ignorance of the benefits of a suitable QCP, company culture that does not promote rigor and evaluation, difficulty in identifying quality cost elements, and difficulty in collecting quality data.

Such models may be considered as a simplification of reality, for example, by not considering machine breakdowns [12] or by not modelling inspection errors [13], resulting in inaccurate and misleading cost models [4]. Thus, the problem is to design realistic and comprehensive models [14] of CoQ that are easy to adapt to specific situations, but there is still a large number of companies with little or no CoQ accounting policy [15]. There are several motives why companies do not measure the CoQ, such as [11, 15]: management ignoring the benefits of CoQ determination, lack of cooperation from top management, complexity of implementation, and lack of adequate computer systems necessary to track CoQ.

Organizations and their contexts are dynamic, leading to rapid changes in models and/or model parameters that are difficult to estimate [16]. Therefore, the model used to determine the CoQ must be robust and understandable so that people can adjust it, either because some of its parameters have changed or because the model is no longer a good representation of reality [17].

Simulation has advantages over analytical models, such as [18]: it allows models to be built from a building-block perspective, with any degree of complexity, even without a deep knowledge of mathematics, allowing the incorporation of random variables modelled by different distributions; it allows explicit consideration of time and the evolution of variables that are not static; it is more easily accepted and understood by decision-makers, especially when accompanied by graphical animation; and simulation models are inherently coherent.

The main objective of this study was to determine, through a simulation approach, the minimum cost of alternative QCPs considering inspection errors and multiple inspections. To limit the size of the paper, the quality control alternatives analysed will be extreme cases (100% inspection and no inspection, but other strategies could be simulated) and two stages of inspection.

The remainder of this paper is organized as follows. The next section presents the description/assumptions of the quality control system. In Sect. 3, a discrete event simulation is used to model such a system, including a discussion of the numerical results of two scenarios with four different QCP. The paper ends with conclusions and directions for future research.

2 Problem Description

This study focuses on multi-stage inspection (i.e., after a certain process at WS_i, inspection can be performed to identify potential defects). However, at a later stage of the manufacturing process (e.g., workstation j or final inspection), the same defect(s) can

be assessed, but typically using other techniques or functional tests (see Fig. 1). The assumptions about the first process and potential inspection are as follows:

- The proportion of nonconforming product at the output of WS_i is Pd_i;
- QCS_i can be assigned to perform inspections of critical quality variables, influenced by one or more upstream WS. It is technically and economic viable to do inspection after WS_i; each inspection costs on average Ci_i;
- QCS_i can determine conforming and non-conforming items. Conforming items are sent to the next stage and non-conforming items may be repaired or replaced by a conforming item with an average unitary cost of Cr_i and sent to the next stage;
- QCS are subject to errors: Fd_i - proportion of compliant parts classified as defective; Fc_i - proportion of defective parts classified as compliant;
- To reduce the total quality costs, different decisions regarding QCS_i can be made: no inspection or 100% inspection.

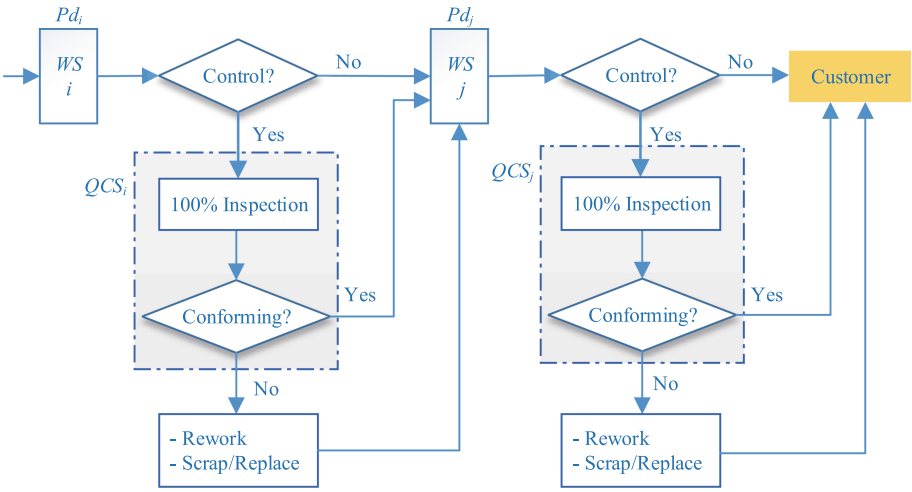

Fig. 1. Problem description flowchart

The assumptions about a subsequent process, where an additional or alternative inspection can be made, are as follows:

- There is a proportion of defects Pd_j generated at WS_j;
- It is technically and economic viable to do inspection after WS_j; each inspection costs on average Ci_j;
- Inspection is not perfect: Fd_j - proportion of compliant parts classified as defective; Fc_j - proportion of defective parts classified as compliant;
- $Cr_j > Cr_i$ repairing or replacing defectives at later stages when product has more value added usually costs more;
- Considering inspection errors, defective units may be sent to customers. The unitary cost of sending a defective unit to the customer is Cn. Typically, $Cn > > Cr_j$.

This corresponds to what occurs in several part manufacturing processes in the automotive sector, which can produce a proportion of defective parts. As a result of a 100% inspection (100%I), parts can be classified as either compliant and sent to the next process, or non-compliant and sent for repair/replacement. Two different types of errors can occur during inspection: sending defective parts to the next process, and sending conforming parts for repair/replacement. After this first production phase, other processes are carried out, and usually during the final inspection, the same quality characteristics can be inspected again using different equipment/methods. To represent this situation, a simulation model was developed using four combinations of alternative controls (Fig. 2), including not doing control (NC) at each QCS.

To minimise appraisal and failure costs, the type of inspection performed after WS_i and WS_j should be analysed and selected the QCP with lower CoQ.

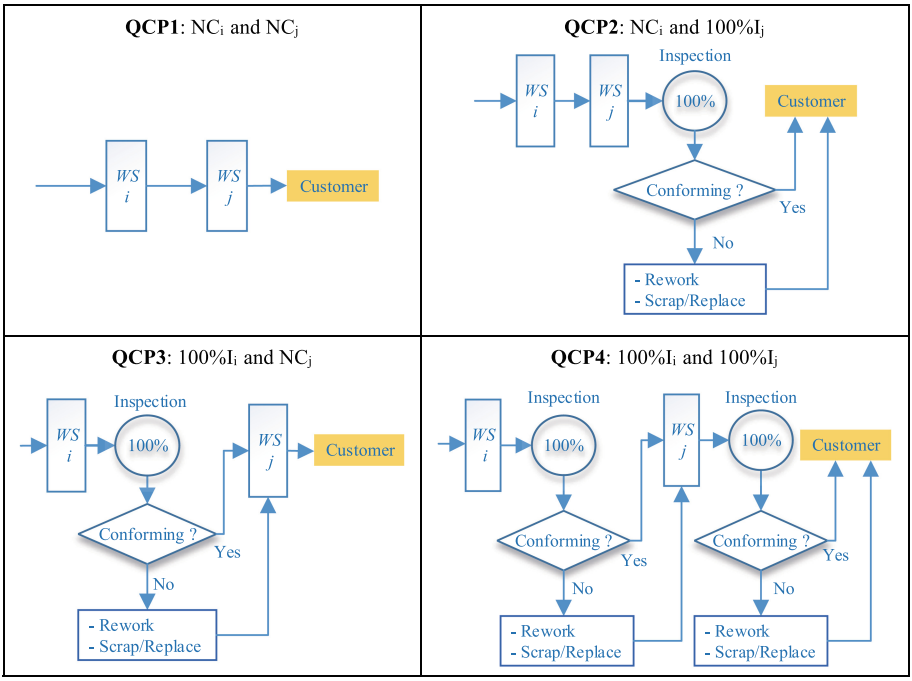

Fig. 2. Alternative quality control plans (QCP)

3 Discrete Event Simulation

3.1 Simulation Model

Four simulation models were developed based on the description provided in the previous section (Fig. 2). The models use standard discrete event simulation blocks.

To perform a systematic analysis, SIMIO software (https://www.simio.com), "Experiment Manager" was used. A set of inputs (Controls/Parameters) and a set of Responses were defined (Table 1). Two scenarios were analysed: the first one corresponds to the baseline, i.e., the current situation; the other scenario may correspond to changes in the current system, which is not static, such as an improvement in the proportion of defectives or variations in the inspection system. For each scenario, the four models, corresponding to four alternative QCP, are assessed through the Responses u_CoQ (unitary Cost of Quality) and #def (Number of defective products delivered). The costs referred in Controls are the estimated unitary costs.

Table 1. Controls/parameters used for each scenario.

Scenario	Pd_i	Ci_i	Fd_i	Fc_i	Cr_i	Pd_j	Ci_j	Fd_j	Fc_j	Cr_j	Cn
1	5%	1	10%	5%	20	5%	3	10%	5%	100	1000
2	**1**%	1	10%	5%	20	**2**%	3	10%	5%	100	1000

Each inspection block is parameterised with the probability of detecting a non-compliant part, as well as Type I and Type II detection errors. Despite considering these inspection errors, each part has properties reflecting its compliance in its appearance (colour), thus allowing these parts to be visualised in the simulation animation for analysis, model validation, training, and CoQ calculation.

In these models, many relevant elements are highlighted, such as the parameters (red), partial pass counters (blue), and cost totalizers (green). Counters were set and costs were calculated at the end of the process, as well as for each activity in each phase. A pie chart showing the total inspection cost per unit was also included.

Figure 3 shows a screenshot at the end of the simulation of scenario 1, model 100%I_i and 100%I_j, where it is visible production/inspection path and defective parts at the end, along with other performance indicators on quantities and quality costs. In this case, for an order size of 1000 parts produced the customer receives five defective parts. At *inspection_i*, 852 parts are classified as conforming (including two false conforming parts) and 148 are classified as non-conforming (including 103 false defectives). Similarly, at *inspection_j* 874 parts are classified as conforming (including five false conforming parts) and 126 are classified as non-conforming (including 81 false defectives). The overall CoQ per unit was 24.56€, and its biggest component (51.3%) is related with cost repairs at *inspection_j* as can be seen in the pie chart or, in blue, at *repair_j*.

The models were based on a case study described in [16] and the simulation results were compared to the expected quantities and costs obtained through an analytical model,

as in [17]. Results suggest the simulation model is valid because the quantities and costs are equivalent to the expected by the analytical model.

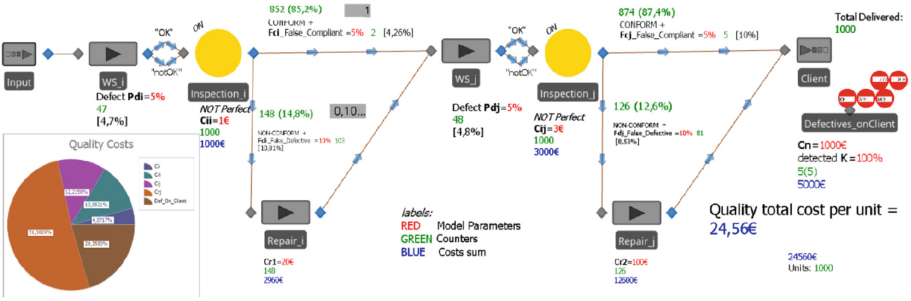

Fig. 3. Simulation run screenshot of QCP4 (100%I_i and 100%I_j)

3.2 Numerical Results

The results of 50 simulation runs for each QCP in each scenario are shown in Table 2.

Table 2. Responses of 50 simulation runs (unitary CoQ and number of defectives delivered) for each QCP / scenario.

	NC and NC		100%I_i and NC		NC and 100%I_j		100%I_i and 100%I_j	
Scenario	u_CoQ	#def	u_CoQ	#def	u_CoQ	#def	u_CoQ	#def
1	98.78	98.78	57.64	53.78	26.29	4.94	**23.99**	2.48
2	29.38	29.38	23.82	20.62	**17.75**	2.04	19.09	1.08

3.3 Discussion of Results

Analysing the average results obtained by the simulation for the four alternative QCP considered (Table 1) it can be seen that the u_CoQ does change significantly within each scenario, varying between 23.99€ and 98.78€ in scenario 1, and between 17.75€ and 29.38€ in scenario 2. A similar behaviour is verified for the average number of deliveries with defect whose values vary between 2.48 and 198.78 in scenario 1 and between 1.08 and 29.38 in scenario 2. Overall, the minimum CoQ for scenario 1 is obtained for the QCP 100%I_i and 100%I_j while in scenario 2 the minimum CoQ is obtained for QCP NC and 100%I_j. Thus, from a baseline where the best solution is to inspect after both workstations, if a reduction in process defectives occur (from 5% to 1% at Pd_i and from 5% to 2% at Pd_j) the best QCP changes.

4 Conclusions

Through a simulation approach, this study determines the minimum CoQ of alternative QCPs by considering inspection errors and two stages of inspection. Four simulation models, corresponding to four alternative QCP, were developed to determine the total CoQ and the number of defective units delivered to the customer. These costs are related to appraisal activities and failures. Two scenarios were simulated, corresponding to different values in model parameters. These scenarios may correspond to potential changes usually happen during mass production, such as a reduction or increase in the proportion of defectives, or to assess the use of different measurement systems.

The analysis of the results show that the average CoQ per unit varies from scenario to scenario, and the QCP that minimizes the total CoQ was selected in each scenario. In this example, for scenario 1, the best QCP is 100% inspection after WS_i and 100% inspection after WS_j. However, when Pd_i and Pd_j are reduced, the best QCP is obtained by no inspection after WS_i, and 100% inspection after WS_j. Thus, the model should be computed using updated parameters to ensure that the best QCP is deployed in dynamic systems.

This work contributes to support decision-making related to quality control in dynamic contexts, a relevant feature of industry 4.0. It transfers a problem from the quality control domain to the financial domain (which is a topic for future research [19]) and uses simulation, with its inherent advantages [18], instead of using analytical models to determine costs. If model parameters are updated, the total CoQ can justify, as shown in the application example, the use of different QCP or improvements in the measurement system.

The limitation associated with this work is the consideration of the specific four QCP alternatives. For different organizations, despite modelling a baseline scenario, other alternatives can be modelled, such as, modelling by sampling (as in [4]), or modelling more QCS. Additionally, depending on the level of detail and available parameters, the models could be simpler or more detailed, as in [17].

As a future research direction, the simulation model could be used to support process improvements by reducing the proportion of defects. This model could also be relevant when defining digital twins of manufacturing processes, because it details relevant parameters of the QCP, often simplified in other models. This work is part of a greater project to design a decision support system to assist in real-time, quality planning and quality control, while minimizing quality costs.

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A Readiness Level Assessment Framework for Zero Defect Manufacturing (ZDM)

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Abstract. In this study, a comprehensive framework for assessing the readiness of production systems for Zero Defect Manufacturing (ZDM) has been developed and presented. The framework includes four pillars of ZDM readiness, namely Personnel, Procedures, Infrastructure, and Company Culture, to help companies understand their level of readiness and plan for successful implementation of ZDM. We argue that a manufacturing company will be better equipped to embrace ZDM if it performs well in these four areas. We propose a tool that uses yes/no questionnaires to assess a manufacturing system's readiness for ZDM. The results of the questionnaire will objectively show the true level of cultural readiness for ZDM adoption, and the level of investment required for implementation will depend on the level of readiness. This tool can help companies gain a clear understanding of their readiness and create a plan for implementing ZDM. Overall, our framework and tool can help manufacturers improve the quality of their products and be ready for ZDM adoption.

Keywords: Zero Defect Manufacturing · ZDM · readiness · quality assurance

1 Introduction

ZDM, or zero-defect manufacturing, is one of the most effective strategies available today for increasing product quality [1]. It is an Industry 4.0 paradigm that uses cutting-edge practices and digital technologies in production settings to go beyond conventional quality management approaches [2]. Most companies make the mistake of implementing quality management measures after the product has entered the manufacturing process instead of starting early in the design phase. To address this challenge, ZDM follows a cycle of continuous improvement synchronized with defined benchmarks and integrates into the manufacturing process from the start rather than addressing issues and faults later [3]. Using a combination of knowledge-based and data-driven approaches, as well as physics-based models, can help create tools and methodologies that prevent, correct, and predict defects in manufacturing processes. This leads to the implementation of Zero Defect Manufacturing (ZDM), which improves the customer experience and the

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sustainability of the manufacturing process [4]. When moving a product from concept to production, the idea of planning for zero defects is quite important yet complex. Zero defect is a goal; many controllable and uncontrollable factors may come into play when producing parts. It is important to develop a solid plan to manage and even get rid of any factors that lead to product defects. Design for manufacturability is crucial in this case, however many legacy items have problems that are unavoidable due to their inherent nature. Engineers can use the tools under the ZDM concept to better control these variables [5].

The current paper aims to create a framework and a tool for measuring the level of readiness of manufacturing systems for adopting ZDM. All the different levels of a manufacturing system will be analyzed from the top level, business – management until the bottom level of the production itself. The goal is to identify all the factors that are contributing to the implementation of ZDM.

2 State of the Art

Many problems may occur in complex industrial environments, causing mistakes that would produce defective products [6]. Companies must adopt the techniques and mindset of producing high-quality products with minimal waste if they want to maintain a competitive edge in the present and future business landscape [7]. The efficiency and effectiveness of manufacturing organizations can be greatly impacted by poor product quality [8]. Poor quality can result in both direct and indirect costs, including those related to repairs, shipping, chargebacks, product returns, and lost sales [9]. Manufacturing defects can be brought on by, among other reasons, process variations driven by faulty equipment, worn out tooling, non-conforming materials, and human error [10]. Except for human error, these variances can be anticipated by applying Industry 4.0 technologies, methodologies, and tools to put corrective measures in place to get rid of the problems' underlying causes. ZDM is the strategy for obtaining Zero Defects by utilizing Industry 4.0 and its associated key enabling technologies [2, 11, 12].

To address the problem of ZDM implementation, many academics have offered general frameworks and architecture for applications in various industrial settings. These frameworks and architectures are generic in nature and frequently applicable to both new and current manufacturing systems. Wang (2013) [13] presented an earlier framework for ZDM that explains the application of DM approaches to produce zero-defect products. On that regard, May and Kiritsis (2019) [14] designed and developed a comprehensive framework and ad hoc approaches that could be used on both new and existing production lines for being able to manufacture products with zero defects by integrating cutting-edge industry 4.0 technologies while also improving the competitiveness and sustainability of manufacturing facilities. Psarommatis and Bravos (2022) [15] created a comprehensive framework that identifies all the essential elements of a manufacturing organization that must be connected for improving the sustainability of a manufacturing system with ZDM principles. Ringen (2022) [16] investigated the progression towards ZDM and the extent of Industry 4.0 readiness in relation to basic data integrity. The analysis revealed discrepancies between digitally defined values and physically measured values at a level demanding a high degree of autonomy and adaptability in decision procedures for the finished product to comply with ZDM. Konstadinidis et al. (2022) [17] provided

a high-level overview of a generic manufacturing ecosystem that combines emerging technologies that are essential to the I4.0 vision to achieve optimal production conditions in industrial contexts.

Even though ZDM has attracted the attention of manufacturing researchers, it is still difficult to apply ZDM in real industrial systems. To speed such a deployment, it is essential to successfully follow the principles for creating ideal manufacturing system environments in a range of industrial verticals. Based on our review of the relevant literature, we found out a dearth of methods and instruments for evaluating the preparedness of manufacturing systems for ZDM deployment. Due to this gap, the current study's objectives include examining various production system levels and identifying the factors affecting the adoption of ZDM. The proposed tool is built on the transformation of qualitative data into quantitative, thus assessing the level of readiness using company's knowledge.

3 Readiness Framework

The current section is devoted on presenting the proposed framework for quantifying the level of readiness of a manufacturing system in the adoption of ZDM. The proposed framework has twofold purpose a) to develop a tool for the quantification of the level of readiness and b) identify the areas that are require improvement for the adoption of ZDM. The level of readiness is a function of multiple variables that are coming from all the different levels in a manufacturing system. A manufacturing system is encompassed by not only its operational and information technologies, but also the organization behavior, i.e., people, procedures, and information flow [18].

In this scope four categories, that all those parameters belong to, have been defined. Those categories describe the four pillars of readiness "Personnel" (PE), "Procedures" (PR), "Infrastructure" (INF) and "Company culture" (CC) (Fig. 1). If a company performs well in these four pillars, then the level of readiness is high for the adoption of ZDM. Quantifying this level of readiness is a challenging and complex procedure, so a straightforward approach was chosen using a Yes/No questionnaire to eliminate subjectivity [19]. Such yes/no questionnaires have been employed successfully for many years in a variety of study fields, particularly in the biomedical and health sciences [20, 21] and in manufacturing [19, 22]. The developed questionnaire can be seen in Table 1, each question might belong to more than one of the readiness pillars. The questions are developed in order to cover all of the aspects that are affecting the adoption of ZDM. The survey is intended to be used by those involved in the design process of facilities for zero defect manufacturing and should be addressed to the relevant stakeholders in the organization. While results and conclusions of the survey are not presented in this paper, the proposed framework and tool will useful for future studies aimed at assessing the level of readiness of a manufacturing system in the adoption of ZDM.

When the primary data involve people's perception on something, questionnaires are a powerful tool, especially in a large number of people that some manufacturing systems may present. This data collection technique involves a number of personal to answer a number of questions via the Internet. For the design of such questionnaire and selection of the target group, the requirements encountered by Psarommatis and May (2022) were used [19]. When formulating the questionnaire questions, the purpose and

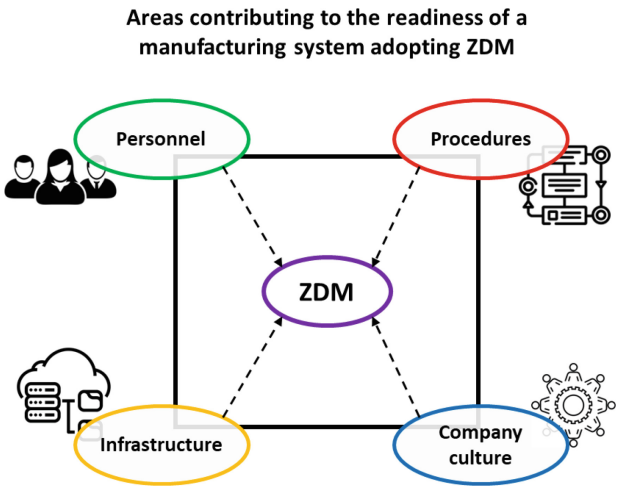

Fig. 1. Key pillars for ZDM readiness

scope of assessing ZDM readiness was kept in mind. Guidelines for formulating the questions were used as suggested by Säfsten and Gustavsson (2020) [23]. If the answer of a question is yes then the value of this question is 1 and if it no then it is −0.5. The calculation of the final readiness level is the sum of all questions values.

Table 1. Questionnaire for evaluating ZDM readiness

No.	Question	Description	Pillar
Q1	Are data collected from the production?	If there are data from the machines and other sources in digital form collected and stored	INF
Q2	Are production data exploited in any way?	The data that are collected and stored are being utilized for improving any process that is happening in the production	INF, CC
Q3	Is 100% inspection is taking place?	If there is in at least one manufacturing stage that all of the products are inspected	CC, PR
Q4	100% at last manufacturing stage?	If Q4 yes, is 100% inspection is performed only to the last manufacturing stage	CC, PR
Q4.1	Physical detection is applied?	If the quality inspection is performed using physical measurements from the product, CMM, vision systems etc.	INF, PR

(*continued*)

Table 1. (*continued*)

No.	Question	Description	Pillar
Q5	Virtual detection is applied?	If quality inspection is performed using virtual metrology approach. Utilizing collected data to estimate the product quality	PR, CC
Q6	Quality prediction is applied?	Utilize any learning method, such as AI, machine learning for predicting when in the near future a defect will be produced	PR, CC
Q7	Are data analytics utilized?	Use data analytics for extracting valuable insights from the collected data	PR
Q8	Are machine learning and AI etc. utilized?	Use machine learning, AI and other learning methods for any optimization process	PR
Q9	Is there a good communication between top management and production?	Whether any information between production an top management is easy to be communicated or not	PR, CC
Q10	Is quality important?	If the product quality is important or not	CC
Q11	Is there a quality assurance method implemented?	Whether there is a quality assurance method implemented to the production or not	CC
Q12	Quality inspection is performed only at the final stage?	Whether quality inspection is performed only at the last manufacturing stage when the product is ready?	PR, CC
Q13	A defected part is repaired or not?	If there is a defected part in the products the product is repaired or scraped/recycled	PR, CC
Q14	Is there a dynamic scheduling tool implemented?	If there is a dynamic scheduling tool that re-schedules the production when a quality event or a set of events happen	INF, PR
Q15	Are workers familiarized with quality assurance?	Whether the workers are familiar with quality assurance and understand quality in depth	PE
Q16	Are workers motivated to implement quality assurance	If the companies motivate workers to implement workers. If for example the only concern of a company is time or cost and pressure for lower then demotivate workers for implementing quality assurance	PE, CC

(*continued*)

Table 1. (*continued*)

No.	Question	Description	Pillar
Q17	Is there resistance to change from workers?	If workers are conservative and afraid the change on adopting new approaches	PE
Q18	Is there resistance to change from management?	If top management is conservative and afraid to implement and adopt new approaches	PE, CC
Q19	Do workers have all the required resources to conduct quality assurance?	If the workers have all the necessary tools for performing the quality assurance	CC
Q20	Do workers understand data driven technologies?	If workers have the knowledge to use and understand data driven technologies	PE
Q21	Is there a specific quality assurance method used?	Is there a specific quality method implemented, such as Six Sigma, Lean etc.	PR, CC
Q22	Is there a need of a specialist for the quality assurance implementation?	If quality assurance is relying on external experts or there is expertise inhouse	PE
Q23	Installing sensors for collecting data is easy?	If the installation of new sensors for the collection of data is easy or not	INF

4 Discussion

The current study developed a tool to assess the readiness level of production systems for Zero Defect Manufacturing (ZDM). The four pillars of ZDM readiness were identified as Personnel, Procedures, Infrastructure, and Company culture. If a company excels in these areas, it has a high level of readiness for adopting ZDM. Affordable and easy to implement ZDM for SMEs will play an important role in the near future. Today we have skilled engineers, technologies, processes, and standards [12] that allow this philosophy to become a reality. Large manufacturing players like China and Germany are adopting a similar approach due to their sustainability goals. As quality and manufacturing support systems become more complex and require real-time control, their integration can be a challenge. According to [24], over 41% of EU companies have not adopted any new advanced digital technologies yet. Such survey does not consider the ZDM paradigm, and it is limited to only technologies. For ZDM to be successful in manufacturing companies, a certain level of readiness personnel, procedures, infrastructure, and company culture is necessary.

The infrastructure in companies and countries can vary. Scandinavian countries have a stronger infrastructure for Industry 4.0 compared to Eastern European countries, as reported by the EU. However, these differences should not be mistaken for the requirements for ZDM. To the best of our knowledge, this is the first survey that will help companies understand their actual level of readiness for ZDM.

Manufacturing companies face socio-technical challenges that vary in form and magnitude, depending on the starting points and goals for Industry 4.0 in different countries. Knowledge is becoming more transient, and the boundaries between disciplines are eroding. The ZDM readiness framework is based on yes/no questionnaires, offering companies a clear picture of their readiness while limiting in-depth information. This can still help companies create a plan for successful ZDM implementation.

Recently, many papers about ZDM procedures have been published in different fields, ranging from general papers [1, 11, 12] to papers focusing on quality inspection [24]. This survey can help companies determine which processes need to be developed for successful implementation of ZDM [1, 11, 12, 25].

The readiness level of a company's culture for adopting ZDM is reflected in the consciousness of its leaders. The use of yes/no questionnaires in the proposed tool objectively shows the true level of cultural readiness [18, 25], and the amount of investment needed for implementing ZDM varies based on the level of readiness. To avoid subjectivity an expert outside the company should conduct the questionnaire [19].

5 Conclusions

In this work, we have provided a designed questionnaire for the assessment of ZDM readiness in large and SMEs companies. Uniquely to ISO9000 family, which do not mention ZDM, we provide a framework that contains the four pillars of ZDM readiness, i.e., "Personnel" (PE), "Procedures" (PR), "Infrastructure" (INF) and "Company culture" (CC). Based on Psarommatis and May (2022) [19], 23 yes/no questions are formulated for the mentioned pillars. This study indicates that as knowledge becomes more transient and the level of company consciousness cannot exceed the one of its leaders, such survey will have a great impact on their assessment of readiness. Contrary to ISO9000 family, external third-party quality audit is recommended for the successful evaluation and deployment of ZDM. Finally, Sect. 5 offers a starting point for new research ideas to be pursued.

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Selection of Industry 4.0 Technology to Support Lean Manufacturing from the Perspective of Enterprise Interoperability

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Abstract. Faced with paradigm shifts in the global manufacturing context promoted by the Fourth Industrial Revolution, many organizations are seeking to meet customer needs through the integration of Lean Manufacturing (LM) philosophy principles with Industry 4.0 (I4.0) technologies. When there is the integration of technological enablers from I4.0 and deep advances in efficiency and productivity with LM, these systems tend to offer enhanced and more assertive results, since they are complementary concepts. The main goal of this paper is the selection of I4.0 technologies to support the LM system, considering the perspectives and barriers of Enterprise Interoperability (EI) and using multicriteria methods (MCDM) to support decision-making. Using the DEMATEL multicriteria method, it was possible to develop a diagnostic evaluation, analyze the existing influences between the elements of the LM, and support the elicitation of weights in the decisional evaluation, with the FITradeoff method. In this way, the decisional evaluation indicated as the I4.0 technology that must be implemented as a priority to raise the level of organizational maturity in LM is Big Data Analytics. Big Data integrated with Business Analytics (BA) can offer several advantages, such as assertiveness in decision-making; Keeping the company updated about the market; Indicating risks and improving data security; Promotes alignment between marketing and sales, among others.

Keywords: Lean Manufacturing · Industry 4.0 · Enterprise Interoperability · MCDM methods

1 Introduction

With the current advance of globalization, manufacturing industries are increasingly dealing with dynamic and challenging scenarios. The need for high productivity rates at lower costs linked to greater customer participation along supply chains is some of the setbacks that companies routinely face [1]. Faced with the popularization of the Toyota Production System (TPS), later named Lean Manufacturing (LM), and the various ways to increase organizational competitiveness provided by this philosophy, the industrial sector is faced with a large volume of industries acquiring this system.

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On the other hand, the concept of Industry 4.0 (I4.0) is disseminated among manufacturing companies so that their passage through the Fourth Industrial Revolution becomes inevitable for those who aim to remain consolidated in the market. According to [2], the basic foundation of Industry 4.0 is that by connecting machines, systems, and assets, companies can create smart networks and thus control production modules autonomously.

The Lean Manufacturing management model is the basis for the implementation of Industry 4.0 in companies [3] and therefore, as I4.0 represents a new paradigm in the global manufacturing context, there is a need to study the relationship between the consolidated tools of the LM approach and the advancement of new technologies that integrate Industry 4.0 [4].

The Lean philosophy and the industrial 4.0 system can offer several isolated improvements, however, both models can provide assistance in a reciprocal way, as Industry 4.0 technologies can support during the elimination of barriers to Lean Manufacturing implementations, while production environments that already have the LM culture are more likely to be modeled and controlled by an Industry 4.0 platform [5].

Given the various tools available to make improvements in the industrial sector and consequently to raise the level of maturity, it is necessary to prioritize the implementation of I4.0 technological enablers to improve organizational performance and maturity (Lean). Thus, knowing how to map the barriers to technology adoption and their impacts is of paramount importance in order to evaluate investments and prioritize Digital Transformation projects [6]. In this case, there is a need to prioritize the implementation of I4.0 technological enablers to improve organizational performance and maturity (LM), which should consider evaluative perspectives of Enterprise Interoperability (EI) [7], consolidating the general goal of this article.

Enterprise interoperability (EI) represents the ability to interact at three different levels, data, services, and processes, all of them with a semantic defined in the business context [8]. Some definitions found in the literature refer to the organizational and operational aspects of a company, reinforcing interoperability as a key success factor and, thus, requiring special attention to meeting requirements that expand the capacity for interoperation and performance improvement [9].

When considering the implementation of Industry 4.0 in industries undergoing processes of application of Lean concepts, it is essential to evaluate the different levels of complexity of the technologies from a previous assessment of organizational maturity. In this case, multicriteria methods offer support for structuring evaluation models and diagnoses in order to contemplate a huge amount of aspects that must be taken into account when proposing an action plan to manufacturers, such as, for example, the level of connectivity.

The subsequent sections are structured as follows. Section 2 presents a brief review of the literature related to the areas of study. In Sect. 3, some considerations are made to contextualize the article in relation to the proposed framework. Section 4 is divided into two parts, which are dedicated to the development of the diagnostic evaluation (Sect. 4.1) and the decisional evaluation (Sect. 4.2) performed. The final section is dedicated to concluding the article.

2 Literature Review

Lean Manufacturing, a system that has its main focus on the maximum reduction of waste, is a widely used solution for the great challenge of the current industries of the twenty-first century: the search to do more (profit) with less (cost), without damage to the quality, workforce or other important elements to maintain the stability of its operations. For this, there is a need for greater integration between entities and industrial processes dictated by the requirements of Industry 4.0, the evolution of communication and information systems follows business trends aimed at dynamic, flexible, and adaptable organizational and operational management to the strategic plan which should consider the organizational 'Intra' and 'Inter' interaction as a success factor [10]. One way to evaluate the attributes related to the collaboration environment and the ability to communicate between entities and the level of information sharing between companies is through the concepts of Interoperability.

Interoperability can have different definitions, but in a broad sense, the term can be defined as the capacity of two or more systems or components to exchange information and use the information that was exchanged [11]. The ability to interoperate can be affected by barriers such as conceptual, technological, and organizational [12] manifested in the perspectives of business, processes, services, and data. Interoperable companies are integrated and have a system for sharing information, achieving common goals, and obtaining mutual benefits. Furthermore, the successful implementation of interoperability helps companies to optimize their business processes, reduce costs and maximize the quality of services [13].

Since 2014, research has investigated the relationship between LM and I4.0 mostly from a qualitative perspective, with few models for evaluating the influences generated between both from a quantitative perspective. In this case, the current proposal is to fill this gap by proposing a quantitative model, which methodologically assesses the impact of the I4.0 concepts and technologies for the improvement of the pillars linked to the LM, considering its organizational barriers through Enterprise Interoperability.

3 Framework

Currently, there are several existing I4.0 technologies, as well as a large volume of LM pillars, which have different levels of implementation complexity. In order to use concepts that can be supported by the company, considering the degree of organizational maturity, it is essential to carry out filters for the selection of some elements of LM and I4.0. These filtered items, when used in the evaluations, lead to a model that only considers concepts that can be implemented in the company, discarding those that are not suitable at the moment, due to the high complexity or some other impeding factor. The use of these filters is indicated in the first part of Fig. 1 (filters), starting with the model criteria filter (LM concepts) from the combined use of the LIM matrix (Lean Interoperability Matrix) and Pareto's chart. In parallel, the proposed alternatives are filtered (I4.0 technologies), using the IPM matrix (Industry 4.0 Performance Matrix) as a support tool. These filtered elements will be used as input data in the diagnostic evaluation with the DEMATEL multicriteria method (Decision Making Trial and Evaluation

Laboratory) and decisional evaluation with the FITRADEOFF method (Flexible and Interactive Tradeoff). The proposed framework is shown in Fig. 1.

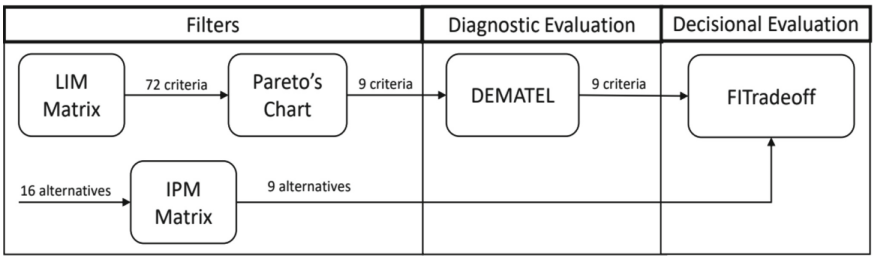

Fig. 1. Framework stages.

The first filter is called the LIM matrix and evaluates the perspectives of interoperability according to the Framework for Enterprise Interoperability (FEI) model in [12] (businesses, processes, services, and data) and their barriers (organizational, conceptual, and technological) based in the principles of Lean Manufacturing, assigning values according to the degree of importance of the criteria in the scenario under analysis. The LM principles considered in this matrix come from the "Toyota House" which symbolizes the Lean Manufacturing philosophy, being: the 5S methodology, heijunka, standardization, and kaizen representing the stability (base) of the system, while Just in Time and Jidoka represent the pillars. Both elements make a strong contribution to achieving the main objective of the Lean philosophy: increased quality, reduced costs, and shorter lead times. When relating these elements of the LM with the perspectives and barriers of interoperability, it is evident the highlight of these principles, which will increase collaboration between systems, machines, and people, thus enabling greater agility, flexibility, and efficiency in the production processes, resulting in higher quality at reduced costs [14, 15].

After listing the six Lean principles selected with the combination of Interoperability perspectives and barriers in the LIM matrix, 72 quadrants were generated, that is, 72 criteria that will be forwarded to the Pareto chart, which is detailed in Sect. 4.1 (DEMATEL).

The second filter is called the IPM Matrix. This method takes into account the industry 4.0 technologies most cited in the literature and the five performance factors proposed by [16] (Reliability, Cost, Flexibility, Quality, and Speed). As input information for this matrix, 16 technologies from Industry 4. Were considered, of which 9 remained as alternatives in the decision-making process after the filter was performed with the IPM matrix. In this way, when interconnecting the LM pillars with the I4.0 technologies in the decisional method, the model will be considering the elements that can integrate with other systems (interoperability), in addition to having high performance in the performance indicators.

4 Results

4.1 Diagnostic Evaluation - DEMATEL

The DEMATEL multicriteria method uses structural modeling to analyze cause-and-effect relationships between factors of a problem under study. In other words, DEMATEL confirms the interdependence between factors, quantifies impact, and allows the development of an intelligible map, which makes the most significant relationships visible [17].

In the present paper, the relevance of using this tool is evidenced by the provided diagnosis, because from the analysis of influences, it is possible to verify the fundamental criteria to reach the elevation of the organizational maturity in the LM. In addition, the diagnostic evaluation stage performed with the DEMATEL method supports the elicitation of weights in the FITradeoff method, as it provides a view of the intensity of the connections between the criteria. In this way, the decision-maker of the problem has a quantitative orientation of the relationship of criteria before the decisional evaluation, offering support to the decision-making and consequently making it more assertive.

To select the most relevant criteria for detailed analysis in DEMATEL, Pareto's principle was used, which states that 80% of the effects result from 20% of the causes, that is, 20% of the criteria listed in the LIM matrix can generate 80% of intended effects.

Considering Pareto's principle, the selected criteria are presented in Table 1. According to the result of the DEMATEL method, two parameters can be used: RI+CI and RI-CI. The first provides the relative importance that each criterion has in the system, while the RI-CI identifies "cause" and "effect" factors in the system, quantifying such elements. To rank the criteria in order of importance, as input data in the FITradeoff decisional method, the "RI+CI" perspective was considered to execute this ordering.

Table 1. Detailed result of the DEMATEL method.

Criteria	Description	RI+CI	RI - CI	Classification
BO_KZ	Business-Organizational-Kaizen	6,33	0,43	Cause
PC_PAD	Processes-Conceptual – Standardization	8,29	– 0,13	Effect
PC_KZ	Processes-Conceptual - Kaizen	6,72	– 1,21	Effect
PO_5S	Processes-Organizational - 5S	8,16	0,28	Cause
BO_5S	Business-Organizational - 5S	7,79	1,47	Cause
BO_PAD	Business-Organizational - Standardization	7,80	0,23	Cause
PO_PAD	Processes-Organizational - Standardization	8,48	– 0,83	Effect
PC_HK	Processes-Conceptual - Heijunka	5,94	– 0,52	Effect
PT_JIT	Processes-Technological - Just in Time	6.69	0,28	Cause

4.2 Decisional Evaluation - FITradeoff

FITradeoff is a multicriteria method developed to obtain constant scales. As the developers explain, "the FITradeoff method uses partial information about the decision maker's preferences for choosing and classifying problems according to an additive model in MAVT (Multi-Attribute Value Theory)" [18]. This method uses partial information about the criteria weights to verify at each step of the elicitation whether a solution is obtained interactively and flexibly, with a continuous search for the optimal alternative within a space of weights [18]. FITradeoff has two main steps: ordering criteria and obtaining criteria weight values. In this work, the first stage was supported by the DEMATEL method, which offers a perspective of the relative importance of each criterion, a value that will be used as a basis for ordering the criteria in the FITradeoff method. In the following, the elicitation of the criteria weights is performed based on the comparison of the criteria in hypothetical consequences by the model's decision-makers, who are academic experts in the Lean 4.0 area.

After executing the methodology imposed by the FITradeoff method, the order of alternatives is obtained in order of importance (Table 2), that is, there is a ranking of I4.0 technologies to be implemented with priority in order to raise the level of organizational maturity in the Lean system.

Table 2. Result of FITradeoff method.

Ranking	Alternatives
1°	Big Data + Analytics
2°	Predictive Maintenance + Smart Sensors
3°	Internet of Things (IoT)
4°	ERP + Analytics
5°	MES/SCADA
6°	Product Lifecycle Management (PLM)
7°	Digital Twin
8°	Virtual Reality
9°	Augmented reality

5 Conclusion

Given the increasing need of companies to develop effectively Lean and technological processes to sustain organizational competition, the Lean Manufacturing and Industry 4.0 concepts (also known as the Fourth Industrial Revolution) have become models with a great adherence. In this way, and considering a large amount of pillars and tools of these concepts, the implementation of the Lean Manufacturing principles represents a big challenge to companies, while the solutions provided by Industry 4.0 can contribute to the integration perspective.

The evaluation framework executed considers the premise that interoperability is a relevant metric to understand what can or cannot be implemented in a system, since the FEI relates conceptual, technological, and organizational barriers to business perspectives, processes, services, and data. With this, there is the prerogative that interoperability barriers may difficult the implementation of LM elements and the insertion of I4.0 technologies, since some processes/systems may share or be dependent on information.

The final stage of this project leads to the decision assessment, which consists of identifying and classifying the industry 4.0 technologies that must be implemented to improve maturity in LM. With the support of the FITradeoff multicriteria method, Big Data + Analytics was indicated as the first technology to be implemented in the company to achieve the improvement of Lean Manufacturing maturity from the perspective of enterprise interoperability.

The mass of information generated by the system is called Big Data and, because they are large and complex, analysis by traditional systems is not possible. The complexity of Big Data analysis grows as it incorporates the analysis of unstructured data, such as images, facial expressions, sounds, digitized documents, and others [19]. Business Analytics (BA) refers to the application of a wide range of techniques and data-oriented analytical methods for different business domains [20]. Big Data Analytics can offer several benefits, such as: assertiveness in decision-making; Keeping the company updated about the market; Indicating risks and enhancing data security; Promotes alignment between marketing and sales, among others.

The relevance of this project resides in assessing how the influences between Lean Manufacturing and Industry 4.0 correlate from a quantitative perspective and considering their organizational barriers to propose a ranking of elements to be implemented as a priority to improve the level of maturity organizational.

This paper presents an assessment approach adaptable to other organizations, and therefore, for future work, it is suggested to carry out this approach in other contexts and different aspects of assessment. The main difficulties encountered in the proposed methodology are related to the definition of the evaluative aspects of the decision-making process, that is, the well-consolidated definition of criteria and alternatives for the problem. Since these parameters directly interfere with obtaining an assertive result, it is essential that there is reliability in the information entered in the model.

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The Quality Manager in the Industry 4.0 Era

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Abstract. Recent advances in digitalization have been causing changes in manufacturing and service processes. Impacting production processes and human resources within organizations, tools such as Big Data, Artificial Intelligence, Machine Learning and the Internet of Things enable improvements in communication and support I 4.0 (Industry 4.0) and Q 4.0 (Quality 4.0).

Traditional quality managers, in particular, must do an effort to adapt their profile according to digitalization demands. The present paper relates to the quality manager skills that will be required at short and medium term as result of digitalization expansion. Using a focus group and semi-structured interviews, the skills needed to Q 4.0 managing were identified. In order to make a final comparison, the focus group contributions and interviewee responses were categorized.

Summarizing the main skills needed to the adaptation of quality managers to the digital era reality, the conclusions highlight the relevance of this study for the target groups.

Keywords: Quality Manager · Skills · Industry 4.0 · Quality 4.0 · Digital Era

1 Introduction

Industry and services are experiencing paradigm shifts due to the emergence of 4.0 technologies and are forced to rethink processes, procedures and core capacities. Being characterized by digitalization, automation and interdependencies between partnerships affecting processes, products and business models, Industry 4.0 supposedly generate benefits [1]. By facilitating the collection and analysis of robust data, technological innovation enables shorter delivery times, timely decision-making and real-time communication. To achieve such scenario, quality management and, consequently, the profile of the quality manager must be rethought. Proof of this are some studies published recently as, for instance, a paper from Santos et al. [2] relatively to perception of Portuguese quality managers about the impact of Industry 4.0 on quality management and the managerial skills that will be necessary and required. Earlier, Domingues et al. [3] described the skill sets that make up the desirable 21st century quality leader profile. Highlighting the importance of quality managers for industrial performance, another paper reinforced the need for them to be able to plan and assess risks to minimize unwanted effects during the transition to the new era [4].

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In the context of the digitalization era, this article focuses on the skills that quality managers will need to have in the short and medium term. Being exploratory and limited to the reality of the Portuguese central-northern region, the study combined different data collection methods such as direct observation, focus groups and interviews. The data collected by the mentioned methods were qualitatively analysed to identify the main desirable skills to adapt the profile of the quality manager to the digital transition.

The present paper is structured as follows: Sect. 2 presents the state of the art; Sect. 3 outlines the methodology applied to the study; Sect. 4 is used to present and discuss the findings obtained from the analysis that has been carried out; Sect. 5 intents to conclude the paper, summarizing the main contributions and suggesting the future research directions.

2 State of the Art

The era of industrial digitalization presents new challenges for organizations, not only at technological level but also at soft and hard skills of workers. According to Siphoro, et al. [5], the fourth industrial revolution indicates a new vision of the world providing digital technology for both production and communication. The transition to Industry 4.0 allows companies to become more competitive in front of their markets.

Combining Industry 4.0 quality models and tools helps organizations to move towards Quality 4.0 and to deliver high-quality products. Quality 4.0 arrives with the aim of combining quality control with the new capabilities of Industry 4.0 to help organizations achieve organizational excellence [6, 7]. Decision-making will become a fast and timely process with all stakeholders involvement facilitated. In turn, Jacob [8] argues that quality 4.0 will make processes more visible, interconnected and relevant, positively impacting management systems as well as the cultural and organizational levels of companies, due to the value delivered by data management.

Romero et al. [9] propose the concept of DQM (Digital Quality Management), defining as the digital management of cyber-physical production assets (smart products, smart operators and smart machines) providing traceability in real-time and reporting about the performance of these intelligent assets relatively to predefined requirements, alerting proactively in case of predictable deviations to avoid the materialization of quality problems. Active leadership roles are required in quality teams to make possible face the transformation for the culture and processes of quality imposed by the technological transformation inherent to Quality 4.0.

The new smart technologies generate a large amount of data needing analysis and requiring new approaches and skills from workers. According to Dias et al. [10], several authors understand that there is a need for a knowledge-oriented leadership style promoting engagement along with collaboration, the development of new capabilities and a culture of learning and innovation. The role of the top management of the organizations will be fundamental to include the necessary resources to reduce the barriers that arise with the application of the new quality methods. In opinion of Dias et al. [10], professionals working in quality must adapt to new technologies and acquire skills such as leader-ship, communication, teamwork, persuasion and analytical skills. For Sony et al. [11], these professionals will also need to have emotional skill and core knowledge. While Santos et al. [2] say that quality professionals in the future should have

skills associated with creative thinking, leadership, communication and team working. Nonetheless, as assumed by Domingues et al. [3], there are also authors who defend that future quality professionals should be aware of product reliability and maintain-ability, Lean Six Sigma, systemic thinking and change management. The study conducted by these authors allowed the identification of 7 dimensions with 27 skills that apply to the quality manager in the 21st century.

3 Methodology

Considering a topic not yet widespread, the study was conducted in the central-north region of Portugal with an exploratory goal. In order to combine different data collection methods (for example, direct observation, focus groups and interviews), the analysis method was based on a qualitative approach.

In the first phase of the study, visits were carried out to industrial organizations operating either wholly or in part in the digital context. The visits had in mind the observation of the reality introduced by the digitalization in these organizations and the screening of the possible participants to be included either in the focus group or in the program of the interviews. As were identified two organizations operating in the public services with relatively advanced digitization processes, it was decided to include them in the program of visits.

The focus group interlocutors were picked for their experience in Industry/Services 4.0 and/or Quality 4.0. As described in Table 1, the focus group included representatives from business organizations, public services and higher education. Semi-structured interviews were conducted with quality managers with some experience related to digital quality management systems or attributes of Industry 4.0. Avoiding any identification to preserve confidentiality, Table 2 characterizes the interviewees.

Table 1. Composition of the focus group.

Elements	Area of activity
Speaker 1 (S1)	University Education/Social Security
Speaker 2 (S2)	University Education/Director of University Academy
Speaker 3 (S3)	Business Association 1/Businessman
Speaker 4 (S4)	Business Association 2
Speaker 5 (S5)	Business Association 3
Speaker 6 (S6)	Business Association 4

The protocols for both the interviews and the focus group were taken from the bibliographic research collection. However, by allowing the perception of the reality of the geographical area covered by the study, direct observation enabled by the visits encouraged the implementation of some adjustments to the questions included in these protocols. The adjustments made to the questions did not affect the structures of the

Table 2. Provenience of the interviewees.

	Operation Area	Dimension
Interview 1 (I1)	Electronics	SME
Interview 2 (I2)	Woodworking	Large company
Interview 3 (I3)	Metalworking	Large company

above-mentioned protocols, which included 27 items related to the skills of the quality manager spread out over 7 dimensions [3]. Finally, volunteers involved in quality management in the industry tested the questions from both protocols.

To carry out a comparison between the various interviewee responses or focus group contributes, the WebQDA software was used to categorize the records previously transcribed. The categorization included the 27 items considered by Domingues et al. [3] for the description of the skills of quality managers in 21st century. Finally, a comparison was made between the information obtained from the focus group, interviews, and literature analysis.

4 Findings and Discussion

The responses obtained from the focus group and interviews were initially categorized according to the skill assigned by each dimension. The focus group participants emphasized that the quality manager "must become more of an organizational manager" (S5) and that "he/she will be a manager of relationships" (S5), "an open-minded person, who involves people, he/she has to be a person who has to adapt to things" (S3). Speakers also expressed about the innovation capacity required to quality manager, being referred that "often what matters is the capacity to innovate" (S6) and "the way in which people manage to find solutions to improve their system, often without the need for major investment" (S6).

Respecting to analytical skill, the speakers emphasize "training for what is critical analysis" (S2). One of the interviewees (I1) identified that the quality manager will have to adapt because "quality can readjust itself and will resort to statistical data analysis and skills to negotiate and lead teams". The second interviewee (I2) believes that the skills will be directed towards the technological and leadership dimension. This interviewee stated "I believe that in this digitalization path, the quality manager must have analytical and data interpretation skills, knowledge of IoT tools, and the ability to go into the field and understand the problems, obviously adding these to the other soft skills that are generally necessary". By generally necessary we mean leadership skills, team management skills and others.

The data collected through focus groups and interviews allowed listing the essential skills for the quality 4.0 manager, facilitating their comparison with those already published. Therefore, the option was to perform an analysis comparing the results of fieldwork (testimonials of focus group and interview answers) with those published by Santos et al. [2] and Domingues et al. [3]. The diverse contributions were categorized

Table 3. Quality manager skills in Industry 4.0: comparison between the published results and those obtained by the present work.

Dimension	Skills	Domingues et al. [3]	Santos et al. [2]	Focus Group						Interviews		
				1	2	3	4	5	6	1	2	3
Leadership	Being able to motivate co-workers	☑	☑			☑			☑	☑		
	Being coordinative with all departments	☑						☑				
	Being able to delegate	☑							☑		☑	
	Being fair and objective	☑						☑			☑	
	Being able to moderate difficulties	☑	☑			☑		☑		☑		
	Being able to congratulate	☑						☑				
	Having good management capacities	☑						☑			☑	
Personality Traits	Being innovative	☑							☑			
	Being altruistic	☑										
	Being ambitious	☑										
	Being able to create social network	☑				☑		☑				
Communicational	Having emotional intelligence	☑	☑									
	Being persuasive	☑						☑		☑		
	Being able to work with teams	☑	☑			☑		☑		☑	☑	
	Being a good communicator	☑	☑			☑		☑		☑		
Quality Oriented	Being an expert on quality tools	☑						☑				
	Being instructive	☑						☑				
	Being customer focused	☑	☑				☑				☑	
Adaptability	Being an expert at complex problem solving	☑	☑		☑				☑		☑	
	Being able to adapt into changing roles	☑	☑						☑			
	Having cognitive flexibility	☑			☑				☑			
Analytical	Having an abstract thought	☑			☑							
	Being good at analytical reasoning	☑	☑		☑						☑	☑
	Being capable of adopting statistical tools	☑			☑					☑	☑	☑
Technological	Being an Industry 4.0 expert	☑	☑								☑	☑
	Being a troubleshooting expert	☑	☑		☑							
	Being able to work with IT tools	☑			☑							

according to the 27 skills mentioned by Domingues et al. [3]. Describing the 27 skills identified as essential for quality managers in the 21st century [3], Table 3 compares these with the results obtained from the focus group and interviews.

Table 3 indicates the highlighted tendency to associate the quality manager skills with leadership, communication, adaptability and analytical capacities. This association is made not only by Domingues et al. [3] but also by those involved in the study. Also, the quality-oriented skills, especially "to be customer-focused" deserve to be highlighted. The "ability to motivate workers" and the "ability to moderate difficulties" are highlighted in relation to leadership skills. About communication skills, the most frequently mentioned are "to be able to work with teams" and "to be a good communicator". As for adaptability, the most prominent skill is "to be an expert in solving complex problems" while in analytical skills, the study participants identify the capacities of "have a good at analytical reasoning" and "to be capable of adopting statistical tools". The skill "being an industry 4.0 expert" in the technological dimension is also identified as essential for a quality manager in industry 4.0.

All the skills listed by Domingues et al. [3] and later analysed by Santos et al. [2] are essential for the quality manager in Industry 4.0 and quality 4.0. However, among these, the technological dimension seems to frame the skills introduced by Industry 4.0.

One of the interviewees (I3) stated that the adaptive and analytical dimensions contain core skills for Quality 4.0 that current quality managers need to strengthen to prepare for the transition phase. In his view, such skills are linked to the ability to use statistical tools, to develop analytical reasoning and to solve complex problems. The remaining dimensions, i.e. leadership, personality, communication, and quality, contain the majority of the skills usually required of quality managers in the traditional industrial environment. The same interviewee mentioned the Six Sigma management skills as being important for a quality manager in Industry 4.0.

5 Conclusions

The focus of the present work was on the skills of Quality 4.0 managers from the point of view of organizations operating in the central-north region of Portugal. The used methodology made it possible to categorize the main skills that will be required to these professionals in the context of Industry 4.0 and Quality 4.0.

To adapt to the digital Era, quality managers, beyond those currently required, should mainly strengthen skills related to:

a) solve complex problems, have analytical reasoning and adopt statistical tools;
b) six sigma management;
c) recognizing the potential of Industry 4.0 to implement a digital quality management system.

The study presents certain limitations, including the fact that it is confined to a region of Portuguese territory where the adoption of the 4th Industrial Revolution by small and medium-sized enterprises is still shaky. Consequently, it is planned to carry out new series of interviews on the subject, to be applied to intelligent system integrators and quality managers in multinational and transnational companies operating on Portuguese

territory. Finally, present work serves as a stimulus to study the relevance of the quality manager role in the transition to Industry 4.0.

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Flexible Manufacturing

Flexible Manufacturing Systems Through the Integration of Asset Administration Shells, Skill-Based Manufacturing, and OPC UA

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Abstract. The advent of Industry 4.0 has created a need for more flexible and adaptable manufacturing systems. This paper proposes the integration of AAS (Asset Administration Shells), SBM (Skill-based manufacturing) and OPC UA (Open Platform Communications Unified Architecture), to enable more flexible manufacturing systems. The integration of these concepts provides a solution for achieving faster and easier dynamic reconfiguration in manufacturing systems, which is essential for fulfilling the demand of customization and flexibility in modern production systems. An Asset Administration Shell provides a standardized structure for describing assets and their administration, while Skill-based manufacturing enables the deployment of task-oriented machines that can self-configure, self-diagnose, and self-optimize their performance. The use of OPC UA as a communication protocol ensures that these systems can communicate with one another in a secure and reliable way. This paper presents a conceptual framework for the integration of these three open technologies. This framework contributes to having a single interface and source of information for every asset, which can lead to increased efficiency by reducing changeover times, thus reducing the overall cost in flexible manufacturing system scenarios. Future work will focus on the implementation and validation of this framework in a real-world manufacturing setting.

Keywords: Industry 4.0 · Flexible Manufacturing · Asset Administration Shell · Skill-based Manufacturing · OPC UA

1 Introduction

Industry 4.0 promises to create value through the cross-manufacturer exchange of information with industry-neutral standards for communication, services, and semantics. One of the most important concepts for meeting this requirement is the Digital Twin, the "digital image" of an asset. An asset is here defined as an

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object that is to be integrated into the information world of Industry 4.0, e.g. machines and their components, products, supply material, plans and schematics. According to the approach taken by Industrial Digital Twin Association[1] (IDTA), and in contrast to frequently chosen illustrations, the Digital Twin is not primarily a realistic virtual image of the object under consideration. This goes in line with the recent view of the researcher who first mentioned the Digital Twin concept back in 2002, Dr Michael Grieve. He states that the combination of digital twins and simulations can create immense value, compared with the traditional physical-based prototyping and iteration during product design, and can yield massive benefits during the product's lifetime, in the form of accurate predictive maintenance and performance behaviour[2].

Within the context of Industry 4.0 initiatives, new business models are being introduced [1], some requiring readily available infrastructures to make the complete transition from mass production to a mass customization paradigm. Such a transition will require increased flexibility in manufacturing environments with shop floor reorganization based on the on-demand product specifications. The machines, workers and workstations will require frequent reorganisation to meet customer needs. There are also companies who do not plan to completely change their business models, although they still need to decrease their changeover times in specific steps of their production process. The work by Dillinger et al. [2], based on expert interviews and identified literature, points to SMED (Single-Minute Exchange of Die) with Plug and Produce as one of the Lean 4.0 methods with the most overall positive impact, specifically in time and flexibility target dimensions. In both scenarios, a modular standard-based approach that increases the flexibility of devices, work cells and entire factories is needed. In order to achieve this goal of a flawless workflow, with reduced downtimes for the companies, some concepts and technologies need to be applied together on the shop floors.

This paper is about exploring ways of designing and deploying manufacturing systems to enhance enterprise production agility, with increased efficiency, decreased overall cost, and the ability to integrate both legacy and new equipment. It starts by providing a critical analysis of the state of the art and current implementations of concepts and technologies that can contribute in this direction. Based on this analysis, the conceptual framework was built and tested on the developed test scenario, showing that having this single interface and source of information for every asset, can lead to increased efficiency by reducing changeover times. The results also pointed to challenges regarding the decision of what skills should be implemented for each specific device, and the heterogeneous nature of the devices available that can lead to integration limitations. These challenges and limitations will be addressed in future developments of this work.

The remainder of this paper includes Sect. 2 which provides an overview of the enabling concepts for this work, while Sect. 3 presents related work on these concepts. Following, in Sect. 4, a test scenario is described and the architecture options are detailed and justified. Section 5 presents the results obtained so far

[1] https://industrialdigitaltwin.org/en/.
[2] https://www.eetimes.com/dont-twin-digital-twins-and-simulations/.

with this setup and, in the final section, the conclusions of the work are presented and future directions are proposed.

2 Enabling Concepts

The industrial landscape is rapidly evolving, and concepts such as Industry 4.0 are paving the way for smarter, more connected and flexible manufacturing processes. In this context, AAS and SBM are two enabling concepts that play a pivotal role in the creation of smart, digitized and flexible factories. Additionally, OPC UA is a communication protocol that ensures these systems can communicate with one another in a secure, reliable and standard way. This section provides an overview of their main characteristics.

2.1 Asset Administration Shell

The Reference Architecture Model Industry 4.0 (RAMI4.0), is an emerging model developed to take into account the new connectivity, interoperability, and data centrist paradigm of Industry 4.0 technology. The factory hierarchy levels, machine life cycle management and data type/instance, and technology layers, are all referenced in this Service Oriented Architecture (SOA) model [3].

In Industry 4.0 an asset is defined as "anything that requires a connection for the Industry 4.0 solution", including machines and their components, materials, products, drawings, among others. All these assets must be identifiable so other systems can read their type, operational and technical data, status and other asset-specific data. To accomplish this, RAMI4.0 introduces a feature that aims to enclose assets in an IT "administration shell" to enable the asset to autonomously cope with new vertical and horizontal integration capabilities and resources [4]. These are also commonly divided into three types in terms of interaction and how AAS can follow different patterns which also have different technical requirements, i.e., file exchange, server-client and peer-to-peer interaction [5].

- **Type 1 (Passive)** AAS can serve as digital datasheet. Usually, a static file serialized as JSON, XML or AASX that is used to exchange information;
- **Type 2 (Reactive)** AAS is a software component where the information exchange is performed automatically by means of external software, which communicates with the AAS by means of API utilization. They enable every entitled entity to push a job to the machine for execution using a skill-based approach;
- **Type 3 (Proactive)** AAS uses peer-to-peer interaction via Industry 4.0 languages (OPC UA, MQTT, REST) with the bidding process involved.

2.2 Skill-Based Manufacturing

The concept of calling machines by their skills or capabilities is known as SBM in the field of automation and robotics. This method entails designing and programming machines to perform specific tasks or functions based on their unique set

of capabilities or skills. Furthermore, "capabilities" are implemented by means of "skills", which contain details at the level of implementation and invocation of automation functions. Additionally, capabilities are offered in terms of "services" to stakeholders in a broader supply chain network, outside a production setup with one shop floor [6]. The goal of this approach is to create more flexible and adaptable manufacturing systems that can respond quickly to changes in demand, while also improving overall production efficiency and productivity. Overall, SBM has the potential to revolutionize manufacturing by creating more flexible, adaptable, and efficient systems that can respond quickly to changes in demand and market conditions.

2.3 OPC UA

OPC UA is a widely adopted open standard for industrial automation and communication that allows for seamless interoperability and integration across a wide range of devices, applications, and platforms. One of the key features of OPC UA is its platform-independence, which allows it to be deployed on a variety of operating systems and devices. Additionally, OPC UA provides a secure and reliable communication channel, with built-in encryption and authentication mechanisms, making it suitable for applications that require high levels of data security. Furthermore, OPC UA supports a wide range of data models, including both legacy and modern data models, providing a high level of flexibility and compatibility with existing systems.

3 Related Work

The papers described in this section resulted from an initial query for works addressing both "Asset Administration Shell", "Skill-based manufacturing" and "OPC UA", followed by selecting, from those papers, only the ones that presented real-world application examples.

The work by Nagrath et al. [7] describes an implementation of AAS for service robots. The authors adapted their service robots toolchain, SmartMDSD, to be able to provide AAS to their software components of service robots. These AASs comprise a datasheet for the system and, furthermore, they collect runtime operational data and provide skill-level commanding of the service robot. The AASs are generated and filled as part of their model-driven development and composition workflow for service robotics. This is an interesting project, as they found a way of having a machine-readable service robot description and, at the same time, being able to operate the same assets by triggering and executing their available skills. However, this solution is tightly dependent on their own in-house developed toolchain, and specifically designed for service robots, which means additional effort is required within a factory scenario encompassing different machines.

The work by Ye et al. [8] proposes the use of AAS as a tool for achieving data interoperability between enterprise and control applications in Industry

4.0. The paper includes a case study to illustrate the effectiveness of the AAS approach in achieving more efficient and flexible production processes. The study highlights the importance of standardization in achieving data interoperability and emphasizes the need for standardization tools like the AAS in Industry 4.0.

Quadrini et al. [9] present a case study on the implementation of the AAS as a key enabler for interoperability in Industry 4.0 software architectures. The study demonstrates that the AAS approach enabled the creation of a flexible and adaptable system that can easily respond to changes in production requirements. The paper provides valuable insights into the benefits of using AAS as a standardization tool for Industry 4.0, highlighting its potential to enable interoperability and facilitate the creation of highly efficient and adaptable production systems.

The work by Jungbluth et al. [10] outlines the design and implementation of a flexible transport system that uses OPC UA as a communication standard. The system enables dynamic reconfiguration and scheduling of transport tasks based on the required skills of the components involved. The paper presents a case study in which the developed transport system was applied in a real-world manufacturing scenario, showing the potential benefits of the skill-based approach in improving the system's flexibility, efficiency, and adaptability to changing production requirements. The study demonstrates the effectiveness of OPC UA in enabling interoperability between different components, making it possible to integrate various devices and software systems into a single system.

Additionally, over the past few years, a number of projects, including DIMOFAC[3], SmartFactoryKL[4] and openMOS[5] demonstrate the EU's dedication to creating cutting-edge manufacturing technologies that can increase production flexibility, efficiency, and sustainability, while also supporting the development of open standards and platforms that allow for interoperability between various manufacturing systems.

4 Developed Test Scenario

This paper presents a conceptual framework and its implementation for the integration of AAS, SBM and OPC UA technologies enabling Flexible Manufacturing Systems. The test scenario described in this section is meant to test each of these technologies and the conceptual framework as a whole in a controlled laboratory environment.

The developed case scenario consists of a combination of a Christiani workcell[6] with some in-house modifications created at the laboratory of the Technological University of the Shannon, used for research, development and demonstration. It is composed by several devices, as shown in Fig. 1, namely: **(RA)** Comau

[3] https://dimofac.eu/.
[4] https://smartfactory.de/en/.
[5] https://www.openmos.eu/.
[6] https://www.christiani-international.com/.

eDo Robotic Arm; **(AU)** Pneumatic Assembly Unit; **(HU)** Pneumatic Handling Unit; **(AW)** Automatic Warehouse; **(PLC)** Siemens S7-300 PLC; **(HMI)** Siemens Simatic Touch HMI; **(VS)** Vision System (in-house development).

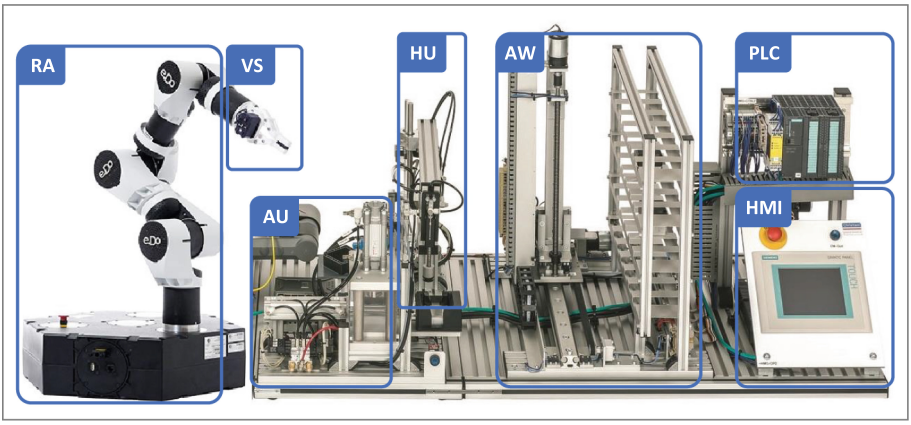

Fig. 1. Test scenario in the Technological University of the Shannon.

The functional block diagram, including device physical interactions, is described in Fig. 2. This diagram summarizes each device's communication and I/O capabilities, while also showing a high-level description of the developed manufacturing process scenario.

An AAS for each device on our test scenario was developed using the IDTA working group approach[7] to the AAS, consisting of a series of submodels that describe all the data and functions of a particular asset, such as characteristics, properties, states, parameters, operational data and capabilities. Each AAS is associated with a .aasx file working as a single source of information that can accompany the entire life cycle of devices, machines and entire factories.

The implementation of the capabilities described by the AAS is done using skills. Each skill's control logic is implemented employing a finite state machine which is visible in an OPC UA server address space. The finite state machine interacts with field-level devices (detectors, sensors and actuators) according to the control logic to perform the device skills. The interaction with the skill of each device is made by calling the OPC UA method acting as a state transition trigger and also by a variable containing the actual state.

The interaction with each available device is done through its own OPC UA server. Every OPC UA server is registered to the Local Discovery Server providing a way of browsing every skill available on a given shop floor. Thus, being the interaction point used by higher-level systems such, for instance, Manufacturing Execution System (MES) and Enterprise Resource Management (ERP).

[7] https://github.com/admin-shell-io.

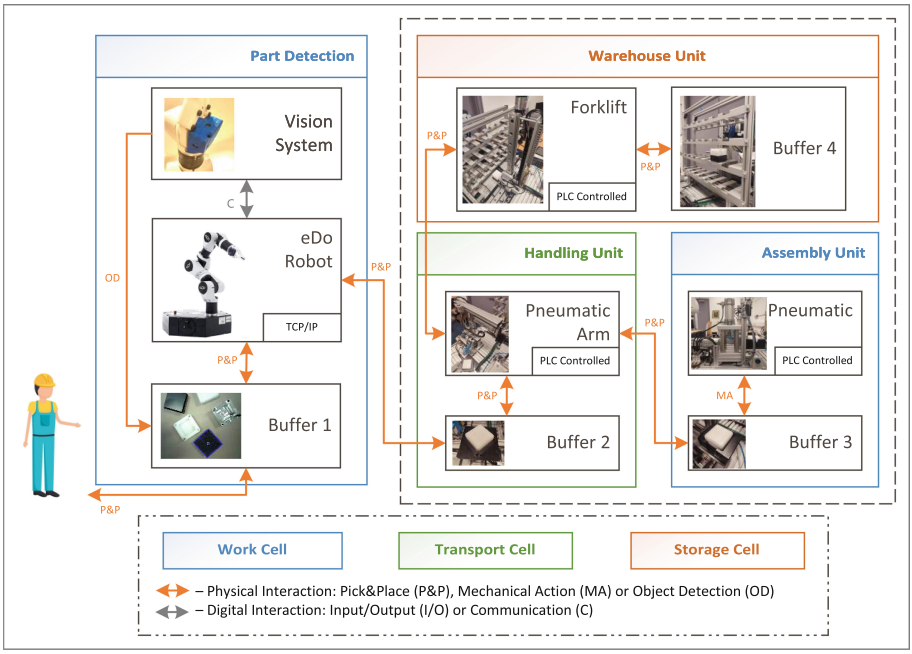

Fig. 2. Functional diagram and interaction between systems.

5 Results

This section presents the results that were obtained from applying the AAS, SBM and OPC UA technologies to the developed test scenario described in Sect. 4 as well as pointing out the limitations and challenges that can be addressed in future developments of this work.

One AAS was developed for each device available in the developed test scenario. Additionally, an aggregation AAS was developed to act as the entry point for the whole system. Each of these AAS, their submodels and their properties can be accessed with appropriate AAS clients, with the AASX Package Explorer client being used in this case. The hierarchically structured aggregation AAS is shown in Fig. 3 as an example. On the same figure, on the left, a list of the created and available AAS can be observed, representing each of the integrated devices.

The application of the conceptual framework to the developed test scenario represents some challenges at this moment, namely regarding the implementation of the finite state machines that implements the device skills interacting with field-level devices (sensors and actuators). This is mainly due to two reasons: (1) the decision of what skills should we implement for a specific device; and (2), the heterogeneous nature of the devices available in the test scenario that leads us to different communication challenges. The third challenge is the integration of the defined OPC UA Methods that implement skills directly on the AAS interface.

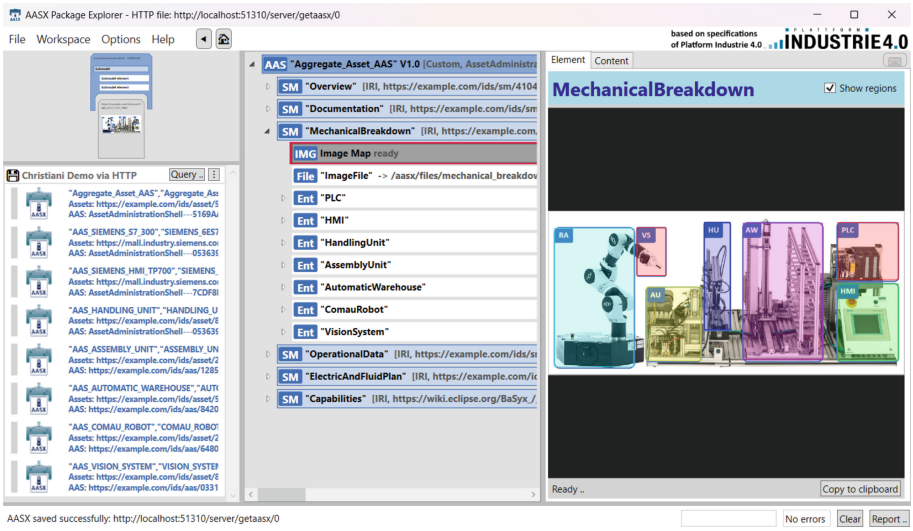

Fig. 3. Asset Administration Shells view in Package Explorer.

6 Conclusion and Future Work

Having a single source of information for every asset instead of dispersing information in silos across departments, contribute to the decrease in time needed to search for schematics and documentation about a specific asset. AAS can be part of an enriched Digital Twin that contributes to mitigating this problem. Several Industry 4.0 use cases require an increase in flexibility in production systems, as well as interoperability across equipment from different generations and manufacturers.

Working groups that are developing their work around this subject seem to agree that there is a need to increase the abstraction level of system design, by focusing on the capabilities required to perform tasks instead of specific resources offered by particular manufacturers. However, it is of great significance to design a general AASX-enabled data interoperability solution, which not only enables consistent data exchange between enterprise and control applications but also extends to the control of field-level devices.

The binding process between the AAS capabilities and the skills implemented by the devices, which will allow controlling field-level devices, is a limitation at this stage that will be addressed in future developments of this work. The developments described in this paper are also being implemented and tested on a complementary test scenario as part of a larger project, the S4Plast project. The natural evolution of this test scenario is the inclusion of more devices with different challenges in terms of capabilities modelling and skills implementation.

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On Reinforcement Learning for Part Dispatching in UAV-Served Flexible Manufacturing Systems

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Abstract. The industrial environment of the past years has been characterized by a high rate of change, pushing the industry to implement innovative technologies to satisfy market needs. Unmanned aerial vehicles (UAVs) and Reinforcement Learning (RL) are being implemented in the manufacturing industry to meet changing market demands for efficiency. This work focuses on using RL for optimal part dispatching in Flexible Manufacturing Systems (FMS) using UAVs. A virtual discrete events model is used to represent the shop floor state and a reward function is defined to maximize production. Proximal Policy Optimization (PPO) is employed to train the RL agent. Results show a production increase of up to 145.16% compared to traditional heuristic rules.

Keywords: Reinforcement Learning (RL) · Flexible manufacturing · Dispatching · Scheduling · Unmanned Aerial Vehicles (UAV)

1 Introduction

Recent advancements in technologies challenge the way companies manufacture and deliver products. In the case of manufacturing applications specifically, unmanned aerial vehicles (UAVs), commonly known as drones, are at the forefront, replacing or supplementing industrial robots, transportation systems, ground vehicles, and humans working as operators in manufacturing plants [1,2]. This ever-expanding technology comes with several advantages, related to improved throughput and higher system productivity, reduced work-in-process inventories, and increased capacity scalability of the production system [3]. It is thus crucial to consider adaptive scheduling and control for dynamic manufacturing environments with the use of drones as key research issues.

In recent years, Reinforcement Learning (RL) has dominated machine scheduling problems in the literature, with an ever-growing tendency to employ RL particularly noted in dynamic production scheduling, as well as flexible job-shop production and adaptive order dispatching [4,5]. Specifically, it has been shown that as the complexity of the production environment increases, the application of RL for dynamic scheduling becomes more and more beneficial, making

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future production systems more flexible and adaptive [6] and significantly reducing the average lead time of production orders in dynamic environments [7].

The central idea of RL is that the learning agent learns, over time, what action to take in any given situation by a process analogous to methodical trial and error. The learning agent tries the different actions available to it in different situations and evaluates the outcome of each action, both in terms of the action's immediate effect on the environment, as well as its long-term contribution to the learning agent's overall goals. In its basic form, RL can be understood in terms of five key elements: 1) *the environment*, 2) *the agent*, 3) *the state/observation*, 4) *the action* and 5) *the reward* [8]. The interaction between the agent and the environment can go on for several time steps, where the agent observes the environment, takes an action and receives a new observation and reward.

This work proposes an RL framework to optimize part dispatching within a Flexible Manufacturing System (FMS) that uses drones for servicing workstations. The study uses discrete event simulation to investigate drone assignment, scheduling, and workstation servicing. The goal of this study is to allow drones to learn optimal decision-making at each process time step. Section 2 introduces the research strategy, simulation environment, and tested scenarios. Section 3 presents simulation results, while Sect. 4 discusses the broader impact of this novel framework.

2 Methodology

2.1 Simulation Environment

The development of our simulation was based on the MathWorks SimEvents library, which allows for a direct interface with the MATLAB RL toolbox and possibilities like generating custom statistics and simulating hybrid systems [9–11]. The manufacturing environments analyzed in our simulation scenarios constitute variations of the basic model described in Bateman et al. [12]. The manufacturing plant studied is assumed to work on an 8-hour workday, 5 days per week, producing shafts for lawnmower machines. Within the manufacturing cell, there are six workstations, where the shafts can be processed.

For the purposes of the current investigation, the tasks of the human operator were replaced by one single drone, responsible for serving the whole manufacturing cell by transferring the material between workstations. The selection of a single UAV is the most conservative scenario that can be tested and is meant to 'stretch' the drone capability to both cover and enhance the production rate within the manufacturing cell. In spite of their potential benefits, however, one limitation to drone capability and subsequent usage is the limited amount of flight time, with 30 min of airtime usually marking the battery life threshold of the drones. Therefore, drone battery life and charging were taken into consideration and incorporated into our problem formulation.

Models. Two SimEvents models were studied and compared: a First-Come First-Served (FCFS) model, where human operators are responsible for transferring parts between immediately available workstations, versus an RL model

implementation. Both models consisted of blocks representing each of the workstations involved in the production line. All the blocks present a similar inner structure, where TA represents the transfer time necessary for the drone to move from its current position to the next available machine and MA the single-product processing time within each workstation (Fig. 1). For simplification, the TA from and to each workstation is bidirectionally considered to be constant and workstation specific. The TA value is formed after averaging the transition times recorded for every workstation and scaling the value to match the simulation parameters.

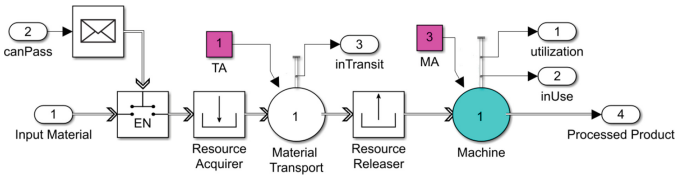


Fig. 1. Configuration of representative workstation structure in SimEvents.

FCFS Model. The FCFS model follows the production flow imposed by Simulink rules and gates that allow item flow via the pathway that is not blocked at the specific point in time when the drone must make a routing decision. To realistically represent the FCFS model, heuristics, such as the battery charging threshold must be determined a priori, since the drone has to return to the charging station to avoid battery depletion and production interruption. After testing a few hypotheses relating to battery life, the threshold was set to 50% of the drone's battery capacity. This allows for higher production rates, compared to a more stringent and conservative charging policy (>50%), while preventing the possibility of total battery drainage (<50%).

RL Model. The RL model follows the production flow imposed by the trained RL agent. The agent seeks to select actions that maximize its long-term cumulative reward. Therefore, expressing the reward in terms of production maximization is intuitively adequate and suitable to train the agent and get the desired result. For the simulation scenarios conducted on the basis of this investigation, the reward was formulated as $R(s, a) = prod_t - prod_{t-1}$, where R represents the total reward and $prod$ the production rate at each time step t. The long-term reward is in that way equated with the total production at each completed RL episode. As the agent's goal is to maximize the long-term reward, production is in this way also maximized.

The 'Observation/State' serves as input for the RL training and it is formed as a 1×7 vector. The first 6 vector elements are binary and represent the values acquired from a logical AND operation between the state (in use or not), the transit (in transit or not), and the request (requesting or not) conditions of each of the 6 workstations involved. The 7th vector element is a real value, representing the drone battery percent at each time. For example, a state of [1 0 1 0 0 0 0.75] indicates that only the first and third workstations are ready

to process material, while the battery charge of the drone is at 75%. In a similar manner, the action space is also a 1×7 vector. The action vector elements represent the servicing of each of the 6 workstations and the drone charging station respectively ([A B1 B2 B3 C1 D1 ChargingStation]). For instance, if the agent takes action "3", it means that it will service workstation B2.

The agent is responsible for optimizing drone behavior by balancing between increasing the production and appropriately charging the battery. Specifically, no battery threshold is set for the RL case, but the RL agent learns to charge the drone battery in an optimal way while selecting the best-suited action to increase its reward every time. A set of charging parameters of the drone battery which the agent takes into account during its training is set a priori; battery draining per time step t is set to 2% while not charging and battery charging per time step t is set to 10% while charging. In terms of training the agent, imposing a stop criterion pertaining to the stabilization of the production to a desired average value increases the confidence level that this particular agent will converge to the desired average production. Additionally, a training episode is terminated if the drone battery reaches 0% and the UAV becomes inactive.

A Proximal Policy Optimization (PPO) agent that uses an Actor-Critic Deep Neural Net model architecture was selected and implemented using the built-in Matlab PPO agent via the function *rlPPOAgent()*. PPO, as a policy gradient method, makes policy updates using a surrogate loss function to avoid catastrophic drops in performance [13,14]. During hyperparameter tuning different learning rates were chosen for the actor ($\varepsilon_{actor} = 0.008$) and critic ($\varepsilon_{critic} = 0.005$) nets to increase average production rates and achieve better results. The PPO framework was chosen due to its robustness since is not too sensitive to hyperparameter initialization, while it achieves a balance between ease of implementation, tuning, and sample complexity.

2.2 Simulation Scenarios

The two scenarios examined in this paper are schematically presented in Fig. 2. The scenarios differ in their transit and processing times (Table 1). Scenario 1 was chosen to evaluate the ability of the RL agent to handle an obvious "trap" situation, while Scenario 2 was designed to evaluate the effectiveness of the studied approach in a more typical production use case.

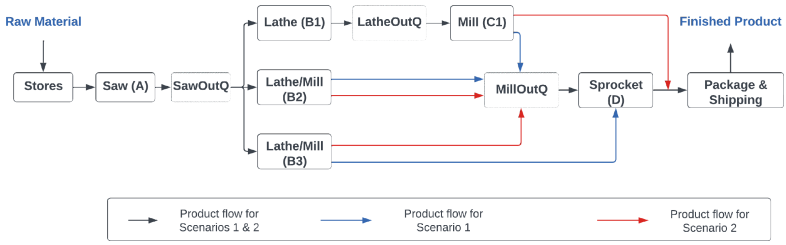


Fig. 2. Production flow within the manufacturing cell model. The dashed lines indicate storage spaces, while all workstations are represented with solid black lines.

Scenario 1. This scenario contains an "artificial trap" after the departure of the product from workstation A1. Specifically, the drone has the choice to serve one of the workstations B1, B2, or B3. Machine B1 seemingly has the least cumulative time (TA = 1, MA = 1), so intuitively this would probably be a good step towards maximizing the cell production, whereas workstation B3 is seemingly the slowest overall (TA = 3, MA = 6), so avoiding it would lead to better results. However, the steps following show that this is a trap, as machine B1 leads to workstation C1 which increases the processing time necessary if this path is followed, while B3 is in fact faster. The goal is to test whether this trap can intelligently be avoided by the RL agent that is supposed to learn on its own by exploring and exploiting different paths according to the average reward it accumulates in each case. For scenario 1 the raw material input is 10 pieces. The theoretical maximum cell capacity for this case is thus the number of raw material pieces (10) × number of bars in which the raw material is cut (3) = 30.

Scenario 2. Scenario 2 constitutes a modification of the system as it has been described so far. The TA and MA transit are formed in a way that creates no 'traps' for the system. The workstations are approximately equal in terms of cumulative transit and processing time. The goal is to test, whether the RL approach will be able to find a better solution in a system where the first-come first-serve basis feels like the most intuitive way of servicing the cell. For scenario 2 the raw material input is 15 pieces. The theoretical maximum cell capacity for this case is thus the number of raw material pieces (15) × number of bars in which the raw material is cut (3) = 45.

Table 1. Transit (TA) and machining times (MA) for simulation scenarios 1 and 2.

	Scenario 1		Scenario 2	
Workstation	TA	MA	TA	MA
A	1	3	1.5	2.5
B1	1	1	0.5	2
B2	1	2	0.5	4
B3	3	6	0.5	4
C1	1	4	1.5	1.5
D	1	2	1.5	1.5

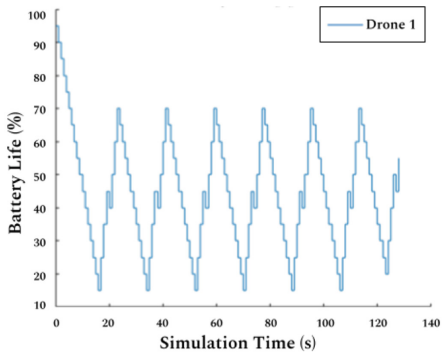
3 Results and Discussion

As the system goal is production maximization and maintenance of the drone battery at a sufficient level to avoid drainage, the ideal scenario would be to acquire a total production of 30 and 45 pieces for scenarios 1 and 2 respectively, while ensuring an adequately charged drone at all times.

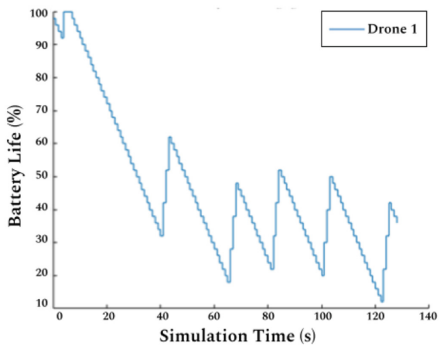
3.1 Scenario 1

FCFS Model. The Average Production Achieved (APA) is 12 pieces per simulation. The FCFS model is able to produce 40% of the theoretical maximum cell capacity (30 pcs.). It is important to note that even though the battery threshold is set to 50%, the drone reaches lower battery loads (Fig. 3a). Apparently, the battery level reaches the set threshold, while the drone finds itself mid-operation. Therefore, the battery continues to discharge until the drone is available again to return to the charging station. This heuristic seems to be safe since the battery never falls under 10%. However, for bigger and more complex systems, it becomes more difficult to find a good estimate for a battery threshold that is equally safe for the battery to not be drained and for the system to maximize its production.

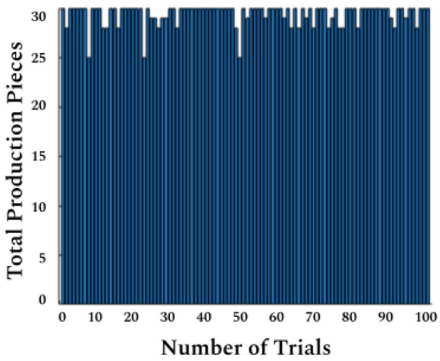
RL Model. The APA across 100 RL trials is 29.42 pieces per simulation, almost reaching the theoretical maximum production of the cell. The RL model outperforms the FCFS model by producing 145.16% more pieces, which is a very



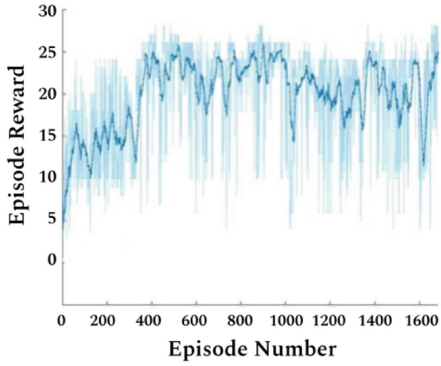
(a) Drone battery life for the FCFS model.



(b) Drone battery life for the RL model.



(c) Total Production for the RL model for 100 consecutive simulation trials.



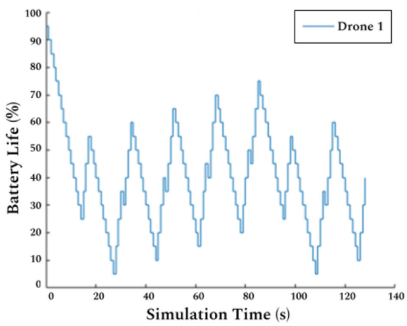
(d) Training progress of RL model agent.

Fig. 3. Simulation results for Scenario 1.

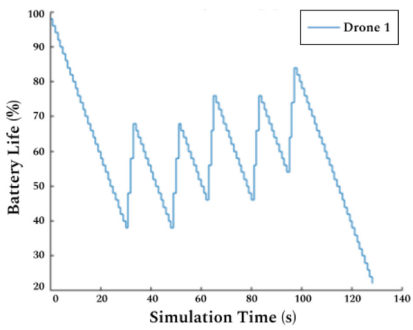
exciting result. Our trained agent is able to consistently produce a high number of final products (Fig. 3c), while intelligently learning on its own how to sufficiently and efficiently charge the drone battery and achieve optimal production (Fig. 3b). Specifically, the agent learned to progressively increase its reward and allow the drone to complete trips of increasing duration between the workstations before returning to its charging station (Fig. 3d). This learning behavior decreased the overall amount of times the drone was required to remain grounded and thus increase the productivity of the cell.

3.2 Scenario 2

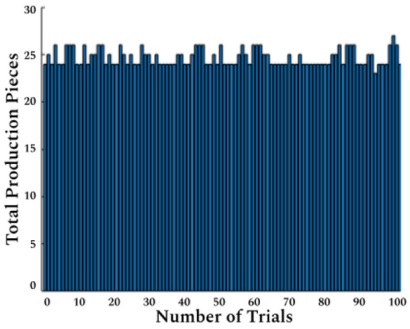
FCFS Model. The FCFS model is able to produce approximately 50% of the theoretical maximum cell capacity for Scenario 2 (45 pcs.) with an APA of 22 pieces per simulation. All workstations are now treated as equal by the system, so a distributed utilization time is observed across all workstations. All workstations share the workload and the system shows no preference when it comes to selecting a production flow path. All paths here are equiprobable and the selection is made upon the condition of whether the machine is blocked or not. A similar battery charging pattern to Scenario 1 is also noted for Scenario 2 (Fig. 4a).



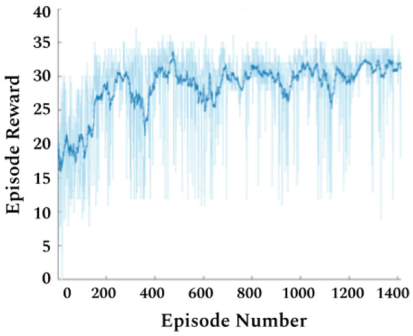
(a) Drone battery life for the FCFS model.



(b) Drone battery life for the RL model.



(c) Total Production for the RL model for 100 consecutive simulation trials.



(d) Training progress of RL model agent.

Fig. 4. Simulation results for Scenario 2.

RL Model. The APA is 24.71 pieces per simulation (Fig. 4c). The RL model is again surpassing the respective FCFS model by 12.31%. It is observed that even in the case of systems where all possible production paths are approximately equivalent, RL outperforms the conventional FCFS model, proving that it is indeed an intelligent approach. As far as the battery is concerned, the agent employs the most efficient charging strategy that it is able to learn. It is particularly remarkable to note that the agent chooses to spend slightly more time in charging the drone towards the end of the simulation, eliminating the need to recharge the UAV in the remaining 40 s of the simulation (Fig. 4b).

4 Conclusions

The simulations conducted for both Scenario 1 and Scenario 2 show that the RL consistently outperforms the FCFS model for every case tested. The RL model is able to approach and even achieve the cell's theoretical maximum capacity presenting little divergence across 100 consecutive trials, while maintaining a healthy battery life. The RL agent successfully learns to balance system requirements and production efficiency. This proves the robustness of the approach and eliminates the possibility of randomly generated production maximization.

This investigation provides a flexible testbed and methodology for developing advanced machine-learning solutions for part dispatching, which can ultimately lead to improvements in production efficiency in manufacturing systems. Simulation analysis proves that the RL approach constitutes a feasible and intelligent production scheduling and dispatching method for employment in flexible manufacturing systems. The results are particularly exciting, as well as promising for extension in more complicated systems, where heuristics become increasingly hectic. Potential extensions include incorporating additional factors, such as energy consumption, into the optimization process, as well as simulating more complex scenarios and the use of UAV swarms.

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Development of Deep Reinforcement Learning Methodology for Co-bot Motion Learning

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Abstract. Today, Korea is facing a time when it is essential to develop new manufacturing technologies and strategies to lead new changes, such as smart factories and manufacturing innovation 3.0, and achieve continuous development of the domestic manufacturing industry. Therefore, many manufacturing companies are promoting process automation using collaborative robots (co-bot) to respond to the paradigm of multi-item, small-volume production. The emergence of co-bots improves the space utilization of production facilities and opens up the possibility of introducing robots without modifying the existing production line. This study aims to conduct primary research on a robot that recognizes and acts on its environment using reinforcement learning to determine its work movements and perform tasks without specific instructions from human experts. In this study, we propose a collaborative robot control methodology using a deep reinforcement learning algorithm. In addition, for the practical application of the HRC system, which is challenging to apply to the production of a single product, the problem of data sharing between collaborative robots and workers based on a process model was addressed. The system proposed in this study is designed to optimize process variables through artificial intelligence-based data learning and is expected to contribute to product and process quality optimization of human-robot collaborative processes in the future.

Keywords: Collaborative Robot · Artificial Intelligence · Deep Reinforcement Learning

1 Introduction

Today, Korea is facing a time when it is essential to develop new manufacturing technologies and strategies to lead new changes, such as smart factories and manufacturing innovation 3.0, and achieve continuous development of the domestic manufacturing industry [1–3]. Influenced by the 4th industrial revolution, IoT (Internet of Things) and CPS (Cyber Physical System) technologies are applied in the mold production and mass production stages to promote a change from the traditional mold production and mass production stages to a more effective manufacturing system [4, 5].

Human-robot collaboration (HRC) system is a system in which a human and a robot perform the same task together in a shared workspace. Humans have outstanding cognitive abilities and adaptability. Moreover, robots can perform repetitive tasks more efficiently with consistent accuracy. Combining human and robot capabilities can improve

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flexibility and ergonomics problems in manufacturing operations [6, 7]. So far, HRC systems for assembly have been implemented in various industries such as automotive and aircraft, electronic and mechanical assembly. However, the application of the HRC system in the mold industry is still limited. The mold industry is characterized by the decreased number of skilled workers required to assemble mold and small-lot production of multiple products. Therefore, it requires the implementation of a certain level of automation. Since mold assembly involves heavy material handling and repetitive tasks that require force, collaboration with a collaborative robot is required. The co-bot used in this study has a maximum payload of 15 kg. Although it can be helpful to workers even now, co-bots payload capacity is continuously developing.

As a method used for existing robot programming, it is impossible to cope flexibly with rapidly changing tasks, so there need to be more successful cooperative robots in the actual process. Currently, the usual robot programming method is direct teaching and offline programming (OLP). However, since this method depends a lot on the knowledge of the programming skills, there is a limit to the design of the optimal process and the time and cost to cultivate experts. In this study, we propose a methodology for optimizing the behavior of cooperative robots based on deep reinforcement learning. The system proposed in this study is designed to optimize process variables through artificial intelligence-based data learning and is expected to contribute to product and process quality optimization of HRC processes in the future.

2 Literature Review

2.1 Collaborative Robot

A collaborative robot (Co-bot) is a robot that can physically interact while sharing a workspace with humans. It refers to a robot that improves productivity through collaboration with workers [8]. General industrial robots are designed to move somewhat autonomously, but collaborative robots' function to enable humans to perform specific tasks successfully. Traditional industrial robots are advantageous for single-item mass production processes, long-term production processes, fast-paced and heavy-duty work, while collaborative robots are advantageous for multi-product small-lot production processes, short-run production processes, human-robot cooperative production processes, and work with small base loads, etc. can be said to be suitable. Collaborative robots have advantages such as ease of operation, high safety, and low cost compared to industrial robots [9]. Based on these advantages, the demand for collaborative robots is increasing in all fields, such as automobiles and electric electronics, and the possibility of using them is expected to increase even more. In addition, in the current situation where low fertility and population aging are on the rise, the collaborative robot system is expected to solve the growing shortage of human resources.

2.2 Object Detection and Reinforcement Learning

CNN (Convolutional Neural Network) is a methodology that applies the idea that only specific neurons in the brain are activated depending on the shape of an object through cat

brain wave experiments conducted in the 1950s [10]. It is mainly used for classification and object recognition, and there is a difference in accuracy and learning time depending on the CNN structure. Object recognition in the conventional image processing method consists of a histogram of oriented gradients (HOG) and uses it or scale-invariant feature transform (SIFT) to recognize objects [11]. Object recognition using recent CNNs has the strength of generalization, has a high recognition rate, and is capable of recognizing various objects. In addition, real-time processing becomes possible when a graphic processing unit (GPU) is used. In this paper, 1-stage detectors, SSD (Single Shot Detector) and Yolo (You Only Look Once), which simultaneously operate the location recognition and object identification functions, are used [12]. This has lower accuracy than two-step detectors such as recurrent convolutional neural network (RCNN) and Faster CNN but has the characteristics of real-time processing.

Machine learning is generally classified into three major categories. In supervised learning, learning proceeds under the condition that an explicit correct answer is given. On the other hand, in unsupervised learning, learning proceeds under the condition that an explicit correct answer is not given. Finally, in reinforcement learning, an agent interacts with the environment to learn the policy to maximize the reward and take optimal action. Figure 1 shows the structure of reinforcement learning formulation. Reinforcement learning is a methodology for solving the Markov decision process (MDP) problem of finding the optimal action with a Markov feature that the current state is independent of the future state or past state. Reinforcement learning is being studied in areas such as robotics and self-driving cars. Representatively, it showed high performance through Alphago and Atari games [13, 14]. In this study, a system was proposed by applying deep reinforcement learning. Deep reinforcement learning is a combination of deep learning and reinforcement learning, and it enables improved expression by approximating complex functions such as action-value function, state value function, and policy with neural networks. In the existing reinforcement learning, as the dimension of state and action increases, there are limitations in obtaining the value function. However, deep reinforcement learning can solve high-dimensional problems by approximating these complex calculations with neural networks [15].

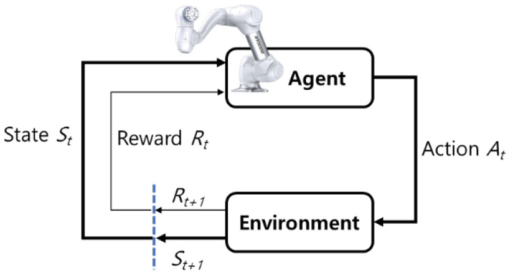

Fig. 1. Reinforcement learning formulation.

3 Object Recognition Method

3.1 HRC Manufacturing Collaboration System Framework

The process model defines the functions of the tools that must be performed to integrate the production system. The goals of process modeling in production systems include understanding operators, managing, and improving processes, and automating guidance and execution. Process models can be used as tools for system design, communication, simulation, and system analysis in manufacturing systems. Figure 2 shows the framework of the process model-based HRC system for mold assembly.

Process Model. When the mold design is completed, a product engineering model such as CAD (Computer Aided Design) is defined. The established process model must clearly define the tasks that make up the process, the subject performing the task, the input and output resources, and whether or not to collaborate. The process model is applied to a predefined template through a model converter.

Model Converter. Model converter refers to a predefined template that extracts necessary variables from Process Model and uses them. Extract Assembly Instruction, BOM (Bill of Material), Robot Control Code and Verification model through an independently defined template.

Communicator. A Communicator is defined as delivering appropriate data to workers and collaborative robots in appropriate situations by comparing the process model, which is the standard process, with object recognizer information. The communicator has the function of determining the time and object to deliver the data produced by the Model Converter. When the current process is identified, the communicator delivers assembly instructions and BOM to the operator, Robot Control Coded, and BOM to the collaborative robot.

Object Recognizer. Object recognizer identifies the process of a shared assembly cell through image processing and recognition technology and prevents worker collisions.

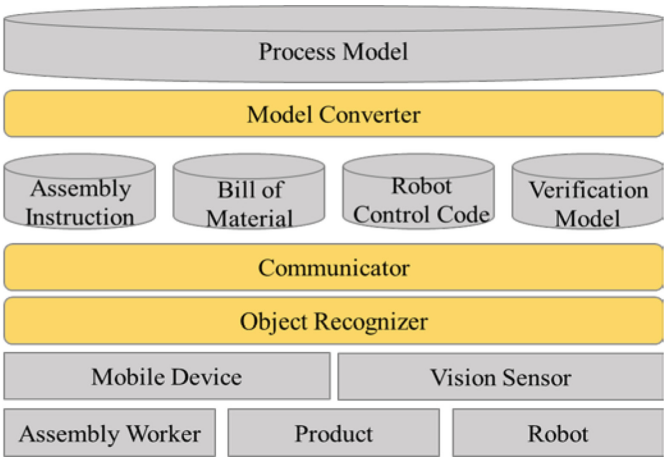

Fig. 2. Framework of HRC system based on process model.

3.2 Machine Learning for Object Recognition

Object recognition uses machine learning of a CNN. CNN applies multiple filters to an image to obtain a different feature map for each object. The learned and extracted feature shapes are compared to return an object with matching features. Until recently, many technologies have been announced for object recognition using CNN, and among them, the YOLO algorithm, which has high recognition accuracy and fast processing speed, is used. Due to its relatively faster recognition speed than other object recognition algorithms, it has the advantage of immediate object recognition when an image is received from a camera. Figure 3 shows the algorithm to estimate the position of an object proposed in this paper. The algorithm presented in this paper proceeds in the following order. First, the image of the experimental environment is transmitted to the RGB (red, green, blue) camera. Using the YOLO algorithm, the existence of objects in the image is determined. If there is an object in the image, the image coordinates of the Bounding Box are returned. Each vertex of the object recognition area is converted into image coordinates composed of pixels, and the object's location is estimated through coordinate conversion between image coordinates and world coordinates. In the case of an image in which an obstacle obscures an object, the location of the current object is estimated through a location prediction algorithm.

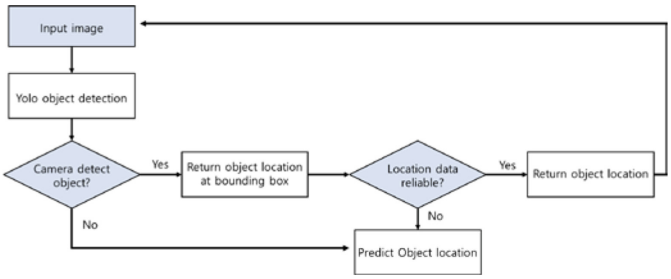

Fig. 3. Algorithm to estimate the position of an object.

4 Reinforcement Learning Application Methodology for Manufacturing Collaboration System Framework

4.1 HRC System Based on Process Model

Part-flow-based Manufacturing Process Modeling (PMPM) is a modeling tool for visualizing a manufacturing collaborative process's workers, machines, parts, and methods (tasks). This study used PMPM to store process information and track part information. The first step is to model the mold assembly process using PMPM. Figure 4 is the result of modeling the target process. Rectangles are tasks automated machines perform, while rounded rectangles and octagons are collaborative tasks between robots and operators. As shown in Fig. 4, information on the type and quantity of input/output parts are defined

in the model. Therefore, this model has the key information of the manufacturing information system and serves as an essential data engine used to track part information and verify image processing results.

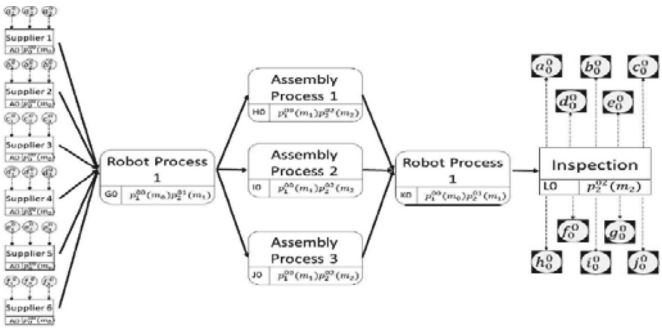

Fig. 4. PMPM model of mold assembly process.

4.2 Reinforcement Learning Using Motion Data

In reinforcement learning, an agent learns to maximize the accumulated reward during an episode. If learning is ongoing without a clear start and end, rewards can be optimized by averaging rewards or depreciating returns over all episodes. In this reinforcement learning problem, an agent and its environment can be modeled as states and perform actions. Moreover, each can be a collection of discrete or contiguous sets and can be multi-dimensional. A state predicts a future state or observable state by including all relevant information about the current state. The reinforcement learning system is implemented according to the following process. First, when the robot performs a task, a learning environment in which rewards are received through interaction is modeled. Next, the agent that observes the state in the environment and acts according to the optimal policy must be modeled considering the specifications and dynamics of the actual target robot. After that, the task completion criteria and task initialization point are set. Design the work performance reward function by setting the reward standard when the task is completed and the reward standard in the middle of the task. Finally, based on the state and reward information generated from the environment, the deep learning-based learning network that finds the optimal action is updated.

4.3 Deep Reinforcement Learning System for Co-bot Motion Learning

Human motion data is collected using the direct teaching of the operator. The collected motion data is classified into motion models based on human motion data in the motion classification interface. The human motion model created in this way is interlocked with the simulation environment. The simulation environment models environments, products, and agents based on physics engines. Next, design the work performance compensation function by defining the work to be performed. Also, by setting the parameters

of the co-bot, it eliminates impossible tasks. Data generated in the simulation environment is passed to the deep reinforcement learning learner every episode. The network is updated using state and compensation information delivered from the simulation environment, and the optimal action policy is delivered to the simulation environment from the learned network. When the robot motion optimization is completed, the robot motion model is saved, and the motion is downloaded to the actual robot using OLP, and the robot performs the task. Figure 5 represents a configuration diagram of a deep reinforcement learning system for co-bot motion learning.

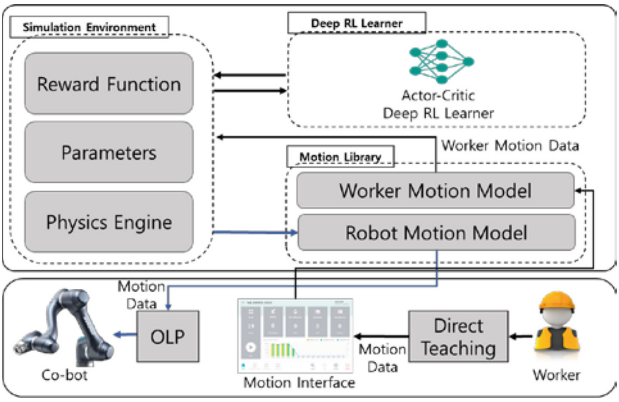

Fig. 5. Configuration diagram of deep reinforcement learning system for co-bot motion learning.

5 Conclusions

This study proposed a methodology for learning cooperative robot behavior using a deep reinforcement learning algorithm. To this end, a system that controls process variables in real-time based on facility variables, major modules constituting the system, and complex functions performed by the modules were designed. In addition, for the practical application of the HRC system, which is challenging to apply to the production of a single product, the problem of data sharing between collaborative robots and workers based on a process model was addressed.

Reinforcement learning of robot motion using simulation is an effective method to save cost and time. However, building a simulation environment that considers the physical environment and noise that can occur in real robots is essential. Reinforcement learning research that collects and integrates environmental data that can occur in the physical environment into data used for learning to perform reliable actions is essential. This study has a limitation in proposing a configuration diagram of a deep reinforcement learning system for co-bot motion learning. In future research, we plan to develop image processing techniques for recognizing parts and workers to effectively and quickly collect facility and process data generated in real-time and data extracted through vision sensors. In addition, it plans to implement an environment that can be linked between actual

manufacturing facility data and actual process plans through linkage with MES. In addition, it is expected that cost reduction and lead time reduction support strategies can be derived through learning performance data by establishing templates for various analysis techniques.

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Deploying Computer-Based Vision to Enhance Safety in Industrial Environment

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Abstract. One of the cornerstones of Lean manufacturing, according to academic research, is the 5S+1, which introduces quality in manufacturing. This study aims to demonstrate how computer-based vision and object detection algorithms, can assist in the implementation of safety as 6th S in 5S+1 by monitoring and identifying employees who disregard accepted safety procedures, like wearing Personal Protective Equipment (PPE). The research evaluated the performance indicators of a detection technique and reviewed and analyzed it. To confirm workers' PPE compliance, the suggested model used the You-Only-Look-Once (YOLO v7) architecture. A deep learning technique was subsequently applied to confirm the safety helmets and safety vests. This strategy is determined to be the most effective when using the VGG-16 algorithm, achieving an 80% F1 score and processing 11.79 frames per second (FPS), making it ideal for real-time detection.

Keywords: Lean Manufacturing · Machine Learning · Industry 4.0 · 5S+1 · Personal Protective Equipment

1 Introduction

The Lean manufacturing idea was first introduced In Japan. Toyota Production System was originally used by the Toyota firm to put the idea into practice. However, the Lean idea is now widely used in industry. Providing high-quality goods while keeping manufacturing costs down is known as lean manufacturing, one of the most well-known and commonly applied approaches in the sectors to increase productivity, improve quality, and reduce costs in organizations. By minimizing waste, improving product quality, and boosting productivity, lean manufacturing tools reduce overall operating costs. According to research findings, the Lean approach increases organizational efficiency, lowers manufacturing costs, eliminates needless downtime, improves resource usage, and maximizes profitability. As a result, the Lean approach increases any organization's ability to compete in the market. Therefore, in order to become economically viable and practical, businesses aim to implement the Lean manufacturing philosophy. After the

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Lean manufacturing idea was implemented, it was seen that firms underwent continual improvement [1]. Total Productive Management (TPM), overall Equipment Effectiveness (OEE), and Jidoka are examples of Lean manufacturing technologies that have a direct impact on the enterprise's environment and social and economic sustainability. As a result, an improvement in employee dedication, morale, safety, and delivery time can be attributed to a safe workplace [2]. Takashi Osada [3] first created the 5S approach in 1970 to support the Lean concept's implementation. Lean tool 5S is made up of components like Sort, Set, Shine, Standardize, and Sustain. Later, the Safety was included to create the 5S+1. Safety is centered on taking preventative steps to safeguard employees from dangerous situations and to give them a secure atmosphere. Studies have shown that keeping a stress-free, secure, and safe atmosphere is crucial to improving the working environment. Extra precautions must be taken during processes like welding, gas cutting, and casting in order to lower the likelihood of occurrences [4]. It is impossible to separate industrial, manufacturing, or building operations from the 5S+1 technique. Safer working conditions are produced by the use of 5S+1 tool. By using 5S+1, it was made sure that employees were using Personal Protective Equipment (PPE) and other tools to prevent mishaps.

2 Background

More than 7 million people work in the construction industry, which accounts for 5% of the entire employment in the US and nearly 6.3% of the GDP ($1.3 trillion) [5]. The construction industry records about 19% of fatal occupational accidents and about 9% of non-fatal occupational accidents, according to the Bureau of Labor Statistics (BLS) [6]. The majority of these accidents might have been avoided if employees had followed the proper safety procedures, such as using PPE such a safety helmet, vest, gloves, goggles, and steel-toed shoes [7]. A recent survey found that nearly 40% of workers do not wear any PPE, despite the fact that governing laws and safety standards hold employers accountable for implementing, monitoring, and maintaining adequate PPE on the job site [8]. A lack of or improper usage of personal protective equipment (PPE) can greatly raise the risk of accidents [9]. Companies can spend less time and money dealing with penalties, lawsuits, and settlements as a result of non-compliance by applying 5S+1, which can help employers avoid workplace accidents and significant non-compliance fines.

Automation and big data integration in Industry 4.0 improved the tracking of PPE compliance. There are now two different types of monitoring methods. Sensor-based monitoring involves using Radio Frequency Identification (RFID) tags that are installed on each piece of personal protective equipment to see if workers are following PPE compliance [10].The second type of monitoring is vision-based, which was previously carried out by a foreman on the job site using his or her human eye. Nowadays, camera systems are employed to record pictures or videos of the job site, which are later examined to determine whether PPE compliance [11].

3 Dataset and Methodology

In the 774 crowdsourced and 698 web-mined images in the dataset Pictor-v3 [12], there are 2,496 and 2,230 instances of workers, respectively. As seen in Fig. 1, the crowdsourced photographs are already tagged thanks to LabelMe [13]. Because annotating is a time-consuming and expensive process, we decided to analyze the crowdsourced portion of the dataset for the purposes of our paper. Web-mined images were retrieved from publicly accessible images on the web, while crowdsourced images were obtained from three different construction projects. Totaling four classes, the dataset includes workers (W) who can choose to wear a safety helmet (WH), safety vest (V), both (WVH), or neither. To avoid overfitting, the data was trained for up to 50 epochs. The split of the dataset for training, validation, and testing was 64%/16%/20% at random.

Fig. 1. Example of annotated images in the training dataset [12].

In computer vision, the object detection problem consists of two stages, identifying an object (classification) in an image and precisely estimating its location (localization) within the image [14]. For example, a region-based detection algorithm such as R-CNN [15] first identifies Regions of Interest (ROI). It then uses a CNN to classify the identified ROI to detect objects in them. Faster R-CNN is an improved version of R-CNN that performs classification and detection tasks faster than R-CNN [16]. Mask R-CNN [17] has also been proposed as a faster variant of R-CNN. However, these algorithms still needed to perform faster and with better performance. Therefore, algorithms of single-stage detectors were introduced; these algorithms include SSD [18], YOLO [19] and R-FCN [20], among others that eliminated the need for designing a set of anchor boxes [21]; such as CenterNet [22], RetinaNet [23], and their different variants. While these fast single-stage detectors often significantly compromise accuracy for achieving real-time detection, to date, only YOLO is faster yet more accurate than other alternatives [24]. In our paper, a detection strategy was put forth to carry out compliance checks by identifying employees who are wearing personal protective equipment (PPE) (safety helmet and safety vest) and those who are not.

To identify the discovered worker as W, WH, WV, or WHV, a CNN-based classifier model is applied to the cropped worker images after the YOLO-v7 model has first detected all employees in the input image. This method sorts them into four classes using a classifier after the YOLOv7 first finds the W class (W, WH, WV, and WHV). For instance, a worker who is designated as wearing both (WHV) would have his practice labeled "SAFE" and noted as complying. If not, the employee would be marked as "NOT SAFE" and would be in violation of the law. The graphical illustration of this method is shown in Fig. 2.

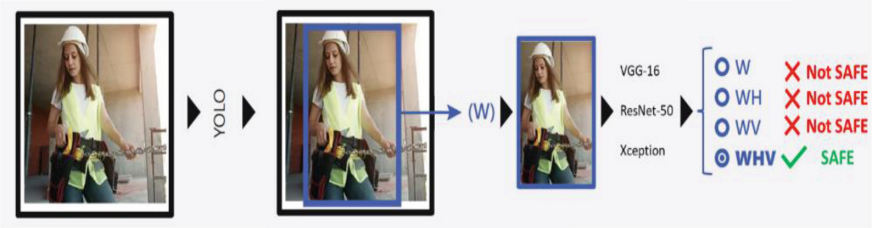

Fig. 2. Illustration of the approach. Photo of worker is from the dataset [12].

VGG-16 is a sixteen layers deep CNN algorithm that is used in many computer vision tasks. VGG-16 can classify images into 1000 object categories and has about 138 million parameters [25]. It has a unique, consistent architecture of 3×3 convolutional layers and 2×2 max-pooling layers [26].

Xception by Google is a CNN that consists of 71 deep convolutional layers [27]. This efficient deep architecture was achieved by maintaining fewer connections between the convolutional layers of the model, thus making it less dense.

VGG-16 and Xception were limited in their number of deep layers due to the vanishing gradient problem with added depth. The vanishing gradient problem happens when the value of the product of the derivative decreases until, at some point, the partial derivative of the loss function approaches a value close to zero before the gradient propagates to the final depth. ResNet-50 is immune to this problem, which could allow us in some cases to get better performance. ResNet is a type of Artificial Neural Network (ANN) that consists of Residual Neural Networks (ResNet) used as a backbone for many computer vision tasks. ResNet-50 consists of 152 deep convolutional layers and has about 25.5 million parameters and one fully connected layer at the end [28].

4 Results and Discussion

Using a specific confidence score, object detectors like YOLO v7 identify the locations of the objects in the four classes in an image. The confidence score represents the classifier's level of assurance and how likely it is that the predicted bounding box will include the desired class. Bounding boxes are used to find the items and determine their positions. As a result, our detection models were described by a number of variables, including item class, bounding box, coordinates, box height and width, and confidence level. As

shown in Fig. 3, where the detected region is represented by a predicted bounding box in red and the item of interest (WHV) is represented by a ground-truth bounding box in blue. The anticipated and ground-truth boxes must be in the same area and location for there to be a perfect match.

Fig. 3. Prediction area in red vs ground-truth area in blue. Photo of worker is from the dataset [13].

These two bounding boxes are assessed using the threshold value, or Intersection over Union (IoU). IoU is calculated by dividing the area of their union by the overlap (intersection) area between the predicted bounding box (red) and the actual bounding box (blue). A valid forecast can still be made with a low IoU value. In contrast, an IoU near one is seen as being more limiting than an IoU around zero. We settled on an IoU value of 0.5 for our research because it is neither too flexible nor too restricted. The components of its confusion matrix serve as the basis for several performance measures of object detection. True Positive (TP), False Positive (FP), False Negative (FN), and True Negative (TN) are among these components. Table 1 displays the TP, FP, FN, and TN values for each class (W, WH, WV, WHV), as well as for each technique and its modifications. After evaluating the results, it has been found that utilizing the VGG-16 algorithm yields the highest effectiveness for this strategy, with an F1 score of 80% and the ability to process 11.79 frames per second (FPS), making it optimal for real-time detection purposes.

Table 1. Values of TP, FP, FN, and TN for the approach.

YOLOv7+	W			WH			WV			WVH		
	TP	FP	FN	TP	FP	FN	TP	FP	FN	TP	FP	FN
ResNet-50	143	8	4	276	45	0	0	4	0	7	11	0
Xception	153	28	0	274	31	0	0	1	0	5	8	2
VGG-16	146	24	1	278	40	0	0	2	0	6	2	1

5 Conclusions

A number of ML and DL techniques are investigated to provide real-time monitoring of appropriate PPE use. In this study, computer vision-based PPE compliance detection methods were suggested. The models discussed in this paper used the Pictor-v3 dataset, which had photographs that were individually captured at various times, locations, and views while also being part of various industry initiatives and PPE styles. The best performance was achieved by the YOLO v7 with the VGG-16 model, which makes it the ideal choice for real-time PPE detection. Future research can concentrate on data with other classes, such as safety shoes, glass, and gloves to draw further applications of the suggested models as the provided approaches were only evaluated on safety vests and helmet classes. Future research can also concentrate on merging Natural Language Processing (NLP) to produce safety reports that might be utilized in root cause analysis to stop incidents from happening again.

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Deploying Optical Character Recognition to Improve Material Handling and Processing

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Abstract. This paper assesses the supporting function of a Machine-based Identification system (MBID) via Optical Character Recognition (OCR) in a Lean manufacturing paradigm. The objective of this paper is to also explore the use of MBID to enable a competitive manufacturing process in a Lean 4.0 environment. Furthermore, a MBID via OCR model is proposed to extract the printed identification number of packages from images captured by a fixed camera in an industrial environment. The method considers different digital image processing techniques to deal with the significant lighting and printing variation observed, followed by a segmentation process that extracts and aligns the characters. Experiments were carried out on a data set consisting of 200 images and achieved an overall detection accuracy of 95% with a very low Character Error Rate (CER) value of 0.0041, clearly supporting the validity and effectiveness of the proposed method.

Keywords: Lean Manufacturing · Big Data · Waste Reduction · Machine Learning · Industry 4.0 · Optical Character Recognition

1 Introduction

The rapid advancement of Information Technology (IT) has contributed to manufacturing enterprise agility in reacting quickly and reliably to changes in demand through increased transparency, visualization, and processing capabilities [1]. Manufacturing organizations now must see the supply chain from a holistic perspective, and business operations should be linked across the supply chain. IT and automation in manufacturing have altered the responsibilities of managers, engineers, and operators, resulting in increasingly knowledge-based workplaces. Therefore, integrating automation deeper into the supply chain's processes is essential [2]. a machine-based Identification (MBID) system can incorporate well into IT environments, offering an option that could help automate Processes for data collection while enabling a simultaneous real-time data transfer.

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1.1 Optical Character Recognition (OCR)

OCR is a technique for extracting text from photos and videos. The OCR process includes image capture, preprocessing, post-processing, character classification, feature extraction, and character segmentation [3]. Preprocessing methods such as noise reduction, skew recognition improvement, and binarization are used to improve the quality of the image once it has been acquired. Post-processing can be considered for enhancing OCR results after classification, often utilizing contextual and vocabulary analysis [3]. Deep Learning (DL) models, such as Convolutional Neural Network (CNN), have recently brought incredible results in image classification and detection [4]. Unlike traditional techniques that use handcrafted descriptors to represent the characters, a DL model can automatically learn feature representation and classify the characters [5]. In addition, it has been shown by Kulkarni [6] that pre-processing approaches may enhance the DL outcomes.

1.2 Applications of MBID via OCR

Machine vision applications play a vital role in industrial applications such as part inspection, part classification, and product assembly. The biggest problem in any image processing is identifying the type of target so that relevant template images can be utilized for pattern matching. This is important when doing the inspection process. Another essential feature for OCR in the industry is the ability to distinguish parts considering their part number, which generally comprises of type number and serial number apart from manufacturing date, customer id, etc., [7]. OCR has been used to read data from captured images of hard drives [8], to extract disk capacity size and part number. OCR has been used in applications such as receipt scanning to extract information from receipts via mobile app and store it on the phone [9]. Acquisition information devices have utilized OCR to extract information for medical devices [10] and medicine [11]. These varied uses demonstrate OCR to be a proven and efficient process that saves time, cost, and other resources by utilizing automated data extraction and cloud storage capabilities. OCR can automatically extract text data from almost any visual source, thus eliminating the need for manual data entry.

1.3 OCR'S Potential in Lean Manufacturing

Lean production can itself be described as both a philosophy and a set of tools and techniques that aim to systematically identify and eliminate all waste in processes, with an underlying vision of one at a time, no waste flow [12]. Table 1 observes how these five Lean principles address the role of OCR in Lean manufacturing.

2 Methodology

2.1 The Dataset

This Kaggle dataset consists of images of packages produced in a virtual industrial production line [13]. The images were built on procedural generation (a Blender code); each image was created procedurally using algorithms in the code itself, rendering diversity

Table 1. OCR's role in lean manufacturing according to the five lean principles

Lean Principle	Description	OCR's Impact
Value	Defined from the customer's perspective	OCRs can locate interest points in the manufacturing process by extracting data from products and allowing that data to move through the cloud while being processed by the appropriate information system
Value Stream	Value Stream Maps (VSM) track the flow of manufacturing processes and materials; a snapshot in time	An OCR system improves the reach of VSMs to convert this data to dynamic, real-time, easy-to-visualize data
Flow	Businesses strive for flow using straightforward, visible solutions	By offering a more precise mechanism that can extract serial numbers (SN), OCR solutions canclose the gap between information and material flow on the shop floor
Pull	Limits production to what is needed by customers, only when needed, Just In Time (JIT)	OCR solutions speed up information acquisition processes with precise timing and quantity knowledge to support JIT deployment
Perfection	Transparency and continuous improvement support the pursuit of perfection	OCR contributes to continuous improvement by removing manual mistakes. OCR improves transparency via real-time data updates

through each image created in light sittings, motion blur, and orientation. The dataset comes balanced and split into two folders: top view images and side view images. Only side view images were selected for this paper since they contained the serial numbers (SN), or the data we were looking to capture and extract. A 90/10 split was used for training and testing, respectively. The dataset has some limitations due to its small number of images (200 side-view images) and the overall low resolution of each image.

2.2 You Only Look Once (YOLO)

Before extracting text from an image, it has to be detected first. All OCR models can be summarized in three significant steps; character position detection, recognition of character orientation and correction, and character content recognition. This paper used a You Only Look Once Deep Learning (DL) object detection model for text recognition, followed by Tesseract OCR and Paddle OCR for text extraction [14]. YOLO v7 looks at an entire image, splits it into n $\times$ n grids, then uses a single CNN to predict the bounding boxes and the class probabilities for these boxes. The bounding boxes are used to locate the class within the tested image and each bounding box has a class label. In this case, only one bounding box around the SN text was needed, labeled as an SN class. Figure 1 shows a sample of the bounding boxes annotated on our training dataset. Note that "0"

is the class label for the bounding box surrounding the SN characters. YOLO has been used in extracting information from tables [15], license plate recognition [16], automated invoice parsing [17], and for automated meter reading [18].

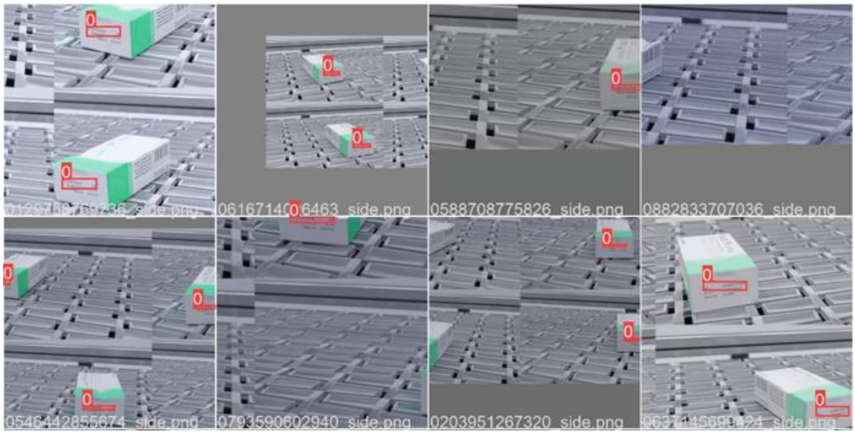

Fig. 1. Sample images with the bounding box around SN text.

2.3 Tesseract and PaddleOCR

Tesseract is an open source Optical Character Recognition (OCR) technology that uses a Long Short Term Memory (LSTM) Recurrent Neural Network (RNN) model (LSTM-RNN) [19] to handle texts of arbitrary character length. The bounding box of the input image is fed line by line into the LSTM-RNN model to generate an output of the readable text [20]. PaddleOCR, PP-OCRv3, is considered one of the most advanced and robust multilingual OCR algorithms that can detect over 80 types of multi-language recognition models. In this study, image detection models combine with OCR algorithms to detect and extract SN from image-based datasets.

3 Results and Discussion

YOLO v7's success as a detection models is characterized by three attributes: object class, bounding box with coordinates and specified dimensions, and a confidence score. In this study, object class is determined by two possibilities: whether SN is detected or not. A perfect match occurs when the area and location of the predicted and ground-truth boxes are exactly the same. The threshold value, or what is known as Intersection over Union (IoU), is used to evaluate these two bounding boxes. IoU is equal to the area of the overlap (intersection) between the predicted bounding box (blue) and the ground-truth bounding box (red) divided by the area of their union. Even a small IoU value still constitutes a valid prediction. However, an IoU close to one is considered more restrictive than an IoU close to zero. The confidence score reflects how likely the

predicted bounding box contains the targeted class (SN) and how confident the classifier is about it [21]. An IoU value of 0.5 was selected for this study. Table 2 shows a summary of the confusion matrix based on how SN classes were detected using YOLO v7.

Table 2. Confusion Matrix Summary for YOLO v7

Method	True Positive (TP)	False Positive (FP)	True Negative (TN)	False Negative (FN)
YOLO v7	20	0	-	0

For object detection in this confusion matrix, TP indicates instances when the model detects SN class when there is an actual SN class in the image; IoU ≥ 0.5. FP indicates when a wrong SN class was detected; IoU < 0.5. FN indicates a true SN class that the model did not detect. TN indicates that no SN class was detected. TN includes all possible negative classes that were not detected. Usually, TN is assigned a null value [131]. Both detection models have performed well in detecting the bounding boxes that contain the SN needed to be extracted. Table 3 summarizes the performance measurements for YOLO v7 and Faster R-CNN. Precision is the ability of the model to detect only the relevant SN class; both models have been able to do this at a 100% with a 0.5 IoU value. Recall is the ratio of the number of TP to the total number of actual SN class. For example, if the model correctly detects one SN class in an image with two true SN classes, then the recall is 50%. Both our models achieved 100% recall values. F1 score is the weighted average between precision and recall, high F1 score values indicate high accuracy, and both of our models reached an F1 score value of 100%, indicating a high detection accuracy.

Table 3. Confusion Matrix Summary for YOLO v7

@ IoU = 0.5	YOLO v7
Precision = TP / (TP + FP)	100%
Recall = TP / (TP + FN)	100%
F1 score = (2 × Precision x Recall) / (Precision + Recall)	100%

Table 4 shows a sample of the results obtained from performing Tesseract v5 OCR and Paddle v3 OCR to transcribe text information from the detected SN class compared with the original information that was in the box to demonstrate the performance level of each OCR engine that has been used.

Text extraction engines achieved consistent results with manual extraction indicating reliable performance. However, neither model could extract text from the blurry SN image. OCR results were further evaluated using error rates to determine the extent to which the OCR-recognized SN and the true SN differ. These error rates consist of substitution errors, deletion errors, and/or insertion errors. The extent of these errors between

Table 4. Original SN information vs. recognized SN information.

YOLO v7		
Manually Extracted	Paddle v3	Tesseract v5
884150938683	884150938683	884150938683
889601418161	889601418161	889601418161
896317926617	896317926617	OPI 7926817
896391052674	896391052674	896391052674
Blur	Blur	Blur

two SN strings is measured using the Levenshtein distance, which is the minimum number of single-figure edits (i.e., substituted, deleted, or inserted) required to change an SN into another. Levenshtein distance can be measured at the word level using Word Error Rate (WER) or the character level using Character Error Rate (CER). Since we are trying to transcribe an SN figure that consists of multiple characters, we will use CER. CER is measured by adding the number of substituted SN figures (S), the number of deleted SN figures (D), and the number of inserted SN figures (I), and then dividing it by (S + D + I) in addition to the correct number of figures in the referenced SN (C). In conclusion, CER = (S + D + I)/(S + D + I + C). In other words, CER represents the percentage of figures in the reference SN that were incorrectly predicted in the OCR output. The lower the CER value (with zero being a perfect score), the better the performance of the OCR model. Table 5 shows a summary of the CER calculations for each model. The overall detection accuracy for each model was calculated by dividing the number of correctly detected SN by the number of overall tested SN.

Table 5. CER calculations for each model

YOLO v7		
	Paddle v3	Tesseract v5
Average CER	0.0041	0.12
Detection Accuracy	95%	53%
Detection Time per SN	1.25 s	0.19 s

For YOLO v7, the Paddle v3 model outperformed the Faster Tesseract v5 in terms of overall detection accuracy of SN. Paddle v3 correctly identified characters with a smaller error rate, as indicated by the lower Average CER calculation. This is validated by an excellent detection accuracy rate of 95%. However, the Paddle v3's better performance with lower CER values comes at an increased detection time per SN.

4 Conclusion

Utilizing an MBID in materials handling and processing is becoming increasingly essential. Therefore, this study employed an object detection model with OCR to transcribe SN information from labels. Furthermore, YOLO v7 with Tesseract v5 OCR, and Paddle v3 OCR, were applied in this paper. The experimental results revealed that YOLO v7 successfully detected SN with an F1 score of 100%. Additionally, Paddle v3 OCR achieved lower CER values and higher detection times than Tesseract v5 OCR. The study also concluded that the YOLO v7 Paddle v3 OCR achieved high detection accuracy for SN of 95% and the lowest average CER value of 0.0041. Further future studies can be carried out with a larger dataset containing a high-quality resolution image.

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Human-Centric Design of Automated Production Lines Using Virtual Reality Tools and Human Data Analysis

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Abstract. The 4.0 revolution is leading to increasingly automated, flexible, and intelligent manufacturing systems that require greater complexity to manage during maintenance and process control. In this context the optimization of the human-machine interaction plays a crucial important role in the design of modern industrial systems. Virtual Reality (VR) offers realistic simulation environments where users can be involved to replicate specific human tasks, detecting and solving problems before they occur. The paper proposes a human-centric digital design methodology that integrates VR technologies with human data analysis tools to support the design or redesign of complex industrial systems. Different wearable devices have been used to collect data about physical and mental user conditions to provide an early assessment of the operators' workload, while comparing different design solutions into the virtual space. An industrial use case related to the redesign of packaging automated machines was used to validate the proposed method and tools: a preliminary correlation between physiological parameters and machines interactions was found.

Keywords: Human-centred design · Virtual Reality · Human data analysis · ergonomics and human factors · digital simulation

1 Introduction

Industry 4.0 (I4.0) paradigm has brought a real revolution in production sites and manufacturing systems, introducing a set of key-enabling technologies [1] to enhance the flexibility and to speed up the production. Despite this great advancement in innovation, humans are still at the core of many industrial processes, due to their inner flexibility and capacity to adapt to new operations without disrupting the production environment [2]. Recently, the Industry 5.0 idea [3] introduces the concept of human centricity as a success factor in modern factories to achieve a more sustainable and resilient system, placing the wellbeing of the operators at the centre of the production process. In this

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context, it is crucial to integrate humans with advanced technological systems at the shop floor, increasing at the same time the level of the workers' wellbeing and the system performance [4]. To achieve this result, technologies like virtual reality (VR) and human data analysis tools are particularly helpful to integrate ergonomics and human factors into the design of complex systems that can be tailored to operator characteristics and needs. Moreover, such technologies can help companies to limit the waste of resources due to the reduction of physical prototyping.

This paper proposes a Human-Centred Design (HCD) methodology to effectively redesign complex systems or machines by combining VR and wearable devices to collect data about physical and mental human conditions and virtual spaces to provide an early assessment of the operators' workload. This methodology was applied in a real case study concerning maintenance and routine operations on an automatic machine for packaging.

2 Research Background

In the last few years, the assessment of ergonomics in manufacturing has continuously increased: nowadays process design concerns not only task planning and layout design, but also the operators' physical and psychological comfort, which have been proved to be strictly connected with factory productivity [5]. So, ergonomics could be an opportunity to enhance the level of modern flexible and advanced manufacturing systems, usually characterised by a significant amount of manual work. Maintenance and routine operations on complex machines or systems are most of all critical because engineers and designers focus primarily on system performance rather than on its maintainability. In order to overcome these issues, VR simulations are particularly helpful because it is possible to immerse operators in a virtual environment and to simulate its actions and reactions in order to test their experience in advance [6]. This approach is usually known as virtual manufacturing (VM), in which the human actions in the virtual scene can be recorded to collect information and find out ergonomic issues. Contrarily to traditional desktop-based digital human simulations (DHS), the use of VR allows to include the assessment of cognitive aspects, such as human reliability, human errors, decision-making, until the quality of the operational performance [7]. Alongside this topic, recent research works started developing platforms for human data collection, post-processing and correlation in an integrated way, supporting factory ergonomics by monitoring human activities [8]. In particular, the analysis of humans' physiological parameters such heart rate (HR), heart rate variability (HRV) or blood volume pulse (BVP), eye activity e.g., pupil diameter (PD) or blink rate, brain activity by EEG data, breathing rate (BR), galvanic skin response or electrodermal activity (GSR or EDA) can indirectly reveal possible criticalities for operators linked to their mental workload [9].

In the recent literature, many approaches to carry out an early assessment of human workload using DHS and VR technologies were proposed. For instance, Caputo et al. [10] proposed an appraisal of a workplace design and ergonomics validation procedure based on DHS to solve ergonomic risks during the design phase in assembly lines. Similarly, Zhu et al. [11] demonstrated the application of DHS can improve the realism and effectiveness of VM, including human factors and ergonomics in various fields of application. Kačerová et al. [12] founds that the combination of VR technology and MoCap

systems allows the ergonomic evaluation of an assembly workstation, and this approach is more accurate than standard methods. These methods are surely innovative, but all primarily focuses on physical evaluation and slightly consider the cognitive counterpart. To overcome this issue, Peruzzini et al. [13] developed a protocol analysis to assess both physical and cognitive workload on digital models to support ergonomics workstation design. The challenge is to bring HCD approaches, considering both physical and mental human performance, at a practical level to leverage VM and explore how to help the system design process.

3 Methodology

The proposed methodology aims at supporting engineers during the design (or redesign) of complex systems like automatic machines, using a human-centred vision is mandatory to prevent design errors and to promote the workers' wellbeing during maintenance and operational tasks. The methodology is inspired by the User Experience Design (UXD) cycle, as shown in Fig. 1, and structured in 4 phases are listed below:

1. User research: analysis of the human-machine interaction during the current situation, on the as-is system, to map the as-is interaction and collect useful data. Digital simulation is adopted to post-process the collected data, to give an ergonomic value for the as-is design and to set the redesign objectives. This phase ends with the definition of the users' requirements and of project goals;
2. Design: considering the interaction issues as detected in phase 1, engineers apply design changes (e.g., machine layout, components' positioning, reciprocal position between the operator and the machine, task execution modalities) in order to better fit ergonomic principles, to achieve a to-be design;
3. Virtual prototyping: a VM simulation of the to-be machine is realized by using VR tools and the novel human-machine interaction is simulated into the virtual environment involving real users to check the new process as designed;
4. Ergonomic assessment: using the VR simulation, the users can replicate the tasks under assessment into the virtual scenario and be monitored using motion capture system and human data wearable sensors. Physical and cognitive assessment can be carried out during the simulation by proper indexes (e.g., EAWS - European Assembly Work Sheet, NAS - Numerical Analogue Scale for stress) to compare as-is and to-be solutions. If the ergonomic assessment does not fully satisfy the user requirements and project goals, the process returns to the design phase and the cycle is repeated until a successful assessment.

During phase 1, the operators are monitored on the field by using the following tools:

- Tobii Pro Glasses 2: wearable eye-tracking device that can be used for various research applications, such as human behaviour and visual attention;
- Beslands SF-500 Dynamometer: digital force gauge capable of measuring pushing and pulling forces up to a maximum of 500N;
- Empatica E4 Wristband: medical-grade wearable device that unobtrusively monitors real-time physiological data, including BVP and EDA, skin temperature, and also movement due to the presence of a three-axis accelerometer.

During phase 3, the VM simulation is realized by involving the following hardware and software tools:

- HTC Vive Pro Eye: 6DOF wearable HMD equipped with 32 markers for 360-degree tracking, a G-sensor, a gyroscope and infrared tracking system, allowing monitoring of exact positions in the space;
- Leap Motion Controller: HCI (Human-Computer Interaction) system that accurately captures hand movements allowing interaction with digital content;
- Unity 3D: cross-platform graphic engine that enables the development of video games and simulations as VR experiences (using SteamVR);
- Vicon cameras: motion capture system that uses infrared cameras and passive reflective markers on the whole body, which allows accurate real-time recording of three-dimensional movements;
- Siemens Tecnomatix® Jack 9.0: software for DHS which allows to import virtual mannequins in a digital environment and carry out ergonomic analysis;
- EAWS Score Calculator: excel worksheet which, through the postures (numerical values of the joint angles) obtained from the Jack software, calculates the EAWS score [14] of the entire task.

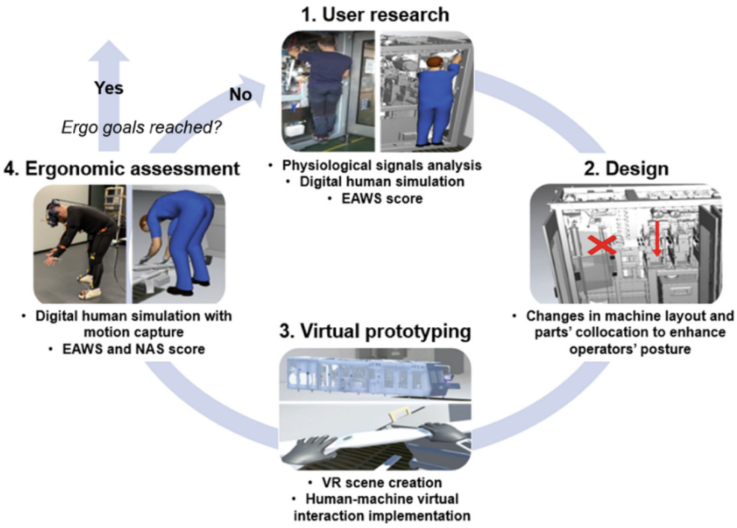

Fig. 1. Phases of the proposed methodology.

4 Industrial Use Case

The use case has been developed in collaboration with a global leader in the design of automatic machinery for beverage packaging. In particular, the aim of the use case is the design optimization of a specific machine to reduce the operators' workload during

maintenance procedures and routine tasks. The analysed task concerns the insertion and unrolling of the packaging material (i.e., a special material composed of paper, polyethylene plastic and aluminium) through the direct injection moulding module of a packaging machine. In particular, the analysis is carried out on the operator during the unrolling operation of the packaging material from the first bending roller through the six stations up to the last bending roller of the module. This procedure is usually performed by the operator every 30 min and requires about 10 min to complete the task. In the next sub-sections, the main steps of the proposed methodology applied to the presented industrial case are shown.

4.1 User Research

This phase involved an operator from the company, with more than 3 years of experience in the field, acting on the as-is machine to complete the task (i.e., refill of the packaging material) in the company machines test area. The participation was voluntary: no reward was given, and an informed consent was signed before starting the analysis. No corrective lenses were provided to the operator, and according to the given consent no cardiac issues were reported. The task was performed while wearing the Empatica E4 and Tobii Pro Glasses 2 devices. After a short calibration of the eye-tracking system, 3-min of signal recording from the wearable sensors in resting condition (upright, being still) were established at the beginning of the task execution to define the baseline of each physiological signal. A video camera recorded his movements during the task execution. Thanks to the dynamometer, the forces applied by the operator during demanding activities were measured. The post-processing phase focused on the operator's physiological data analysis: for instance, HR, EDA and PD data were graphed in time-domain to understand the main criticalities during the procedure. Data analysis was carried out highlighting the most significant trends in parameter variation, in the same way as reported in [15]. Moreover, the DHS of the considered task was modelled in Jack Siemens with different percentile from different male populations (i.e., 5th Thai, 50th German, 95th Dutch) in order to extract postures and to carry out the physical ergonomic evaluation through the EAWS Score Calculator [16]. Finally, the comparison between the physiological parameter trends and EAWS score distribution along the entire task allows the individuation of the main issues to solve in the redesign phase, such as incongruous postures, poor visibility and reachability, dangerous behaviours. In the considered task, the main issues detected referred to: 1) poor accessibility to the internal part of the machine; 2) poor reachability of the upper bending rollers and the lever, which lead to dangerous behaviours of operators; 3) uncomfortable postures during maintenance.

4.2 Design

A set of redesign actions were defined considering the ergonomic issues detected in the previous phase, to solve the problems without influencing the machine performance. As a result, they improved the accessibility adding a large platform on the base of the machine that helped the operators during the process in reaching high bending rollers. In addition, this change promoted a safer behaviour since a more stable foot placement zone was guaranteed. Engineers also introduced sliding doors to improve the accessibility to

the injection stations, which is the most time-consuming area of the entire task. Finally, the rollers release pressure lever was repositioned to be reachable during the process without moving on the other side of machine.

4.3 Virtual Prototyping

The new 3D CAD model of the to-be machine was imported as a.fbx file in Unity 3D and the VR scene was developed, introducing a set of scripts that allows user to interact with the virtual machine. The behaviours of objects in the scene were defined considering their role in the simulation: machine parts involved in the maintenance process were made interactable thanks to Leap Motion SDK, in order to have a realistic virtual experience. Finally, the virtual scene was developed for the HTC Vive Pro Eye headset.

4.4 Ergonomic Assessment

A set of tests were carried out in Lab within the developed VR scene involving a sample user performing the task in the virtual environment. Collected human data about body positions and movements were streamed from Vicon software to Jack Siemens software to virtualize the operator with a virtual manikin. The postural data files are exported from Jack Siemens into a semi-automated worksheet [16] and evaluated through EAWS ergonomic index and compared to the first step (the current machine version, as-is). The cognitive one, is evaluated by NAS stress questionnaire and the analysis of human physiological data trends. The results of the comparison of the human physical performance on the as-is and to-be design are reported in the next paragraph.

5 Results and Discussion

A synthesis of the results obtained by the post-processing of the operator's physiological data and postural analysis during task execution is shown in Table 1 and Fig. 2, according to the selected ergonomic indexes (i.e., EAWS, HR, PD and EDA). Table 1 sums the results of the comparison between the as-is machine and the to-be machine in term of EAWS score. It shows a significant reduction in the ergonomic value (especially for 50th and 95th percentile population), enhancing the workers wellbeing and reducing the risk of developing musculoskeletal disorders.

Table 1. Comparison between current and new machine model in term of EAWS score.

Percentile and population	EAWS score as-is	EAWS score to-be	Improvements %
50th German	92,3	61,5	-33,37%
5th Thai	65,0	64,4	-0,92%
95th Dutch	61,7	41,1	-33,39%

In Fig. 2, experimental correlations were found between the HR and PD parameters, while the EDA graph was omitted since it didn't show significant trends in any sub-task.

Concerning the HR parameter, it showed a significant increase during the most physical subtasks, such as the unrolling of the packaging material in the first bending rollers and in the last ones at the end of the module, while a relevant decrease was reported while the operator was waiting for the completion of machine's automatic procedures and during tasks that were primarily mental demanding, such as the material insertion in the injection stations. As for PD, it showed an increase during the execution of the most physical activities and where greater cognitive effort were required. Similarly to HR, PD decreases in moments of rest due to the activation of the parasympathetic nervous system (PNS). Both reported the analogous trends especially where a high physical effort was required: at the contrary, the activity was primarily static (not physical demanding) at the entrance of the injection stations while more cognitive during the material insertion.

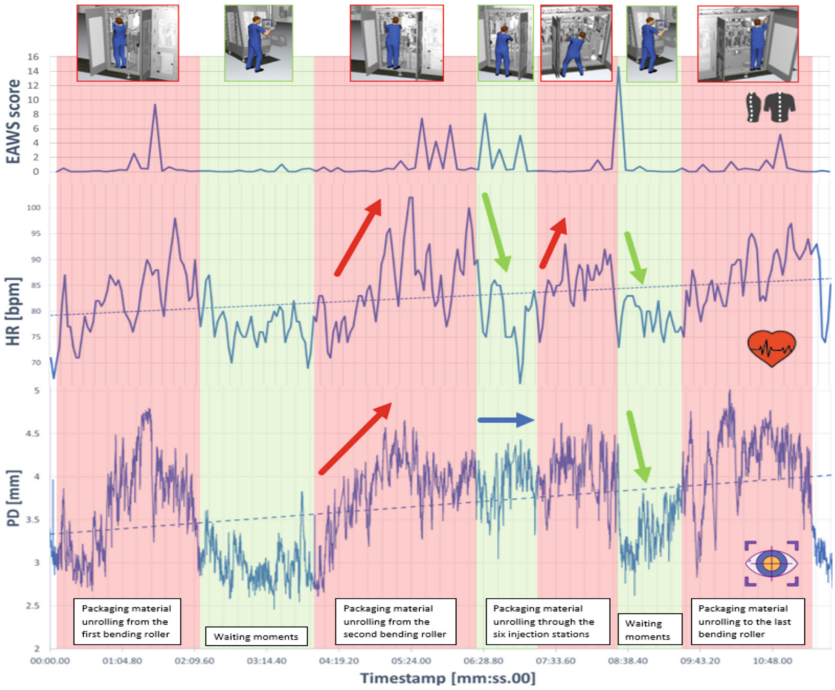

Fig. 2. Results from the post-processing of the operator's physiological data and EAWS score.

6 Conclusions

The paper investigated the application of VM approach to redesign complex systems to enhance the operators' physical and cognitive wellbeing. In particular, the paper proposed a human-centred methodology that drives engineers into a structured design procedure, from the identification of the main redesign goals to the virtual validation using VR tools and motion capture systems. The method is a step forward in the state of

art because it combines the use of human monitoring systems and VR design validation in industry, which is a scarcely investigated topic at the time. The application of the proposed method to a real industrial case study demonstrated its usefulness. The main limitations of the study are mainly related to the complexity of the technological set-up. Future works will address the use of low-cost devices and the further analysis of the physiological parameters, collected during the VR simulation, to provide a more robust evaluation of the mental workload.

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Conceptual Ontology-Based Context Representation for Human and Two Heterogeneous Cobots Collaborative Mold Assembly

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Abstract. Plastic injection molds are assembled manually because of the high variety and low volume operation that require frequent change and comprehensive mold knowledge. The lack of skilled workers and ergonomic problems in the mold assembly requires a certain level of automation to improve the working condition and operating performance. However, the knowledge within mold assembly application is not systematically organized to automate the operation. The use of two non-identical collaborative robots is considered to assist and collaborate with a human worker during the mold assembly operation. Data containing information on components in the collaborative assembly must be collected and represented in a form that can be interpreted and understandable by all resources. Besides, relations of entities within a specific context also must be included to extract correct and useful information for every decision-making step. This study aims to provide a systematic ontology model to acquire and represent knowledge of mold assembly operation with human-robot collaboration implementation that enables expansion, learning, and generalization of created ontologies in future practical applications. A simple trial use of created ontology for positioning parts into regions in the workspace is included. This proposed conceptual context modeling acts as a stepping stone to developing a context-aware system for human-robot collaborative mold assembly operations using multiple cobots.

Keywords: Ontology · Context representation · Human-robot collaboration · Mold assembly · Heterogenous collaborative robot

1 Introduction

Traditional robots are used to fully automate processes in mass production to increase efficiency, but full automation is facing a bottleneck to cope with production diversity in mass customization [1]. The development of advanced collaborative robots (cobots) which are equipped with torque sensors and hand-guidance function [2] allow cobots to

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work aside humans by ensuring human safety and enabling the adaptability of automation in the human-robot collaboration (HRC) systems. Besides, the lightweight and easy-programming characteristics of cobots can be easily reconfigurable to deal with diversity in mass customization production [3]. HRC systems have been implemented in assembly, inspection, welding, and coating operation of low variety and large volume mass production to improve quality and solve ergonomic problems caused by heavy-weight handling [4, 5] and awkward posture [6], and hazardous tasks [7] during operation. However, the HRC implementation in the tool industry is yet to explore [8]. Until now, molds are assembled manually because custom-made molds require human cognitive and adaptability ability to understand and cope with changes in mold structures and production demands. The lack of personnel with comprehensive skills and the ergonomics problem caused by heavy-weight handling and repetitive force-exerting tasks motivates the application of an automated system to mold assembly operations. However, the wide variety of mold designs and low-volume production challenge the implementation of automation. This study focuses on the implementation of the HRC system in the mold industry to provide a certain level of automation in mold assembly.

The most common HRC workstation in the existing implementation consists of one human worker and a cobot (1H:1R). In this study, the use of two cobots to collaborate with a human worker (1H:2R) in a mold assembly is considered. In the proposed HRC assembly, the human and cobots share workspace and time, where resources can execute subtasks sequentially or simultaneously through collaboration with other resource to execute a same task [9]. There were few studies related to multiple cobots in HRC systems, but these studies considered multiple identical cobots. Practically, consideration of multiple heterogenous cobots is advantageous from the management's perspective because an HRC system can be expanded from a single cobot to multi-cobots to meet the requirements of operations from time to time. By using two heterogenous cobots, the HRC system can assemble products with wide range of part weights such as molds, where parts are assigned to each cobot according to the specifications. Knowledge management of the mold assembly is yet to be improved to a systematic structure that can be understood by both human and cobots. For HRC mold assembly operation, we must arrange the mold parts and resources within the HRC assembly station instead of workstations and machines as in process or product layouts for mass production. Thus, we need information about HRC configurations, parts, assembly sequences, resources (human and cobots), tools including manual and end-effectors, and workspace region to decide the location of parts. Moreover, as the molds are still manually assembled, knowledge of the mold assembly operation relies on the skills and experience of human workers. As a result, this knowledge is not well-structured in a way that can be easily understood by cobots. To implement the HRC mold assembly, we must gather and organize the human knowledge into a systematic structure that can be accessed, retrieved, used, and updated to enable communication among human workers, cobots, and developed models. Therefore, the main contribution of this study is to develop an ontology-based context modeling for human with two heterogenous cobots collaborative mold assembly that includes knowledge about all information in the HRC mold assembly operation that enables expansion and generalization of created ontologies in future practical applications.

The structure of this paper is as follows: In Sect. 2, we review the existing literature about the ontology approach in the industry. An overview of ontology and an application using the proposed approach is described in Sects. 3 and 4, respectively. Finally, Sect. 5 presents the conclusion and future works of this study.

2 Related Research

In industrial production, an ontology-based context model was proposed to provide information for monitoring operations [10]. Liau and Ryu [11] proposed a conceptual framework of semantic knowledge representation to connect task assignment, task execution, and status monitoring modules in HRC assembly operation. The conceptual framework included semantic networks of resources (human, robot, and tools), mold parts, assembly tasks, and execution status. Angleraud et.al. [12] proposed knowledge representation and reasoning to enable robots to identify corresponding skills according to human command in natural language format and execute the command if a skill is available. The study was demonstrated using coffee making process, but implementation in industrial applications is limited because of the wide range of speech commands that depend on products, operations, and environment. In HRC systems, knowledge representation and reasoning are used for task planning of simple collaborative assembly operations. Akkaladevi et al. [13] proposed an assembly process learning framework that consisted of perception reasoning for understanding the current state of the environment and assembly task, knowledge management for representing the assembly process and environment, task state reasoning for reasoning about the current assembly state based on information obtained from perception reasoning and knowledge management, and action execution module for HRC assembly task planning. They expanded their study to allow human-robot interaction, including teaching and guidance functions using a semantic knowledge-based reasoning framework [14]. The existing studies in applications other than the industry domain have been well developed because a large amount of existing knowledge and information is available. In the industry domain, the knowledge and information vary with the types of products and operations. Studies using a knowledge-based approach in the HRC domains focused on the task planning, execution, and monitoring stages of single or identical cobots HRC assembly, but knowledge about layout and workspace is excluded. Therefore, this study focuses on ontology-based context modeling for HRC assembly operation to provide comprehensive and systematic knowledge management for multi heterogenous cobots to enable future development of effective layout and task planning, assembly execution, and monitoring stage.

3 Classes of Context Representation for HRC Mold Assembly

Figure 1 describes the overview of the proposed ontology-based conceptual context modeling for HRC collaborative mold assembly. At present, molds are assembled based on the comprehensive knowledge and experience of the assembly worker. To implement the HRC system in a mold assembly operation, we first gather related knowledge of the components in the HRC system, then define the knowledge into four classes with the data acquired, and the connections between classes are represented by dotted lines.

The Mold class is the most fundamental class in the context modeling for HRC mold assembly. A mold consists of parts and these parts are assembled during subtasks which are decomposed tasks according to the assembly sequences. In this study, the context modeling for the operational planning and execution models, such as task assignment, monitoring, and execution are excluded. Thus, the assigned resources are input manually based on the result from the task assignment model. Knowledge and information related to the Mold class are grouped into three categories, which are part-related, subtasks-related, and assigned resources as listed under the Mold class. Since the parts of subtasks are assembled by assigned resources, hence Resources class must be included. In traditional mold assembly, the human worker is the only resource to perform the assembly. However, the HRC mold assembly proposed in this study requires a human, and two heterogenous collaborative robots (Cobot A and B). The technical specifications of cobots include a payload that determines the maximum weight that can be handled by a cobot and the reachable distance of cobots from the base. The existing studies considered shared parts, but tasks were performed sequentially by assigned resources. However, this study considers the collaboration of two resources to execute the same subtask on the same part at the same time. Hence, we have a total of six resource options for the subtasks assignment, which are three individual resources and three collaborative resources. The next class is the Tools class which contains knowledge about tool types and specifications. Tools are categorized into manual tools that are used by human and end-effectors that are used by cobots. A workspace class is included to divide the workspace into regions according to the reachable distance of resources with the consideration of collaborating resources. Workspace class is important to secure the occupancy of parts at the regions of assigned resources.

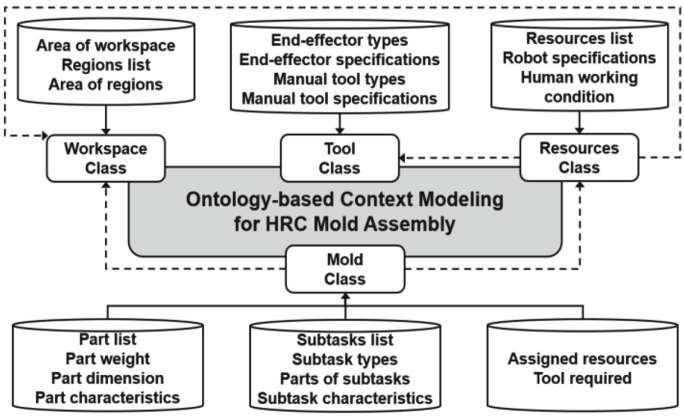

Fig. 1. Classes in ontology-based context modeling for HRC mold assembly.

4 Ontology-Based Context Modeling

Protégé [15], an open-source ontology editor equipped with built-in reasoners and visualization tools is used to construct the proposed ontology. First, classes with sub-classes are constructed, then object and data properties are added to represent the relations between classes and data. Finally, a built-in Pellet reasoner is used to check the consistency of the developed ontology.

Figure 2 shows the developed ontology-based context modeling for HRC mold assembly which is visualized using the VOWL plugin in Protégé. The four classes are marked using dotted circles, and the boxes represent the data types of the data properties. Table 1 lists the some of the relations between classes (represented by circles in Fig. 2) which can be defined as domain and range in the ontology using object properties (represented by connecting arcs in Fig. 2), and some object properties have inverse object properties. The domain of an object property is the range of the corresponding inverse object property and vice versa. Referring to Table 1, the statement "A subtask X assembles a part Y" is represented by an object property "assemblePart" which links a domain "SubTask" to a range "Part". In the opposite order, the statement can be defined as "A part Y is a part of Subtask X", and this is represented by the inverse property "partOfSubTask".

Based on the developed ontology, individuals belong each class are added and the object and data properties of each individual are defined. The following rules are defined to search the ontology using DL (description logic) Query:

Rule 1. If Part X "partOfSubtask" Subtask Y, and Subtask Y "assignTo" Resource Z, then Part X "partAssembledBy" Resource Z.

Rule 2. If Part X "partAssembledBy" Resource Y, and Resource Y "hasRegion" ResourceRegion Z, then Part X "partLocatedAt" ResourceRegion Z.

Rule 3. If Part X "partAssembledBy" Resource Z, and Resource Z is CobotA or CobotB, and Part X "hasPartShape" PartShape Y, and PartShape Y "reqEndEffector" EndEffector Z, then Part X "assembleUsing" EndEffector Z.

Rule 4. If Part X "partAssembledBy" Resource Z, and Resource Z is Human A, and Part X "partOfSubtask" Subtask Y, Subtask Y "hasSubtaskType" SubtaskType Z, and SubtaskType Z "performAction" Action A, Action A "reqManualTool" ManualTool B, then Part X "assembleUsing" ManualTool B.

In this study, the developed ontology is used to extract related knowledge such as subtasks of parts and resources assigned (Rule 1), positioning main parts into resource regions (Rule 2), and end-effector or manual tool to be used when a subtask is assigned to cobot or human, respectively (Rules 3 and 4). Part positioning in HRC mold assembly is important before the task execution stage to minimize assembly time and ensure the parts of the subtasks are positioned within the reachability of assigned resources. This study focuses on using two heterogeneous cobots to assemble a two-plate mold. Two models of Doosan collaborative robots used in this study are M1013 [17] and M1509 [18] which have payloads of 10 kg (Cobot A) and 15 kg (Cobot B). The reachable radius of Cobot A is 1,300 mm, whereas Cobot B has a smaller reachable radius which is 900 mm. The subtasks are assigned to resources using the task assignment model we developed in a previous study [16]. Based on the subtasks to the resources assignment

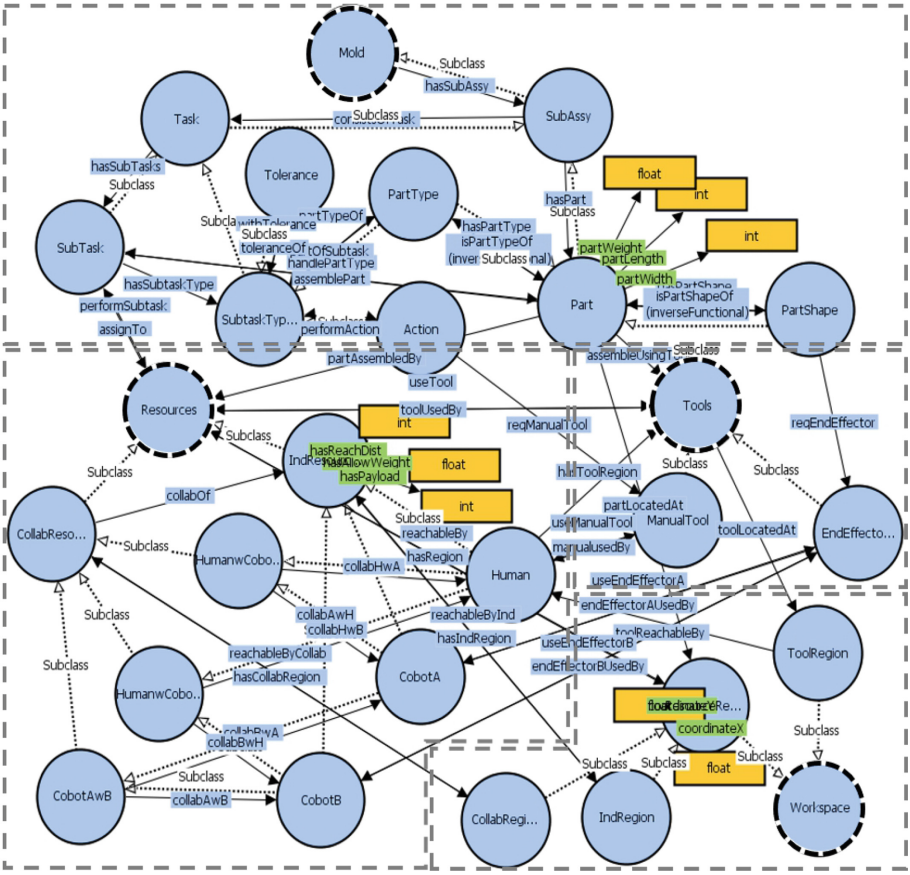

Fig. 2. Ontology-based context modeling for HRC mold assembly.

Table 1. Representation of some of relations between classes using object properties.

Domain	Object property	Range	Inverse object property
Mold	hasSubAssy	SubAssy	
SubAssy	hasPart	Part	
SubAssy	consistsOfTask	Task	
Task	hasSubTasks	SubTask	
SubTask	assemblePart	Part	partOfsubtask
Subtask	assignTo	Resources	performSubtask
Part	hasPartType	PartType	isPartTypeOf

(*continued*)

Table 1. (*continued*)

Domain	Object property	Range	Inverse object property
Part	hasPartShape	PartShape	is PartShapeOf
Part	partAssembledBy	Resources	
IndResources	isA	Resources	
CollabResources	isA	Resources	
CollabResources	collabOf	IndResources	
Resources	hasRegion	ResourceRegion	reachableBy
Part	partLocatedAt	ResourceRegion	
Part	assembleUsingTool	Tools	
Resources	useTool	Tools	toolUsedBy
Tools	toolLocatedAt	ToolRegion	

plan, we input the main parts one by one into an ontology to decide the regions to be located. Figure 3 illustrates the main parts positioning result in the HRC mold assembly using two heterogeneous cobots.

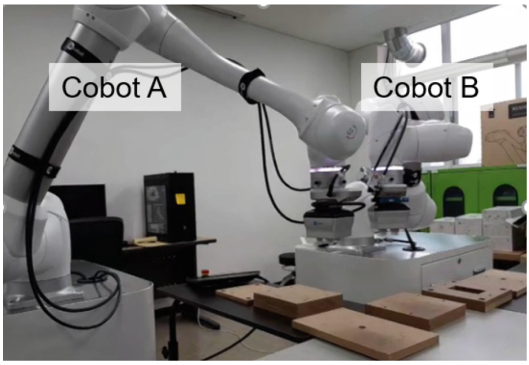

Fig. 3. Illustration of two heterogeneous cobots HRC mold assembly.

5 Conclusion

This study constructed an ontology for the context representation of HRC mold assembly operation that included knowledge related to mold, resources, tools, and workspace classes. The ontology contributed to the retrieval and use of human knowledge that is organized in a systematic form for decision-making purposes. A simple example of using the ontology for part positioning into resource regions according to assigned resources and part properties is presented. In the future, the developed ontology will

be expanded to include task assignment, execution, and monitoring models by adding rules and constraints to enable a comprehensive context-awareness system in the multi-cobots HRC assembly operation. Besides, a graphic user interface to visualize the results of ontology-based context modeling for practical HRC interaction will be developed. After the implementation of the developed system for HRC mold assembly, the ontology model will be generalized for other HRC assembly domains such as home appliances and mechanical parts.

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Industry 4.0/5.0

Industry 4.0 in the Automotive Sector: Development of a Decision Support Tool for Car Dealerships Using Simulation

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Abstract. The concept of Industry 4.0 promises to transversally revolutionise industries. Simulation, as one of the main pillars of Industry 4.0, allows improvements in the organisational and production processes of companies. This research work develops a decision support tool based on system dynamics, that address the problem of car dealership sales forecast and evolution depending on the commercial strategies adopted. This decision support tool considers main variables that are expected to influence car sales in Portugal. To develop this tool several interviews were conducted with the people responsible for the commercial sector of different dealerships while considering existing literature on the subject. This allowed us to parameterize a system dynamics model with the most influential sales factors. The developed tool is expected to contribute to car dealerships to evaluate their commercial policies and define adjustments to these to improve profitability.

Keywords: Industry 4.0 · Car Dealerships · Simulation · System Dynamics

1 Introduction

Nowadays, the success of a company is not only judged by the price and quality of its products (goods or services), but also by its ability to address customers' expectations [1].

Industry 4.0 aims to digitalise companies' production processes [2]. Simulation, as one of the main pillars of Industry 4.0, allows the creation of models that can reproduce the behaviour of real systems [3]. This makes simulation a widely used tool for decision support [4], allowing to reproduce the dynamics of complex systems by modelling the interactions of its subsystems [5–7]. Within the context of simulation, system dynamics

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(SD) allows to assess the dynamic behaviour of a complex system and predict which variables influence it to improve performance [8, 9], by representing a system as a collection of stocks and flows where state changes occur continuously over time [10]. The behaviour of the model is determined by a complex feedback structure resulting from the interactions between the most influential variables [11].

The automotive industry plays an important role in the socioeconomic development of countries, being a reference in terms of technological development [12]. In Portugal, it accounts for 6% of the Gross Domestic Product (GDP), 8% of employment in manufacturing and 16% of national exports of tradable goods [13]. Having such an impact, it will be beneficial for car dealerships, to take advantage of Industry 4.0 technologies to improve their profitability. Therefore, this work seeks to understand the factors that influence car sales in Portugal and develop a decision support tool, based on systems dynamics, to forecast and analyse the evolution of car dealership sales, depending on the commercial strategies adopted. This evaluation makes it possible to adjust behaviours and decisions that aim for the maximum performance of the business structures [14], allowing to consolidate decision-making, supported by several areas, such as behavioural sciences and others, to create and generate value for their economic groups [15].

The remainder of the paper is organised as follows. Section 2 introduces the fundamental concepts of systems dynamics and makes a concise literature review. Section 3, presents the developed model, identifying the application range level, as well as the evaluation of the achieved results. Finally, in Sect. 4, the main conclusions and directions for future research work are put forward.

2 Literature Review

Industry 4.0 promises to revolutionise industries' business models, due to its high level of digitalisation, connectivity, and decentralisation of decision [16]. This is due to the plurality of Industry 4.0 pillars and their level of application [17]. The main pillars of the concept are the following [18]: Internet of Things (IoT); big data; radio frequency technology; embedded systems; additive manufacturing; robotics; augmented and/or virtual reality and simulation. With the increase in the digitalisation of manufacturing processes and all adjacent operations, companies need to use simulation to design and analyse their production processes [19, 20]. However, simulation is currently changing from a purely design and analysis trend to a control in real-time trend [21].

Discrete event simulation (DES) and SD are becoming widely used tools [22]. DES allows for deterministic or stochastic modelling, where state changes occur at discrete points in time [23]. On the other hand, SD models the average flows in the system rather than individual events, representing delays and feedback within a system to discover patterns and behaviours over time [24]. SD can reproduce complex relationships between large numbers of variables in complex systems, being widely applied to non-linear systems, and being able to make better forecasts than DES in the medium or long term [25]. In view of the above and since DS adopts a top-down approach, this type of modelling was adopted for the development of the decision support tool, with the aim of understanding the full set of interactions that enhance car sales [26].

3 Decision Support System Developed

3.1 Conceptual Model

Simulation models are generally defined to study and explain a set of current observations and/or predict their behaviour [27]. With this in mind, a decision support system based on system dynamics was developed for a car dealership. It allows the evaluation of a complex system, giving the perception of all the interactions of the variables that influence it as a whole [28]. Regarding system variables, they were obtained through the existing literature on the subject and that eventually allowed to identify several consumer behaviours towards a possible purchase of a car, such as brand experience [29, 30], loyalty factor [31, 32], brand equity [33, 34] and purchase intention factor [35, 36]. This information was later crossed with the one generated through 17 interviews with sector specialists, thus creating a first perception about the model validity.

The contact with the companies' structures allowed us to assess their complexity level in attracting and retaining consumers in their respective dealerships and how their business development models were parameterised. To obtain a perspective of the degree of importance of the parameters obtained from the literature, during the interviews they were evaluated using a Likert scale, where 0 was defined as having no importance and 5 as having very high importance. This type of quantifying subsequently made it possible to assess the measure of the different variables of the model in a real context.

The developed model is based on the use of stocks and flows, which allow the system to be characterised and provide all the logic of its decision process. Stocks are associated with the different levels or accumulative states of system information, responsible for preserving its memory over time, while flows can be defined as the amount of information entering and leaving the system, thus creating its dynamics [37, 38]. The model consists of two stocks and 79 variables, so it is necessary to understand the dynamics between the two. A commercial transaction of a car encompasses a set of associated costs for a company. These may be direct, as the case of the acquisition cost from the manufacturer, or indirect, as the case of the promotions and personnel costs, among others. These costs define the base price charged by the dealerships, hoping to support all costs and obtain a certain profit. Notwithstanding to this type of economic balance sheet, the construction of the model required the elaboration of a submodel that could encompass the total associated costs, with the due profit generated, thus enabling the calculation of the operational cost of each sale to be evaluated.

Another important submodel is the one related to the purchase of units from manufacturers. The connectivity between dealers and manufactures is practically permanent since there is interest from consumers in customising the final product. The units ordered directly from the manufacturer assume relevance in the model developed. In addition to this type of orders, there are always units ready for almost immediate sale at the dealerships, and therefore they are also included in the developed submodel, which has as an entry condition the level of demand generated.

Given that one of the key variables of the model is the dealerships' ability to generate interest in their marketable units, the demand is based on another submodel. This submodel results from the existing literature on consumer purchasing behaviour in the automobile industry, but also from the case study using interviews, where it was possible

to verify all the dynamics existing in the real context. It takes into consideration several factors connected with the typology of the vehicles, as well as the reputational aspect of each dealership. It also covers the different types of credit and financial incentives that may be offered to captivate consumers, one of the most referred to criteria throughout the interviews carried out, and all these criteria and particularities are connected to the ability to promote cars through Marketing. Connecting these submodels, results in the Stock-Flow diagram in Fig. 1.

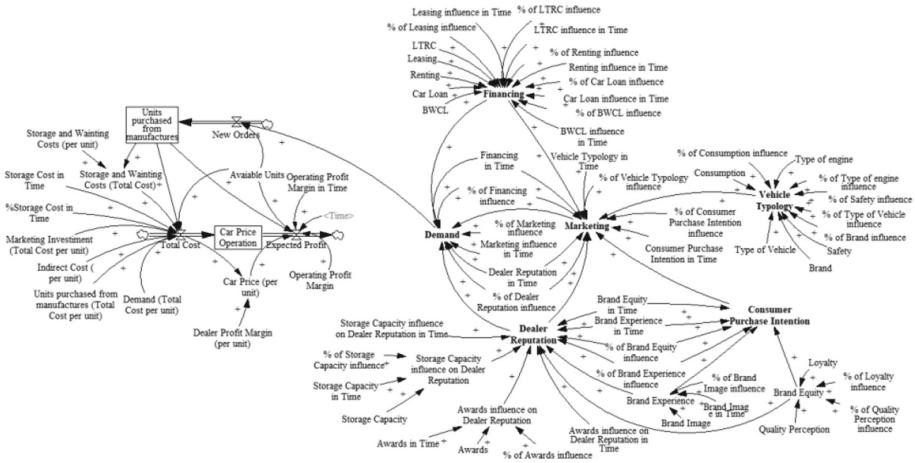

Fig. 1. Stock-Flow diagram.

In the diagram it is possible to verify all the system dynamics provided by the connections of the different parameters and their level of affectivity. In addition to the constraints previously mentioned in the submodels, it also has variables that allow adjusting their weight over time, defined in Time, as previously mentioned, since there are specific periods of greater buying interest by consumers, such as the end of year periods because of deductions in tax obligations, among others. The model built is versatile enough to be adapted to the different realities of each company.

3.2 Validation of the Model with the Real System

The developed model was validated with real sales data from one of the interviewed companies of a specific marketing segment. The data refers to the sales of a semi-new Toyota Yaris 1.0 Comfort. A period of 24 months from 2018 to 2019 was considered for analysis. It was defined with the company's manager the parameterization of demand according to its reality and the sales of this specific vehicle, that is on average six units per month, thus adjusting all the variables exhibited in Fig. 1. In addition, the associated costs and the applied margins were also specified. Table 1 compares data generated through simulation to real data, for the same time period, while Table 2 provides the Mean Absolute Percentage Error (MAPE) values for the variables under analysis.

Table 1. Comparison of values between real and simulated data.

Month	Real data			Data generated by *Vensim*		
	Total Costs per unit (€)	Vehicle unit price (€)	Profit per month (€)	Total Costs per unit (€)	Vehicle unit price (€)	Profit per month (€)
1	11326	12250	8702	13650	14333	7733
2	11300	12750	5915	11532	12109	6294
3	11132	12000	6208	11544	12121	6400
4	11168	11500	6242	11553	12130	6433
5	11204	12000	5833	11560	12138	6455
6	11186	12000	6259	11565	12143	6471
7	11347	12000	6481	11569	12148	6483
8	11363	12000	6016	11573	12152	6491
9	11352	12000	6127	11576	12155	6498
10	11327	12000	6195	11578	12157	6504
11	11369	12000	5833	11580	12159	6509
12	11285	12000	6646	11582	12161	6513
13	11809	13000	7146	11583	12199	6516
14	11393	12500	6644	11585	12185	6519
15	11658	12750	6552	11586	12165	6522
16	11624	12750	6755	11587	12166	6524
17	11675	12750	6450	11587	12167	6526
18	11705	12750	6270	11688	12168	6528
19	12469	13750	7688	11861	12365	6530
20	12525	13750	7351	11889	12469	6532
21	11564	12750	7116	11590	12670	6533
22	11585	12750	6992	11590	12401	6535
23	11604	12750	6879	11591	12388	6536
24	11681	12750	6415	11591	12255	6537

It is possible to verify a similar behaviour of the simulated values with the real ones, for most of the periods. In the initial period, a disparity of values relative to the initial cost is observed, since the model does not consider the existence of a structure capable of supporting the initial impacts of costs, as is the case with real data. After the value of month two, this situation is normalised, and the data becomes closer. In the period corresponding to month 13, the cost rises sharply compared to the previous month, since it was necessary to carry out a small corrective repair on the units sold. For months 19 and 20, the sharp rise was due to the entry of the pandemic condition, which resulted in a

Table 2. MAPE for the variables under study.

	MAPE (%)
Total costs per unit	2,72
Vehicle unit price	3,96
Profit per month	5,75

higher cost to the concessionaire per unit. The simulated model follows the same upward cost trend, since it was programmed for the same purpose, with a small discrepancy with the real value. The MAPE for the profit per month is slightly higher in relation to that calculated for the other variables; however, this is relatively small (less than 6%), and can be explained by the financial margins considered in the simulation by the manager and which might not correspond to those applied, especially in the first year of analysis. Given the obtained results, the model, in general, meets the proposed objectives and serves as a solid basis to aid decision-making through the simulation of implemented strategies.

4 Conclusions and Future Research Work

A fully customised decision support tool for car dealership was developed using systems dynamics. The statistical analysis of the results allowed the validity of the model to be assessed, since the MAPE for the parameters analysed revealed a reliable proximity between the data generated by the model developed and the real data, with a maximum deviation of less than 6%. Through the results achieved and a subsequent analysis of the MAPE, it was possible to verify that the software developed acts better for each type of vehicle typology marketed than for a generalised strategy, since the buyer's attitude changes according to the typology of the vehicle they are looking to buy. However, the model's time frame is twenty-four months and some parameters linked to the elapsed period, defined in the model with the parameter's name plus in Time, may need a longer time frame. In the developed model it is assumed that companies manage to meet all demand, which may not occur, occasionally, in some dealerships with less expression of a given brand. The user of the programme may pre-set it according to its size in the model. However, it would be useful to associate a mathematical formulation based on forecasting software, thus evaluating patterns and characteristics such as seasonality of sales, among others, and for validate the economic model followed in the applied credit policy. Moreover, future research work should test alternative methods to predict sales.

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Industry 4.0 for Energy Productivity: Insights and Future Perspective for Australia

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Abstract. This study aims to explore various domains within Industry 4.0 (I4.0) and energy productivity in Australian context. In doing this, the study analyses I4.0 technologies & services, barriers to I4.0 for energy productivity, regulatory framework, multiple benefits of I4.0 technologies, relevant business models, and roadmap to I4.0. The findings show that inadequate IT infrastructure, cyber security, complex supply chain and contracting, uncertainty about return on investment (RoI) are significant barriers. When it comes to productivity benefits, this study has highlighted macroeconomic impact, industrial sector impact, public budget impact, health and well-being impact, and energy delivery impact stemming from I4.0 technologies. In terms of regulatory framework, this study finds that given the near-ubiquitous data generation and use across the digital economy, it is quite difficult to exhaustively address all legal and regulatory issues relating to I4.0 technologies in the energy sector. However, there are several business models (e.g. X-as-a-service or pay per X) which can be applied to adopt I4.0 technologies. The study concludes with a roadmap to I4.0 with future research directions.

Keywords: Energy productivity · Industry 4.0 · Manufacturing · Australia

1 Introduction

Energy sustainability is arguably among the most pressing socio-environmental concerns of modern times. In Australia, the major portion of the energy comes from fossil fuel which leads to very high anthropogenic carbon emission. The Australian energy sector must transition so that it can provide consumers with reliable affordability and clean energy into the future. The Australian government has set a target to increase energy productivity by 40% within 2030 [1].

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International Energy Agency (IEA) found that digitalization in energy could cut energy use by about 10% by using real-time data to improve operational efficiency and system flexibility [2]. Thus, the sustainable energy transition and I4.0 share important characteristics that can be interconnected to attain both economic benefit and socio-environmental benefit.

This study aims to present the major findings of a research project sponsored by "RACE for 2030 Cooperative Research Centre" for energy and carbon transition in Australia [3]. The aim of RACE for 2030 is to drive energy innovation across the supply chain to deliver improved, lower cost and lower emission energy services. Five research themes are mainly highlighted in RACE for 2030, which are I4.0 technologies for energy productivity, decarbonization of industrial process, energy productivity in value chain, demand control, and anaerobic digestion for utilities. However, this study outlines the major services and benefits that I4.0 technologies offer, together with the analysis of the most relevant barriers, major regulatory issues, and emerging business models following with the research roadmap outlining prioritized potential research initiatives. Figure 1 shows the approach that we have taken in this study. The research roadmap is built upon four main pillars. For each of the pillars the approach has been started of doing the literature review and the interview with focus groups and policy experts to understand the relevant issues in Australia. The study represents a first-of-a-kind attempt to assess the major elements for improving energy productivity in Australia in businesses based on the adoption of I4.0 solutions. The study would help the industrial decision makers and policymakers to adopt I4.0 technologies in their organizations, in particular tackling barriers, finding suitable business model, setting the regulatory framework as well as shaping the strategy towards I4.0.

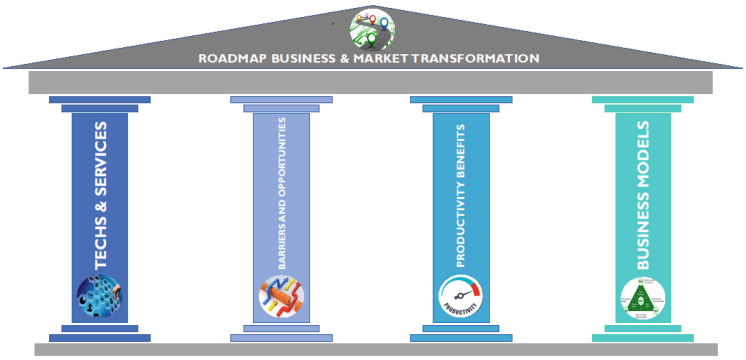

Fig. 1. Approach taken in the study

2 Industry 4.0 Technologies and Services

The International Energy Agency (IEA) explained the concept of I4.0 as "*the increasing interaction and convergence between the digital and physical worlds*", where the digital world has three fundamental elements which are data, analytics, and connectivity [2].

Cyber physical system, Internet of Things (IoT), additive manufacturing, automation, cloud technologies, visualization technologies, Artificial intelligence, and big data are the core part I4.0. The set of I4.0 technology offers several services which are not limited to energy efficiency, real time monitoring, resource management, interoperability, autonomization, and flexibility.

3 Barriers to Industry 4.0 for Energy Productivity

In this study, barriers are categorized into technological, economical, regulatory, and social. The specific barriers within each category are ranked based on the feedback of focus group. In all focus groups, a series of questions were administered using "Slido" live polls. In addition, qualitative responses were elicited from focus group participants with regards to specific questions. The responses to the "Slido" polls are presented in Fig. 2.

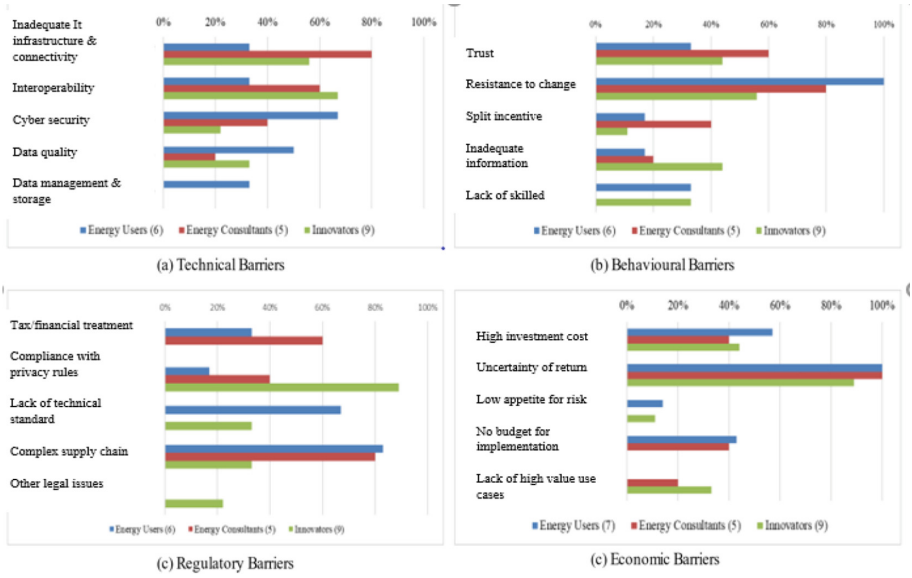

Fig. 2. Barriers to I4.0 for energy productivity

In Fig. 2, the greatest disparities between the groups were in the higher importance attached by the energy users to cyber-security and data quality as technical barriers to adoption, while the energy consultants' group saw inadequate IT infrastructure and connectivity as the largest barrier. While all groups saw the greatest behavioral (or social) barrier as being resistance to change or new processes, with a lack of trust also being regarded as important, the energy users and innovators were more concerned than the energy consultants about the lack of skilled workforce. On the other hand, the greatest regulatory barrier perceived by energy users and consultants was the complex supply chain and contracting. Innovators were most concerned with privacy rules and more

broadly, access to data that may be controlled by other service providers – which could also be seen as complexity in contracting. Furthermore, all groups agreed that the most important economic barrier was the uncertainty about the return on investment (ROI) from I4.0 technologies, which often also applies to energy productivity investments, with the high cost of introducing new technologies of particular additional concern to energy users. This reflects a common Australian business concern about up-front costs, also reflected in a focus on short payback periods for energy productivity investments.

4 Productivity Benefits from Industry 4.0

Certain technologies identified as 'energy-efficient' because of their positive impact on energy reduction, will also bring several additional benefits (e.g., production yield improvement, reduced maintenance cost) to the production or business process [4, 5]. These additional benefits are collectively referred to as 'productivity benefits', 'multiple benefits' or 'non-energy benefits' (or NEBS), because in addition to reducing energy consumption and/or costs, they all increase the productivity of the firm [6].

The applications of I4.0 technologies simultaneously manifest in various sectors and across multiple levels [7]. However, taking inspiration from the previous literature [8], the study has considered five different dimensions to assess the impact level of energy-efficient technologies stemming from I4.0, which are macroeconomic impact, industrial sector impact, public budget impact, health and well-being impact, and energy delivery impact. Multiple benefits stemming from I4.0 technologies are presented in Fig. 3.

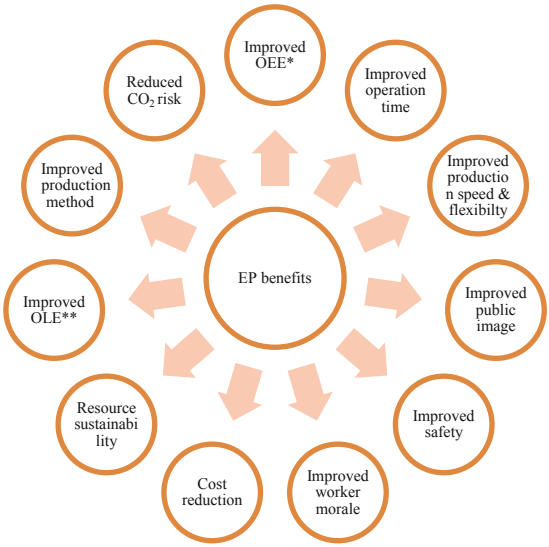

Fig. 3. Multiple benefits associated with energy productivity measures [8]. Note: * OEE is Overall Equipment Effectiveness and **OLE is Overall Labor Effectiveness

5 Regulatory Framework for Industry 4.0

I4.0 technologies incorporate the collection, processing and use of data at large scale. Therefore, there needs to have an emphasis on the main framework for regulating large-scale data collection, processing, analysis and use under Australian law. However, given the near-ubiquitous data generation and use across the digital economy, it is impossible to exhaustively address all legal and regulatory issues relating to I4.0 technologies in the energy sector.

Large-scale data practices – including the collection, analysis and use of data – form the core of I4.0 technologies. Given that these technologies and business practices are both recent and continuously evolving, it is unsurprising that there is an ongoing need for legal and regulatory frameworks to adjust. Consequently, there are completely new regulatory regimes – such as the Consumer Data Right (CDR) and critical infrastructure regimes – that have been specifically developed to achieve policy objectives, such as promoting data use and sharing, and securing data. Moreover, existing legal regimes, such as data privacy laws, are being challenged by evolving data practices, contributing to current proposals for fundamental law reforms. In addition, there is increased use of less formal (and more flexible) rules, often known as 'soft law', such as voluntary codes and standards.

6 Business Models for Industry 4.0 Energy Productivity

The business models are all designed to leverage the mass of data that stems from the adoption of I4.0 technologies and multiple data streams from other sources that support data analytics– from the digital design of a product, through digital monitoring and control of production, to digitally enabled after sales service, maintenance and finally disposal or recycling. This so-called "digital thread" acts as an enabler for improved communication, monitoring, understanding and ultimately decision-making. However, it is also important to note that business model patterns such as these are rarely found in isolation, typically there are multiple patterns being leveraged within a single business model e.g., the X-as-a-service [9] and pay-per-X business models [10].

In addition, whilst these business models hold great market potential, some are yet to secure a strong foothold in extant markets. The flexibility of the servitization approach, for example, has often been met with challenges in terms of the ambiguity customers may experience whilst trying to decipher the value proposition of some service offerings, as Langley [11] mentions "many new servitization solutions result in a worse customer experience as new ways of working have not yet been optimally designed". This, combined with the operational and managerial nuances associated with the shift to a servitization strategy result in the persistence of considerable barriers to uptake, particularly in the case of manufacturing organizations and the steel industry. Along the collaborative front, when it comes to the necessity for collaborative activities in leveraging I4.0 enabled business models, such activities, and the formation of collaborative networks in particular, are still being treated as a burden on organizations. Other challenges to the implementation of I4.0 enabled technologies include the likes of conflicting business models with traditional modes of operation, potential for significant impact on

entire value chains, impact on prices and regulatory concerns as well as the intellectual property rights and patent considerations stemming from the democratization of production that may be a core existing activity [12].

Nonetheless, the opportunities associated with their adoption hold the potential to also be of significant benefit for participating stakeholders. Digital platforms, for instance, are already well-established in many industrial contexts and are a pillar of effective I4.0 application. Blockchain (and other similar emerging models), has opened up the potential for greater transparency in supply chains, decreased operational costs and the provision of better monitoring and performance control. It also facilitates trust and financial transactions that reflect value identified through data analytics and other I4.0 mechanisms. These complement developments of "Circular Economy" business models as well as increasing focus on addressing Scope 3 carbon emission due to activities of agents upstream and downstream from an individual business.

7 Roadmap to Industry 4.0 for Energy Productivity in Australia

A critical success factor for the adoption of I4.0 solutions for energy productivity is the cooperation between stakeholders operating in the energy efficiency market. Indeed, investors, utilities, governmental agencies, financial institutions, local authorities, research and development organizations, equipment manufacturers, market institutions, Energy Service Companies (ESCOs), and international institutions can all play vital roles. It is thus important to try enlarging as much as possible the perspective, identifying which stakeholders may be in the best position to develop and stimulate the most effective drivers to promote I4.0 solutions for energy productivity. In fact, to draw the roadmap towards I4.0, it is necessary to reframe what is possible to open new possibilities. Moreover, raising the priority level of I4.0 is also crucial along with shifting the balance for the decision makers to capture the benefits of I4.0.

IEA has suggested several strategies for digital energy efficiency deployment [13]. By taking inspiration from IEA, this study has emphasized six strategic focus areas which are (i) cybersecurity frameworks and guidelines, (ii) methodologies for valorizing energy efficiency/productivity, (iii) removal of interoperability barriers, (iv) stakeholders' awareness and capacity building, (v) institutional arrangements and platform for data sharing and data management, and (vi) pilot projects. In fact, eleven research projects (e.g., "I4.0 energy productivity networks – sharing knowledge to improve competitiveness", "smart metering and Artificial Intelligence for industry decarbonization") are proposed for future roadmap covering the focus areas (see Fig. 4). Each of the focus areas serves the CRC RACE for 2030's work of creating the ground for and accelerating the deployment of I4.0 solutions for energy productivity in industry and non-residential buildings, for transformative performance, energy productivity, and sustainability of all Australian businesses.

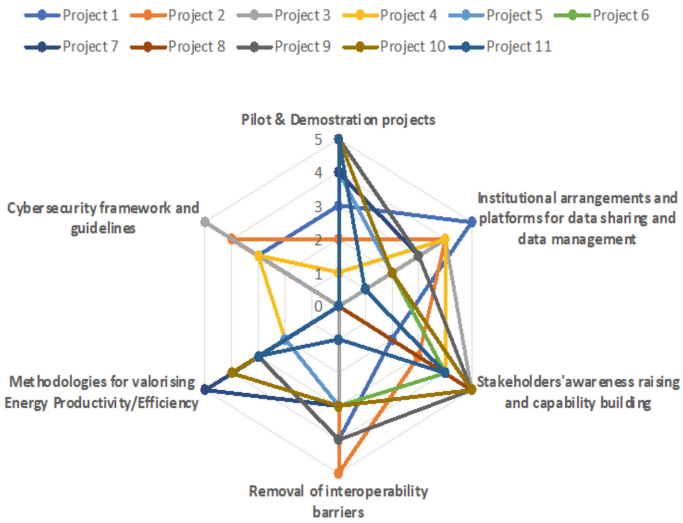

Fig. 4. Proposed projects covering the focus areas of IEA

8 Conclusion Discussion and Future Research Perspective

The present study discusses the barriers, regulatory models, business models, productivity benefits, and roadmap to I4.0 for energy productivity in Australia. In fact, the findings of this study are very crucial to shape the future roadmap of I4.0 in Australia. In addition, while the specific goals and policies of this study might be different, the concepts and approaches used in this research can certainly serve as an inspiration and guidance for other countries looking to address similar challenges and transition to I4.0 for energy productivity.

The future work around energy productivity and I4.0 will be about motivating the integration of use cases and functions relating to energy productivity within already digitally transformed (or transforming) business and sites. However, much more often in the present Australian context future work by RACE for 2030 in harmony with others will have to simultaneously promote energy productivity via I4.0 and the actual adoption of I4.0 in a broader sense. That is, energy productivity and I4.0 adoption are interdependent, with I4.0 being the broader issue, as it impacts on broader aspects of business value and productivity than does energy productivity. RACE for 2030 efforts to encourage energy productivity improvement must fit within this broader I4.0 context and will need to dovetail with the already-extensive public and private sector activity that seeks to move businesses up the I4.0 staircase.

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New Approach on I.40 Migration Projects Using Agile Concurrent Methodology

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Abstract. The industry worldwide is undergoing continual changes owing to the emergence of new technologies and the globalization. Industry 4.0 is transforming the way things are done at the industrial level, and combined with the advancements in communication networks and the internet, it enables complete digitization of manufacturing processes. Nevertheless, the lack of appropriate management procedures and methodologies is hindering the implementation of digitization solutions, making it difficult to simplify requirements analysis and the incorporation of improvements using I4.0. Based on a literature review, the most crucial characteristics of migration projects have been identified, which are based on the I4.0 enablers. Currently, any technological system migration requires the use of an appropriate management methodology, which either replaces or complements the conventional. In this research proposes a new agile concurrent methodological procedure that relies on concurrent engineering and adapted Scrum to execute technology migration projects based on I4.0 enablers. It will be easy to applied in three level of management, and giving a faster and more efficient technology migration. Other benefits are a short periodic feedback for error correction, cross-functional teams, and simple implementation.

Keywords: Enabler I4.0 · Scrum · Concurrent engineering · Methodology

1 Introduction

The current transformation of industry in the world, based on the 4th industrial revolution (I4.0), is not just a continuation of the Third Revolution [1]. Technological and economic elements were developed and popularized, becoming key to their rapid adoption, implementation and expansion, not only in industry but also in mass consumer and practical products such as communications and networked sensors. Thus, the advent of new technologies that facilitate the creation, distribution and management of information facilitated the advent of I4.0. Networking and dialogue cannot only take place between machines, devices and tools; it is also intended to provide the connection to the operators, the production processes and also to connect the internal functions with other companies and branches of industry [3].

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Therefore, human capital of organizations need to acquire new skills and knowledge to cope with constant technological change. Their career paths require different skills and competencies, which is a consequence of the current trend towards automation and digitization in the industry. Therefore, there is expected to be an increasing demand for positions that require skills and expertise in software and data analysis. It is believed that the automation process will displace current occupations towards more technical ones [4], especially those characterized by simpler and more repetitive tasks, but there are also fears that so-called technological unemployment [5] will emerge in the long term. Intelligent systems will replace humans for some tasks and improve the work environment, especially for boring, tiring and repetitive manual tasks. I4.0 revolution relies on the digital world, thanks to the continuous advancement of computers, sensors and the massive use of the internet [6].

The I4.0 revolution relies on the digital world thanks to the continuous development of computers, sensors, and the massive use of the Internet [7]. Smart factories harness new technological forces that enable the production of customized products that can be customized from customer to user in terms of product design, configuration, manufacturing, operations, and even product recall and recycling. Studies confirm that I4.0 not only influences the manufacturing industry, but also revolutionizes the way we understand business practices [8].

Industry 3.0 was a multipolar process led by the European Union, the United States, and Japan, and it represented the "intelligence revolution," a concept proposed by Jeremy Rifkin [6]. In the field of renewable energies, Joyanes et al. stated that this revolution is based on the development of information and communication technologies and innovations [8]. I3.0 can be summarized into four major technologies: microelectronics as the technological basis, computers as the ultimate machine, the internet as a catalyst for change, and the use of renewable energies [9]. The transition from the I3.0 paradigm to the I4.0 paradigm involves the evolution of production processes in the industry to adapt to new global trends in the production and management of information [10]. To ensure this process is satisfactory, it is necessary to identify the main technological levers required by the sector. The term "enabler" refers to technologies that enable the consolidation of a new type of industry. In other words, enabling technologies are the fundamental technologies that enable the development of a new industry. Therefore, they are the best components or elements to analyze to develop tools that facilitate the migration of technologies from I3.0 to I4.0 for organizations with the largest digital divide compared to the current industry.

I4.0 is defined as a collective term for value-added technology in organizations, and its components are Internet of Things, Cyber-Physical Systems, Internet of Services, and Smart Factory [11]. However, reference [12] in his project "Connected Industry 4.0" defines digital enablers as a set of technologies that enable the consolidation of a new type of industry (I4.0) that exploits the potential of the Internet of Things. I4.0 is described by nine related concepts or aspects, which are big data, autonomous robots, simulation, horizontal and vertical integration, Internet of Things, cloud, additive manufacturing, augmented reality, and cybersecurity [7].

Based on the initial diagnosis of the organization's situation under the I3.0 paradigm, here are the nine known pillars of I4.0 and then the nine reference technologies for

migration to use I4.0 technology. Traditionally, product development occurs in strictly sequential or cascading phases, which limits the integration and coordination between different functional areas [13]. Poor communication and understanding between product design, manufacturing, and customer needs due to poor involvement of key stakeholders can cause problems related to meeting needs and user-perceived quality. These problems are usually due to the use of traditional management methods that do not contribute to the minimization of development times [8].

This scientific contribution suggests a new hybrid methodology for managing and implementing technology migration projects from I3.0 to I4.0. The proposed methodology uses I4.0 technology enablers as a top-level reference for defining the main pillar or technology to improve each organization, and applies the concurrent engineering approach for medium-level management in the design of the solutions. Additionally, the Scrum methodology could be applied day-to-day project to optimize the use of human resources during the execution phase of the technology migration project, focusing on generating high-value increments in each result delivery. The aim is simplify implementation of technology migration projects, Establishing different levels of operation and decision-making for each management level.

In the next sections, rational causes are presented for the adaptation of the hybrid management method after the appropriate choice of the I4.0 technology enabler companies wishes to migrate, and the document will conclude by discussing the need to hybridize, and to appropriate extent, the benefits of both management methodologies.

2 Methods and Materials

As an alternative to using traditional methods in projects of technological to improve product or service, new practices have been introduced, such as concurrent engineering. According to [14], it refers to a "systems approach to the integrated and concurrent development of related products and processes", including manufacturing and support. This approach is designed to push developers to consider all elements of the product lifecycle, from concept to disposal, including quality, cost, schedule, and user requirements. The main benefit of concurrent engineering is to increase the company's competitiveness by reducing lead times and costs, as well as increasing user satisfaction and the perceived quality of the products. Product and process planning should go hand in hand and most of the time happen in parallel. To reduce the complexity of developing a new product, it is suggested to break it down into smaller parallel assemblies that are easier to manage and troubleshoot [15]. It is a method of systematizing the product, process, and methodology based on four phases of actual product implementation. Also, emphasize the importance of using 7T call resources: talents, assets, teamwork, techniques, technology, time, and tools.

Concurrent development phases overlap, in contrast to traditional methods of product or service development, where the phases are strictly sequential. Layering is defined as the process of initiating the next activity before completing the previous activity [16], reducing project duration and improving coordination, communication, and interaction between stakeholders. Information accumulates gradually and is constantly transferred between activities [17]. Another, more modern approach is "concurrent engineering or

concurrent development" with multidisciplinary design teams, which contributes to a good understanding of the larger problem and early identification of potential deviations. Concurrent Engineering also sees the benefits of integrating customers and suppliers into the process so that customer requirements can be completed more quickly and efficiently [18]. Successful parallel development requires effective communication and active collaboration between all stakeholders [11], which can be achieved with frequent meetings and constant information sharing.

In contrast to traditional methods, which no longer guarantees the development of new high-performance and competitive products [19], the agile methodology is based on an iterative and incremental approach. Instead of extensive planning at the beginning of the project, agile development embraces changes and adapts the project plan to the impact [8]. Several Agile methodologies have been developed around software development, including Scrum, Kanban, Xtreme Programming, and Crystal Method [20]. These methods share the same idea of continuously delivering value and responding to change but differ in the depth and breadth of cycles, but Scrum as the most useful agile method for physical products [21, 22]. Compared to other methods, Scrum is relatively simple and straight forward. In the Scrum methodology, the development process is broken down into timelines called sprints. The duration of the sprint is fixed, typically 2–4 weeks, depending on the product complexity and risk assessment [23], with each sprint culminating in a project or work increment, a useful preliminary product release for customer evaluation. Project requirements contained in the product backlog are broken down into individual prioritized items, and then they are assigned to each sprint. During last years, attempts have been made to make progress in adapting the agile approach to better manage the development of physical products, integrating user experiences through the use of modern technologies such as simulations, computer tools, and 3D printing. According to the authors [24], Scrum has the greatest potential impact on the physical products development compared to other agile methods. Agile approach in the manufacturing industry does not necessarily mean giving up the traditional management methods. Through the commissioning of hybrid methodologies, it can be obtained competitive physical products [11, 20].

Fig. 1. Agile-concurrent concept in I4.0 Migration Projects.

This contribution proposes a future hybrid methodological procedure that facilitates the management and implementation of technology migration projects from I3.0 to I4.0, using I4.0 enablers as technology references, concurrent engineering approach to manage design solutions and also includes adapted Scrum methodology for the execution of daily tasks, see Fig. 1.

3 Discussion

Implementing agile in manufacturing isn't necessarily about deviating from traditional development models, it's about reaping the benefits of agile development without sacrificing the robustness of traditional models. Hybrid models can be created by combining agility and traditional models. This enables powerful and competitive physical products that are well documented in the scientific literature [9, 18]. The most widespread agile method for the development of physical products is anyway the Scrum methodology. According to several authors, compared to all other agile methods, it has the greatest potential to influence the physical development of the product [18] and is combined with the traditional stage-gate model in most cases. Research shows that the key benefits of these hybrid models are improved implementation of changes, team communication and productivity, and faster time to market [25]. This academic paper proposes the future development of a hybrid methodological approach to facilitate the management and implementation of I.30 technology migration projects.0 to I4.0, using I4.0 technology as a benchmark, using a concurrent engineering approach for the high-level management and adapted Scrum methodology to ensure daily growth of project execution. Since a technology enabler is a technical solution or technology that enables a company to adopt a new process or business model, it can be said that in the context of a migration to I4.0, a technology enabler denotes the technology the a companies to adopt I4.0 principles and practices.0 and become a smart and connected business. Adopting these technological advantages enables companies to streamline their production processes, increase efficiencies and reduce costs, and improve the quality and personalization of their products and services. All in all, business-enabling technologies are key to a successful migration to Industry 4.0. In the manufacturing industry, some of the most common enablers of technology are: Internet of Things (IoT), Automation & Robotics, 3. Data Analysis and Big Data, Production Management Systems (ERP), Virtual and Augmented Reality.

These are some of the most common requirements for technology in manufacturing, but it should be noted that the adoption of advanced technologies can vary by industry and country. It should be emphasized that the successful implementation of technology requires a well-planned strategy, investment in education and skills development.

Identify important technology drivers that support the migration to Industry 4.0 and are relevant for the company. Set clear goals and priorities for industrial migration 4.0 and the acquisition of technological skills. Build cross-functional teams of technology, business, and operations experts to address the challenges of migration while engineering education. Identify a product owner who will represent the company's interests and ensure that goals and priorities align with company goals. Define short, regular sprints to work on technology migration and adoption. During each sprint, teams work on specific tasks and measure progress against goals and priorities. Encourage continuous feedback and collaboration to identify and respond to challenges and opportunities.

Adopting a suitable Scrum methodology for migration to Industry 4.0 by technology enablers ensures an agile and collaborative approach to implementing technological solutions and improves the efficiency and quality of production. Although Scrum is the most widely used methodology for the development of software and physical products [18], there are a number of challenges that must be considered before using Scrum as a methodological tool for technology migration through the use of I4.0 catalysts is selected and used. The variety and high complexity of projects, especially in physical product development, can be a difficult obstacle to the success of the Scrum methodology [25] and this is the main reason why there is a need to provide tailored methodological procedures that organizations use in the application supported by Scrum.

The main difference when using Scrum is that the functional product is often intangible (such as the code in the software), while with a physical product it is often impossible to produce a functional and potentially marketable product [10]. It is therefore necessary to redefine the terms "deliver value", "increase" or "sprint completed". The end result of physical product development should be a version of the product, from concept to prototype or protoconcept [13], that can be demonstrated or tested.

Other contrasting is agile software development uses a modular architecture that allows code to be broken down into smaller, independent modules. Physical products are much more difficult to modularize because there are many dependencies between different functions; Changes or modifications to a module generally involve a change to another module, subset or part [26]. Of course, some changes in project roles are required during Scrum integration, often requiring significant reorganization and retraining of the business organization. Organizational culture and individual resistance to change can be barriers to successful implementation, although results show that reorganization leads to product improvement. [27]. It is noted that physical product development requires even more specialization than software development. While it's highly likely that many people could do the same job in software development, with physical products the experience isn't as universal for all functions. This can create bottlenecks in the workflow, so it is necessary to train the HR department to acquire high skills in their field as well as general knowledge in other areas [28].

Finally, if it is carefully analyzed the differences between agile and parallel development, it can be concluded that the agile approach has some characteristics that parallel development can benefit, such as, agility emphasizes, active involvement of customers, scope is no longer fixed, and others. In this way, the customer gets the product that he really needs. Another important question concerns the scope of planning for technology migration projects. While concurrent development creates a project plan at the beginning of a project, the agile approach reduces planning to a minimum and iteratively adjusts the plan.

4 Conclusions

Based on the bibliographic data presented in this document, it can be concluded that the use of technological enablers in the companies' technological migration projects towards I4.0 is a natural trend. The pre-diagnosis of each organization's existing level in I3.0, based on the five main pillars on which I3.0 is based, and the structuring of

I4.0 into hybrid layers, encourages the use of I4.0 enabling elements as a tool to change or improve productivity. Additionally, designing new practices based on consolidated project management models that offer complementary approaches and functionalities will facilitate the migration of production systems and reduce the technology gap for less modern or competitive organizations, especially SMEs. This, in turn, will help promote the introduction of a culture of adaptation to constant change in industrial organizations. Procedures that facilitate the technological migration of SMEs, combining the benefits of the agile methodology and concurrent development, represent a powerful alternative tool for any organization wishing to improve its competitiveness. This research proposes the initial basic idea of a new methodological procedure resulting from the hybridization of models based on concurrent development for designing I4.0 solutions and the Scrum methodology adapted to the specific needs of the business and social environment. This procedure will help migrate technology in industrial organizations through faster and more efficient implementations.

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Success in Industry-Academia Collaboration: A Design Science Approach for Industry 4.0 Research Projects

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Abstract. Collaborations between Industry partners and University researchers are common to address Industry 4.0 research projects. Such collaboration facilitate access to expertise across domains. However, there is often a mismatch of expectations around language, processes and deliverables. One of the reasons is that academics treat these type of research projects as traditional Knowledge Seeking Research. Treating the research as Solution Seeking Research is a better approach, which ensures that the needs of all participants in the project are met. Solution Seeking Research can be implemented using a Design Science approach. Collaboration must be encouraged, which requires effort around communication, coordination and cooperation. Using a Framework for Evaluation ensures that all guidelines of Design Science are achieved. In this paper, we outline how we managed successful Industry 4.0 collaboration projects. We extend the framework for evaluation by recommending suitable research methods for ex-ante and ex-post evaluation. In doing so, we provide a model for future researchers to deliver collaborative research projects to the satisfaction of all partners involved.

Keywords: Design Science Research · Industry 4.0 · Innovation · Solution Seeking · Evaluation

1 Introduction

Organizations wishing to embrace Industry 4.0 innovations are faced with a dilemma. Despite having an understanding of the value add of ongoing Industry 4.0 research to the business, they face innovation barriers. First, there is a lack of interdisciplinary skills and knowledge within the organizations with respect to information technology, systems integration, artificial intelligence, digitalization of the factory floor. Second, Industry 4.0 innovations by their nature are new and unknown, which pose difficulties in specifying requirements, and in drawing knowledge from interdisciplinary domains, and the necessary research rigour. On the other hand, academics have expertise in seeking out knowledge, problem solving, and research rigour, but lack practitioner expertise. The solution may be in Industry-Academia Collaboration (IA) Research. IA permits

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access to and exchange of knowledge with the experts in their fields, and supports the development of artefacts that are relevant to the context. However, these collaborations are not without challenges [1]. IA suffer with respect to a mismatch of expectations. The organization has expectations in terms of the relationship, adherence to certain expected procedures or decision-making processes, inflexibility and expectations around the utility of the practical artefacts [2, 3]. Academics see success once the solutions have been conceptualized, evaluated and communicated, with a resulting partially implemented proof of concept. They have a desire to add to the Body of Knowledge. So whilst there are advantages in access to the domain knowledge and competencies available in a wider pool, the mismatch of expectations need to be managed.

In this paper, we outline how we successfully delivered a large collaboration research project approaching it as Solution Seeking Research, and by applying a Design Science Research method. The impact of this paper is that we set out a model for future researchers to deliver collaboration research projects to the satisfaction of all partners involved in the research.

The rest of this paper is structured as follows: first, how Solution-Seeking Research differs from other research is laid out. Next, we describe how a Design Science Research project should be employed, and then how it should be evaluated by a Framework of Evaluation. We extend that framework by outlining what research methods might be applicable.

2 Unique Requirements of Solution Seeking Research

Industry 4.0 innovation research has expected outputs of research contributions and design artefacts, which distinguishes these type of research projects from routine systems design, and knowledge seeking studies. As such, these type of research projects are solution seeking, where solutions to Industry 4.0 challenges are designed, created and/or developed [4]. The differences are captured in Fig. 1.

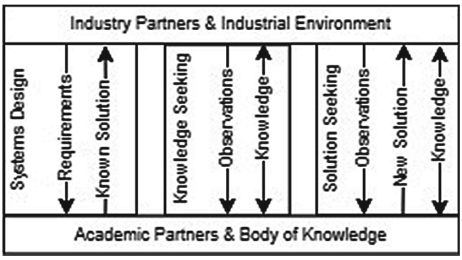

Fig. 1. Comparison of Routine Systems Design, Knowledge Seeking Studies, and Solution Seeking Studies for Industrial Research Projects, modified from [4]

Further, these type of research projects differ from routine systems design, where requirements are known in advance, or evolve through an agile development methodology. Systems are developed based on technology and knowledge that exists already. There is no requirement in routine systems design to add to the Body of Knowledge.

In Solution Seeking research, the aim is to use knowledge to design and create useable value-adding solutions to industry problems, and add to the Body of Knowledge [4]. The Body of Knowledge contributions are based on design knowledge gained through building and evaluating ensemble artefacts.

Solution Seeking research are also distinguished from Knowledge Seeking studies. In Knowledge Seeking research, the aim is to learn, create, evaluate and share knowledge. There is no expectation to generate value-adding solutions to industry problems. Researchers who approach Industry focused collaboration research problems from a Knowledge Seeking perspective may leave the Industry partners disillusioned with the absence of useable artefacts.

3 Design Science Research Method

Design Science Research (DSR) is a research method suitable to determine unique and innovative solutions to unsolved important business problem innovations [5, 6], which are termed 'wicked problems' [7], or in industry language 'pain points'. As Industry 4.0 innovation requires artefacts to be designed and constructed to solve these problems, DSR is a good fit. Further, DSR suits transdisciplinary projects [8]. As the participants in collaboration research cross disciplines, the common language of DSR provides a framework for communication about the process.

Whilst the research problem can be articulated, there is often difficultly is specifying requirements for the 'wicked problems' of Industry 4.0, due to the unknown nature of any solution. A cyclical approach of diagnosis, design and development, demonstration of implementations, evaluation and communication fits with the iterative problem solving approach when the domain and expectations are unclear from the outset [9]. The process followed is modified from that recommended by [9], as shown in Fig. 2.

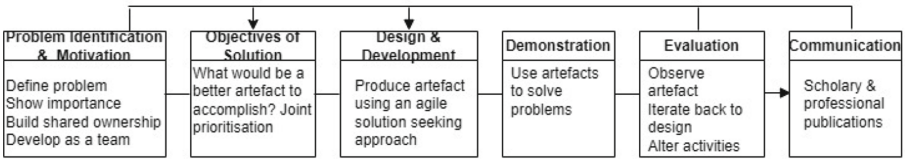

Fig. 2. Design Science Research Methodology, adapted from [9]

The notion of shared ownership of the project, and seeking mutual benefit is key early in the Problem Identification and Motivation stage. Efforts must be during the scoping and fund application process to build a collaborative team. Trust must be built early. Involving all parties in the Objectives of Solution phase ensures that there is a clear understanding and expectation. An agile approach is useful where all parties are aware of, and are involved in the planning of sprints and the roadmap for the project. Further, this agile approach ensures that there are small deliverables early on in the Design and Development phase. These are demonstrated and evaluated at each sprint. This periodic evaluation of the artefacts helps to gain a better understanding of the problem, builds the sense of co-ownership, and gains feedback on the iterative improvements on product

quality and the design process, before the final design artefact is generated [6, 10]. Thus, feasibility of the solution can be demonstrated early by construction of an artefact, which can then in later iterations, be improved upon. These early outputs encourage the industry partner. The final phase is Communication through scholarly and professional publications, albeit care and the appropriate respect should be awarded to all parties on their background and foreground intellectual property.

DSR allows for multiple artefacts, the outputs of the process, which are broadly defined within the guidelines as constructs, models, methods and instantiations [6, 11]. Constructs, models and methods are described as meta-artefacts which exist as "things" with a separate existence [12]. Constructs are the vocabulary and symbols that define the problems and solutions. These constructs are then be used to create models, which are abstractions and representations of the problem. From the models, methods which are algorithms and/or practices can be defined that will enable the instantiations. The instantiations are typically IT systems existing as implementations, prototype or proof-of-concept systems, and rarely a full-fledged system [6]. The artefacts developed must have utility, i.e. be a purposeful IT artefact that solves problems [3, 9].

3.1 Collaboration Model

There is a misconception that having chosen the appropriate research method, a successful outcome will follow. We know from experience that this is not the case. Fundamental to achieving the win-win required of an IA research project is how well collaboration is fostered and managed. We use a version of the 3C Collaboration model, illustrated in Fig. 3. Collaboration is a function of communication, co-ordination and co-operation. There is a requirement to build a mutual beneficial relationship, based on trust. This is enabled early by a clear communication plan around weekly sprint planning meetings, monthly sprint reports, and full transparency around outputs through the sharing of code and document repositories. The sharing of power, resources and tools is fundamental to the co-operation process, and builds that sense of shared ownership for mutual benefit. To foster joint ownership in all the activities requires deference to the partners' availability and guidance. Learning from the partner allows for exploitation of their knowledge for the betterment of the project. The partner has domain knowledge, often tacit, which will often only be uncovered in conversation. For instance in one of our meetings, we proposed a change to a process that made sense from a technical perspective. The partner's reaction was 'can't do that'. Using basic Five Why's technique, we uncovered that the cost of reaccreditation with the FDA would be too exorbitant and would outweigh any opportunity costs. Leveraging this knowledge led to an alternative and better design, which avoided the need for reaccreditation.

4 Framework for Evaluation in Design Science Research

DSR rigour is applied not only in the development and application of the artefact, but also in its evaluation guided by the DSR Guidelines, as listed in Table 1. Each of the artefacts developed should be rigorously evaluated against these criteria of utility, quality, and adequacy [9, 13]. Venable's Framework for Evaluation in DSR (FEDS) [13, 14] supports

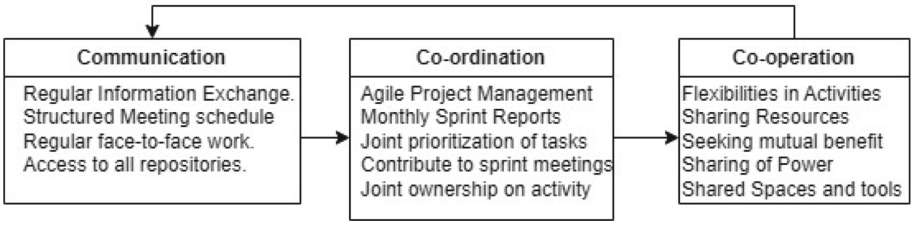

Fig. 3. Collaboration Model

decision making around the most appropriate evaluation strategy in DSR, and thus is suitable for these type of research. FEDS proposes a four-step process: 1. Explicate the goals of the evaluation; 2. Choose the evaluation strategy or strategies; 3. Determine the properties to evaluate; and 4. Design the individual evaluation episodes.

In Step 1 the goals are identified. FEDS identifies four competing goals – rigour, uncertainty and risk reduction, ethics, and efficiency. Whilst the end goal is to achieve all four, some goals will be more relevant to some stages of the project than others. The primary goal early on in the project is 'uncertainty and risk reduction' as there are design uncertainties and technical risks. Laboratory evaluation and stepwise research are suitable approaches as design uncertainties are significant risk factors.

In Step 2, the choice between four strategies is made - the Quick & Simple strategy, the Human Risk & Effectiveness evaluation strategy, the Technical Risk & Efficacy evaluation strategy, and the Purely Technical Artefact strategy. These choices are illustrated in Fig. 4. Each research project will have its own applicable strategy. In this research, Technical Risk & Efficacy strategy is applied. The risks in this research are primarily technically orientated in that it was not known whether an adequate system can be built to support the operator in the way proposed, or even how to go about that. It can also be expensive to evaluate the technology with real users in real contexts.

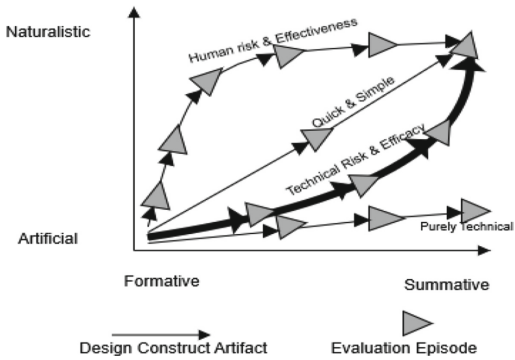

Fig. 4. Alternative Strategies within FEDS Framework, with chosen highlighted [13]

In Step 3 the properties to be evaluated are identified. These are the features, goals and requirements of the artefacts, and as such is unique to each artefact and its position in

the development lifecycle. For example, the goal of *ex-ante* evaluation of a software layer are to establish whether it will function. Leveraging the partners' domain knowledge is useful here. For example, there are quality models that apply to Industry 4.0 software that may not apply in other contexts, such as the ISO/IEC 9126 Software engineering, GAMP 5, or the 21 CFR Part 11. The properties for evaluation should be completed on an experiment basis, but should be framed by these quality models so that that are no compliance or commissioning issues for the industrial partner. *Ex-post* evaluation of the same artefact are around its utility when used in context.

The final step, Step 4 involves designing the individual evaluation episodes. These episodes, shown as triangles on Fig. 4, are effectively the experimentation plan. In the primary research conducted herein each research method has a corresponding evaluation episode, so four triangles on the strategy are each represented by one research method each.

4.1 Extending the FEDs Model with Primary Research Strategies

Under the DSR umbrella, the rigour of scientific evaluation is required. There is a misconception that using DSR is a research method in itself. It is not. Scientific rigour is to applied to all research strategies employed. FEDS provides a framework for evaluation. The primary goal is to establish that utility/benefit is due to the artefact. Formative evaluation fits with the agile method adopted. Problems/inefficiencies with the artefacts can be identified and resolved before implementation into the field. Thus the research may follow the appropriate trajectory of the framework as shown in Fig. 4 commencing at the lower left corner (the state of no evaluation), followed with artificial formative strategies, towards the upper right corner, towards naturalistic/summative strategies, representing a more comprehensive and rigorous evaluation. We extend FEDS by suggesting appropriate research methods along the trajectory.

The appropriate research method will depend on the context. Methods should be chosen with a mix of real and contrived work settings each with their own goals, realism of context, realism of behaviour and efficiency of the software artefacts. Each triangle on the FEDs trajectory represents an evaluation episode, which should have its own appropriate research method mapped to the hypothesis. There is no right or wrong research method, each should be chosen based on the goals of the research and the context of the particular research [5]. In this section, recommendations of potentially suitable research methods are made, but it is up to the researcher in each individual context to make that educated decision. For example, a mixed methods approach may be taken which uses triangulation as an analysis technique. Triangulation allows for different and complementary data about the research to be gathered. The methods are distinct, yet follow a sequential nature which maps to the evaluation episodes on the trajectory followed in the FEDs model, as seen in Fig. 4. Evaluation episodes 1, 2 and 3 are *ex ante*, with episode 4 *ex post*. The converging different methods allows for a direct comparison of the artefacts in different environments [15].

Artificial evaluation involves reductionist abstraction from the natural setting, and as such, is easier to control for the multiplicity of variables, and therefore is less susceptible to misinterpretation and bias. However, with respect to evaluation of utility, quality and adequacy, these methods are unreal as they can be missing the realism of context, humans and behaviour. Notwithstanding that, they are appropriate for early formative evaluation of artefacts, in this example, evaluation episodes 1, 2 and 3. Methods include laboratory experiments and computer simulations.

Naturalistic evaluation is the study of subjects in their natural environment, here operators on the factory floor, in this example, evaluation episode 4. FEDs naturalistic evaluation explores the artefacts in real, contrived or natural settings. Performing evaluation in natural settings allows for maximum potential for realism over context, and/or maximum potential for realism over behaviours. Thus, it tends towards interpretivism relying on understanding the meanings that real users attach to their actions in real contexts [4]. It must be implemented in a manner that untangles the effects of the numerous variables in a real world setting, and therefore there is risk of misinterpretation, which may lead to an imprecise evaluation of the artefact. Reductionism may be required to determine the variables for study. Suitable research methods may include observation, case studies, field studies, field experiments, and surveys. The transition in FEDS from formative/artificial following a trajectory towards summative/naturalistic, fits with the iterative process of the DSR methodology adopted in this research [9].

4.2 Evaluation of The Design Science Approach

The success of the DSR method to solution seeking Industry 4.0 problems is very much subjective – whether the partners are happy with the outcomes. Our research project was described by the Head of Innovation of the multinational medical device company as the "*most successful collaboration we have ever had with any University*". From a measurement perspective that research project has led to more projects with the same partners. We recommend that research projects following the DSR approach should evaluate not just at the primary research method level, but also whether the research project has met with the seven guidelines of DSR [6, 16]. In our research, these guidelines were evaluated and met as outlined in Table 1.

Table 1. Confirmation of Design-Science Research Guidelines

Guideline	Confirmation of Guidelines
Guideline 1: Design as an Artefact	Viable artefacts produced: Construct - > vocabulary of terms, symbols to represent the system Method - > Data Augmentation, Neural Net Training Model - > Requirements, Database Design, Neural Networks, Systems Architecture Models, UML Class Diagrams, Entity State Diagrams, Data and MetaData Instantiation - > Proof-of-concept, Prototype, Demonstration Units
Guideline 2: Problem Relevance	The solution address the problems experienced in industry such as high number of human errors in complex assembly
Guideline 3: Design Evaluation	The utility of the artefacts evaluated by authentic & concurrent evaluation of feedback from the industry partners and user testing
Guideline 4: Research Contributions	Patent searches and a State of the Art review is conducted to verify that this work is original design and the contribution of the newly designed artefact. Contributions arise from its novelty, generality, and/or significance of the designed artefacts
Guideline 5: Research Rigour	Rigorous methods applied include: a literature review conducted, an agile development method used in the construction, evaluation of each artefact conducted using individual evaluation episodes
Guideline 6: Design as a Search Process	A gap analysis is conducted on the results of the literature review. Research on competing approaches. Cyclical problem solving approach in which solutions are compared to test for efficacy
Guideline 7: Communication of Research	Research communicated to the industry made up of technology-oriented and management-oriented audiences in presentations, demonstrations and reports. Conferences and journal papers published

5 Conclusion

Collaborative Industry 4.0 innovation research projects should be treated as Solution Seeking. Approaching the research as routine systems design will not satisfy the requirement of the researcher to add to the Body of Knowledge. Approaching the research from a Knowledge Seeking approach will not satisfy the requirements of the partner for useable outputs. DSR provides a common and easy to understand multidisciplinary framework

for such research. We achieved the necessary win-win [17] where the needs of all the parties are met by approaching the research as a Solution-Seeking research project using DSR.

Fundamental to IA collaboration, is a conscious effort to enable and manage the collaboration processes. Joint governance, co-creation, communication and relationship building are key tools to managing the relationship and expectations. We modified the DSR process by building trust early and developing a sense of joint ownership of the project, this led to an unhindered exchange of domain knowledge.

Leveraging the partners' domain knowledge leads to a more successful product. There are quality models and regulatory constraints that apply to Industry 4.0 software and processes. In order that there are no compliance, commissioning or adoption issues for the partner, these should form the basis of any system requirements.

Using FEDS with DSR ensures academic rigour in the evaluation process. We extend FEDs by recommending suitable scientific research methods that can be used. In doing so we add clarity as to how to apply it to ensure academic rigour. Further, we suggest that evaluation should not only occur at the primary research level, but also an abstracted evaluation of the application of DSR to the project is required. We illustrate how that can be done using our own project as an example. This guidance will be beneficial to future researchers who wish to apply DSR to their own collaborative research projects.

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Development and Analysis of Predictive Models for Industry 4.0 with an Open-Source Tool

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Abstract. Industry 4.0 brought modernization to the productive system through the network integration of the constituent entities that, combined with the evolution of information technologies, allowed an increase in productivity, product quality, production cost optimization, and product customization to customer needs. In this paper a model was created using the open-source tool Knime that, based on a set of data provided by Bosch, parameterized the model with several pre-processing techniques, resource selection, and minimization of over-fitting, allowing the development of a final improved model for internal product failure prediction at Bosch production line. The study shows that model efficiency improved with the application of resource selection and reduction techniques, with Logistic Regression and PCA resource selection techniques standing out, obtaining a Recall of 100% and precision and accuracy, both with 99.43%.

Keywords: Machine Learning · Knime · Artificial Intelligence

1 Introduction

In the contemporary industrial environment, there is a demand for continuous improvement of quality standards simultaneously with the increase in production volume, and therefore a tool capable of predicting non-compliant products will be extremely useful to ensure corrective actions on the production line that minimize these occurrences.

The concept of a smart factory emerged with industry 4.0, boosted by the search for digitization of the process, based on the collection and analysis of data in real-time, with the aim of moving towards product customization and flexibility of the production chain, using intelligent machines, maintaining the efficiency of the production cycle. The power of information resulting from database processing by AI techniques, transforms the current value chain, with continuous improvement resulting from information processing [1].

Artificial intelligence was revolutionizing some industries, such as manufacturing, retail, and telecommunications, where increases in profitability, efficiency, and security can be achieved, using machine learning (ML), knowledge-based systems, computer vision, robotics, and optimization [2, 3].

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ML is a field of AI that studies algorithms capable of autonomously learning from a database [4]. Over time, ML began to be adapted in order to be able to integrate the industrial field, allowing it to evolve towards Industry 4.0 [5], increasing profitability, efficiency, and safety. This area of science encompasses computing, logic, biology, and psychology which creates new solutions for speech recognition, language processing, and intelligent robots [6].

Traditional production methods are becoming inadequate, in the sense that more dynamic and customer-oriented production processes are required, so new technology and methods are being implemented in the industry, such as sensors, software, wireless connectivity (IoT), moving towards the creation of smart factories [1].

Artificial intelligence seeks to replicate human thinking in machines [5, 6], resorting to a combination of mathematics and engineering, resulting in a large amount of data, requiring an increase in the computational power associated with this science [7].

The low quality of the products has a high impact on an economic and environmental level since resources and labour are wasted, observing the sustainability of the process [8, 9]. This subject refers to the concept of Zero Defect Manufacturing (ZDM), and its implementation was driven by the evolution of industry 4.0 as it brought the ability to manage a large amount of data for the application of ML techniques [9, 10].

ZDM is a concept that focuses on the quality of the process and products, reducing defects using corrective, preventive and predictive techniques, integrating data analysis techniques so that no defective product leaves the production line and is delivered to the customer [8]. This approach focuses on preventing the occurrence of defects through continuous improvement of the process and the use of quality control techniques, while ML models intend to identify patterns in the collected data, predicting potential defects. That said, ML models are used as a support tool for the implementation of ZDM principles, allowing industries to make better decisions, and improve their processes and, consequently, product quality.

The development of predictive models is becoming more and more useful in the industrial world, as their main focus is on predicting anomalies in machines and products, anticipating critical events and defects in products, and preventing economic losses [11]. Predictive analytics uses statistical models to predict the size of production or the remaining life of machines [12], which depend on past failure event data.

ML is one of the subfields of AI that focuses on creating systems that, using statistical models and mathematical algorithms, are able to learn autonomously from a database [4].

ML techniques allow automatic detection of patterns in data and act without having to be explicitly programmed, making decisions more efficiently. The ML algorithms development means to map the knowledge acquired from the learning process to prediction, boosting the development of categorized approaches [7]. The quantity and quality of data collected for the database influences the accuracy of the ML model's decision-making [13].

Based on historical data, ML techniques are a powerful tool to support decision-making in complex problems, using prediction algorithms adjusted by training data collected by sensors [13]. In order to avoid misleading information of machines, tools and

industrial processes, by predicting the need for intervention, ML offers an intervention plan to minimize economic losses [11].

In general, the model is trained from a database, that is, the input data (input) which is known as features and the output data (output) which is also known as the forecast [1, 14]. The model identifies relationships between input data and output data and uses this relationship to make new predictions from data never seen by the model before. The quality of the predictions is obtained by comparing the results of the model output data with the actual output data from the training database [13] and this is being adjusted to increase its accuracy and effectiveness. When an acceptable level of accuracy is reached, learning is stopped, and the model is primed to make predictions from previously unseen new data. ML, when used for classification, categorizes the data by dividing it into several classes, estimating the class probabilities with a training dataset. When used for forecasting, ML provides a predictive capability for decision making [15].

2 Development

To evaluate the benefits of the ML techniques, some of these were applied to a Bosch database, formulating models, which were then evaluated. The proposed solution allows identifying different patterns in the database to recognize compliant and non-compliant products, identifying defects and problems in the production line. The predictive model will be developed from a Bosch database, which represent records of measurements and tests carried out on each part along the assembly line. In a first phase, the characteristics of the database used, its pre-processing and the workflow built in Knime are presented, contemplating the different ML models used in the prediction of compliant and non-compliant product. To develop more efficient and less computationally demanding models, several resource selection techniques were applied, and the results were presented according to several evaluation metrics.

2.1 Adapting a Predictive Model to a Case Study

Bosch collected information that gave rise to a large dataset with the goal of predicting non-conforming products on a production line where each line in the database is representative of a product going through its production path. This information comes from an assembly line divided into 4 segments and 52 stations, where each of these performs a variable number of measurements on a given part or product totaling 4265 features. The characteristics of this data set are: Numerical Features 968, Categorical Features 2140, Time Features 1157, Observations 1.183.747, Missing Values 78,5%, and Conforming products 99,42%.

Due to the large number of resources, the database was provided with numeric, time, and categorical resources separated into three different tables, allowing their processing with less computational power. The data processing will be done in the software, Knime, so in a first stage it is necessary to adapt the input data through data preprocessing techniques. As this presents a high percentage of missing values, it was decided to only consider the resources that have more than 10% of available data, thus improving the quality of training data for the model.

2.2 Data Preprocessing

Data pre-processing is a process of preparing the raw data, making it suitable to be read by the ML models, allowing them to run faster, more accurately and efficiently. The first phase of pre-processing consists of importing the files in CSV format into the Knime software, specifically the numerical, time, and categorical databases, reducing the need for computational power.

In the next phase, the outliers were ignored and replaced by missing values, avoiding the loss of information based on only one feature. Simultaneously, the lines with more than 90% of features with no information were eliminated, going from 4268 features to 814 features.

In the third preprocessing phase, the three databases were merged into a single table integrating the numerical, categorical and time parts in order to include all the features that were used to predict the target variable (Response). Finally, in the fourth preprocessing stage, two duplicated columns resulting from the joining process and irrelevant for the analysis were removed and then exported in CSV format for use in the different models.

2.3 Evaluation Metrics

The developed model will be evaluated according to the evaluation metrics represented in the Table 1. There are four possible scenarios for classifying the values predicted by the developed model, including: 1) the true negative (TN) which indicates that the model correctly predicted the actual negative value; 2) the true positive (TP) which indicates that the model correctly predicted the true positive value; 3) the false negative (FN) that indicates that the correct real value is positive, however the value predicted by the model was a negative result, which means it failed; and 4) the false positive (FP) which indicates that the actual correct value is positive, but the value predicted by the model was a positive result which indicates that it failed.

Table 1. Evaluation Metrics

Metrics	Formula	Definition
Precision	$\mathrm{TP}/(\mathrm{TP}+\mathrm{FP})$	Indicator that defines the ratio between the number of true positives and the number of identified positives
Accuracy	$(TP+TN)/(TP+TN+FP+FN)$	It is the ratio between the values correctly identified by the model in relation to the total number of observations

(*continued*)

Table 1. (*continued*)

Metrics	Formula	Definition
Recall	$TP/(TP + FN)$	A high recall is an indicator of a high percentage of true positive identification, which demonstrates the ability to correctly identify conforming parts
F1-Score	$2 \times (\text{Precision} \times \text{Recall})/(\text{Precision} + \text{Recall})$	It is an indicator that combines the accuracy and recall of a model in a single metric, being a reference in comparing the performance and quality of classification models

2.4 Evaluating the Influence of the Different Models

The supervised learning models used were Decision Tree, XGBoost, Naive Bayes, Logistic Regression and Random Forest to develop a model to predict failures of non-conforming products adequate to the database, being evaluated by the following parameters: accuracy, recall, precision, and the F1-Score.

To build the models we first used the shuffle node to shuffle the rows of the database, avoiding the overfitting of the model to a certain order of classification of the data patterns. Subsequently, the "Normalizer" node was used to place the values between [0,1], as it condenses the data in a range of values and does not allow that some data features assume greater preponderance by presenting higher values, influencing the effectiveness of the model.

The database used presents a high imbalance in the distribution of classes, that is, about 99.5% of the data are conforming products. Therefore, the algorithms may find it difficult to predict the non-compliant products due to the imbalance of observations between classes, corresponding to a binary variable "Response". Due to the disparity in the volume of observations, the model tends to categorize the class with the highest expression, leading to a false sense of accuracy.

To minimize the imbalance between classes one must use methods that balance their distribution by sampling methods that aim to increase the minority class (oversampling), which in the Knime case corresponds to the Smote node. The Table 2 shows a summary of the performance metrics of the database classifiers, after adjustment to improve their performance.

Feature Selection Applying the Linear Correlation Filter
After identifying the linear correlation between the resources, a filter was applied for correlation higher than 0.9, so as not to double the computational load of the model, increasing its efficiency. The Table 3 shows the evaluation metrics of the different models applied to the database after resource selection using Linear Correlation.

Feature Selection by Applying the Low Variance Filter
Alternatively, dimensionality reduction can be achieved using a low variance filter to

Table 2. Performance of model evaluation metrics

Complete Dataset (814 features)				
Evaluation Metrics				
Models	Accuracy	Precision	Recall	F1-score
Decision Trees	99.297%	99.451%	99.844%	99.647%
XGBoost	99.428%	99.432%	99.999%	99.715%
Naive Bayes	99.280%	99.433%	99.845%	99.639%
Random Forest	99.280%	99.456%	99.818%	99.637%
Logistic Regression	99.419%	99.436%	99.999%	99.717%

Table 3. Performance of model evaluation metrics

Resource selection technique - Linear correlation (394 features)				
Evaluation Metrics				
Models	Accuracy	Precision	Recall	F1-score
Decision Trees	99.324%	99.446%	99.876%	99.66%
XGBoost	99.432%	99.431%	100%	99.715%
Naive Bayes	99.432%	99.431%	100%	99.715%
Random Forest	99.278%	99.459%	99.817%	99.638%
Logistic Regression	99.430%	99.433%	100%	99.714%

eliminate the resources that are below a certain limit. The Table 4 shows the evaluation metrics of the different models applied to the database after resource selection using Low Variance.

Table 4. Performance of model evaluation metrics

Resource selection technique – Low Variance (763 features)				
Evaluation Metrics				
Models	Accuracy	Precision	Recall	F1-score
Decision Trees	99.305%	99.450%	99.850%	99.651%
XGBoost	99.427%	99.433%	100%	99.713%
Naive Bayes	98.680%	99.440%	99.232%	99.336%
Random Forest	99.268%	99.460%	99.806%	99.633%
Logistic Regression	99.423%	99.436%	100%	99.711%

Feature Selection by Applying the PCA Filter
Principal Component Analysis (PCA) is an unsupervised learning algorithm which generates through a statistical transformation, finding strong patterns in a data set. Applied to the case study database, the dimension was reduced to a total of 28 dimensions, managing to preserve at least 90% of the information contained using the "PCA apply" node. The Table 5 shows the evaluation metrics of the different models applied to the database, after the database dimensions have been reduced using the PCA technique.

Table 5. Performance of model evaluation metrics

PCA Dimensions Reducion (28 dimensions)				
Evaluation Metrics				
Models	Accuracy	Precision	Recall	F1-score
Decision Trees	99.346%	99.438%	100%	99.672%
XGBoost	99.432%	99.432%	100%	99.715%
Naive Bayes	99.410%	99.432%	100%	99.704%
Random Forest	99.273%	99.459%	99.812%	99.635%
Logistic Regression	99.432%	99.432%	100%	99.715%

3 Results Discussion

In a general way, all the developed models presented satisfactory results once they presented values higher than 99%, evidencing a reduction in the processing time after the application of the feature selection techniques.

As the database presented, the most indicated evaluation metrics are recall, precision and F1-Score, so if accuracy was used there could be a misinterpretation on the part of the user. The F1-Score allows the joint analysis of recall and precision metrics, being mainly useful when false positives and false negatives have different impacts, as is the case of the database used.

Although before applying the feature selection techniques the developed models already presented results around 99%, this value increased to 100% when the Linear Correlation technique associated with Logistic Regression, XGBoost and Naive Bayes algorithms was used. With the goal of reducing the need for computational power by increasing the efficiency of the models and eliminating irrelevant features, the Linear Correlation technique was applied, evidencing the non-occurrence of false negatives.

The application of the Low Variance technique did not obtain as good results as the previous technique, evidencing a lower recall value even when compared to the database without any processing technique. Finally, the PCA technique used to reduce the feature sizes demonstrated high effectiveness in all models as they achieved 100% recall (except Random Forest) and improved F1-Score.

The study demonstrated that the effectiveness of the models improved with the application of the previously described techniques, highlighting the Logistic Regression model combined with the PCA resource selection technique with a recall of 100% and an accuracy of 99.43%. However, all models studied showed that it would be advantageous to apply them in the processing of this database.

4 Conclusion

ML techniques seek to identify opportunities to increase the efficiency of pro-duction lines at any stage of the process, as they will identify situations in which predictive maintenance is required. The proposed solution makes it possible to identify different patterns in the database, making it possible to recognize com-pliant and non-compliant products on the production line. The adoption of this type of solution is relevant since the occurrence of a defect in the product is a waste of materials, features and manpower.

In general, the creation of predictive models for production lines promotes automation of monitoring, effective control of product quality, analysis of collected data recognizing patterns, to avoid future stoppages in the production line and, finally, a promotion of sustainability to the extent that it becomes possible to optimize the use of essential features.

The database used in the case study showed an imbalance in the binary classification of data, with many compliant products and few non-compliant products, which makes it difficult to apply the forecast model. The pre-processing of the database contributed to the lower need for computational power, increasing the efficiency of model execution, and, also, to avoid the occurrence of overfitting.

Data normalization makes it possible to maintain the same scale for all input variables and the application of filters based on the correlation coefficient pre-vented the appearance of redundancy in values, which is one of the resource extraction techniques, Linear Correlation. The remaining Low Variance and PCA techniques allowed an increase in the performance of the models, namely in the recall indicator which obtained a performance of 100% for almost all models. ML has shown to be able to increase the speed of processing a big amount of data.

From the perspective of the practical implication of this study, it is possible to enhance some important results. Firstly, it is possible to create production models for the prediction of product quality by using an available open-source tool. Secondly, large computational processing capacities are required if the database is becoming more complex. Thirdly, resource selection techniques were used to make the model more accurate and efficient and the model that obtained the best accuracy was the Logistic Regression combined with PCA. And finally, a manufacturing company can avoid economic losses and waste of resources by adopting these types of predictive models.

For future work, the development of new models with different parameters and other forms of pre-processing the database are foreseen, to increasingly improve the precision and effectiveness of the predictive model.

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Artificial Intelligence and I4.0 in Manufacturing: The Role of Sustainability

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Abstract. Sustainability has become a critical issue for manufacturing companies in recent years, as they strive to meet government-mandated targets. With the rise of Industry 4.0 (I4.0) in the digital age, companies are turning to artificial intelligence (AI) techniques to optimise production processes. In order to support the concepts of I4.0, AI and sustainability, major databases such as Web of Science and Elsevier's Scopus were consulted. The aim of this study is to investigate the relationship between I4.0, AI and sustainability by highlighting the direct and indirect links between these concepts. The study shows that the adoption of digital approaches can significantly improve the sustainability of production systems, provided the right balance is struck. This requires investment in both technology and sustainability measures to achieve a holistic, globally sustainable production system. The study therefore concludes that manufacturers must continue to invest in innovative technologies, including I4.0 and AI, while ensuring that these investments are aligned with their sustainability goals. The research highlights the importance of a balanced approach to digitalisation that optimises production processes, while ensuring that sustainability is not compromised. Ultimately, this research provides valuable insights for managers seeking to navigate the complex relationship between I4.0, AI and sustainability in their manufacturing operations.

Keywords: Sustainability Manufacturing · Industry 4.0 · Artificial Intelligence

1 Introduction

Sustainability is widely recognised as a concept of global importance. The term refers to the ability to address environmental, social, and economic problems, while ensuring their long-term viability. It is a global approach that will affect the entire planet, not simply a local focus. In recent years, there has been a growing awareness among individuals, businesses, and governments as to the importance of sustainability. As a result, concerted efforts are being made toward sustainable development, growth, and the adoption of green technologies. This research paper focuses on analysing the concept of sustainability in the context of I4.0. As natural resources become increasingly

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scarce, managers in the manufacturing industry have recognised the importance of prioritising sustainable practises and products. In this regard, adopting renewable energy sources, reducing greenhouse gas emissions, minimising the generation of waste and implementing circular economy principles have become critical issues in the achievement of sustainability [1]. With the digitalisation of processes, managers can improve process efficiency. The Internet of Things (IoT) and data analytics have shown promising results, not only in monitoring and optimising productive systems, but also in achieving sustainable practices. This research highlights the importance of sustainability in I4.0, and its potential impact on creating a sustainable future. Furthermore, the paper highlights the importance of investigating effective approaches to balance the adoption of AI techniques, and thus establish a leading manufacturing company related to Industry 4.0, without compromising sustainability. Numerous studies have been conducted to assess the impact of AI and I4.0 on operations management, particularly in terms of improving efficiency and productivity. In addition, organisations need to embrace emerging technologies such as AI in I4.0 in order to remain competitive in the global marketplace. Ultimately, companies that successfully integrate and adapt to these technologies will gain a significant competitive advantage in the foreseeable future [2–4].This paper is divided into seven sections. The second section explains the basic concepts of Industry 4.0. The third section provides a general summary of sustainability, explaining its main importance. The fourth section enumerates the main principles of the triple bottom line (TBL) and identifies the most relevant indicators. Sections five and six describe the concept of AI and its potential applications in the industrial domain, with a view to achieving more sustainable systems. Finally, Section seven contains a conclusion on the subject under study.

2 Industry 4.0

This section explores some of the key concepts. I4.0 is widely recognised today for its ability to follow a product across its lifecycle. Furthermore, I4.0 is closely linked to the application of strategies that facilitate industrial transformation, such as the use of new technologies - for instance automation and digitalisation - to optimise production processes and ultimately enhance the competitiveness of the various manufacturing companies in the sector. I4.0, is also known as the fourth industrial revolution, which focuses on improving process efficiency and productivity [5] by using various technologies such as automation, data exchange, cyber-physical systems, IoT and cloud computing [6]. The creation of an intelligent factory involves the monitoring of physical processes through cyber-physical systems, thus creating a virtual copy [7]. This allows for more efficient and connected equipment and enables managers to make decisions more quickly and efficiently [8, 9]. In the context of I4.0, it is extremely important to upskill in general terms, as well as to train operators to work with new technologies. In addition, organisations must create a supportive working environment that will make it possible for operators to adapt to the new reality of the I4.0 context [10]. I4.0 is also characterised by the integration of smart production systems, as well as the horizontal and vertical integration of data in the value chain. Vertical integration is one of the main characteristics of I4.0, which allows data to be acquired and analysed, leading to better decision-making and efficient production management (Fig. 1) [11, 12].

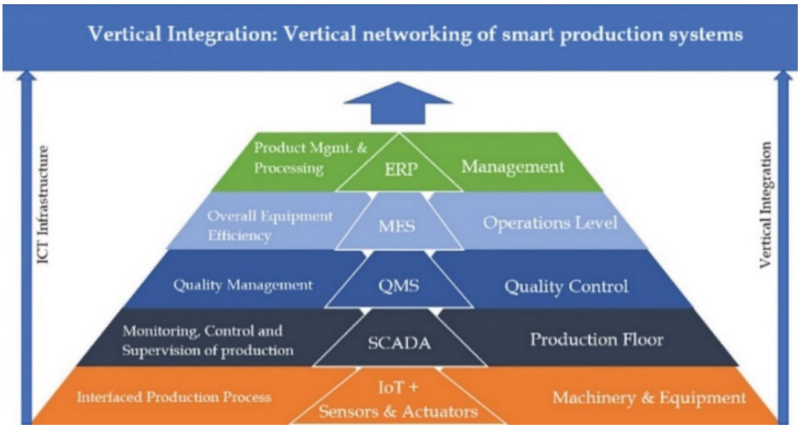

Fig. 1. Vertical integration (I4.0) [12].

I4.0 horizontal integration occurs at different levels, in which different machines are connected and communicate with each other [13]. This integration allows for more flexible systems, and facilitates the optimization of the production processes (Fig. 2) [12, 13]. Another characteristic of I4.0 is the ability to follow a product across its entire life cycle, which is made possible by collaboration between the production process and all the other related processes [14].

Fig. 2. Horizontal integration (I4.0) [12].

Furthermore, I4.0 is associated to the adoption of strategies that facilitate industrial transformation, such as the use of digitalisation and automation technologies to enhance production processes, thus improving industrial competitiveness. These characteristics contribute to the significant role of technology in modern industrial operations, and the

need for companies to adopt innovative solutions to ensure greater competitiveness in today's market.

3 Sustainability

Sustainability is a complex and multifaceted concept that has evolved over time. Its origins can be traced to several different areas, including environmental, economic, and social contexts. At its core, sustainability is about addressing the needs of the present, without compromising the ability of future generations to meet their own needs. It requires a balance between economic growth, environmental protection, and social equity. This section explores the evolution of the concept of sustainability [15]. The idea of sustainability can be traced back to the early days of human civilisation, when communities had to manage resources in a way that ensured their survival over time [16]. The modern concept of sustainability, as it is understood today, began to take shape in the 1960s and 1970s with the rise of environmentalism and a growing awareness of the negative impacts of industrialisation and economic growth on the planet [17]. Nowadays, the concept of sustainability has continued to evolve and has gained more attention from governments, businesses, and individuals around the world. The current focus is to achieve the United Nations Development Goals (SDGs), which were adopted in 2015 to create a more sustainable future for all [18]. Recognition of the negative impact of human activities, as well as the scarcity of natural resources and governmental impositions have led many manufacturing companies to begin to alter their business practices towards more sustainable models [19]. Over the years, manufacturing has been changing to reduce waste, taking into account the entire life cycle of the product. The evolution of sustainable manufacturing strategies over time is shown in the Fig. 3 [20].

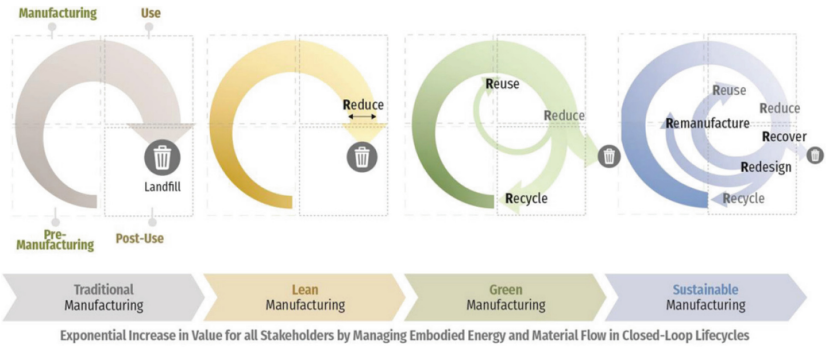

Fig. 3. Evolution of Sustainable Manufacturing Strategies [20].

The manufacturing industry has recently placed greater emphasis on sustainability due to the significant waste generated by traditional practices. Lean and green manufacturing aims to reduce waste and promote 3R. The 6R methodology has emerged as a more comprehensive approach to sustainability, which seeks to maximise the recovery of value from end-of-life products and create closed-loop material flow systems. This paper

also examines the evolution of sustainability in manufacturing, from prefabrication to the current focus on the 6R methodology.

4 Triple Bottom Line Business Sustainability

Elkington [21] was the first to propose an approach to the TBL in the 1990s as a framework to measure the sustainability of business operations. This approach is divided into the economic, social and environmental impacts of manufacturing production. Balancing these three aspects promotes the long-term sustainability of the industry. The TBL approach is aligned with the SDGs, which aim to create a more sustainable future. It should be noted that the manufacturing industry is one of the most important industries in the world and plays a key role in economic development. Figure 4, clearly illustrates how sustainability fits into the three dimensions and how they interact. It also presents some of the key factors that contribute to sustainability in industrial manufacturing companies within the industrial community [22].

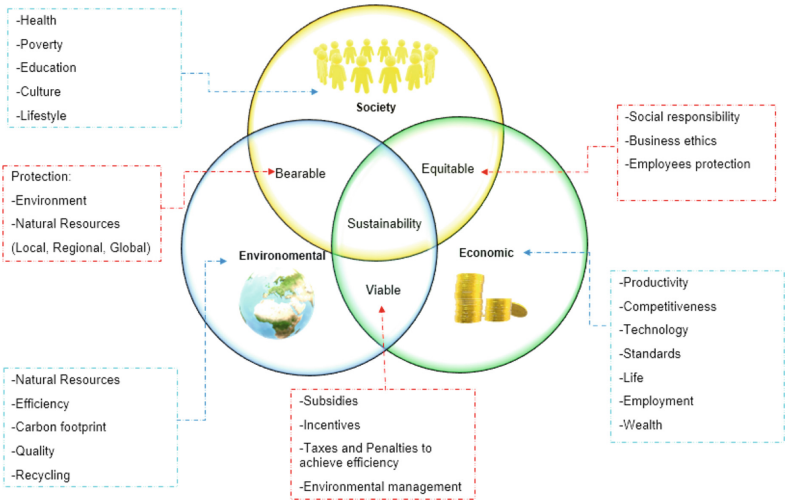

Fig. 4. Intersection of sustainability pillars Approach adapted from ([22]).

The integration of sustainability into industrial decision making is a growing trend. The TBL framework identifies three fundamental pillars of sustainability: economic, social, and environmental. However, measuring sustainability remains a challenge owing to a lack of standardisation and clear definitions, thus resulting in ambiguity. The literature studied suggests that the social and environmental dimensions of sustainability are often neglected due to this lack of standardisation.

5 Artificial Intelligence (AI)

In recent years, the use of AI has grown exponentially in various industries, with a particular focus on improving production processes and systems. AI-powered systems have shown great potential in improving operational efficiency, reducing costs, and increasing productivity, thus constituting an attractive solution for making companies more competitive. This section explores some approaches in which AI is being used to transform industries and improve production processes. One specific example is the use of AI for quality control, where it can be implemented for visual inspection to detect production failures [23]. Due to manufacturing competition and the emergence of I4.0, industries are constantly faced with new challenges, so they have become more connected and dynamic [24]. By integrating I4.0 technologies with AI, one will be able to achieve more effective, efficient, flexible, and greener operations in industries [25]. However, AI still only plays the role of an assistant, as it still needs human supervision to validate the suggested decisions [26]. AI algorithms have been developed to construct smarter manufacturing plant systems or equipment [27]. AI allows for the modelling and monitoring of the inputs and outputs of different processes. By integrating AI into machines, they are then capable of deciding and solving, from the simplest to the most complex problems, while avoiding possible failures [28]. According to this AI research, there is considerable potential to improve a wide range of processes. From the point of view of the authors, the most promising strategy for harnessing the power of AI is that of collaboration between humans and machines. By leveraging the unique perspectives and knowledge of different stakeholders, such partnerships can facilitate the creation of more efficient and effective solutions. Taken together, these findings suggest that AI represents a significant opportunity to improve processes across a range of domains, with collaboration emerging as a critical factor in unlocking its full potential.

6 Sustainability using AI

In recent years, the integration of AI technologies has become increasingly common in the manufacturing industry. With its ability to analyse large amounts of data and make real-time decisions, AI has proved to be an efficient way to improve product quality and employee well-being [29]. AI is used to predict potential equipment failures and facilitate quick repairs to avoid costly unplanned downtime [23]. Wang [30] highlights the benefits of using AI in the manufacturing industry, and provides evidence on the evolution of manufacturing processes and the significant role of intelligence science in the development of intelligent manufacturing systems. Wang [30] also discusses the challenges that must be overcome to achieve the potential of AI in this field. Choi, Yang and Yu [31] conducted a study to examine the ongoing challenges facing the manufacturing industry in terms of energy efficiency, sustainability, and environmental impact. The authors found that these factors are closely linked. As well as minimising the environmental impact of manufacturing systems, the improvement of energy efficiency constitutes an essential step in achieving sustainability. In the author's view, the spread of digitalisation to various industries makes it highly likely that the use of AI techniques will become essential to ensure the optimal performance of production systems.

7 Conclusions and Future Research Work

In conclusion, Industry 4.0 is characterised by the ability to track products across their lifecycle through collaboration between production and related processes. The adoption of digitalisation and automation technologies is key to improving production processes and enhancing industrial competitiveness. Owing to the growing emphasis on sustainability in manufacturing, approaches such as the 6R methodology have emerged to reduce waste and promote closed-loop material flow systems. However, measuring sustainability remains the challenge due to a lack of standardisation and clear definitions. Future research could focus on addressing this gap by developing standardized methods to measure sustainability in manufacturing. This could include exploring ways to better integrate the social and environmental dimensions of sustainability into industrial decision-making by using frameworks such as the TBL. Additionally, further research might examine the potential of AI to improve a wide range of processes in manufacturing.

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Framework for Implementing Digital Twin as an Industry 5.0 Concept to Increase the SME Performance

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Abstract. Compared to emerging countries, European companies must digitally transform their organization to be competitive. Industry 4.0 concepts have been developed to encourage this company's transformation and ensure the improvement of their performance. Indeed, these concepts have been successfully implemented in large companies, but their deployment in SMEs has to be increased. Some of the barriers to this implementation can be solved with the addition of sustainability as proposed by the European commission through industry 5.0. This paper focuses on the development of a framework for implementing digital twin as an industry 5.0 concept in the SME efficient transformation. Digital twin is one of the industry 4.0 pillar that can be easily combined with sustainability to increase the company performance. This article presents the industry 5.0 methodology developed for the SME digital transformation, the intelligent system designed to support the company changes and to elaborate the digital twin that will facilitate the enterprise sustainable transformation. An example based on a carpentry manufacturing SME is exposed to validate the results of the concepts and tool that have been presented.

Keywords: Digital twin · Artificial intelligence · performance optimization · sustainable digital transformation · intelligent system

1 Introduction

New technologies such as robotics, artificial intelligence or Internet of Thing (IoT) are exploited for improving the company performance [1]. Industry 4.0 concepts are described in the literature through 9 main pillars identified by the Boston consulting group (BCG) [2] and other concepts such as artificial intelligence and cyber-physical systems (CPS) can be added to these pillars [3]. These concepts are generally exploited in large companies with a real success in terms of performance. Indeed, the digitization contributes to the efficient integration of the "present interconnected intelligent systems on the shop floor and in the workspace area" [4]. In the process manufacturing, the digital twin becomes very important [5] and is presented through various studies [6–8] as a tool for increasing the company performance.

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Despite the benefits that could be obtained by using these industry 4.0 concepts, SMEs are not enthusiastic to implement them. Numerous reasons can be pointed out [9]. This paper aims to find brakes for the industry 4.0 implementation in SMEs, to define levers for the implementation acceleration and to contribute to the company performance improvement. For instance, Pinto et al. [10] have established a model for a gradual implementation of industry 4.0 in SMEs. Indeed, this gradual implementation also requires to take into account sustainable aspects in the company transformation.

The next sections of the paper are organized as follow. After a literature review based on organizational methods, sustainability and industry 4.0 concepts, this paper focuses on the architecture of an intelligent system being developed to support the industry 5.0 methodology that has been elaborated for the digital transformation of SMEs. A zoom is made on the digital twin concepts and module used to improve the company performance. An example based on a small pharmaceutic company will be shown for illustrating the digital twin concepts and tool and presenting how they could improve the company performance.

2 Literature Review

This section focuses on concepts, formalisms, methods and tools which contribute to the company improvement and that could be combined in the definition of the sustainable methodology for SME digital transformation. These formalisms are also used in the development of the intelligent system to support the company digital transformation. The parts presented are about the organizational methods such as lean manufacturing, the industry 4.0 concepts including physical and informational transformation tools (digital twin, robotics, IoT), the concepts of sustainability and intelligent systems development concepts.

2.1 The Organizational Methods in an Industry 4.0 Environment

Lean manufacturing methodology is defined in Womack et al. [11] and Langlotz and Aurich [12] as a concept for reducing the production systems complexity, due to the customer versality, by implementing a set of methods in order to reduce waste and improve the production processes performance. Lean manufacturing is considered as a continuous improvement system that integrates the physical and information flows in order to identify and eliminate waste affecting lead time, material cost, and product quality [13]. As explained in Monden [14], lean production system (LPS) allows to adjust value creation with customer demand and to eliminate non added values in the manufacturing system. For instance, Value Stream Mapping (VSM) tool is used to define the existing flows organization and to find added and non-added values. Despite the use of these different tools lean manufacturing methodology is not clearly a problem-solving method and needs to be adapted for soling concrete company difficulties (specific problems). DMAIC (Define, Measure, Analyze, Innovate, Control) method appears as a possibility to complete lean manufacturing concepts for increasing the company performance improvement. Indeed, this method is described in Krueger et al. [15] as a "scientific, systematic, statistical and smart method that is suitable for the enhancing product's quality,

innovation and improving customer's satisfaction. DMAIC corresponds to a methodology that "filter a complex problem with many uncontrolled variables to a situation where quality is controlled" [16]. Six sigma method that contains DMAIC tool is presented as an "organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates" [17]. For instance, this systematic method contributes to define an optimization framework for improving supply chain performance [18]. This method is complementary to lean manufacturing by focusing on quality process improvement in addition to the QCD (quality, cost and Lead time) optimization by exploiting lean manufacturing tools. The combination of both methodologies allows to optimize the operational production system but needs to be completed with another methodology for managing mid and long terms decision of the company transformation. Methodologies such as CIMOSA [19] focusing on organizational and scientific dimensions, PERA [20] exploiting human aspects in the company transformation and GRAI ("Graphe de Réseaux à Activités Interreliées") methodology [21] focusing on all dimensions such as functional view, physical system, process view, informational system and decisional system could be used for the company modelling. The GRAI approach, based on five models, consists in the existing system modelling, the model analysis for finding Strength and weaknesses, and the definition of future models that will be implemented step by step, with a short, mid and long terms action plan. The company transformation also requires the integration of real time data and the definition of actions that will take into account these data. Design of experiment (DOE) appears as one way that could be used in this case. DOE corresponds to a "structured and organized method to determine relationships between variables that influence a process with the output of that process" [22].

This paper proposes to combine lean manufacturing, DMAIC, DOE and GRAI methodology in the SME digital transformation process. Indeed, new technologies will contribute to this transformation. The following section presents technological concepts and tools that have been exploited for the company performance improvement.

2.2 The Industry 4.0 Concepts

The main concepts of industry 4.0 are respectively named, internet of things, big data, CPS, system integration, immersive reality, blockchain, additive manufacturing and 3D printing [23]. They contribute to the performance improvement in large companies. The industry 4.0 companies are generally structured to respect four main characteristics [24]: the vertical structuration of the smart production systems, the horizontal integration through the optimization of the global value chain networks, the through-life engineering across the entire value chain and the impact of exponential technologies [25]. The vertical integration involves the structuration of all decision and information levels of the company (from the operational to the strategic including monitoring, control and supervision of the company functions). Indeed, this vertical networking contributes to the company flexibility and adaptation to the market [24] and facilitates their ability to respond in a customer specific and individualized manner [26]. The horizontal integration allows to optimize the relation between all processes, entities and services of the company global value chain [27].

The company digital transformation requires the use of the previous industry 4.0 concepts. This paper focuses on the CPS that exploits five principles for its elaboration [28]: the connection (agent and communication protocol for sending information, the conversion (data acquisition with sensors, controllers, etc. and conversion for exploitation), the cyber (digital twin or cyber avatars), the cognition (detection of failures and use of decision aided system)and the configuration (feedback loop between cyberspace and physical space; self-configuration and self-adaptation.

The benefits of digital twin exploitation in a company have been clearly presented in [29, 30]. Some of them correspond to the use of simulation to increase the system model accuracy, internet of things for advancing preventative actions and analytics, and digital twin for providing a substantial return of investment by decreasing test duration and verification cost.

The concepts of industry 4.0 that have been presented above can be exploited mainly by combining them with the sustainability (social, economic and environmental) aspects as described in [31] for elaborating a new hybrid industry 5.0 methodology integrating digital twin as a tool for increasing the performance of SMEs. The three sustainability pillars are concerned in the SME transformation. The next section focuses on the concepts of the sustainable methodology that has been developed for transforming SMEs.

3 The Hybrid Industry 5.0 Methodology

3.1 The Sustainable Methodology

The concepts presented in the previous section have been combined for elaborating a hybrid sustainable methodology based on industry 4.0 concepts for transforming SMEs [32]. Both sustainability and industry 4.0 concepts generally used with success for large companies are integrated in the new methodology. Indeed, most of industry 4.0 companies focus exclusively on the use technological tools in the company transformation, but none on the social, societal and environmental dimensions. The company sustainable transformation is realized through three dimensions: the physical by exploiting organizational methodologies (Lean manufacturing combined with DMAIC and DOE), the decisional by using GRAI methodology and the informational by introducing new technologies for improving the company performance.

The specificity of the hybrid methodology is to use the positive sustainability concepts as the base of the three transformations. The idea is to optimize continuously all the company processes in a sustainable way. Sustainability is exploited as the kernel of the company transformation. Sustainability parameters are social, societal and environmental dimensions and are combined with new technologies, flexibility and aspects related to change to increase business performance. The company digital transformation starts with the global context acquisition and the definition of the objectives. Then, the company existing system is modelled, analyzed and its performance is measured with the sustainable industry 4.0 performance indicators. The digital transformation steps are defined and realized for increasing the company gradually. Indeed, for ensuring the success of the transformation, this framework has to be supported by an intelligent system for managing all data that will be associated to the company transformation.

The consequence of the focus on sustainable aspects during the industry 4.0 transformation is the adaptation of the methodology to all companies, mainly SMEs. Then, according to an SME objectives, expectations and capacities, the implementation of industry 4.0 can be realized progressively. Indeed, integral ecology including sustainable criteria (social, societal and environmental) for the human and nature well-being is clearly exploited in this transformation. This new transformation philosophy is called industry 5.0 by European commission and corresponds actually to the new efficient way being exploited for making European companies competitive in the globalization context, Covid pandemic context and the geopolitical situation. In this new methodology, Sustainability is defined as the 12th pillar of industry 4.0 for SMEs (see Fig. 1).

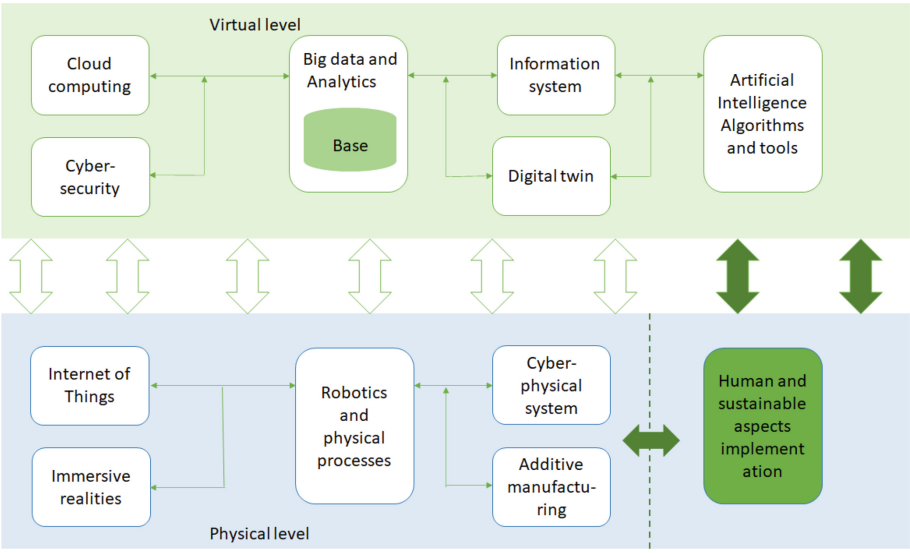

Fig. 1. Industry 5.0: Sustainability as the 12th pillar of industry 4.0

3.2 The Cyber-Physical Module

Based on these pillars, an intelligent system is being developed for supporting the sustainable methodology. This intelligent tool is composed of modules that are used to interact with the transformation actors during the company evolution phases. This paper will focus on the CPS. This module contains three parts: the digital twin builder for elaborating the digital twin (processes and flows) of the company is related to existing simulation tools such as Flexsim and Anylogic, the information systems data converter which allows to integrate data from the information system (ERP, MES, etc..) in the physical processes, and the new technologies data converter which is used for acquiring data of the physical system and the operators for integrating them in the information system. The new technologies data converter requires the implementation of the physical new technologies in the company (IoT, Robots, cobot, machines, etc.). Data coming

from these physical new technologies will have to be uploaded in the information system and to be used to take the right decisions for improving the company performance. The information systems data converter is used to integrate data of the information system in the physical processes. It creates the link with new technologies for translating orders and instructions to machines, cobots, and humans. The digital twin module contributes to elaborate for each part of the company a virtual equivalence of the physical processes. The digital twin sub-parts are at three levels (see Fig. 2):

- The operational level as a tool for aiding operators in the decision they will take. It is an efficient operational decision aided tool. This part exploits the digital twin (simulation flows) of the manufacturing or the supply chain through tools like Flexsim, or Anylogic. A virtual model of the existing company is made and linked to the physical system for integrating data in real time. This tool allows the operator to follow the state of each machine, cobot, mobile robot, IoTs and adapt his decision to the real context. The operator can also test his choice on the virtual tool before making decision.
- The tactical level for representing a real time supervisor and a decision aided tool for managers in their decision-making processes. The link with the information system is created and the information coming from the physical system are added in real time.
- The strategic level corresponding to a real tie blackboard and decision aided tool for the company direction. It contributes clearly to the decision-making process, but also to follow the impact of the investment in industry 4.0 technologies and sustainable aspects on the company performance. The objective is to know exactly the results of the company modernization process during the digital transformation. The tool will also allow to test the potential impact of future investments before making them.

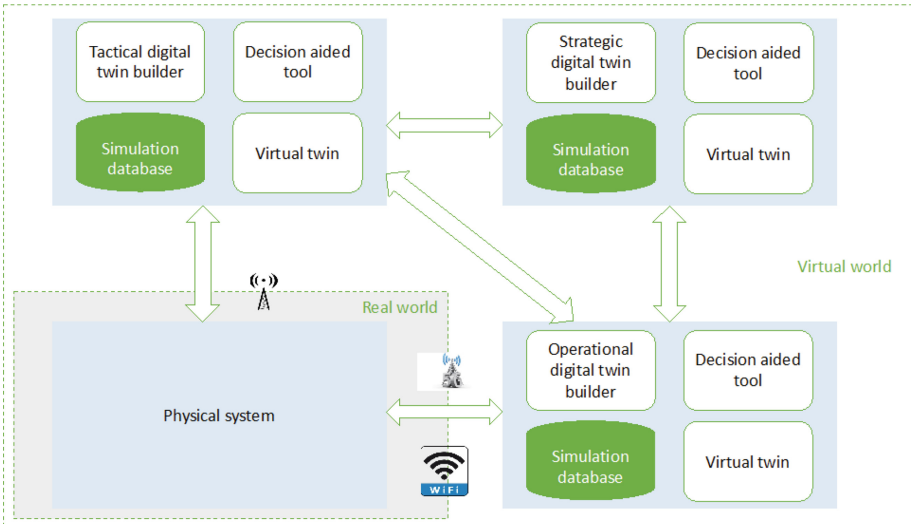

Fig. 2. Structure of the digital twin builder

The CPS containing the digital twin builder is being developed and operational digital twins have been already elaborated by exploiting Flexsim and Anylogic tools for simulating the real company flows. The next step corresponds to the validation of the company performance increasing through the use of the digital twins as performance tools.

4 Illustration

This company is specialized in carpentry for almost 40 years. It practices the second transformation by machining and assembling exterior joinery. At the latest result, the turnover is 3.221.113 € and it currently employs 34 administrative and technical employees with an average age of 40 years. The company targets an exclusively professional clientele: carpenters, craftsmen and merchants. It offers tailor-made products in the south and center of France, as well as in the Paris region. The company offers windows, patio doors and doors in oak, moabi, movingui or pine. The most requested species is moabi, then movingui, oak and then pine. The window market has been growing at a rate of 9% per year since 2006. This market has a sure potential because in 2021, we should reach a volume of 25 million windows sold. The diversity of the customer and the quantity of products to elaborate encourage the company to decide the modernization of its manufacturing lines. In the workshop, there is a main flow for standard products and specialized workshops for more complex products. The workshop remains semi-industrial despite a very efficient production tool. The company manager has decided to transform digitally his enterprise by introducing new technologies such as mobile robot, IoTs, Cobots and information systems. But he expects to increase his company performance with this transformation without excluding the workers. Indeed, he thinks that the highest value of his company is the know-how of his employees and their qualification to specific tasks.

The sustainable Industry 4.0 methodology presented above, and its intelligent system have been used in this SME to make its digital sustainable transformation. At the beginning of the project, the intelligent system has been used as a support for the data acquisition through documents recording and semi-directive interviews (qualitative methodology) for understanding all the company needs and expectations. The existing system modelling has been done through the model representation and the use of the sustainable methodology concepts and tools (such as lean manufacturing). The next step was the analysis of the existing system with the detection of inconsistencies, the elaboration of strengths and points to improve, and the measure of the company global performance by using the performance measurement module.

The design phase corresponds to the step during which the CPS has been used to elaborate the workshop digital twin in addition to the implementation of RPA (Robotic Process Automation) tools in the administrative processes for increasing the company performance. Indeed, lean manufacturing has also been used with the implementation of a new Kanban organization, the use of value stream mapping tool for finding added-values and suppressing non-added value, the definition of production takt-time, the implementation of components supermarket, the use of Poka-yoke to ensure that products will be well-done by the operators, the procurement delivery on the production line (by train), the use of single minute exchange of die tool (SMED) to increase the level

of flexibility in the production lines. Non added values or repetitive tasks have to be suppressed or done by cobots or mobile robots. And added value tasks could be done by operators and cobots are used as human collaborators. The manual processes detected at the beginning are being transforming into hybrid processes integrating human and cobots. The exploitation of the intelligent system allows to define a human machine interface for operators in order to give them the opportunity of decision in operational tasks. The digital twin that has been developed is used by managers to adapt the manufacturing lines to the customer orders (flexibility) and to define how many cobots, mobile robots, IoTs, etc. are required for increasing the company performance and keeping operators as the main responsible of the production system. The digital twin contributes to aid operators during their production. For instance, with the digital twin, the operator can test the impact of his decision before elaborating the product.

With this new methodology focusing on the sustainability aspect, it was easy to convince the director and the operators on what the new technologies and digital transformation would give to the company. On the environmental dimension, a focus has been done on energy reduction with an action plan to be implemented on electricity, gas, re-lamping of factories, etc. but the other environmental axes have also been studied (see Fig. 3). The orange curve corresponds to the company initial situation, the gray represents the situation after the changes and the blue the ideal situation. This measure has been done for the company modernization degree associated to the integration of new technologies and also for the other pillars of sustainability (social and economic).

On the social dimension, the company is composed of both young and senior employees who are daily transforming the company culture. Young people need to switch,

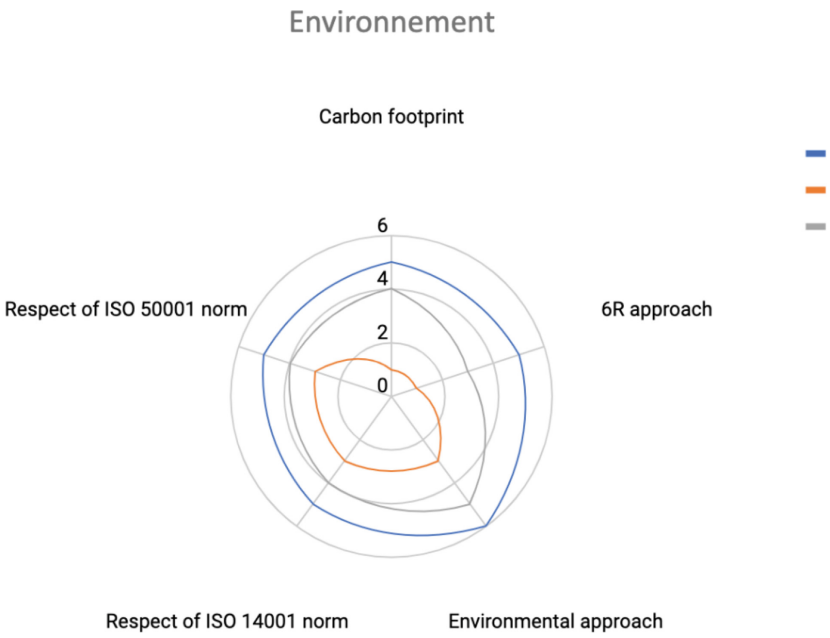

Fig. 3. SME performance measurement through environmental criterion

to go from one task to another, and this is possible with the introduction of the new technologies. The simulation with the digital twin allows to validate these flexibility decisions.

The case study in the company was a success and confirms the efficiency of the hybrid methodology and the intelligent tool developed to transform digitally the company. Indeed, in this case digital twin clearly appears as a tool to increase the company performance.

5 Conclusion

The existing economic situation in the word is not flourishing because of the covid crisis and the geopolitical atmosphere. But the European companies also confronted to the concurrence of the emerging countries companies. Industry 4.0 concepts have been developed for transforming these companies in order to increase their performance. Indeed, these concepts are a real success in large companies with significant results. But their implementation in SMEs has clearly to be improved. In this paper sustainability has been proposed as the kernel of a hybrid methodology for accelerating the industry 4.0 concepts implementation in SMEs. An intelligent system being developed for supporting this methodology has been presented. A focus has been done on its module allowing to develop the digital twin of the company manufacturing system. An example has been presented for illustrating concepts that have been shown.

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Optimization Patterns Enabled by Industry 4.0/5.0 Data

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Abstract. Design patterns are widely adopted in software engineering and can be defined as "general design solutions to recurrent problems". We extend this approach to improve the modeling activities required for addressing optimization problems, specifically those coming from production planning in manufacturing firms. We propose a general framework for optimization patterns, including general, problem and solver specific patterns as well as data connection patterns used to collect and effectively use the large data sets that can be provided by firms that adopt Industry 4.0 paradigm, or also the newer and complementary 5.0 paradigm. We then provide a vertical application of such patterns to address a strategic planning problem inspired by a real application in a manufacturing company operating in Italy. The case study shows all the main activities that begin with the problem description, continues through data definition and optimization patterns selection, finally leading to a prototypical solution to the problem.

Keywords: Production planning · Industry 4.0/5.0 · Modeling systems

1 Introduction

A pattern has been defined as "an idea that has been useful in one practical context and will probably be useful in others" [1]; though design patterns were first introduced for the design of buildings in [2], they've found great success in software engineering during the last decades and the usage of the term is by now preeminently related to this area. It was originally popularized by the famous "Gang of Four" authors in their book [3] and hence widely adopted in the software development community as a best practice.

We extend this approach to improve the modeling activities that are required when an optimization problem needs to be modeled (and then, subsequently, solved). The basic idea is to avoid or, at least, reduce the time and effort spent addressing parts of the formalization that can be better obtained selecting the right pattern or set of patterns for the problem at hand, but also exploit the best practices gathered over the years to translate such formal models into different possible software implementations to solve actual instances of the problem. We focus on production planning related optimization problems that commonly arise in manufacturing firms. The proposed approach can be more effectively used within Industry 4.0 and 5.0 contexts, thanks to the large availability of data regarding the production process in firms that adhere to these initiatives.

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A pioneering work in the adoption of patterns in constraint programming modeling can be found in [4], where general, high-level usages of patterns are proposed to address matrix models and symmetry related constraints. A possible use of constraint patterns to model and solve domain specific problems, namely scheduling problems, is presented in [5].

Industry 4.0, also known as the fourth industrial revolution, aims to improve operational productivity and efficiency through increased automation and the connection of virtual and physical worlds in industry. A vast amount of literature has been produced on Industry 4.0 over the last ten years, including several reviews. We used [6] as a reference, as it examines the progress, benefits, drawbacks, needs, and existing techniques for implementing the Industry 4.0 initiative with a focus on production planning research. Industry 4.0, however, is unable to fully meet the growing demand for personalization or the management of factories where human labor highly pervades the production process. As a result, Industry 5.0 was created to focus on personalized manufacturing and the empowerment of human involvement in manufacturing processes. The review in [7] provides a very up-to-date, in-depth examination of the various factors that are driving the development of Industry 5.0, including current trends, practical applications, desired outcomes, technical obstacles, necessary technologies, ongoing projects, academic research, established standards, and areas for future study.

Enterprise information systems such as ERPs (Enterprise Resource Planning), WFMs (WorkFlow Management) and MESs (Manufacturing Execution System) typically support the planning and execution of operations within industries, but their wider and wider adoption within Industry 4.0 adherent firms, and even more with the complementary Industry 5.0 paradigm, lead to the availability of vast amount of data, which can be effectively used to apprehend the business process as it is being executed. This promising research is called process mining: an early introduction can be found in [8], while an updated review on the most promising works in the field is reported in [9]. Data delivered by IoT devices in a highly automated Industry 4.0 firm can be used by appropriate patterns (namely, data patterns) to feed problem specific patterns that include intelligent algorithms that are typical of an Industry 5.0 "smart factory".

In Sect. 2, we introduce a general framework for optimization patterns, including general, problem specific and solver specific patterns as well as data connection. Section 3 shows how to model a real world, manufacturing problem using optimization patterns and then, in Sect. 4, this model is used, along with specific patterns, to implement a first, working, prototype of a Decision Support System to support the user in addressing and solving real instances of the described problem.

2 Optimization Patterns

We introduce domain-specific optimization patterns, that portray recurring problems, provide modeling approaches and consequential possible implementations to solve them. Optimization patterns aim to describe the best practices of how to model various aspects of an optimization problem: e.g., the organization of tasks and subtasks in a project scheduling problem, or the management of processing and setup times in a single machine scheduling problem.

Formally similarly to traditional software design patterns, an optimization pattern is characterized by four elements: the identifying *name*, the *problem* that describes when to apply the pattern, the *solution* that explains how the pattern solves the problem and the *consequences* that include relations and trade-offs with other patterns.

The term *optimization pattern* needs to be declined to better distinguish different types that are all needed, at different levels, to address a typical optimization problem: general patterns, problem specific patterns, solver specific patterns and data patterns. Using and combining optimization patterns, the largest effort must be put into the analysis of the optimization problem to be solved, both in general terms and in detail, matching each aspect to be modeled with a specific pattern, but then avoiding the time usually spent translating each feature into mathematical expressions and then developing an algorithm to solve the problem.

General patterns are used to represent concepts that may occur in any optimization problem, not specifically targeted to formalize an issue that is peculiar to just a detailed problem, e.g., a numeric or a logic *decision variable* pattern, a *sequencing decision* pattern, or a unique *assignment* pattern.

Problem Specific Patterns are used to represent a well-defined feature of a problem, including any general pattern the specific problem requires, but not detailing any aspect that is specific of the solver used to solve the problem.

Solver specific patterns are used to *translate* general and problem specific patterns into more detailed patterns, that use the capabilities offered by the adopted solver. For instance, an *activity* pattern would effectively translate into an *OPL CP Interval* pattern when using IBM OPL CP solver, while it might translate into a combination of numeric decision patterns when using the MiniZinc solver.

To better clarify the difference between the last two types: patterns suitable to model a project scheduling problem will include the general patterns needed to represent the hierarchy connections among activities (namely, a *container* pattern), but will not include the solver specific ones that could be used to better represent them in order to subsequently solve the problem: e.g., an *OPL CP Span* pattern that models an efficient way to implement this type of constraints if we adopt the IBM CP solver.

Data patterns represent a typology of information that is characteristic of some problems: e.g., a production order pattern is typically encountered when dealing with production planning problems where the underlying enterprise software includes an Enterprise Resource Planning (ERP) module.

The proposed approach is being currently and actively used on several case studies, that are providing the opportunity to define several patterns. The aim of this paper is not to introduce the whole library of these patterns, which is still currently being developed and enriched, but rather to show a possible usage of this approach to address a specific production planning problem coming from a real case. In Sect. 3, the case is presented, along with the patterns used to model its characteristics, while Sect. 4 will focus on the patterns used to create a DSS to solve actual instances of the problem.

3 Modeling Through Patterns

The proposed approach is used to model and solve a production planning problem in a manufacturing firm. The planning problem is summarized below and then the most suitable optimization patterns are selected to describe their usage to model and solve the problem.

3.1 Problem Statement

The problem at hand requires the selection of a subset of the available production orders and their allocation to different production plants and, within each production plant, to different production lines, pursuing both efficiency and customer related objectives, while satisfying technological and capacity constraints that are specified below. A production order is characterized by:

- the product type it manufactures (only one product per production order);
- the work effort it requires (the time needed to complete the order);
- the planned order that includes it, along with other associated production orders

Capacity Related Constraints and Objectives
Each order must be assigned to a specific production line within a plant. For each line, three capacity values need be considered: the minimum, desired and maximum capacity. Hard constraints are enforced to guarantee that the overall effort required by the orders assigned to the line is in the [minimum, maximum] interval, while the desired capacity is pursued as one of the objectives.

Furthermore, the minimum and maximum static capacity introduced above can be "modulated" on a daily basis according to a calendar, which allows the user to specify variations on such values that consider day offs or maintenance times during which one or more production lines in a plant need to be stopped, and hence should not be considered in the total amount of production orders assigned in that specific time.

Product Type Related Constraints and Objectives
Some features of the product produced by the order determines which plants and which production lines can handle it both in terms of hard technological constraints, that allow some product types only on some production lines, and in terms of preference levels to be targeted when choosing among different production lines.

More specifically: the product model determines the plants enabled to produce the order and indicates a preference ranking among them, while the product technological features allow its production only on specific lines and can possibly determine a preferred line.

Another objective to be pursued is the minimization of different product types to lines in each plant, in order to reduce the logistic overhead required by each product type and to allow for a better productivity of the assembly line.

Grouping Constraints
Production orders are the single items to be selected and assigned, but some grouping logic must be considered during the process. Namely: once a production order is selected

(i.e., it is assigned to a line), all the production orders that are included in the same planned order must be selected as well, and their assignment to specific lines is independent but limited to lines of the same plant.

3.2 Patterns for the Problem

In order to show a possible usage of optimization patterns, we introduce only the optimization patterns that are needed for the problem at hand, since a comprehensive presentation of all the available, or in development, optimization patterns is not the focus of this paper.

Assignment patterns are used to model the decision to manufacture an order on a specific plant and line; such a pattern includes the concept of exclusiveness: once an order is assigned to a line, no other line can be selected. Furthermore, an assignment pattern may be optional or mandatory, modeling the possibility for the decision tool to exclude the order from the selection or not; e.g., to model the case in which some specific orders are required to be present in the selection (typically because they are overdue).

A *counting* pattern is used to model the need to count how many times a given event occurs within the solution or the amount of a decision related quantity. In this problem, counting patterns are used to model the number of different product types assigned to a plant and to calculate the work effort assigned to each line.

The minimum and maximum capacity constraints required for each production line are modeled by *linear combination* patterns involving the counting patterns and the given minimum/maximum quantities.

The grouping constraints introduced in the problem statement are effectively translated by means of *logical* patterns, namely *if-then* patterns.

As in most real problems, several objectives are to be pursued: when all the required objectives can be reconducted to a same type of measure (typically a cost), a *linear combination* pattern can be used to model the situation. In the case study, however, the objectives include aiming at capacity targets as well as minimizing the number of different product types assigned to each production plant. Each objective can be modeled through a *linear minimization* or *linear maximization* pattern, while a *hierarchical multiple-objectives* pattern can be used to model the relation among all the objectives, following the approach presented in [10]. This pattern allows to define a ranking among different objectives, so that the solving process can proceed to a new solution only if this one improves a secondary objective while not worsening those with a higher priority.

4 Implementing Through Patterns

Once the logical structure of the problem has been described, solver specific and data driven patterns are needed to proceed to a software implementation, allowing real data to be used to create actual instances of the problem and to be able to solve them using the selected solver.

4.1 Data Driven Patterns

The firm providing the test case adopts SAP as its ERP, so data patterns designed for this popular system have been used, specifically the *production order* pattern and the *work center* pattern, while the custom tables defined in the company's system to keep track of capacity related constraints and forced assignments were managed by *interval data* patterns and *force/forbid* patterns.

Production orders data are provided by the user, conveniently filtering the ERP data: specifically, the user defines a time horizon and all production orders that have a due date within this time interval are selected as input for the planning. A subset of these orders, the ones already overdue or due within a parametrized number of days from the planning start, are automatically forced to a previously assigned plant, while they still remain freely assignable to one of the available and compatible production lines within that plant.

Custom tables in the ERP, and the corresponding *parameter* patterns, allow the user to specify:

- Minimum/maximum number of minutes to be assigned to each line.
- Target capacity to be pursued for each line.
- Priority among the specified objectives, to be considered by the multi-objective pattern.
- Calendars-related data, to be considered by the capacity related patterns in order to modify the available production times according to day offs and programmed maintenance.
- Preferences to be considered when assigning orders to different plants or lines according to some of the features of the order.
- Solution related parameters such as a time limit or tolerances to be considered in the objective function.

The data needed to manage the possibility for each plant and line to manufacture the different product types, as well as the data regarding preference levels in the assignments, are modeled through data patterns that take advantage of the data from previous historical assignments available in the ERP of the business, as well as more shopfloor level data available in the MES event logs.

Previous assignments historically saved in the ERP data are used to define which product types can be planned on each plant and, reversely, which are not assignable (*enable* pattern).

MES event logs allow to characterize aspects modeled by *preference* patterns:

- which product types are preferably assigned to specific production lines;
- which assignments are more frequently modified by the user on the shopfloor;
- which types of assignments typically generate problems in terms of delay or machine stops.

4.2 Solver Specific Patterns

The next, and last, step to achieve an implementation able to solve real instances of the problem consists in the adoption of a specific solver and hence using the most

suitable solver specific patterns, to translate the general and problem patterns into actually solvable instances of the problem.

The choice of the solver depends on various aspects to be considered: e.g. the focus of the project, solvers that are possibly already available in the company's system, performance issues, etc. In the case study, the company already had licenses of the IBM CPLEX Optimization Studio suite (CPOS), which is a leading commercial tool including both mixed integer linear programming and constraint programming modeling and solving capabilities, as detailed in [11].

The production planning problem used to illustrate the proposed approach is an assignment problem, not including any time-related aspect, that would require scheduling specific patterns. Hence, the CPOS specific patterns used to create an interface between the problem data and the solver are the ones related to integer linear programming, namely: the self-explanatory binary and integer decision variable and the integer linear expression patterns and the CPOS multi-objective pattern, which defines a multi-criteria policy, ordering the different criteria and performing lexicographic optimization. This solver specific pattern takes advantage of the *StaticLex* feature provided by the solver, that handles the defined multiple criteria while exploring the solution space. The following table shows an example of how this optimization pattern is specified.

Name	CPOS multi-objective pattern
Problem	A multiple-criteria optimization is required in an Integer Linear Programming problem solved by CPOS
Solution	The pattern considers the provided order among the different criteria and performs lexicographic optimization using the StaticLex feature provided by the CPOS solver
Consequences	The pattern requires an ordered list of objectives defined through the CPOS Linear Expression pattern

The proposed implementation was used to provide the firm with a Decision Support System that was tested on real instances of the problem coming from the weekly planning problems actually addressed by the partner company over the last two quarters and typically involved the assignment of thousands of orders to more than 50 departments. The key point here is not the computational complexity of the problem, but the ability to rapidly and consistently define the problem and hence obtain a valid tool to solve the problem by simply selecting, tuning and applying the right patterns for the problem at hand.

5 Conclusions and Future Developments

The proposed approach was successfully used to design and implement a decision support system that is being currently tested and tuned in the company that provided the test case.

The general and problem specific patterns helped effectively identifying and modeling the main aspects of the problem, without the need to think and write a full mathematical formulation. Data patterns allowed a fast implementation of an interface between the

company's systems and the developed tool, leading to the generation of real instances since from the early stages of development. Finally, the solver specific patterns enabled the tool to provide solutions to these instances, that provided valuable hints to validate and tune the problem specific patterns.

The definition of a first comprehensive set of optimization patterns for production planning related problems will be the focus of the next work on optimization patterns, with a deeper presentation of the library that includes them.

The real problem presented in this paper will be addressed with different solvers, and future work will show how to select and use the suitable patterns to effectively implement the different options and then benchmark their efficiency.

On the other hand, different problems resulting from other industrial cases will be analyzed, leading to the development and test of other problem specific patterns: project planning and production scheduling problems are the main candidates for the next works.

Finally, the formal definition of a library of general patterns and their related solver specific patterns could lead to the release of a well documented open source repository of optimization patterns.

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Industry 5.0: Aspects of Collaboration Technologies

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Abstract. Technological developments and methodologies for manufacturing processes have changed the understanding and use of technology and the paradigm of human-machine interaction. Industry 4.0 has exacerbated the problems of human-machine interaction, especially in terms of interaction between humans and robots. The concept of Industry 5.0 overcomes the challenges of human-robot interaction by focusing on improving the usability, ergonomics, and accessibility of the machine, considering human needs. The article analyzes current trends in the development of collaboration technologies that can bridge the gap in understanding between humans and robots. The interaction of man and robots is considered from different points of view, which makes it possible to identify the main aspects of such interactions, problems, and possible benefits. The relationship between interaction problems, aspects of perception, and possible technologies that allow successful cooperation is also revealed. It was revealed that the key technologies in this direction are implementing artificial intelligence, machine learning, and digital twins. At the same time, there remain problems in interaction, such as ethical problems, which cannot be solved only through the development of technologies.

Keywords: Sustainable Manufacturing · Robots · Digital Twin · Artificial Intelligence · Manufacturing Innovation

1 Introduction

Automation of production processes makes it possible to produce better quality goods in less time and at a lower cost. Three industrial revolutions have shaped the current state of production. Industry 4.0 is believed to have started in 2011, initiated by the German Government. The achievements of Industry 4.0 [1] have made it possible to automate major technological processes and make them more productive through the use of artificial intelligence technologies and the transformation of technological systems into cyber-physical systems [2]. Although Industry 4.0 is in its early stages, there is already talk of Industry 5.0, where the key idea is Human-Robot Co-working [3].

Industry 4.0 is the intelligent networking of machines and processes focused on overall productivity, adaptability, and flexibility. Whereas Industry 5.0 is resilient, sustainable, and human-centric manufacturing, where social values are placed at the center

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of the production process with a focus on the future [4]. Industry 5.0 aims to overcome the problem of human-machine interaction by focusing on improving the usability and accessibility of the machine, taking into account human needs and ergonomics, and ensuring that human-machine collaboration brings mutual benefits [5]. Particularly interesting in this context is the interaction between humans and robots controlled by artificial intelligence-based technologies [6].

Problems in the interaction between humans and robots include the following:

- Safety issues. It is the first-priority issue because it is vital for ensuring human safety during the interaction process and corresponds to the first law of robotics. However, in practice, it is pretty difficult to comply with safety requirements, especially if the robot's design does not consider all the risks and threats that technology can pose. Robots can inadvertently become a source of danger if they are not designed with appropriate safety features or if they malfunction. To prevent mentioned above, a robot must be able to detect the presence of a human and analyze a possible threat to stop its threatening actions that pose a source of danger in time. In other words, the robot must "see" a person entering its working area and react accordingly [7].
- Lack of empathy. Robots lack emotional intelligence. They are unable to understand and respond to human emotional behavior. Therefore, there is a problem with the appropriate behavior of the robot in cases where a person behaves emotionally differently from the traditional sequence of actions [8].
- Limited ability to adapt. It is difficult for robots to adjust to changes in the situation or environment, which makes them less flexible than humans. Human assistance, which consists in training the robot, can increase the robot's adaptive capabilities [9].
- Communication barriers. It can be challenging for robots and humans to communicate because humans can use different communication channels simultaneously, such as verbal and non-verbal, as well as hints or analogies that are not easily understood by the robot [9].
- Lack of trust. This problem relates to humans' limited perception of technology [10]. Lack of trust also includes concerns about the security of personal information and trust in how the robot will perform tasks.
- Ethical issues. The robot is not able to take into account humanitarian aspects in decision-making [11].
- Job redistribution. The use of robots in some industries can lead to the transfer of repetitive or low-skill jobs from humans to robots. On the one hand, this frees people from routine labor, but on the other hand, it requires people to move to a higher level of the production hierarchy. In such conditions, a person ceases to be the main production force and becomes a responsible decision-maker or a mentor for a robot.

Solving these problems requires a thorough analysis of collaborative technologies in terms of their capabilities or limitations. It is important to consider interaction in the context of data transfer from human to robot, from robot to human, and mutual information exchange. The interaction issues identified in this section are the main aspects of analyzing collaborative technologies.

This study is relevant because it aims to analyze current trends in developing collaborative technologies that can bridge the gap in understanding between humans and robots. The interaction between humans and robots is considered from different perspectives,

which allows us to identify the main aspects of such interactions, problems, and possible advantages.

The paper is organized using the following structure. Section 2 "Towards Collaboration Technologies" presents an analysis of current technologies for human-robot collaboration in the context of the Industry 5.0 paradigm. Section 3 "Results and Discussion" describes the obtained results and provides a comparison with other research studies. Section 4 "Conclusions" summarizes the findings and highlights the scientific novelty and practical relevance for the industry.

2 Towards Collaboration Technologies

2.1 Human to Robot

To ensure human and robot interaction in the collaborative workspace, it is necessary to track the body position and actions of the person. A safe environment can be guaranteed only by knowing the current position of a person's body. Several levels of human-robot interaction can be defined, and therefore several levels of risk in such interactions. The system must process and react accordingly to prevent human injury [12].

Research has already been conducted on recognizing and classifying human movements using various technologies. These include video-based recognition of human actions [13], a Kinect sensor [14], depth maps [15], and combined position sensors attached to human body parts [16]. They mainly use machine learning algorithms [17] and various human pose classification methods [18]. Self-Organizing Maps System [19, 20], Bag-of-Visual-Words model [21], and other described algorithms work on a similar principle. All of them extract a person's position from the stream and then classify the action according to the sequence of positions of the human skeleton. This approach allows tracking a person in a shared workspace with a robot.

Knowing the human's position in space is not enough for full-fledged human-robot collaboration. A specific communication tool is needed between the human and the robot, with the help of which the human could give control commands to the robot. Standard means of entering commands through a stationary control panel or through portable controllers with buttons are still relevant. However, this method of command input makes it impossible to fully interact with the robot in one workspace, as envisioned by Industry 5.0. One of the available ways to enter commands is to analyze the position and movements of the hands from a head-mounted camera [22]. Another reliable and convenient method of data input to ensure human-robot interaction with human hands free is speech recognition tools [23] or a brain-computer interface with a helmet to read brain waves and transmit them to a data processing device [24].

2.2 Robot to Human

Another extremely important process is the transfer of information from robot to human. Low-cost cameras with high-quality images and Virtual Reality/Augmented Reality (VR/AR) technologies enable the transfer of visual information from robot to human. AR technology can add visual cues to humans in a collaborative human-centered workspace, increasing overall system performance and workflow safety [25].

Regarding remote robot control, visual information transfer is critical because the first thing we need to navigate in space is an image of the surrounding objects. Controlling a robot is very similar to a game process using virtual reality technology, which helps to immerse yourself in the environment [26]. Therefore, VR/AR technologies are a great way to transfer visual information from robot to human.

An auxiliary technology in transferring data from a robot to a human can be the transfer of tactile sensations. Seeing and feeling the force you press on objects with a manipulator is crucial. It will allow you to perform precise actions or manipulate fragile objects and reveal the properties of objects hidden for visual perception, as well as read contacts with the environment over the entire surface of the robot [27]. Several samples of artificial skin have already been developed. For example, scientists use conductive fabric and deep learning algorithms to analyze touch and pressure on the surface of the fabric [28]. And also multi-contact technology, the large surface haptic device from a few sparsely placed deformation sensors [29].

Research and development are also underway in touch sensors for gripping objects. There are rather crude prototypes of devices that are used to control the force of gripping objects [30, 31], but such devices do not allow for precise manipulation of gripped objects. At the same time, there are also prototypes of devices that read the force of pressing on objects with your fingers [32]. This approach allows the creation of devices for more accurate manipulation of objects and their careful gripping.

2.3 Collaboration Technologies

To create a common workspace and ensure the conditions for human-robot cooperation, a technology is needed to track the actual state of equipment and malfunctions and the relative positioning of all objects in the workspace.

Digital Twin is a digital analog of an actual physical object. A bidirectional real-time connection is established between the Physical and Digital Twins. The concept of a Digital Twin is scalable, meaning that there can be Digital Twins for a single machine, a production process, or even a group of plants [33].

For a digital model to be transformed into a Digital Twin, it is necessary to use auxiliary technologies to ensure real-time communication and data analysis. In this case, the Internet of Things (IoT) provides bidirectional communication between Digital Twin and Physical Twin. Artificial Intelligence (AI) is an excellent adaptive tool for analyzing Cyber-Physical Systems (CPS) data [34].

Digital Twin has a wide range of applications, e.g., manufacturing, aviation, health-care, etc. [35]. In addition, introducing this technology brings benefits throughout the entire production process, from design to equipment status monitoring and product service [36]. There are a number of scientific papers describing the methodology to create digital twins for serial and parallel manipulators [37] and even systems of two manipulators operating in the same workspace [38].

Digital Twin technology, in combination with auxiliary technologies, can prevent operators' risks [39]. This technology allows the creation of a Digital Space as a reflection of physical space. Simultaneous tracking of equipment status, human actions, and the placement of other objects in the workspace will significantly increase the safety of

human-robot collaboration. Digital Twin is a "glue" that combines the technologies required to implement the Industry 5.0 paradigm.

3 Results and Discussion

The modern collaborative technologies discussed in the previous section can solve most of the challenges of the Industry 5.0 paradigm.

Action tracking systems, Artificial Intelligence, and Digital Twin are tools that can solve safety issues in the workplace by continuously tracking the workspace and adapting robots' actions to the changing environment.

The limited ability of robots to adapt is becoming less acute with the development of artificial intelligence and machine learning algorithms. It also helps to solve the job redistribution issue by making a human a mentor for a robot, and VR/AR technologies are auxiliary and facilitate the mentoring process through visual cues.

Haptic technologies, VR/AR, speech recognition, and Brain-Computer Interface help overcome the communication barrier and make communication between humans and robots simpler, more intuitive, and more familiar.

Instead, lack of empathy, lack of trust, and ethical issues are not currently solved by technology and require either other tools or better technology development.

Figure 1 shows the interconnection of research aspects, interaction aspects, and technologies that can help solve the problem of productive and safe human-robot collaboration following the challenges of Industry 5.0.

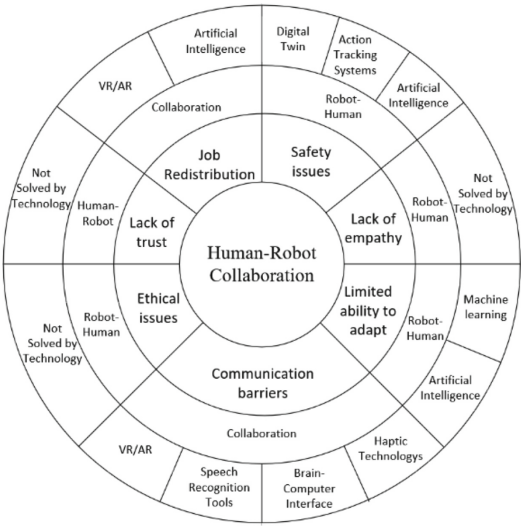

Fig. 1. Connection of aspects of the human-robot collaboration with modern technologies

The analysis of technologies that help solve the challenges of Industry 5.0 showed that most issues could already be solved with the help of technologies. Unsolved or

poorly developed technologies have a mental component (lack of trust in technology on the part of people, lack of empathy in robots, and ethical problems).

Collaborative technologies are constantly evolving, and it is expected that numerous trends will impact the future of collaboration in the coming years. Notably, the statements formulated in this study are supported by previous research findings [40], which outlined a range of human-robot collaborative techniques and evaluated their suitability for diverse manufacturing methods. The research study [41] identified applications, enabling technologies, and future directions for Industry 5.0. The research authors [42] highlighted future trends and predictions regarding implementing emerging technologies and their role in human-robot collaboration. As per the findings of [43], collaborative robotics has been shown to play a crucial role in quality assurance. Its main application is in-process visual inspections to enhance the system's overall efficiency.

4 Conclusions

Collaborative technologies play a critical role in the emergence of Industry 5.0, as they enable seamless communication and coordination among various interconnected systems, including humans, machines, and other systems. By collaborating with humans, robots can perform tasks that require agility and flexibility while learning from human actions to adapt to changing manufacturing processes. In addition, Industry 5.0 collaboration technologies leverage the potential of Artificial Intelligence and machine learning to enhance decision-making and operational efficiency.

In summary, collaboration technologies are vital to Industry 5.0, as they enable effective communication and coordination between diverse systems, with robots and Artificial Intelligence serving as essential components. They facilitate faster decision-making and enhance operational efficiency, ensuring businesses remain competitive and innovative in today's rapidly evolving market.

This research study analyses information technologies that can address the challenges of Industry 5.0. The result of the study is the systematization of information about the already available technologies that can solve the problems of Industry 5.0 and the problems that are not currently solved by technology. The study results can be used as a basis for further research on collaborative technologies in the context of Industry 5.0.

This study addressed some of the challenges and issues surrounding Industry 5.0 while also suggesting potential technologies that could be utilized to address these problems. This scientific research is the basis for further research on creating a collaborative robot-human system for metalworking and assembly processes.

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Digital Transformation

Change Management in a Pet Food Plant: A User-Centric Phenomenological Approach for a Digital Transition

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Abstract. Change management represents a challenge in most organizations, especially when implementing fundamental tools for transitioning to an Industry 5.0 context, such as a newer and more modern enterprise resource planning (ERP). The current paper documents and investigates the change management while implementing an ERP in a plant for industrializing food in Brazil. This approach was phenomenological and focused on the users' perspective, applying a questionnaire after the training and implementation of an ERP. The findings suggest users declared that they were ready to put energy into this change. However, at the same time, they also stated that they see no need to change. This raises doubts about how this change was implemented. The energy and desire might be there for the change, but it needs to be directed to the necessary targets through adequate guidance. Practical orientations for applications in similar contexts and further research directions are pointed out.

Keywords: Change Management · System Implementation · Human Factors in Manufacturing

1 Introduction

The natural evolvement provoked by technological leaps demands companies to adjust and adapt to new environments. In this context, several concepts emerged, "digitization", "digital transformation (DT)", "digitalization", "Industry 4.0 (I4.0)", and "Industry 5.0 (I5.0)" [1, 2]. The most basic idea is "digitization". It describes the process of turning analog data into digital data. Activities are not made more valuable by digitization. Usually, it is used to describe the process of digitizing internal and external procedures in any business [1]. The terms "digitalization" and "DT" are often used interchangeably and allude to a broad idea that affects a business ecosystem [1, 3, 4].

I4.0 enables the integration of several application systems, and it is frequently understood as the DT phenomenon applied to the manufacturing industry [1, 5]. The development of I5.0 is predicated on the observation or assumption that I4.0 places less emphasis

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on social justice and sustainability and more on DT and digital technologies for enhancing production flexibility and efficiency. So, the idea of I5.0 offers a distinct perspective and emphasizes the significance of research and innovation to assist the industry in its long-term service to human well-being within the bounds of the planet [6].

To keep up with the new technologies, in many production systems, a system that allows integration between the digital environment and human beings throughout several factory areas is still often enterprise resource planning (ERP). An ERP is a united system that attempts to provide an integrated solution encompassing a business's processes and functions. ERPs can be customized according to the company's needs [7]. In the I4.0 and I5.0 contexts, the ERP still has a spotlight, and it certainly accompanies the evolution of a company. This evolution can be perceived on several levels, from smart objects to smart factories [8].

However, implementing an ERP represents a system change and requires learning new skills. Resistance to change is expected by reducing comfort and loss of status or pay [9], especially when changing from one system to another. Literature has already highlighted the little importance given to users through the implementation of an ERP in a company. Different from previous efforts [10], the current paper focuses on the human factor while registering the change management while implementing an ERP in the Brazilian pet food industry. Thus, the research question is: How did users experience this system change management? This is investigated based on a user's perspective through the application of a survey.

The results of the research contribute to two aspects. First, this study enriches the literature on the implementation of ERPs through the hermeneutics phenomenology approach. This study documents the system change as an important precursor to other industries' transition to ERP to start a new approach, more user-centric. In other words, it is based on the central question of the employee's experience during a system change. Additionally, this study contributes to recognizing influential variables related to human factors that improve the process of transition toward a new ERP.

This research is structured as follows: the next section presents the background necessary to understand this article; afterward, the materials and methods are described; finally, the results and discussion and the final remarks are stated.

2 Background

As technology evolves, so do the production systems and society. One concept related to this evolution is I4.0 and I5.0: technological advances are the base for integrating physical objects, human actors, and other systems involved [11]. Both concepts are strongly related to new technologies, which transfer information through a system, possibly in real-time [12]. Appraising the relevance for integrating humans, especially through systems [11], such as interconnecting software information along a company.

Authors already pointed out the need to effectively manage the human effort to obtain the full benefits of technology, in this case, advanced manufacturing systems [13, 14]. It is important to highlight the role of human factors, especially when deciding and considering the interaction between a system and human beings [15]. Other authors stated the importance of the involvement of top management and a team's competencies

to accomplish a project's success [16]. Thus, the human factor can boost the effectiveness of a project's success, such as a change in the system.

A downside to this approach is when the human factor resists a change and delays its benefits. Resistance to change comes from middle managers [17]. The success factors towards change are performance integrity (leadership and team motivation), senior management commitment, local-level commitment, and effort [17]. Some authors pointed to challenges to I4.0 as technology adjustments and management matters [18]. According to other authors [19], to ease the change, it is necessary to have a common purpose, understanding, and language.

The learning process of change is complex and may include challenges like leading toward an unknown future and operating "from that altered state" [20]. In our case, this state would be the altered outcome. It is also necessary to learn at different company levels to achieve the change [19]. The author also highlights the power of communication in changes as a powerful tool to be understood and used [20].

There are several possibilities for a changing environment, and it can go through this change and build a stronger business environment. Moreover, change can modify relationships across a group of workers, as well as misalign old expectations, and lead to rebuilding trust among employees [21]. Beyond great communication" [20], a plan on how to proceed with the change [21] is important to achieve success.

3 Materials and Method

This study is characterized as phenomenological because of the focus on the user. This methodology captures similar experiences lived by a group of individuals. The outcome includes details as to how and what the individuals experienced the phenomena studied [22]. It aims to analyze the transition of systems and the change management involved in the process of changing a managerial system to a new one in that all areas are fully integrated into the pet food industry. The enterprise analyzed is a multinational company that produces pet snacks, among other products. The company has three primary manufacturing plants in Minas Gerais, Brazil.

The system's transition was informed by supervisors directly to some employees seven months before inserted the information into the new system. The questionnaire was applied within five days, starting September 5th, 2022. The new system's enterprise provided two training sessions. The coach first trained a group of people. Afterward, he taught every employee that had access to the new system individually. In sequence, the coach tested the employees, helping them enter the data into the new system.

The previous system was not fully integrated. There were several sets: storage, production, costs, quality, and managerial. Despite many possibilities, the different parts were not communicating among themselves. For instance, if an ingredient was not available in the stock, the employee could still open the production order. The objective of the new system was to combine all the functions in one place. For instance, the intermediate storage and expedition would have access to the same data. More details of the differences between systems are presented in Table 1.

After training sessions, questionnaires were applied to employees with access to the old and new systems. A term of consent accompanied those questionnaires to disclose

Table 1. Differences between the old and new systems.

Characteristics	Old system	New system
Data availability	Adjustable by the login. An employee could change the permissions on each login. Each person had available a certain amount of information necessary to fulfill their job	Adjustable by the login. Only the third party responsible for the system could alter the login permissions. Each person had available a certain amount of information necessary to fulfill their job
Areas controlled by the system	Production, quality, managerial, storage (partially), and financial	Storage, production, costs, quality, managerial, sales, manufacturing planning and control, and sales
Is it an ERP?	No	Yes
Is the server of the system local or in the cloud?	Local	Cloud

the data provided, which once agreed should fill the questionnaire. It was explicit that the answers were not reflected in their performance or salary at the enterprise. This was done by multiple questions delivered to the respondents and ensuring the answers were anonymous to make sure employees were comfortable answering the questions. All these measures were taken to prevent employee bias and preserve the enterprise's ethical standards.

The questionnaire was applied to 14 employees, including the experience of the researcher, who worked in the company at the time. It is important to highlight that the people answering the questionnaires were previously known by the researcher and had at least two years in this company. Six people preferred not to answer. One of the questions was open to better-acquiring employee experience. The answers to the questions were created using the Likert scale from strongly disagree (1) to strongly agree (5). This method was applied due to its speed since the enterprise only released a limited amount of time for each employee.

This research focused on a questionnaire of 360° feedback to obtain better feedback on the employee's experience [23]. This website has more than twenty-three years of experience in online surveys for human resources. Questions about leadership and interpersonal matters were carefully read and selected by the researchers, whether applicable to the context. The questions applied are listed in Table 2 and are inserted and adjusted to the purposes of this research from [23].

Table 2. Questionnaire applied in this research.

Question
1-Can you communicate clearly and openly about the problems without being held accountable?
2-Are you informed when there are changes in the system or schedule?
3-Do the managers involve you in deciding what will be done when there are changes?
4-Does your manager help and comprehend you throughout the change processes and activities?
5-Is it clear to you when the change must be in motion?
6-Do you learn about a change through rumors?
7-Does the management support the change?
8-Are the managers involved in the process of change?
9-Your emotions about the change: Is this change essential?
10-Are you ready to put energy into the process of change?
11-Do the people in your sector help you?
12-Do employees from other areas help you when you request?
13-What are the advantages and disadvantages caused by the change?

4 Results and Discussion

Answers from questions 1 to 12 are presented in Table 3.

Table 3. Answers to the questions of the questionnaire (1–12).

Question	E1	E2	E3	E4	E5	E6	E7	E8
1	4	3	5	3	3	5	5	5
2	4	4	5	3	5	3	4	2
3	4	4	4	3	4	3	5	1
4	5	5	5	3	4	3	5	5
5	5	5	3	3	4	3	5	2
6	1	1	5	3	3	3	4	5
7	5	5	3	3	4	3	5	5
8	5	5	5	3	4	3	5	4
9	1	5	3	3	3	3	4	5
10	5	5	4	5	5	4	5	5
11	5	5	5	3	4	5	5	5
12	3	5	5	3	3	2	5	4

Based on the obtained answers, some practical approaches that worked and needed more effort are described below.

Considering the initial communication of the change to some sectors in March and the questionnaires applied in September, the change was broadly communicated throughout the company. Different results related to how a change is informed and explained by the fact that several hierarchical levels answered the questionnaires (Question 6). Therefore, higher hierarchical levels learn from a change directly from the owners, whereas lower hierarchical levels will first learn it from rumors. The key takeaway is to make sure all users are aware of the change and when it will happen.

As stated in the Background section, high management must support the change, as it happened here. Measures such as the enterprise's culture of accepting mistakes and communication encourage employees to embrace the transition. It is reflected as a lack of resistance towards the change and shows the employee's effort to adapt.

Furthermore, variations were noticed in the communication related to the change in different areas. For instance, the changes in packaging are lower than in the production sector due to a different response for these areas. Thus, it is important to align the message throughout all company sectors, especially about the need to change. Another aspect is to also align the communication through different hierarchical levels.

The support given by other employees in the same and different sectors was equally important in this change process. Help was more easily obtained within the same sector, whereas, in other sectors, there was more resistance. These answers were expected since every sector had goals and tasks to be completed, and stimulation of collaboration across sectors was not encouraged or could delay those tasks and goals for helping a colleague from another sector, eventually causing punishments.

Considering the open Question 13 (Table 2) and the final comments open to the employees, the results were:

Advantages of the Change: It is easy to shift products from one storage station to the other, an easier process of weighing products and creating new production orders, and the integration of sectors makes the information easier to access.

Disadvantages of the Change: The internet connection impairs the new system's functionality; the new system often halts; the new system is easily disconnected; it is not user-friendly; some shortcuts of the old system do not exist in the new one; the new system is slower than the old one.

There were comments about the preference to operate only one system instead of both systems at the same time. This approach was applied until the new system was fully functioning. Once this was achieved, the old system would be deactivated. It is important to highlight the interference of the internet connection or halts on the system, cited by five people, which represent 62% of the total.

Considering all questions, there was a consensus on the answers to 1, 4, 7, 8, 10, and 11. Thus, questions 2, 3, 5, 6, 9, and 12 do not have a consensus and reflect on the communication of change, the necessity to change, and the collaboration of employees across sectors, which reflect the personal points of view of employees. Generally, questions about managers were well evaluated, but the personal aspects about the culture of the company, help among sectors, and communication about change have divergent opinions. Despite communicating that the answers would not reflect on an employee's

paycheck or position in the company, two respondents answered neutrally to most of the questions (E4 and E6), reflecting a possible fear of consequences about their real opinion or confusion about what they believed about the topics.

5 Final Remarks

This study aimed to deepen the understanding of change management related to implementing a new system in an enterprise. Resistance to change might not be seen as most people answering that they are ready to put energy into this change. Despite that, the view of the necessity of change (Question 9) causes doubts about how this change was communicated. The energy might be there for the change, but with the proper guidance, it might be directed to the necessary points. Therefore, reflecting the need to improve the communication about the change through the parts.

Another aspect highlighted is the support given by the same and different areas, reflecting an environment more competitive than collaborative. Leading to more difficulties in the change process. This type of culture differs from collaborative cultures. A comparative investigation is suggested since the competitive environment might originate difficulties in the implementation of changes.

As a powerful integration of systems, people, and physical things is required to enter the new industrial revolution (I4.0 and I5.0), it is also with great caution that the transition should be addressed. When transitioning from a system that is not fully integrated to an ERP, it is necessary to comprehend the complexity of the change. Integrations are not a day of work for a company. It is important that the transition occurs, and good practice is both systems operate until the information is fully transferred to the new system. This leads to a more demanding transition, more open communication, and the posture accepted, as stated by the acceptance of problems without blaming employees.

The results of this application in a pet food industry transition to an ERP are an enriching application towards a better comprehension of practical aspects adopted. As a user-centric approach, different perspectives originated from the different hierarchical levels of the respondents, as well as the other areas they worked in. Therefore, communication might be useful for one user but not for another. Measuring this aspect should improve the general comprehension of the situation. Thus, it is important to verify every user's comprehension of the changes and other important information before moving on with the transition process, to facilitate this transition.

However, the results reflect the experience related to the specific environment of this enterprise and software. The number of respondents is a limitation. Another limitation is the translation of the questions described here since they were in Portuguese and might reflect different content. Future studies include comparing these results to another system's change implementation results. Another suggestion is to compare these results to an interview method.

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Digital Transformation and Organizational Challenges. An Exploratory Study

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Abstract. Successful survival and competitive advantages are the greatest challenges societies and organizations face. A cultural and strategic paradigm shift is needed, particularly in work relationships and the organizational environment. Industry 4.0 remains too linked to technology, even if the biggest challenge seems to be related to people. Higher Education Institutions are key players in this transformation process and the present study aims to understand the perception of higher technical professional students just before entering their final internship. Quantitative research of descriptive nature was used, and a questionnaire was conducted at a Polytechnic Institute in Portugal between November and December 2021. The results show that students who have heard about Industry 4.0, perceive it mainly from a technological perspective, even if they have developed leadership skills, communication, decision-making facility, and analytical skills in the courses they attend. The results achieved within the questionnaire provide a basis for improvements and innovations in Higher Education, which can be a key point for the development of Industry 4.0 strategies in the future, namely regarding the redesign of some curricula or pedagogies to overcome challenges and prepare students to be successful in the future.

Keywords: Digital Transformation · Innovation · Industry 4.0 · People · Skills

1 Introduction

Digital technologies have changed the way companies work, how people connect and exchange information and how they interact with the public and private sectors [1]. In this sense, digital transformation can be understood as integrating digital technology in all areas of a company, fundamentally changing its functioning, and delivering value to customers. This is a civilizational change that requires a continuous challenge *to the status quo* of organizations and is, above all, a cultural and strategic change [2], which strongly impacts society, particularly in labour relations and in the environment [3], tending to be seen as the epicentre of a new industrial revolution [4].

The digital transformation has changed the paradigms of the industrial era, by questioning rigid business models, with Covid-19 having accelerated the digitization process of many businesses that were unthinkable until recently [5]. Regardless of size

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and activity, companies had to adapt to three significant structural changes: customer behaviour, reorganization of the supply-demand relationship in an unpredictable way, and the adoption of remote work [5].

The introduction of industry 4.0 often shows differences, and many authors have a pessimistic perspective on its adoption in Small and Medium Enterprises (SMEs) [6]. SMEs will only be able to operate in an industry 4.0 environment if they follow customized implementation strategies and approaches and adapted technological concepts and solutions [7]. Many of the traditional industries are still not ready to migrate directly to Industry 4.0. And for micro and small enterprises, resources (tangible and intangible) and infrastructure can be major obstacles, requiring specific measures to help them in this transition period [8]. People seem to be the major problem in this ongoing challenge [9] and Higher Education should provide qualified people with the needed skills to surpass with success their tasks.

The present study aims to understand the perception of higher technical professional students just before entering their final internship and concerning the impact of digital transformation, regarding industry.4.0. Quantitative research of descriptive nature was used, and a questionnaire was conducted in the Technical Professional High School (ETESP) at the Polytechnic Institute of Cávado and Ave (IPCA). After the introduction Sect. 2 deals with the concepts of digital transformation. Section 3 presents the case study and Sect. 4, the main conclusions, and directions for future research work.

2 Literature Review

Digital Transformation is becoming a relevant topic for companies worldwide [9] and one of the most important topics for researchers, analysts, and business leaders [10]. The internet and technology have altered the business scene, impacting the world at a unique rate [11] while companies are responding at very different velocities [12]. Technology has been used as a tool to help companies in the race for competitiveness [13], but the barriers are immense, mainly due to how organizations themselves and their Human Resources react differently to change [13, 14].

Researchers agree that the change process itself is complex [15], and several studies argue that the success of projects does not depend mainly on technology, but on successful transformation projects that depend largely on people [16]. The existing scenery of transformation has placed enormous stress on companies and their organizations to modify their technology, their systems, and their conventional habits of working, with their methodology to solutions leading to quicker changes, formally concerning not only the organizational structure but also the different stakeholders [10].

The shift involves new value propositions, higher relationships with customers, and innovative business models, among other factors [17, 18]. Undoubtedly, any attempt to introduce change involves significant challenges for leaders at all levels, as well as for the organisation itself [19]. Resistance is a normal response to change, as change typically involves moving from the known to the unknown [20]. Successfully managing organisational resistance and addressing the Human Capital perspective on change is arguably more relevant than managing other aspects of the digital transformation challenge and is crucial to the successful implementation of change [21].

Qualifying people to work is one of the main requirements and can be considered a challenge for industries, knowledge institutions and governments, which should create incentives and policies that target these issues. Many of the jobs today and soon will require specific skills such as (i) technological knowledge, problem-solving and critical thinking; (ii) persistence, collaboration, and empathy; (iii) communication, creativity, innovation, ease of decision-making, analytical skills, and leadership. These skills are fundamental for the progression of digitisation 4.0. And for working in industry 4.0 [22]. Various industrial sectors face global competition for mass customisation and responding to dynamic customer demand. Improving process operations, enhancing decisions, and optimising productivity, while maintaining product/service quality, are dominant factors for differentiation between companies in an increasingly global market [23].

3 Literature Review

3.1 Methodology

The phenomenon under analysis can be defined as the perception of 2nd-year students of the Escola Técnica Superior Profissional (ETESP) - IPCA, on the impact of digital transformation, particularly concerning industry.4.0, as a driver of this same transformation by organisations. In this context and within a positivist paradigm perspective, the observation of this phenomenon aims, considering the collected data, to analyse, according to the Student's perception and experience, whether the *curricula* and pedagogies of the different courses are effectively promoting their soft skills. This analysis intends, additionally, to identify key competencies to redesign some *curricula* or pedagogies to overcome challenges and prepare students to be successful in the future. In this sense, quantitative research of descriptive nature was used, as the researcher is simply studying the phenomenon of interest and no attempt is made to manipulate the individuals, conditions, or events [25]. It was applied a questionnaire survey [24], pre-validated by two academics and two experts in the field. It was distributed between 10 November and 10 December 2021, on the Internet, through the ETESP website. The population comprises a universe of 700 students.

The questionnaire was mostly composed of closed questions, namely dichotomous questions (yes/no), questions with Likert scales, multiple choice questions and "open answer" questions, allowing respondents to express themselves through their own opinions and ideas. The questions were grouped into 4 sections, namely sociodemographic data, digital transformation, digital skills and future professional.

3.2 Escola Técnica Superior Profissional (ETESP) IPCA

ETESP IPCA is part of the network of Public Polytechnics Higher Education, having emerged from a strategic desire for collaboration between IPCA and the business community of the Cávado and Ave region, responding to the training needs for higher professional technicians. It is a Higher Education-oriented School, offering Professional Higher Technical Courses in the areas of Design, Management, Hospitality and Technology, seeking to support the entrepreneurial fabric in the preparation of qualified labour and accordance with the increasing market demands.

ETESP is differentiated by its learning model in a real context, where collaboration with companies is fundamental, through partnerships that allow the realization of internships for all its students and the teaching of curricular units in a company environment. This connection with companies is also materialized in the implementation of training directed to specific profiles, and the requalification of human resources, responding to the constant technological evolution. The commitment to get closer to the business world of the Cávado and Ave region is assumed through the geographical presence in Braga, Barcelos, Guimarães, Vila Nova de Famalicão, Esposende and Vila Verde.

3.3 Data Collection and Discussion

To obtain a better inference and statistical analysis of the collected data, it was decided to divide the questionnaire responses. Thus, given the high number of courses (23), they were divided according to the scientific area to which they belonged, which corresponds to 4 groups, namely: Technology (I), Design (II), Management & Marketing (III), Tourism & Hospitality (IV).

The population was composed of all the students from all the ETESP IPCA, distributed by the different geographic regions, and attending the second year of their higher technical courses, a total of 700 students. A sample was obtained with 124 responses and the percentage of respondents was similar in both genders. The courses represented in the sample are as follows: Business Consultancy and Communication, Digital Audiovisual, Food Innovation and Culinary Arts, Digital Marketing and social media, Plastic Injection Moulding, Collaborative Robotics and Industrial Intelligence, Data Security and Protection for Information Systems and Computer Technology and Innovation.

Table 1 presents the main findings, and Fig. 1 complements the information with some details concerning the age of respondents.

Table 1. Sociodemographic data (global)

From a population of 700 students, 124 responses were obtained = 17.71%	
Attended courses per group*	I = 52; II = 12; III = 37; IV = 23
Gender	Male = 50% | Female = 50%
Age	[18–25] years old = 83.9%
Professional *status*	Employed (partial or total) = 79%
Professional experience	YES = 59.7%
Years of Experience	> 6 years = 24%

* I - Technology; II – Design; III - Management & Marketing; IV - Tourism & Hospitality.

Before starting to discuss the results, it is important to emphasise that, although the students' attendance and professional situation were an integral part of the questionnaire in the sociodemographic data section, it was found after processing and analysing the data that these two parameters would not influence the obtained results and were therefore not considered in the analysis to be carried out below.

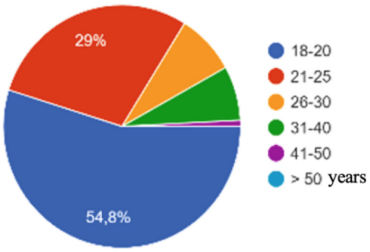

Fig. 1. Age of respondents (own elaboration)

The collected data may lead us to infer that even though the students are still quite young, a large percentage admit to having professional experience. In this case, 24% have 6 or more years of professional experience (Fig. 2), which may mean that this group of students are looking for reskilling or upskilling in their professional careers.

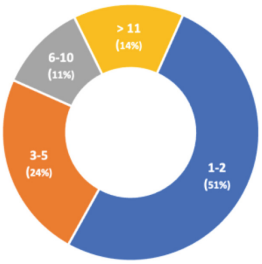

Fig. 2. Years of experience (own elaboration)

Regarding digital skills, the study aimed to obtain data from students through self-assessment, recognition of the importance of digital transformation for organisations, how the topic is addressed in the course and what activities should be developed for the development of digital skills. Table 2 presents the main findings.

In the present research, 20% of the students recognise that empathy, persistence, and leadership itself are not worked on at all in the courses they attend. This data should lead us to reflect, bearing in mind that 43.5% of the students have on their horizon the ambition of creating their own job.

The topic of the last section of the questionnaire is concerned with industry 4.0. The main objectives were first, to understand the students' concepts and knowledge about this subject. Secondly, to find out the influence of digital transformation on industry 4.0. When asked whether they had ever heard of industry 4.0, a high percentage (64.5%) of students answered that they had never heard of it. A curious fact is that this number (64.5%) of students never having heard of industry 4.0 is very similar to the rate of students who have never heard of digital transformation (62.9%).

This may lead to raising several questions for reflection, for example: Is the concept of industry 4.0 allocated to a certain industrial "elite"? or economic groups? or specific Universities? - not sharing the knowledge acquired with the remaining stakeholders. Are

Table 2. Digital Transformation

Self-assessment	86,9% admit having skills 10,9% admit having many kills
Importance to organizations (only in parameters above 75%)	In customer relations (76%) In research/development/innovation (72%) In the organisation and management of the company (74%)
Course approach (only in the parameters above 65%)	65% recognise that leadership and communication are very well developed 72% recognise that decision-making and analytical skills are very well developed 74% recognise that critical thinking is being worked on a lot of units 76% recognise that problem solving is being worked on in a lot of units
Activities to promote the development of digital skills	Leadership workshops (30.4%) Project management and planning workshops Workshops on sharing good business practices Teamwork workshop Workshops focusing on topics related to digital transformation and technological knowledge

educational institutions not keeping up with technological evolutions and do not transmit/teach them to their students "within the timeframe" that the labour market requires? Are our political institutions (namely the European Union) aware of the discrepancies that exist within the member states, particularly the inequalities in access to new technologies, leading to digital transformation and the industry 4.0 concept having different implementation timings? Table 3 presents some other findings.

Table 3. Industry 4.0

Concept	Fourth industrial revolution/Cyber-physical systems/ Data exchange/Internet of things/Cloud computing/ Machine monitoring/More modern and automated industry
Influence of digital transformation on Industry 4.0	88.8% acknowledge that they will have influence and even a lot of influence

4 Conclusions and Future Research Work

The current times immerse us in a new world - the digital world, supported by a set of technologies that does not stop evolving every day. Human beings are constantly challenged to demonstrate in themselves characteristics such as leadership, creativity, communication, empathy, collaboration, and persistence, among others. These skills are transversal to the whole of society and, as the results of this study seem to show, it is not gender, age, the course attended or the fact of having a professional experience that may be factors that influence the need for constant adaptation to the demands of the digital world.

When asked about the importance of digital skills in organisations, the most referenced areas are customer relations, research/development/innovation and business organisation and management. Regarding how digital skills are addressed in the respective courses they attend, the main skills mentioned are leadership, communication, decision-making and analytical skills. Also recognised are skills such as critical thinking and problem-solving. Regarding the activities to be promoted within the scope of the course for the development of digital skills, the workshops on leadership, project management and planning, sharing of good business practices, teamwork and digital transformation/technological knowledge are highlighted.

The results obtained seem to show the recognition of the students of the importance of the higher technical course for their professional growth. A significant proportion of students expect to create their jobs, which leads to the recognition of the entrepreneurial aspect that higher technical courses can induce in students who attend them. The present research provides a basis for improvements and innovations in Higher Education, which can be a key point for the development of Industry 4.0 strategies in the future, namely regarding the redesign of some curricula or pedagogies to overcome challenges and prepare students to be successful in the future.

The main limitation of this study is pointed out the sample size. However, since this is an exploratory study, the results allow us to make a first approach to the subject under analysis and, perhaps, serve as a reference for an internal reflection of the Institution itself. In future work, it is suggested to try to replicate separately the same study in each of the scientific areas and, subsequently, try to understand if there are significant differences in the perception of students from different areas. Use the same instrument for a longitudinal study, to monitor how digital competencies are being worked in the ETESP IPCA itself. The same analogy would be interesting to compare other IPCA Schools and eventually with other Higher Education Institutions.

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The CrossLog System Concept and Architecture

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Abstract. Logistics chains are being increasingly developed due to several factors, among which the exponential growth of e-commerce. Crossdocking is a logistics strategy used by several companies from varied economic sectors, applied in warehouses and distribution centres. In this context, it is the objective of the "CrossLog – Automatic Mixed-Palletizing for Crossdocking Logistics Centers" Project, to investigate and study an automated and collaborative crossdocking system, capable of moving and managing the flow of products within the warehouse in the fastest and safest way. In its scope, this paper describes the concept and architecture envisioned for the crossdocking system developed in the scope of the CrossLog Project. One of its main distinguishing characteristics is the use of Autonomous Mobile Robots for performing much of the operations traditionally performed by human operators in today's logistics centres.

Keywords: Logistics · Crossdocking · Automated Mobile Robot

1 Introduction

Recently, there has been a proliferation of proximity stores/supermarkets, characterised by being more numerous, smaller than traditional hypermarkets, and for having reduced storage capacity. In these cases, replenishment is carried out according to the previous day's consumption. Keeping large levels of inventory is seen as a waste of space and money, and does not allow to respond quickly and agilely to changes in customer consumption patterns. The faster you can replenish, the lower the required minimum inventory level. However, increasing the replenishment rate requires more effort from logistics operations, such as identification, palletising and handling. We are therefore faced with an increase in the volume and mix of these operations, which have no added value. Furthermore, this supply chain must operate in a synchronous just-in-time concept, which poses a significant challenge to the distribution centre. This raises the question

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of how to supply this type of shop efficiently and effectively, reducing the effort associated with logistics operations in a context of high volume and mix. The concept of cross-docking emerges as an answer to this problem, as a strategy of minimum handling of loads, with little (or no) storage between unloading and loading them. The full automation of this concept is not yet possible, requiring various technical-scientific advances in the subsystems necessary to materialise the cross-docking system for retail.

Given this need, the CrossLog project's objective is to investigate, develop and implement an automated and collaborative crossdocking system (CS), capable of moving and managing the flow of products within the warehouse in the fastest and safest way. The handling of objects will be carried out using a set of modules (industrial conveyors, advanced robotic units and artificial vision systems), interacting with each other, and communicating with a management software responsible for calculating the route of each product. This project breaks with today's concept of automated distribution centres, based on static automated warehouses. It also represents a change in cross-docking distribution centres, highly dependent on human operators due to their ability to interact with the numerous diversity of products. The automation of this process will be a new milestone in the logistics sector, where unpredictability has proven to be a major obstacle to evolution.

Bearing these ideas in mind, this paper presents the development of a novel architecture for a CS, based on the use of Automated Mobile Robots (AMR) with distinct capabilities. Following this introduction, Sect. 2 details the crossdocking concept, and Sect. 3 presents the model architecture. Next, Sect. 4 discusses the AMR fleet under development. Finally, Sect. 5 exposes the main conclusions and some future developments of the CrossLog Project.

2 Crossdocking

Crossdocking is a logistics strategy used by companies from varied economic sectors, applied in warehouses and distribution centres [1,4]. Its objective is to receive products from the inbound trucks and send them directly to the outbound trucks, without any intermediate storage, thus increasing the efficiency of the operations. Incoming vehicles usually transport products from a certain supplier, which are placed in a CS and consolidated with products from another vehicle, and possibly another supplier. This consolidation allows products from different origins to be grouped together and distributed to different final destinations. This strategy has proven to be extremely important, and the fast movement of products allows the stock to be reduced, reducing the associated costs. Thus, crossdocking has provided distribution companies with several advantages, such as reduced storage, stock and handling costs, reduced delivery time, improved customer service, reduced storage space and reduced risk of loss. The key to success is to have the shortest possible dwell time at the product receiving and shipping facilities. The shorter this period, the less temporary storage time is required. In practice, the ideal is rarely the case, so limited temporary storage is necessary and minimised as much as possible.

It is possible to distinguish CS through the number of touches or existing phases [2–4]. Number of touches means the times that the product is transported from one place to another, inside the system, and CS can be divided into three types: one-touch, two-touch (or one-stage) and multi-touch (or two-stage) crossdocking, and any one of these will have a direct bearing on the operation and layout of the system. One-touch crossdocking is considered "pure", because the ideal concept of this type of system is to receive the products and move them directly to the defined shipping vehicle, without any kind of intermediate storage. However, the "pure" (one-touch) systems are rarely used, due to the need for temporary storage of most products, which is mostly promoted by the vehicle scheduling, which has consequences, like a possible lack of coordination between inbound and outbound vehicles. As for temporary storage capacity, when a vehicle is not ready to pick up and transport the products to their destination, they are stored in a limited area, usually on the warehouse floor.

3 CrossLog System

3.1 CrossLog Project Objectives

This project will result in an innovative concept and a technological kit (materialised in a set of prototypes, both software and hardware) allowing to validate the application of the developed research in the design and development of CS (aligned with the principles and concepts of Industry 4.0), namely:

- Present an alternative to manual CS in order to respond to the growing demand of this sector;
- To generate an automated and modular system capable of managing and moving products within a logistics centre, throughout their entire route.

To respond to these general objectives, the following specific objectives were established:

- Implementation of an identification, weighing and dimensional measurement station (here the precision and accuracy of measurement becomes a decisive factor);
- Design of an accumulator station with optimised positioning;
- Development of a multiformat gripper capable of handling the most varied products, ensuring the adaptability characteristic of the human being;
- Design and development of a set of mobile manipulators and the respective coordination and management software;
- Development of an online three-dimensional mosaic generation software;
- Design of a progressive wrapping station, a process that will be carried out simultaneously with palletisation, allowing for the time reduction associated with the final pallet wrapping process, as well as ensuring the integrity of the pallet during its construction.

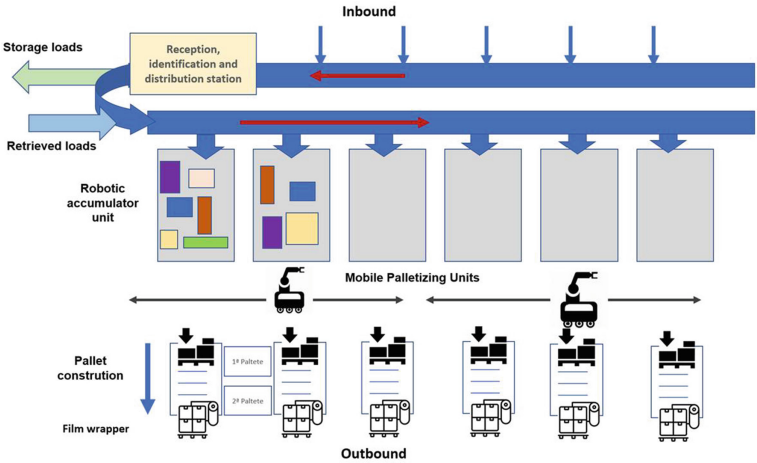

Fig. 1. CrossLog system architecture

Given the characteristics of the CrossLog system architecture, it will be possible to achieve hybrid implementations from the point of view of the possibility/need for human intervention. The consideration of functional requirements that enable this function, but that do not restrict the full automation and potential of the CrossLog system, is related to achieving a faster commercial dissemination of the solution, allowing less prepared logistics operators to make use of the solution until they are organisationally capable of a complete migration to what the proposed solution allows.

3.2 CrossLog System Architecture

The model of the CS follows the layout depicted in Fig. 1. It has an I-shape, an automated internal product movement, a unique service mode, and operates on multiple touches. As for the type of storage, it is hybrid (some items go directly to shipping and others to storage).

Regarding its functional architecture, it is constituted of three main blocks, illustrated in Fig. 2: a reception, identification and distribution station, an accumulator unit equipped with an optimised handling, movement and management module, and a fleet of AMR responsible for feeding the palletising stations with empty pallets, for the actual palletising task, and for transporting the finished pallets from the palletisation stations to the output bays.

The product reception and distribution system is responsible for correctly routing the products from the point of entry to the respective palletisation station. To this end, a set of conveyors with a sorter system was designed at specific points. From the point of view of the identification station, this consists of a set of artificial vision cameras to identify incoming products, through the 3D measurement of products and barcode reading, together with a weighing station in order to allow the correct dynamic weighing of products that move over it to confirm the product reference identified with artificial vision.

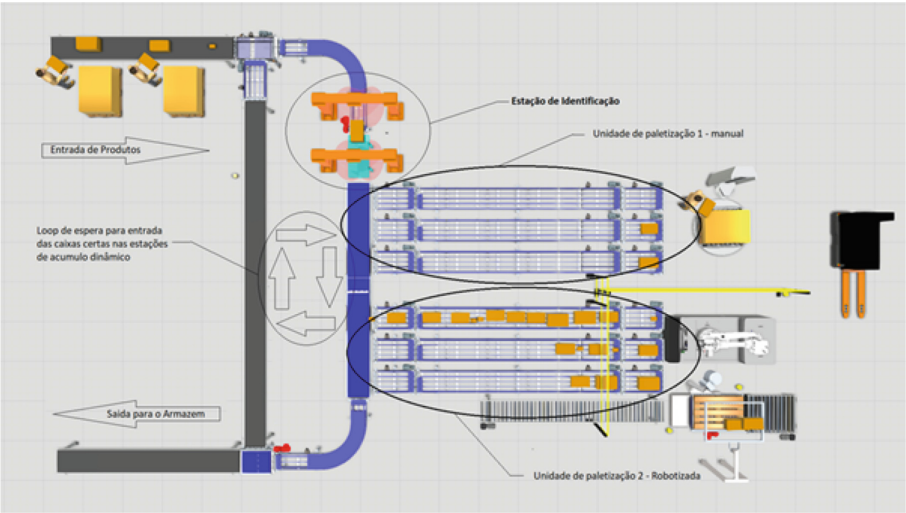

Fig. 2. Final layout developed - reception, identification and distribution

Regarding the accumulation unit, it was decided not to use a robotic manipulator to pre-position the boxes. The handling and management of the boxes will always be carried out using conveyors and sorters. Each accumulating unit will be made up of three rows of conveyors, responsible for accumulating all the boxes necessary to form a complete pallet (see Fig. 3). The boxes will be arranged on these conveyors in a row, in the correct order of palletisation. These conveyors will work in an intermittent, step by step logic. That is, the conveyor motor is only activated when a new box enters the respective unit, moving forward just enough to accommodate the new box.

4 AMR Fleet for Cross-Docking Operations

The CrossLog project consists of three AMR (depicted in Fig. 4), each performing a distinct function. The first of these AMR is responsible for feeding the palletising stations with empty pallets. The second is a mobile manipulator (*i.e.* an AMR with an attached robotic arm), and is responsible for the actual palletising task. Finally, the third AMR is an autonomous forklift responsible for transporting the finished pallets from the palletisation stations to the output bays, previously selected by the system. The main characteristics of each of these vehicles is presented in the next subsections. All platforms have an integrated industrial PC that uses Ubuntu as the operating system. The Navigation Stack software (whose architecture is presented in Fig. 5) is based on ROS and is the same in all robots, differing only in the parameters of each algorithm, since each AMR characteristics and operations are taken into account.

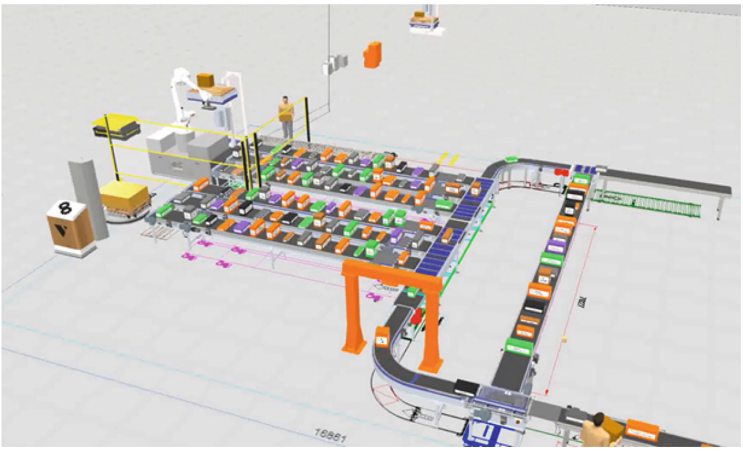

Fig. 3. Simulation of packets flow for dynamic accumulation units

(a) Tansport AMR (b) Palletizer AMR (c) Stacker AMR

Fig. 4. Fleet of AMR developed in the scope of the CrossLog Project

4.1 Transport AMR

This robot will transport empty pallets from the pallet warehouse to the different palletizing stations. Each of these stations has an integrated wrapping machine, an industrial machine that wraps the pallet with plastic film as it is filled with products. The wrapping machine is made up of an industrial conveyor that receives the empty pallet supplied by this mobile platform. For this exchange to take place, an industrial conveyor was installed on top of the mobile platform (depicted in Fig. 4a), at the same height as the wrapping machine conveyor. Both have two sensors incorporated that allow the detection of the pallet. If both sensors of the AMR or the industrial machine are active, this means that the pallet is present; if only one of them is active, it means that the pallet is in a transition movement; if there is no pallet present, all sensors are deactivated. Regarding the autonomous mobile platform, it is equipped with two safety lasers, in two opposite corners, capable of covering the entire safety zone of the robot. As a way of optimizing peripherals and minimizing costs, they are also used for mapping and localizing the AMR itself in the environments where it is inserted. The differential traction system is composed of two central drive wheels and four free wheels, placed in each vehicle corners, allowing for greater stability of

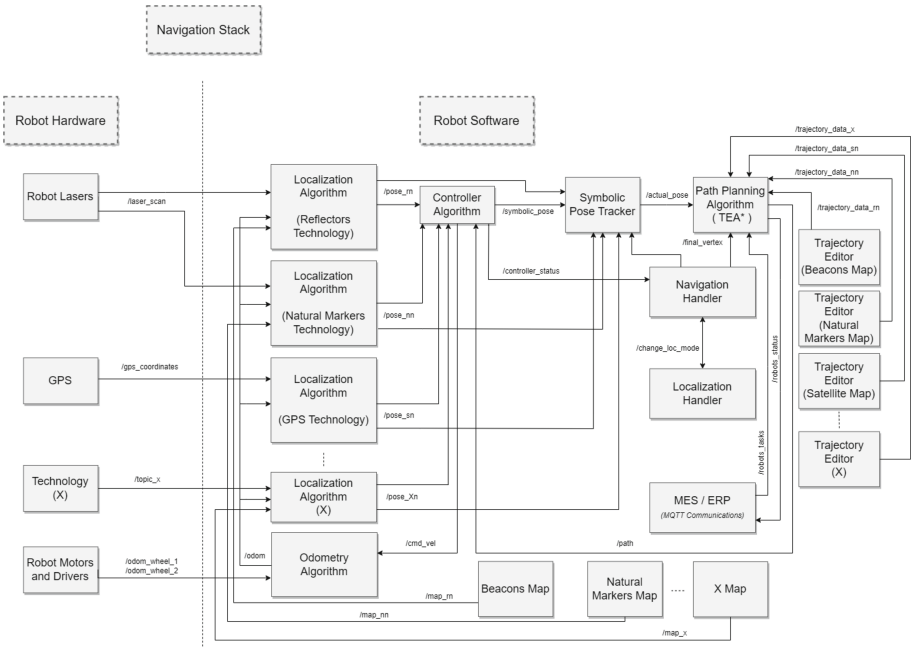

Fig. 5. AMR Navigation Stack Structure

the entire structure. All the control, navigation, localization, supervision and trajectory management software is based on ROS and C++, and is called the Navigation Stack (Fig. 5).

4.2 Palletizer AMR

In terms of chassis, this AMR is very identical to the previous one, differing only in its size and robustness, and by having an industrial manipulator attached, used for palletizing tasks, instead of an industrial conveyor. The safety and navigation systems are the same, because the Navigation Stack is the same on all robots. However, because docking was required at critical points in the layout, with little space for the mobile manipulator to manoeuvre, the adopted traction system is the omnidirectional one. This enables the platform to rotate on itself and move in all directions. To reduce the weight on this vehicle (by avoiding the need for an inverter and batteries to power the manipulator arm), the power supply to the robotic arm is performed only when the AMR docks in its charging station, which has two functions: (*i*) charge the mobile platform batteries, and (*ii*) directly power the manipulator, so it can perform its palletizing tasks.

4.3 Stacker AMR

This vehicle was developed to transport the finished pallets, from the different palletizing stations to the different exit docks of the logistic warehouse. This AMR, as the manual forklifts, is composed of a tricycle traction system, allowing the necessary stability when moving large loads. It is the most complex of the three platforms, as it has a vision system dedicated to pallet detection, between the two forks, and a specific navigation laser (see Fig. 4c) on its top, for the platform to locate itself during docking tasks on the pallets, as one of the safety lasers has no favourable field of view due to the pallet, forcing the localization system to be switched. The fork lifting system has an associated driver that performs the position control of the forks and receives the same feedback through a position encoder.

5 Conclusions and Future Developments

This work presented the CrossLog Project concept and architecture, focusing on the hardware envisioned for automating a cross-docking system.

To be possible to test all the software modules in a simulated environment, even before the physical system is assembled, a simulation was developed with all the hardware components developed in the design phase, so as to have a Digital Twin (presented in Fig. 6) in 3D simulation of the real solution.

In terms of hardware, practically all the necessary automation components have already been defined and the purchase process has begun for most of the items necessary for the project, such as the robotic palletising arm, PLC, inverters, variable speed drives, motors, etc. The mechanical and electrical projects of the AMR/AGV were also finalised and their industrialisation was also carried out, now missing the manufacturing process and their mechanical and electrical assembly. Meanwhile, the management and supervision software of the

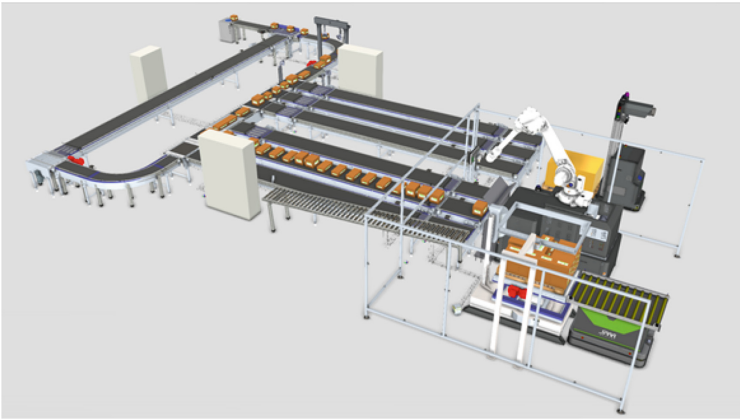

Fig. 6. Digital Twin of the CrossLog system in a simulated 3D environment

integrated system was also developed, and the integration of the hardware and software modules is now underway.

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Digital Transformation for Textile Small and Medium-Sized Enterprises: A Case Study Based on Dynamic Capability Perspective

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Abstract. Digital transformation is having an increasing impact on industries. Previous studies have explored how enterprises implement digital transformation using technology. The perspective on organizational management continues to evolve. Small and medium-sized enterprises often face resource constraints and the dynamic ability to integrate resources is important for enterprises to implement digital transformation. This study uses case study on Taiwan's textile industry and propose the important dynamic capabilities of launching digital transformation strategies. The results suggest that collaborating with external knowledge experts and leveraging employees' knowledge and experience in digital transformation are crucial for promoting innovation and transformation. This study provides useful managerial implications for small and medium-sized enterprises seeking to launch digital transformation initiatives.

Keywords: Digital Transformation · Innovation · Dynamic Capabilities · Small and Medium-sized Enterprises · Case Study

1 Introduction

Digitization enables fast and convenient information flow [1]. Recently, the manufacturing industry has developed automation to improve production and manufacturing capabilities [2]. This involves the integration of sensors, Internet of Things (IoT), cloud computing, networking, and data simulation in manufacturing plants [3].

Smart manufacturing presents both opportunities and challenges to enterprises [2, 4–7] as they need to leverage their physical resources, human resources, and organizational structure to create value and build competitive advantages [8–10]. Dynamic capability is the ability of an enterprise to apply resources to satisfy or create a market [6]. Enterprise innovation transformation goes through the three processes of perception, capture, and maintenance [9].

Small and medium-sized enterprises (SMEs) have limited resources, limiting their ability to develop digital transformation [2, 10]. Organizational design also affects firm dynamic capabilities [11]. Research on digital transformation of small businesses has mainly focused on the driving factors and outcomes that affect digital transformation

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[12]. SMEs require cases and experience to gain a more specific understanding of digital transformation implementation [13].

SMEs in Taiwan account for more than 95% of the total number of enterprises and are important to economic growth [14]. The textile industry in Taiwan has been developing for more than 60 years. It is one of the most complete production systems in Taiwan's industrial structure [15]. In 2021, the output value of this industry increased by 20%, reaching NT$359.9 billion [15].

Research on how smart manufacturing improves organizational human resource capabilities and demand characteristics is under development. To understand the dynamic capability factors required for the digital transformation of SMEs, this study focuses on the institutional, strategic, and operational drivers of dynamic capability of textile enterprises implementing digital transformation by case study. The remainder of this article is organized as follows: theoretical background (Sect. 2), research methodology (Sect. 3), empirical findings (Sect. 4), and main conclusions and future research suggestions (Sect. 5).

2 Literature Review

2.1 Digital Transformation and SMEs

Digital transformation is how enterprises use digital technology to transform activities such as strategies, processes, capabilities, products, and services [17, 18]. By adopting digital technology, enterprises can create new innovations and improve their long-term competitiveness [3, 27]. Scholars believe the effective use of information technology to be a key element of business success in the 21st century [18]. In a study on Korean SMEs, [2] found that companies with mature digital manufacturing capabilities achieve better operational and financial performance. Intelligent manufacturing systems can help SMEs improve their financial performance and operational efficiency [10].

Information technology has brought about major changes in corporate human resources. The traditional practice of human resources management is no longer sufficient for coping with the trend of intelligent production. According to [19], by 2030, 400 million jobs around the world will be replaced by automation, and 75–370 million workers will be at risk of changing jobs. Therefore, employees must improve their skills to adapt to the future digital working environment. [21] has identified transportation and warehousing, manufacturing, and construction as the top three industries most affected by automation.

Smart manufacturing and digital transformation have emerged as a key area for SMEs to build competitive advantage [20]. However, a survey conducted by [21] on Taiwan's manufacturing industry showed that companies are not eager to adopt emerging technologies. Additionally, large manufacturing companies in Taiwan have accumulated experience in digital manufacturing and play an important role in the international supply chain [21, 22], traditional manufacturing industries and SMEs face challenges such as declining production growth rate and lack of incentives for digital transformation [21]. To address these challenges, this study uses the dynamic capability theory as a framework and relevant theories to investigate the factors driving digital transformation in SMEs.

The results provide insight into the dynamic capabilities that influence an organization's digital transformation.

2.2 Dynamic Capability

Teece [23] believe that dynamic capabilities are the ability of enterprises to adapt to changes in the external environment, consequently integrating, establishing, and re-allocating internal and external capabilities and resources. Enterprises learn and respond to environmental changes, enhance their internal adaptation, innovation, and coordination capabilities, and ultimately cultivate competitive advantage capabilities [1, 8, 11]. Dynamic capabilities could use to explore enterprises' capabilities of digital transformation [13].

Dynamic capabilities are important for corporate innovation and transformation [1, 9, 11]. To adapt to the changes in the external environment, an enterprise establishes a specific process or a combination of processes. These processes or their combinations reflect the ability of enterprises to adapt to changes in the external environment [13]. [11] have explored business model innovation from a dynamic capability perspective and points out that institutional elements, strategic elements, and operational elements affect innovation. Dynamic capabilities are multi-faceted and enterprises are not required to be strong across every aspect. However, they still needs to perform better than their competitors [24]. [25] have pointed out that dynamic capabilities must be cultivated through organizational learning mechanisms. This research analyzes the process of enterprises implementing digital transformation, which is related to the internal design of the organization. Therefore, the case is analyzed using the dynamic capabilities framework proposed in [11].

3 Methods

Given that research on the dynamic capabilities of digital transformation is currently developing, qualitative research is suitable for exploring this topic [26]. This study uses a Taiwanese textile company as a case and collects its primary and secondary data. The primary data include semi-structured, in-depth interviews with three senior executives of the company in August and September 2022. The interviews lasted 60 to 90 min and were recorded with the consent of the interviewees. The secondary data include case company publications, news, magazine reports, and official website materials. The interviews were compiled into verbatim transcripts for analysis.

3.1 Case Company Profile

The case company has been established for 68 years and is a downstream manufacturer in the textile industry. It has factories in Taiwan, Vietnam, and Southeast Asia. Its main customers are internationally renowned brands [27]. The number of employees is about 270, including around 70 foreign migrant workers. Previously, the company was a family business. Since 2014, family members have withdrawn from the business [27]. Currently, all cadres are professional managers.

4 Results

Based on the concept of dynamic capabilities related to enterprise innovation and transformation and referring to the framework given [11], this study analyzes the dynamic capabilities that propel enterprise digital transformation from the perspectives of institutional systems, strategies, and operations systems.

4.1 Institutional Systems

Institutions encompass important rules that affect organizations' decision to promote digital transformation. The case company places great importance to its sustainable development in Taiwan and uses this goal as a guideline for digital transformation. Regarding the value of stakeholders, all interviewees emphasized that that *"all managers are professional managers, without the burden of a family business……The company focus on the overall interests of the company in decision-making. The textile industry is a labor-intensive industry. There are only a few textile factories left in Taiwan, and there are even fewer factories capable of smart transformation. Small and medium-sized enterprises are facing a severe phase-out period in this wave of trends."*

In terms of corporate communication, adopting openness and transparency is crucial. Two interviewees also mentioned that *"it is important to share digital transformation results with employees so that everyone can move towards the same goal"*. The executives pointed out during the interviews that *"the biggest difficulty for enterprises to carry out digital transformation is to let employees understand the importance of digital transformation and make employees willing to participate in the transformation"*. Employees who have never used computers will resist and complain if asked to use them suddenly. In the process of helping employees adapt to new types of operations and transformation, companies need to spend considerable time communicating with employees.

4.2 Strategy

The driving elements of corporate strategy can be perceived, seized, and transformed during the digital transformation process. The first digital transformation strategy of the case company is collaborative innovation. Two interviewees explained that *"enterprises cultivate internal digital transformation capabilities through collaborative innovation. Moreover, the strategy reminds employees to consider the current business and work content and the future business. Accordingly, the senior leadership needs to direct and the supervisor must be able to carry out the execution"*. The enterprise implements the strategy from top to bottom to ensure continued progress in digital transformation.

Companies conducting digital transformation choose to partner with research institutes. The interviewees pointed out that "they (research institutes) have expertise in information and communication, and have a lot of experience in assisting industrial technology development and mentoring….. When we started cooperation in 2015, we started with one production equipment. At that time, we didn't know what smart manufacturing was. Through the cooperation between companies and research institutions, we explore and learn together. In the process, let us grasp the production information

starting from one machine and then gradually expanding to the machines of a department. From one machine to hundreds, data that used to be recorded on paper can now be directly inputted in a computer or mobile phone." Presently, the application of digital manufacturing in case company has been extended to other manufacturing equipment, such as dyeing machines, looms, and more.

The digital transformation projects implemented by the company are all introduced from bottom-up so few decisions will cause employees to fight or complain. The interviewees mentioned that *"the organization culture and atmosphere is key. The company's philosophy, core value, and sincere attitude to implement this matter are influential. We encourage employees to participate in the transformation process from the bottom up, instead of imposing it from the top down."*

4.3 Operation System

The operational factors include innovative structures and cooperation mechanisms and personnel capacity development.

Innovative Structures and Cooperation Mechanisms

The case company developed its own software for the production process information system. One interviewee mentioned that *"When we started our digital transformation, we chose to develop our own software. In the textile industry, our information system should be relatively sophisticate in Taiwan. We know our needs for data management, so we develop related systems independently through cooperation with research institution"*.

Furthermore, the company established an innovative R&D center in 2018. This brand-new unit integrates the innovation transformation planning tasks. The main task of the innovative R&D Center is to plan and execute related projects for product transformation, service transformation, and process improvement. It acts as the brain for planning and driving digital transformation in the company.

During digital transformation, a large amount of data is collected from machines and equipment. The interviewee explained that *"regarding the analysis and application of smart manufacturing data, there is funds from the Industrial Bureau of the Ministry of Economic Affairs in 2021–2022….. Furthermore, we have experience in smart fabric inspection. The previous smart fabric inspection was all done with overseas equipment, so this year (2022) we cooperated with a foreign company to develop the first domestically-made fabric inspection equipment"*.

Personnel Capacity Development

Considering that the biggest obstacle in promoting digital transformation is employees, the case company also attaches great importance to human resources training, which emphasizes existing staff education and training.

The two interviewees explained that "for employees with problems, we communicate individually. There is still not enough experience or knowledge that the outside world can give us to promote digital transformation in the industry, so companies try to educate themselves to solve employee problems". *"Following the digital transformation,*

talents in information management, data analysis, business management, or science and engineering were considered as recruiting targets" the interviewee mentioned.

Talent Acquisition Difficulties
The biggest problem in the textile industry is the lack of workers, and the company is also facing difficulties in recruiting talents. All interviewees mentioned that *"Without the right talents to enter the enterprise, the promotion of transformation will be affected. To increase employee retention, we are changing the employee welfare system"*.

The Effectiveness of Digital Transformation
The effects of digital transformation on companies are significant. The interviewees mentioned that digital transformation brings about brings about a noticeable change in the company. Two interviewees explained that *"before the epidemic, we had 320 employees and a production capacity of 1.8 million US dollars. However, after the epidemic, we can still achieve the same production capacity as before with only 270 employees"*.

Compared with 2012, when there was no transformation, the revenue of the company increased and the cost decreased. The smart cloth inspection system and fabric production line can now be connected in real time, allowing for production and inspection to be completed simultaneously. Using 1,000 yards of fabric as an example, manual inspection took 40 min in the past, but now the detection rate has increased from 60% to 70% [27].

5 Conclusion

Dynamic capabilities are key to the digital transformation of enterprises [14]. However, a deeper analysis is needed to understand the specific dynamic capabilities that drive digital transformation. This study explores the factors related to the dynamic capabilities of enterprises' digital transformation from the perspective of institutional systems, strategies, and operational factors, and reveals the difficulties faced by enterprises. The key findings of this study are summarized as follows:

- Digital transformation needs to be a company priority [17]. Enterprises should convey the direction of digital development from the top and implement it from bottom to top. Executives need consistency and persistence to execute digital transformation effectively.
- Collaboration with external knowledge experts is required for the implantation of digital transformation [14]. By using an effective collaboration mechanism [11], enterprises can propose the required intelligent scenario from the demand side [24]. This can be ultimately combining the capabilities of external organizations to build a suitable intelligent system for the enterprises' production system.
- Employees' knowledge and experience of digital transformation factors affect their acceptance of new technologies. Enabling employees to understand the current situation of the industry and accept new technologies and knowledge can helpful promote innovation and transformation.
- The organizational structure and values of the enterprise should be consistent and clear [11]. The leadership system and managerial support are the driving factors of organizational dynamic capabilities.

- Future research may explore the interaction of dynamic capabilities in digital transformation, as well as use quantitative research to address the effectiveness of dynamic capabilities in the digital transformation of SMEs.

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Application of Augmented Reality to Support Manufacturing Resilience

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Abstract. European industrial value chains and manufacturing companies have recently faced critical challenges imposed by disruptive events related to the pandemic and associated social/political problems. Many European manufacturing industries have already recognized the importance of digitalization to increase manufacturing systems' autonomy and, consequently, become more resilient to adapt to new contexts and environments. Augmented reality (AR) is one of the emerging technologies associated with the European Industry 5.0 initiative, responsible for increasing human-machine interactions, promoting resilience through decision-making, and flexibility to deal with variability and unexpected events. However, the application and benefits of AR in increasing manufacturing resilience are still poorly perceived by academia and by European Manufacturing companies. Thus, the purpose of this paper is to contribute to the state of the art by relating the application of AR with current industrial processes towards manufacturing systems resilience. In order to cope with this objective, the industrial resilience and augmented human worker concepts are first presented. Then, through an exploratory study involving different manufacturing companies, a list of relevant disruptive events is compiled, as well as a proposal with specific ideas and functionalities on how AR can be applied to address them. In conclusion, this research work highlights the importance of AR in coping mainly with disruptive events related to Human Workforce Management and Market/Sales Management. The AR application ideas shared a common thread of availability and delivery of information to the worker at the right time, place, and format, acting on the standardization and flexibility of the work to support manufacturing resilience.

Keywords: Augmented Reality · Augmented Worker · Manufacturing Resilience · Human-Centered Manufacturing · Human-in-the-Loop

1 Introduction

Recent events related to pandemics outbreaks, unexpected wars and other geopolitical issues, climate change and its impact on the planet, as well as social and human behavior changes, have challenged the manufacturing industry as we know it. Considering said

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events, it was observed that industrial companies and value chains generally present a low level of resilience to cope with the impacts caused by these disruptive events [1, 2]. Since that this general lack of resilience directly affects the autonomy of the European industry, research on this topic has become of pivotal importance. In this line, digital technologies such as connectivity, automation and robotics, virtual and augmented reality, and digital twins have been positioned as a top priority in the European industry agenda to mitigate this issue. [3, 4].

In this paper, autonomy is perceived as a critical enabler in transitioning to a more sustainable and resilient industry [5]. We can identify and strive for three different types of autonomy: technology autonomy, which encompasses self-awareness, self-healing, and self-learning processes, systems, machines, and components; autonomy of future work, which refers to more independent and conscious human decision-making, easy access to information and knowledge, well-being, and the focus on individual preferences, capabilities, needs, and job roles; and geopolitical autonomy, that is related with self-sufficiency in critical resources, technological know-how, and infrastructures.

The relevance of digital technologies and the digitalization of information and knowledge toward the autonomy of future work and, consequently, the impact on European industry resilience are discussed throughout this paper. Specifically, the paper will analyze and characterize the importance of Augmented Reality (AR) in the current manufacturing landscape and its importance for the future of the manufacturing industry's evolution toward technological autonomy. In this sense, the research question of this study is: how can AR technology increase European manufacturing industry autonomy and resilience? To answer this research question, an exploratory study, including a design thinking workshop and exploratory interviews, was carried out within the scope of a national innovation project strongly driven by industry.

This paper is structured into a further four sections. After the introduction, sections two and three presents, respectively, the main concepts along with relevant research related to industrial resilience and augmented workers in manufacturing. Section four presents the methodology and results of this study, discussing the importance of AR to the manufacturing industry's resilience. Finally, section five synthesizes the main contributions and the further steps foreseen in this research context.

2 Industrial Manufacturing Resilience

The use of Industry 4.0 technologies, such as Cyber-Physical Systems, the Internet of Things, Machine Learning, Artificial Intelligence, and AR, has enabled industries to achieve exceedingly flexible production with greater levels of automation. However, even when achieving high levels of flexibility, low probability disruptions events with high impact can still occur, disrupting the supply chain and damaging the enterprises' performance [6]. Disruption events are unwanted events (that can occur either inside or outside of the supply chain), expected or unexpected, that disturb the performance of the manufacturing processes [7]. The ability to withstand, adapt, and avoid/overcome these disruptive events is resilience [1]. Resilience is characterized by two critical capabilities:

- Robustness, a manufacturing system/industry is said to be robust when it is capable of being stable by absorbing, mitigating, and enduring disruption shocks [1] without changes to the initial configuration, all while maintaining the desired output of the system performance [6]. Thus, a robust system can withstand negative impacts [8].
- Agility refers to a system's ability to respond and recover from a disruptive event that the system's robustness cannot endure/mitigate [6]. Consequently, agility is the ability to quickly respond to a disruptive event through reconfiguration of the damaged area [6].

Post-disruptive event, if a system is not robust enough to endure, it is necessary to be agile [8]. Robustness can be coupled with autonomy, i.e., the capacity of a manufacturing system to recover quickly and autonomously from disruptive events while avoiding a complete stoppage of the manufacturing process [5].

3 Augmented Human Worker

With the ongoing digital transformation, manufacturing systems have been introduced with a higher level of autonomy and automatization, thus granting a certain level of independence and flexibility [9]. Therefore, human workers will be in a more intelligent and autonomous environment characterized by using a significant range of technologies [10], resulting in a growing volume of data and information available [11]. This information must be understood to be used in a more complex and likely, cognitively overloaded decision-making process [12]. Hence, new challenges are rising regarding the human worker and these complex industrial environments:

- Transformation of the workforce through empowering the creation of innovative human capabilities that enable today's workers to coordinate work digitally.
- Development of industrial systems that follow a human-centered vision, allowing more room for meaningful human interactions in all industrial processes while providing them with suitable resources to expand their decision-making and action skills.
- Promotion of intelligent, efficient, and highly flexible human-robot collaborations, enabling significant improvements in the added value of products and services.

Regarding these challenges, technologies such as AR are being used to increase the human worker's capability to succeed in an autonomous and digital manufacturing environment in a manner that is more cognitively ergonomic and more effective [13]. In this sense, AR enables the evolution of human labor into a digitally augmented human worker that immersively integrates and interacts with an increasingly complex and autonomous productive environment and systems [14, 15].

AR can be perceived as the link between the digital and the physical worlds, resulting in an augmented/enhanced sense of reality [16]. AR is regarded by the Europe Union as an essential driver of smart factories [17], and it can augment the shop-floor worker's [18] overall performance by delivering relevant information in a simplified/straightforward and context-specific manner [19] to his immediate environment [16].

Therefore, the augmented worker is the empowered version of the worker with enhanced performance using context-sensitive information [14] provided by immersive

interfaces (i.e., smart glasses) that support their cognitive, physical, and sensory abilities [20]. In conclusion, the use of AR technologies has the potential to increase workers' cognitive capabilities to enhance decision-making autonomy, flexibility to adapt to different contexts and improve process quality and robustness. But the question remains: can we say that the augmented human worker contributes to greater industrial resilience?

4 Augmented Human Worker Towards Resilient Smart Factories

To answer the question "how can AR technology increase European manufacturing industry autonomy and resilience?" an exploratory study focused on understanding the problem of industrial resilience and identifying potential disruptive events was driven. The adopted research design was qualitative, where data was collected through a workshop and semi-structured interviews. The workshop was conducted in the scope of a national innovation project called DEO - Digital Enhanced Operator. The consortium comprises a research center, an AR technology company, and a car manufacturing company in Portugal. A design thinking method [21] was used with the participation of approximately ten experts with different roles and back-ground: production manager, innovation manager, processes and quality manager, researchers, and the technology company CEO and CTO. In addition to the DEO consortium, the research team complemented the workshop results with qualitative analysis from exploratory interviews involving production managers and innovation managers from five other manufacturing companies from sectors of aerospace, automotive components, cork, and machines and equipment.

The workshop consisted of two distinct stages. First, participants were asked to identify disruptive events, which were classified according to their origin (inside or outside the supply chain) and the degree of prediction (expected or not expected). These disruptive events were then compiled from the workshop and the interviews, clustered, and are presented in Table 1.

In total, twenty-one types of disruptive events were consolidated and grouped into seven topics from the point of view of impact: Human Workforce Management, Market/Sales Management, Assets Maintenance, Infrastructure Security, Crisis Management, Compliance Management, and Supply Chain. Most of the events identified as unanticipated disruptive were related to two main areas: the human workers and information related to products, i.e., processes and assets (machines, systems, and robots). These disruptive events are somehow transversal to big and SME companies. However, these become more critical to manage within complex manufacturing systems, both in terms of processes, resources, raw materials, and variety of final products.

The most prominent topics are Human Workforce Management and Market/Sales Management. From the events identified by topic, it is possible to understand the importance that the human worker still has in the factories, but also that humans are potentially a weak point that needs to be mitigated. Issues identified in market/sales management derive from the constant product innovation, specialization, and diversification that contribute to the complexity of production processes and require greater flexibility.

Crisis management is also one of the highlights, strongly motivated by the most recent worldwide disruptive events such as COVID-19 or the semiconductor crisis, which

Table 1. Consolidation of Possible Manufacturing Disruptive Events by Origin and Prediction

Disruptive Events			
Inside Supply Chain		**Outside Supply Chain**	
Not expected			
Topic	**Description**	**Topic**	**Description**
Human Workforce Management (absenteeism/turnover/ motivation)	Worker absenteeism / turnover	**Crisis Management**	Political-social, economic, natural, or public health crisis (e.g.: transport strikes, wars, blizzards, earthquakes, pandemics)
	Intra and inter-task worker turnover		
	Monotonous tasks leading Lack of motivation/stagnation. The workforce of the future needs to captivate the youth generation		
	High Risk jobs / stress or accidents involving workers and/or assets (machines, systems, robots)		
Market/Sales Management (demand/competition/ product innovation)	Fluctuation in demand (production increase/decrease/mix of production)		Lack of production and supply of raw materials, parts, machinery, and equipment (e.g.: semiconductor crisis)
Assets Maintenance (systems, machines, equipment, robots)	Unscheduled maintenance of assets		
	Breakdowns/need to replace assets		
	Process automation malfunctions (Quality Assurance)		External communications infrastructure failures (internet, 5G, satellites)
Infrastructure Security	Cyber-attacks on assets (machines, systems, robots)		
Supply Chain Management	Routing/schedule issues from suppliers		Big distributors related issues (e.g., Suez canal)
Inside Supply Chain		**Outside Supply Chain**	
Expected			
Topic	**Description**	**Topic**	**Description**
Market/Sales Management (demand/competition/ product innovation)	Entry of new products for production	**Compliance Management**	Government bans/restrictions (e.g.-, Paris agreement) that result in significant changes in production processes due to innovative and differentiating characteristics of the production of new products (e.g., production of electric cars, hydrogen cars)
	Changes in product characteristics		
	Introduction of New Technologies in the plant and production processes		
	Increased digitalization of the factory and production processes	**Market/Sales Management** (demand/competition /product innovation)	Threat of new entrants (competitors)
Human Workforce Management (absenteeism/turnover/m otivation)	Workers strike		

revealed the inability of many companies to respond efficiently and effectively to a lack of raw material when political, social, or economic events occur. These events have urged companies to establish contingency plans that force changes in their business models, develop and introduce new products, or even promote new services based on digitalization. Finally, Assets Management highlights the increase in digitalization and diversification of information systems, machines, and robots. This fact forces companies to recruit new people and invest money to manage, maintain and integrate these new technologies, which represents a risk, mainly to SMEs, which could subsequently lead to a disruption event.

In the second stage of the workshop, the participants were invited to suggest ideas to enhance the company's resilience to previously identified disruptive events. To facilitate the brainstorming, participants were encouraged to focus on augmented reality technology capabilities and identify how the related technologies and features can be implemented to increase resilience towards these disruptive events (Table 2).

The resulting ideas were grouped into major strategic intervention areas: i. standardization; ii. workstation flexibility; iii. product operations traceability; and iv. data analytics and continuous improvement. From the thirteen ideas identified, companies focused mainly on the standardization and flexibility of the work and workers. Particularly in these two domains, the ideas mentioned shared a common thread of availability and delivery of necessary information to the worker at the right time, place, and format. As a result, with improved information access, the human worker will benefit from better decision-making conditions with greater cognitive ergonomy.

Standardization of the work reveals the transformation of the human worker into an augmented human worker. Moreover, collaboratively connecting the ideas of an AR application/functionalities, we realized that all the ideas that came up related to more impact on disruptive events of Human Workforce Management, Market/Sales Management, and Assets Management.

These contributions are, by definition, transversal and generic, capable of being applied in all industries and sectors. Nevertheless, their relevance and application are strictly dependent on the digital maturity of the organizations. Therefore, it is recommended to perform, at the first moment, a digital maturity assessment and define a roadmap for digitalization to identify the specific features to be implemented, as well as all the dependencies for its successful implementation and the reliable calculation of the associated costs and benefits (ROI). It is recommended to perform different proofs-of-concept (POCs) with controlled use cases before investment and industrialization of the solution.

These results reinforce that human workers play an essential role in factories as factory digitalization and automation increase. Industrial resilience can be increased by adequately managing the information and knowledge delivered to the worker. Consequently, the role of AR technologies is a critical enabling technology that facilitates access to information delivering contextualized information to workers in the most effective way in a timely manner is fundamental to succeed in both reinforcing the robustness of manufacturing companies and improving the agility to respond to disruptive events. However, with the ever-increasing complexity and richer contexts, the adoption of enabling technologies such as AR is not sufficient, and cognitive ergonomics becomes central when considering industrial resilience. Based on the state-of-the-art analysis, the authors concluded that there is a lack of research work focused on mapping the benefits and innovative use cases for AR tools implementation towards European manufacturing industry resilience and sustainability. Therefore, this research paper intends to be a starting point to promote this discussion between academia and industry.

5 Conclusions and Future Work

The world has been facing significant events imposing critical disruptions in the economy and the manufacturing sector. Industry 4.0, as we know it, cannot deal with social and political tensions, economic inflation, stagnation, or even health issues. In this sense, it is mandatory to redirect the future of the manufacturing industry, using the technology evolution to promote a more transformative view - Industry 5.0. This view should be focused on enhancing human capabilities and improving well-being as factors fostering the increase of businesses' sustainability, agility, and robustness towards a more

Table 2. Consolidation of AR Possible Ideas to Increase Manufacturing Resilience

Strategic Intervention Domain	Idea	AR Application / Functionality	Disruptive Event Topic Addressed
Towards Standardization	Promote standardization of workstations for greater effectiveness and efficiency between shifts	Deliver on job training with faults detections and personalized recommendations	**- Human Workforce Management** **- Market/Sales Management**
	Eliminate paper and all not relevant data and information on the shop floor	Give access/view/listen information/knowledge/documentation (e.g.: manuals) - augmented information/documentation	**- Human Workforce Management** **- Market/Sales Management**
	Guarantee the existence of standard work instructions for all workers in an agile manner	Deliver contextualized and standardized work instructions that can be adapted to the level of worker expertise/training (i.e., different workers might required different levels of assistance)	**- Human Workforce Management** **- Assets Maintenance**
Workstations Adaptability	Ease the process of workstations rotations (i.e., turn covers)	Deliver contextualized and standardized work instructions that can be adapted to the level of worker expertise and decision making needs	**- Human Workforce Management**
	Training on the job	Deliver contextualized and standardized work instructions that can be adapted to the level of worker expertise to training on Job	**- Human Workforce Management** **- Market/Sales Management**
	Streamline communication between workers and leadership	Retrieve/deliver knowledge (priorities, experiences, comments, ..). AR system to facilitate the communication/collaboration on site (e.g: videocall)	**- Human Workforce Management** **- Market/Sales Management** **- Assets Maintenance**
	Improve Human-Human and Human-Robot Collaborations in shop-floor	Give possibility to Augmented Workers and a physical asset to work in symbiosis (i.e., smart systems where digital data-driven systems can divide work instructions between humans and robot and showcase in real-time the task that each individual should be doing)	**- Human Workforce Management** **- Market/Sales Management**
Product & Operations Traceability	Tracking of worker tasks/physiological data (stress, temperature...) for continuous process improvement	(With wearables) do real-time monitoring of worker tasks/quality assurance (process/product) using audible, kinetic and visual warnings	**- Human Workforce Management** **- Market/Sales Management**
	Ease the supervision process (i.e., supervisors can overview the workers performance through the shift)	Real time monitoring of worker tasks/quality assurance in high resolution (process)	**- Market/Sales Management** **- Assets Maintenance**
	Register evidences (videos and images) of processes and product towards quality assurance	Capture video, sound, and pictures in predefined timestamps of process tasks	**- Market/Sales Management**
Data Analytics and Continuous Improvement	More effectively and efficiently Development of new equipment/tools for the production processes in the factory	Development of new equipment/tools for the production processes through VR/AR on the shop floor or together with simulation techniques	**- Human Workforce Management** **- Market/Sales Management**
	Monitor processes standards implementation and relevance, against targets	(With wearables) do real-time monitoring of worker tasks/quality assurance (process/product) and compare with standards via process mining.	**- Market/Sales Management** **- Compliance Management**
	Training on the job	Deliver continuous improvements recommendations to the augmented worker based on best practices	**- Human Workforce Management** **- Market/Sales Management**

resilient and competitive manufacturing sector. Thus, it is necessary to deliver digital solutions that will enable humans to cope with the digitization challenges and enhance their cognitive capabilities to use, in a timely way, all the digital information available, both internal and external.

The results of this research point out that there is still a lack of studies pointing out the main opportunities to implement AR technologies towards European manufacturing resilience. Moreover, it is identified that AR technologies, in the different available configurations (head-mounted displays, projections, and others), are, in fact, promising

instruments that can streamline the information exchange and knowledge communication between humans and machines and, ultimately, foster knowledge sharing between humans. The development of innovative features, such as those presented here, can significantly impact operations standardization, workstation flexibility, product, operations traceability, data analytics, and continuous improvement.

As further work, the research project consortium will define specific use cases related to the automotive assembly factory and specifies, develops, and validates the augmented reality functionalities that can support industrial resilience. The consortium believes that this is the proper time to develop this type of research, considering the uncertainty of the economic situation and the volatility of the automotive sector, with the introduction of new types of cars (electric, hybrid, and hydrogen) in existing production systems. The research team will also include the outcome of this research in the current digital maturity assessment and digital roadmap tools.

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An Operating System for Cloud Manufacturing (OSCM)

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Abstract. Factory technologies have evolved to incorporate a great deal of manufacturing flexibility. Programmable automation in the form of Computer Numerical Control (CNC) and (Programmable Logic Control (PLC) coupled with hardware and process innovations (quick-change tooling, for example) enable a high level of shop-floor flexibility. Possibly, the most inflexible part of a factory is the manufacturing information system. In this paper, we develop an approach to a flexible and extendible architecture for shopfloor information systems. The Operating System for Cloud Manufacturing (OSCM) is a full-stack, distributed platform that tracks and facilitates the interaction between manufacturing jobs and resources (physical machines, humans or software apps). It uses an event-based architecture and a message exchange/broker to enable flexible and configurable distribution of to capture, distribute, curate and store information about shop floor events. The event-based architecture makes it easy to provide context to data emanating from the shop floor, while the message broker gives it flexibility, scalability and extendibility. This paper describes the architecture of the operating system and its services. Further, it demonstrates how shop-floor data can be flexibly routed to manufacturing apps that need it before drawing up conclusions.

Keywords: Cloud Manufacturing · Industry 4.0

1 Introduction

Manufacturing environments are complex, interconnected systems in which events and information related to manufacturing jobs/transactions must be distributed to many different resources that, in turn, perform activities related to the job generating events and results, which must be communicated to different decision-makers. As the number of jobs executing concurrently in a manufacturing facility increases, and each job becomes more complex with a larger number of processing steps on larger numbers of resources, organization and coordination becomes a challenge. The task of capturing the relevant events and information, curating, storing and routing them to the relevant operational decision-making entities also becomes increasingly complex. To alleviate these problems, hierarchical frameworks (e.g., the Purdue Enterprise Reference Architecture or PERA [1]) are used to organize, control, and monitor resources, functions, and activities. Such hierarchical decomposition leads to layers such as (in PERA, Levels 0, 1, 2, 3, 4) equipment, operations, and enterprise layers at which decision-making systems might reside.

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Central Repository Architectures: The information system architecture used in manufacturing most frequently parallels that of the framework used for organizing and controlling the behavior of the manufacturing environment [2]. The MRP/ERP approach where most of the information and decision-making functions reside in a central system is one that has been commonly used and commercially available for quite a few decades. The corresponding information system framework uses a 'repository-type' framework, with a centralized database optimizing access to information by collocation the data and decision-making. This has worked well for traditional manufacturing environments with primarily top-down information flow and only periodic capture of job and resource states, and little or no communications and messaging in real-time.

Dynamic Point-to-Point Architectures: As new manufacturing concepts evolve, they create new patterns for decision-making in the system. As a result, information architectures must adapt to accommodate these new and evolving needs. For example, with the concept of agile manufacturing, to address the need for more detailed communication of states of interacting resources and activities, Song and Nagi [3] propose the use of a virtual information system. They use object-oriented methodologies for modeling information and the concept of 'partners' for interrelated tasks. Similarly, to facilitate more dynamic information needs in autonomous and distributed manufacturing, client-server type communications have been proposed to support distributed decision-making (see, [5] for holonic manufacturing, [6] for ISA 95 and [7] for CIMOSA). Additionally, older frameworks like repository-type systems may adapt to this need for more intensive communication between the planning and decision-making function and the actual resources (machines, workstations, etc.) on the shopfloor by using an interposing system called the Manufacturing Execution System (MES) [4].

Distributed Event-Based Architectures: Manufacturing automation has undergone significant changes over the years, moving from mechanization to Detroit-style hard automation, and then to computer-driven programmable automation. While the first two of these phases dealt primarily with automation of physical tasks, programmable automation opened up the possibility automating decision-making too. This has led to concepts such as flexible manufacturing with decision-making functions like process planning, scheduling and quality management, etc. being automated. The latest development phase in industrial automation is what we call perceptual automation. Here, with cyberphysical systems technologies combining physical components with computational systems [8, 9] the Industrial Internet of Things (IIoT) making sensing capabilities ubiquitous in manufacturing environments, and artificial intelligence and machine learning (AI/ML) tools becoming pervasive and easy to access, perceptive automation not only addresses physical and decision-making tasks, it also builds the perceptive layer necessary to enable them. It does so by assembling various sources of information and data into perceptive networks that detect and refine patterns and relationships that permit one to perceive and anticipate problems and opportunities and construct control actions to avoid/exploit them. In this emerging paradigm of perceptive automation, the information architecture cannot be constructed on preconceived assumptions of information flow. Rather, it must be built to enable flexibility in both, information generation/collection and its consumption. It should allow for the flow of high-resolution and volume of information out from

work-centers and support the flexible access to this information by several decision processes operating at various temporal scales. Event-driven architectures use a broker to decouple the publishing of information from its consumption. Using different routing techniques, the published information is made available to all consumers want access to it in a flexible, stable and reliable manner.

Modern implementations of event-driven distributed systems suggest using one of two open-source technologies [10, 11]: RabbitMQ or Apache Kafka. RabbitMQ is a message broker that supports multiple communication protocols [12] Apache Kafka is a distributed event-streaming platform for high-performance data pipelines, streaming analytics, data integration, and mission-critical applications [13]. Even though several cloud-based architectures have been proposed [14, 15], most such architectures use a pt.-to-pt. approach for communicating data and events, rather than broker-based event and data distribution.

Given the aforementioned trends and challenges in manufacturing automation, this paper develops a distributed information infrastructure using an event-driven systems architecture for organizing, monitoring, and controlling resources of a manufacturing company. Called the Operating System for Cloud Manufacturing (OSCM), this event-based infrastructure aims to integrate operation technology (OT) and information technology (IT) in modern manufacturing environments. OSCM is envisioned to facilitate and track the interaction between a manufacturing job and resource by logging, distributing and storing their states and state transitions. The remainder of the paper is structured as follow: Sect. 2 provides the scope and general design considerations for OSCM, including the details of OSCM's hierarchical resource and complex transaction models. Section 3 details the architecture for the event-based distributed system and finally Sect. 4 draws up conclusions.

2 Overview of Operating System for Cloud Manufacturing

OSCM is a full-stack cloud-based operating system for manufacturing that services and virtualizes manufacturing resources such as computer numerical control (CNC) machines (i.e., 3D printers, CNC mills or lathes), robots, or other such manufacturing resources, so they can be assembled into a scalable cloud of manufacturing capability. As a manufacturing OS, OSCM performs several tasks, including shielding the end-user and application programs from the low-level complexity of the hardware and its operations. OSCM assembles the following services around a resource-transaction pair:

- Information services: A rich and extendible object representation for manufacturing resources and transactions. The resource object information encompasses mechanical and controls configurations, operational information and behavior, and dynamic state information. The manufacturing transaction object carries processing instructions, workflow, specifications, scheduling, and business/payment information.
- Messaging, event, and communication services: These services are broadly necessary for bringing information necessary for transaction processing to the resources and distributing information about resource and transaction state, and data streams from the resource and its sensors during operation.

- User management: These services control who has access to a resource or a transaction and with what privileges. OSCM platform supports multiple types of users: providers, customers, developers, and administrators.
- Access management, authentication, and authorization: This overlaps with user management, but must also cover authentication and authorization services for applications that connect to, or interact with, the OSCM cloud.
- Interfaces: To be functionally effective, OSCM provides interfaces to humans, software, and hardware, browser interfaces for resource owners, customers and system administrators and application program interface (API) for end-user applications.

2.1 OSCM Architecture

OSCM has a four-layer architecture: hardware, virtualization (edge), cloud (server), and application (end-point or end-user), as shown in Fig. 1(a). The underlying concepts and strategies used in the architecture of the software components and abstraction models of the operating system are described below.

Hardware Layer: The hardware layer consists of the manufacturing machine or device (resource) to be virtualized. OSCM currently supports heterogeneous types of resources such as machine centers, 3D printers, incremental forming machines, micro milling and tuning machines, chemical vapor deposition (CVD) furnaces, ultrasonic welding machines, and waterjet machines, among others.

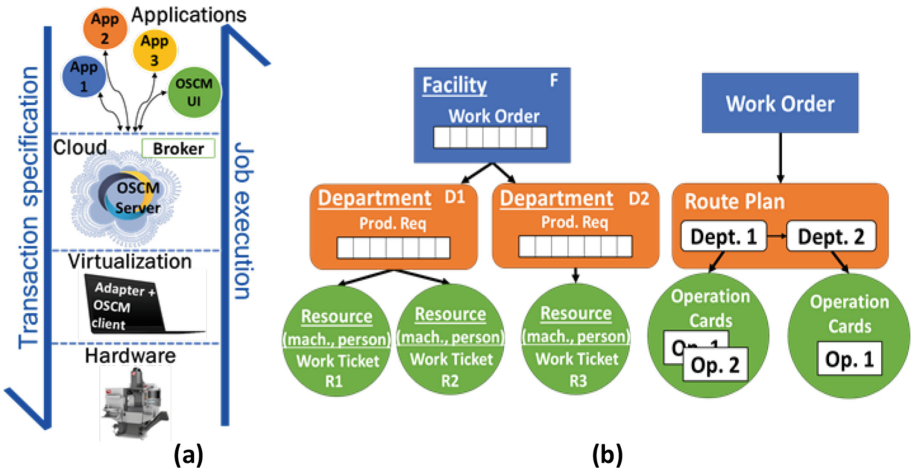

Fig. 1. (a) OSCM four-layer architecture: Hardware, virtualization, Cloud and Application, and (b) Hierarchical organization of transactions and resources on a manufacturing shopfloor

Virtualization Layer: The virtualization layer aims to connect to the resource's controller and embedded software to collect, filter, and structure state and sensor data to finally deliver it to the cloud layer. We use two software components to be able to virtualize the resource, the adapter and the resource client. The adapter has a component that directly talks to the resource API and a component that talks to the resource

client. The component facing the resource's API is resource-specific. The resource client communicates with OSCM platform and does not interact with proprietary data.

Cloud Layer: The kernel of the operating system is the OSCM cloud. A backend server, it is implemented in Node.js [16] and the Express.js [17] routing framework. For the database, the OSCM server uses MongoDB [18], a NoSQL database capable of handling structures, semi-structured and unstructured data. The resource model and transaction operation located at its core, are accessed through different server interfaces. Both abstract models, resource, and transaction, are the connection between the end-user applications and the actual resource data coming from the hardware layer.

Application Layer: The application or end-point layer of OSCM is vital to the packaging the machine as a service (MaaS). OSCM has its own native user interface (OSCM front end UI), but its main strength lies in virtual assets (OSCM end-user applications). Virtual assets allow any developer to create manufacturing applications within the OSCM ecosystem. The OSCM user interface (OSCM-UI) is an example of an application that allows users configure and mange resources and transactions manually.

2.2 The Resource-Transaction Model

In OSCM, both the resource and transaction models are hierarchically organized to reflect the layers in the manufacturing environment. Thus, at the lowest level, a resource may represent a machine or a work-center. This basic resource is a sibling to other similar resources embedded in a composite resource such as a department, which in turn may be embedded in a root resource such as a facility. All resources in a system have owners, and the owner affords different levels of access privileges to other users in the system. OSCM provides resources with certain basic services such as description, and location services, encrypted credentials for OSCM client authentication, adapter configuration parameters, process parameters, calendar object, operator panels, data-streaming and tooling, among others. Resources at all levels can be 'decorated' with assets or software apps to extend the services available on a resource. The transaction model is a second important abstraction of the operating system and is also hierarchically organized with layers that correspond to those in the resource model. A transaction is an instance object established by the agreement between a provider (department/resource) and a customer (order manager). The content of the transaction instance varies depending on the provider's configuration, however, in general, it contains information regarding times, dates, status and manufacturing job information. Figure 1(b) captures the structure and the interaction between these two important objects in OSCM.

3 Event-Based Distributed Architecture

To adapt the hierarchical resource and transaction models as well as the end-user applications into the distributed system, OSCM implements the architecture shown in Fig. 2. The basic workflow allows events/messages to be generated from atomic and composite resources and operator panels associated with them. All the messages/events generated in the system are broadcast through a message broker so flexible coupling of OSCM

with decision-making and other applications are preserved. The consumer entities in the basic workflow are the end-user applications interested in consuming specific data from authenticated and authorized resources. The role of the broker is to distribute messages among consumers using topic-based routing. Finally, the OSCM backend server plays the role of authentication middleware. In particular, it verifies user's and resource's credentials before producers' and consumers' apps connect to the broker. The selected broker for the distributed architecture is RabbitMQ because of its scalability, flexibility with message routing and the fact that it is programming language and operating systems agnostic. RabbitMQ (RMQ) supports multiple messaging protocols such as STOMP, MQTT and AMQP. For the event-driven architecture in OSCM, the AMQP protocol was selected. This gives the OSCM ecosystem flexibility to adapt to the needs of different applications and organizations.

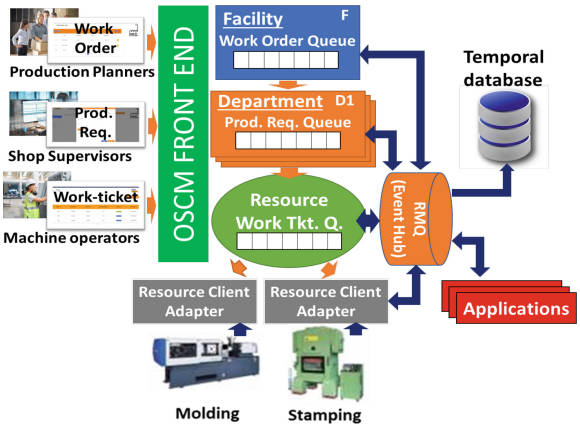

Fig. 2. Event/Message driven architecture for hierarchical resources and transactions

In OSCM, the topology (internal composition of exchanges, bindings, and queues) expands as the network of resources grows by using the RMQ API. When a provider registers a resource (could be a facility, department, or resource) a new exchange corresponding to this entity is created and bound to its resource parent, if any, with a wildcard #. This means that all messages emanating from child exchange are routed to the parent exchange. Then, if a message is generated in a machine (resource) and published to its corresponding exchange in RMQ, the message will be routed first to the department exchange and then to the facility exchange in which this resource is located. This topology is possible because, in OSCM, a provider must register first a facility, then a department, and finally a machine. Figure 3 shows the systematic evolution of this process in step 1–3.

On the other side of the topology, queues are created using the RMQ API when a developer registers a virtual asset (end-user application) in OSCM. Thus, it is guaranteed that each application has at least one queue to consume data from. Finally, when providers want to use a virtual asset in their resources (at any level of the tree), they must attach the virtual asset to the corresponding resource, i.e., for use at a facility level, the app must

be registered in the facility. In RMQ, a binding is created when the provider connects the virtual asset to the corresponding resource. The routing keys used for the binding depends on which type of messages the virtual asset supports, and are defined upon app registration (types of messages are described in next the subsection). Figure 3 shows the evolution of queue and bindings registration in RMQ in steps 4 and 5.

OSCM uses a standard message structure containing two parts: properties (metadata) and message (data). When putting all this together one ends up with a distributed system of micro-services, where applications (virtual assets) provide targeted services to a multilevel resource model, where IoT data merges with operational data for the decision-making functions in a modern manufacturing ecosystem. One of the main advantages of this microservice model around manufacturing resources and operations is the possibility of rapid development of services to decorate or enhance manufacturing resources. In this model, developers do not need to deal with the difficulties of scripting algorithms to collect and bring process and operational data to their applications. Instead, developers can focus on the core services of their applications. In addition, developers can use almost any programing language to support their services. The only constraint is that the programming language supports AMQP libraries or TCP-socket connections. Expert developers can use C++, Python, or JavaScript, while less experienced developers can opt to use low-code frameworks like Node-Red [19].

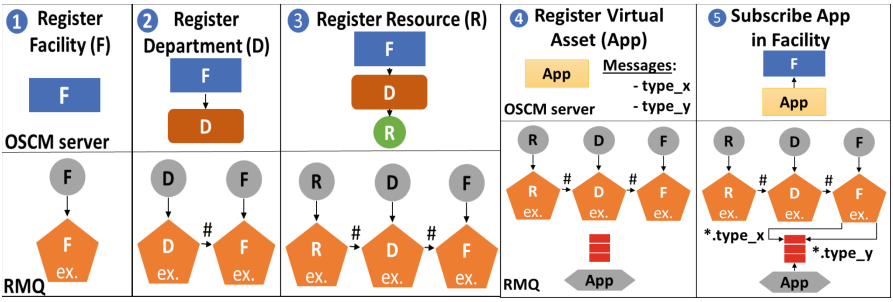

Fig. 3. Steps in evolution of the RabbitMQ exchange topology as resources are added to OSCM (Steps 1–3) and the binding of an asset queue to a corresponding exchange when applications are attached to a resource. Here, an application is being attached to a facility (Steps 4–5).

4 Conclusion

We have reported on the development of a flexible manufacturing information system infrastructure we call Operating System for Cloud Manufacturing (OSCM). This full-stack manufacturing infrastructure is designed to assist and track the interaction between physical resources, transactions, and software services. The implemented resource and transaction models in OSCM map directly to a typical manufacturing multilayer organization, where hierarchical or parent-child models are required.

Our implementation of OSCM is easily accommodate throughputs of 400 messages/s (reaching around 60 Mb/s) with a single instance. In different tests, the system easily

supports monitoring and visualization services [20]. It has also been used to facilitate multi-site gathering of data to support machine learning in CVD synthesis of graphene [21]. Our current work addresses event-based architectures for monitoring and logging photographs and sensor measurements at stations for high cycle rate (>20 cps) production lines. Our future work addresses the development of reactive schedulers and supervisory controllers for flexible manufacturing cells.

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Simulation-Based Approaches to Enhance Operational Decision-Support in Healthcare 5.0: A Systematic Literature Review

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Abstract. The objective of this study is to systematically evaluate peer-reviewed literature and analyze the current research on the thematic area "Simulation-Based Approaches to Enhance Operational Decision-Support in Healthcare 5.0" using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses. This systematic review was conducted in compliance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) statement and implemented with the aid of the StArt software. Appropriate keywords were used in a search of the Science Direct, SCOPUS, and Web of Science databases. A total of 357 papers were retrieved from the databases and evaluated automatically. Eventually, 79 papers were analyzed according to their title, keywords and abstract. After the full-text analysis, 33 papers successfully met the inclusion criteria in the study. The review showed that healthcare providers and decision-makers can be guided by applying the Key Performance Indicators (KPIs) obtained from the simulation-based platforms to ensure quality and resilient health system.

Keywords: Decision-Support · Healthcare 5.0 · Simulation

1 Introduction

Over the years, healthcare systems have experienced evolutionary changes in line with the industrial evolution from healthcare 1.0 to healthcare 5.0. This translates to the evolution of healthcare system from traditional healthcare system to smart healthcare system. Healthcare 5.0 is described as the introduction of the Artificial Intelligence (AI) principles in the healthcare system, coupled with the use of smart intelligent technologies and the integration of high-speed (5G) data transfer networking protocols [1].

The evolutionary smart healthcare system which have paved way for remote healthcare services have brought about a decrease in the number of patients that would naturally be present physically in the hospital. However, improving quality healthcare while minimizing costs still remains a universal challenge. As a result, it is paramount that decisions are made to review and boost the performance of various healthcare processes and services at all the strategic and functional levels. Healthcare providers need suitable tools,

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such as simulation, to successfully investigate different scenarios in order to forecast the influence of these decisions on the overall system performance of health facilities in healthcare 5.0 [2, 3].

Simulation is a decision support tool that enables key players in an industry to carry out investigations with models that imitates or duplicate large parts of the actual situation or real-life's systems under study. Simulation modelling in the scope of healthcare covers the area of Healthcare management [4–6]. Simulation in healthcare creates a safe learning environment in which researchers and practitioners can test new operational processes and enhance their decision support system for a resilient healthcare system [7–9].

2 Methods

2.1 Protocol

The objective of this study is to systematically review and analyze the current trend in the thematic area: "Simulation-based Approach to Enhance Operational Decision-Support in Healthcare 5.0" The systematic review technique followed the guidelines stated in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocol) to trace the appropriate literature in the research area and tries to answer the following research questions:

- What are the possible set of KPIs that will aid decision support for a resilient healthcare system?
- How can hybrid simulation approach be used to improve the quality of lives of the patient and healthcare providers?

2.2 Literature Search

For the review, online research engines such as Science Direct, Web of Science (WOS), and SCOPUS, were explored using the keywords; Simulation, Healthcare 5.0 and Decision-support. Search criteria were developed to consider the demographic and outcomes of interest in order to generate an exhaustive list of all original literature pertinent to the research questions. The following terms were part of the search algorithm used: "Simulation" AND "Modelling" AND "Decision-Support" AND "Healthcare". The stated algorithm was applied in the search engine of all 3 databases used for this study. The search for articles was restricted to those published between January 2017 to June 2022 with the assumption that healthcare 5.0 which is an evolutionary concept will be tackled within that range.

2.3 Eligibility Criteria

The systematic review was conducted in accordance with the inclusion and exclusion criteria as shown in Table 1.

Table 1. Inclusion and exclusion criteria for eligibility

Criteria	Inclusion	Exclusion
Language	English	Languages other than English
Access	Open access	Access blocked
Literature type	Articles, Conference paper, Review	Books, Abstract only, Thesis, Websites, Duplicate articles
Publication Year	January 2017–June 2022	Articles earlier than or later than the stipulated range
Search String	Articles that contains at least a keyword in the search combination	Articles that do not contain in its keywords any of the component of the search string

2.4 Data Extraction

The search results from the database searches were collected and recorded in the Microsoft Excel Professional format with the following data columns: title, authors, publication, year of publication and status selection. Next, the studies were scrutinized for inclusion or exclusion at the selection stage by evaluating the title, keywords and abstract. Furthermore, for the final extraction, the papers were critically evaluated to ascertain their level of relevance for inclusion in the present review, focusing on the following components: objectives of the article, healthcare 5.0, methods and KPIs for decision making.

3 Results

3.1 Study Selection

In the study, predetermined eligibility criteria were used to evaluate the title, keywords and abstract of publications discovered through electronic databases to determine their eligibility for selection and extraction (Table 1). In the event that the publication's title, keywords and abstract lacked sufficient information to determine selection eligibility, they were exempted. Full-text publications that met the extraction criteria were collected and the complete article was screened. Full-text articles were retrieved and evaluated for bias risk if the abstract or article met our eligibility requirements. Tools and methods for data extraction were designed and validated. It was implemented with the aid of the StArt software.

On 22 June 2022, a search was conducted on Scopus and Science Direct databases using the combinations of key words, while Web of Science database was accessed on 24 June 2022. A total number of 357 papers were sourced in the following order: Scopus 177 papers, Science Direct 80 papers and Web of Science 100 papers. Following the initial screening from the search databases, and limiting the search to open access articles and articles published within the last 5 years in English, a total of 79, were extracted in a RIS format and saved on the software for the systematic review.

The 79 remaining articles were screened for eligibility criteria. The articles excluded from the reviewed were articles that did not meet the inclusion criteria. After the screening for eligibility, 38 articles were accepted and 41 excluded from the full-text evaluation. The search result is presented in the Fig. 1, which is a PRISMA 2020 flow diagram for systematic literature review.

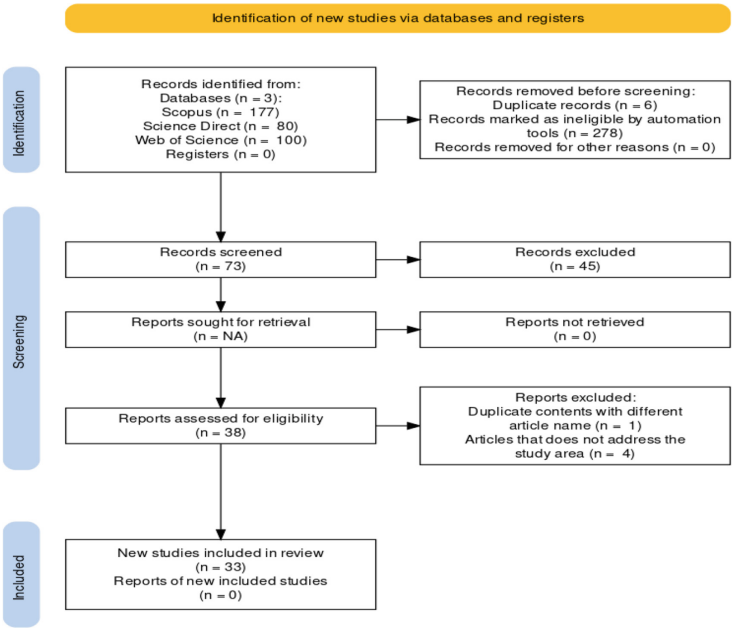

Fig. 1. PRISMA flowchart of the study selection for eligibility

3.2 Simulation Approaches

Simulation-based models provide a broad picture of the interactions between variables and the processes [10]. Discrete-event simulation is a valuable tool with regards to enhancing patient flow, and effective utilization of facility resources [11]. Discrete event simulation is a reliable decision support tool to improve healthcare quality [12, 13]. Most of the studies, approximately 50% of the studies reviewed, utilized the discrete event simulation approach in carrying out the simulation goals. Multi-agent programmable modeling environment and artificial intelligence methods is useful for the provision of recommendations about more effective policies from the standpoint of a decision support system [14]. The intricate situations that occur in hospitals, involving non-linear correlations and numerous interconnections, may be depicted using system dynamic modeling [15]. Hybrid simulation is a modeling strategy that incorporates two or more of the following techniques: agent-based simulation, discrete-event simulation, and System dynamics. The current and most effective technique is to merge ABS, SD and DES

models [16]. The greatest advantage of hybrid modeling is the ability to integrate different simulation approaches and empirical data from different sources [17–19].

3.3 KPIs

Key performance indicators (KPIs) are dimensions used to categorize and evaluate business performances. Key performance Indicators can be categorized and analyzed based on process, outcomes and structural indicators [20, 21]. KPIs that will make for a resilient healthcare can be classified based on quality, time related KPIs, Patient related KPIs and budget Related KPIs [22]. 70% of the studies reviewed presented patient related KPIs and time related KPIs. The quality and resilience of any healthcare system or service is largely dependent on the metrics chosen for evaluation and decision support. [23–25]. A study presented three main elements for developing healthcare simulation; medical activities, service times and arrival times [26]. As the stress on the health system increases, the standards of care decreases [17]. The deduction here is the determinant which is the level of healthy, satisfied and properly managed healthcare facilities, services and healthcare providers. It is a patient centric health system that degenerates to a population centric system when under stress (Heavy Demand). Operational quality KPIs such as staff, power outage, operating room and availability of patient record is considered for the achievement of a more resilient healthcare sector. The quality of care can be improved when the patients and healthcare providers are put into consideration when identifying key performance indicators [27]. This is in line with the holistic approach expected of the healthcare 5.0 concept.

4 Discussion

From the results, it is evident that most studies adopted the discrete event simulation approach when compared to the other simulation approaches. To address the dynamics of social-technical systems, insufficient research has been carried out on agent-based simulation, system dynamics, and hybrid modeling. The interplay between people and technology in the delivery of health care would shift in numerous ways as a result of digital transformation. The promise of future healthcare delivery that eliminates institutional borders and the methods used currently to test and demonstrate functionality are at odds with each other. A deeper comprehension is needed from the interrelated relationships between care providers in order to model individual level requirements, which will help close this gap.

The findings indicated that while there are only a limited body of empirical studies on determining the specific KPIs that will make for a resilient healthcare operation in the context of industry 5.0, this body of work can therefore be regarded as emerging, and does exist, however, a small body of empirical work that reports on the possible sets of KPIs. The body of literature accessed is not sufficient enough to tackle healthcare 5.0. This is as a result of lack of articles addressing the subject area because of its novelty. This can be deduced from the Fig. 2 which is a bibliometric analysis of articles available on the database via Vos viewer. Another key limitation of this study is that, only literatures obtained in line with the PRISMA guidelines were reviewed. As a result,

the search results were limited to Scopus, Science Direct and Web of Science databases. Though, they are the most frequently used in literature search [28, 29]. Hand searched or manually extracted articles were not included in the systematic literature review. The review only evaluated studies published after 2017. This approach was taken because the evolution of healthcare 5.0 started in the year 2020 [30]. The years preceding this time experienced industry 4.0 evolution. Hence, an integration of the literature after 2017 should not contort the analysis.

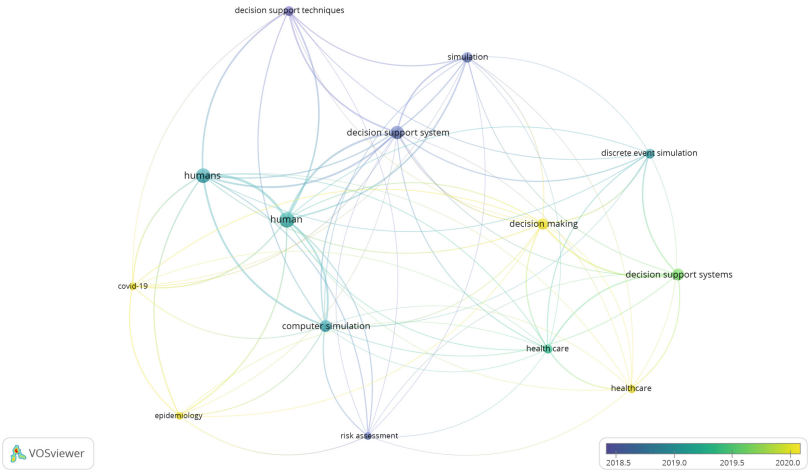

Fig. 2. Availability of articles on the search data base using the keywords

5 Conclusion

This study explored a systematic literature review, covering studies that addresses the overall improvement of decision-support in healthcare 5.0 using simulation-based techniques, and answering the research questions described in the literature review planning protocol. As a result, it was possible to identify that to have KPIs that will aid decision support will have to cut across all classifications of the KPI consideration and not only patient-centered or time related KPIs. This review showed that the studies that employed a hybrid simulation approach had a more formidable result as compared to the single approach [31, 32]. For future work, it is necessary to have a robust hybrid simulation approach that will account for all ramifications of the health system i.e. diagnosis and intervention for specified illnesses, human factor and infrastructure.

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Semantic Asset Administration Shell Towards a Cognitive Digital Twin

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Abstract. Manufacturing industry is experiencing another revolution towards the digitalization of industrial processes. Different value chain actors must share specific and sensitive data according to business and data requirements. Digital architectures must ensure seamless and comprehensive communications between actors according to agreed-upon vocabularies. The digital representation of machines and other types of equipment, including crucial information about their static and dynamic operational data, is made possible by the ontological modelling of Asset Administration Shells (AAS), which is proposed in this paper as modular and semantically interoperable resources. These Cognitive Digital Twins are herein defined with de facto domain ontologies that model the semantics of the current operation, status and configurations of assets. This paper reports a proof-of-concept technical implementation that demonstrates an innovative digital architecture that connects and communicates active and modular Digital Twin of a machine in a bi-directional, connecting this asset to a digital manufacturing service provider.

Keywords: Industrie 4.0 · Cognitive Digital Twin · Asset Administration Shell · Ontologies · Semantic Interoperability

1 Introduction

Manufacturing systems are becoming increasingly complex, where different endogenous and exogenous variables establish non-linear relationships, further aggravating humans' capability to comprehend and process them, significantly increasing the time required to identify inefficiencies, root-causes, and define mitigation and corrective plans. Factories of the future must evolve to achieve higher levels of autonomy and flexibility to cope with internal and external disruption events, and as a result, become more resilient. This means that the next generation of factories must become self-aware of their own behaviour and capable of inferring the main reasons for non-expected performances, identifying root causes, and prescribing potential corrective measures. In order to achieve these objectives, as well as to contribute to the research on this domain, the following research question (RQ) is proposed:

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RQ - *How can the CDT concept be implemented whilst integrating semantic technologies and the AAS standard and what are its benefits?*

The double objective of this research question is to understand how to build Semantic Asset Administration Shells (SAAS) that describe the internal behaviour of a machine, while also explaining how these systems interact externally with other elements of the production system. On the other hand, it also aims to demonstrate how semantic technologies can be used in combination with the Asset Administration Shell to provide richer knowledge of the machine's internal status contributing to better problem-solving and, ultimately, fostering knowledge reuse. The main outcome of this research is a proof-of-concept that demonstrates the application of SAAS to define the CDT of a simple industrial machine. An additional result is the information system architecture capable of capturing the data on the shop floor, generating the SAAS and using it at the business layer.

2 State-of-Art

2.1 Asset Administration Shell as an I4.0 Component

The Reference Architecture Model for Industrie 4.0 [1] (RAMI4.0), introduced by the Platform Industrie 4.0, was developed to ensure standardisation between enterprises. Within the RAMI4.0, the Asset Administration Shell (AAS), turns an asset into an I4.0 Component. Details of the Asset Administration Shell - Part 1 [2] defines AAS as a "standardized digital representation of the asset" whereas an "asset" is anything that requires some kind of "connection" for an Industrie 4.0 solution (e.g., machines and their components, contracts, orders, and supply materials). Within the notion of an I4.0 component, the AAS is the basic element of Digital Twins (DT), serving as an asset identification card whilst providing a digital representation of the asset's complete lifecycle. Thus, offering standardisation within the digitalization era we are currently facing. Data assets are hereby conformed to a predetermined set of standardised elements, resulting in a common understanding and enabling partners in value-creation networks to share meaningful data [3].

An AAS can be composed of multiple information models, so-called "Submodels", representing different parts of the asset (e.g., properties, actions, and events). Each of the submodels can be composed of multiple collections of "SubmodelElements" that correspond to a specific domain. As a result, a series of submodel templates can be created. The AAS also supports the use of external dictionaries such as eCl@ss and IEC CDD, easing the process of assigning semantic descriptions to the AAS properties. Currently, the AAS can be serialised into different formats (JSON, XML, RDF, AutomationML, OPC UA node-set, AASX) [2] and can be shared according to the application programming interface (API) defined in the Details of the Asset Administration – Part 2 [4]. Table 1. Displays the currently available tools for the deployment of Asset Administration Shells.

Table 1. Available tools for AAS instantiation.

Tool	Description
AASX Server	C# based server for AASX packages, accessible via REST, OPC UA and MQTT protocols. Developed by the Industrial Digital Twin Association (IDTA)
Eclipse BaSyx	Open-source middleware which provides SDK in different programming languages (Java, Python, Rust,.NET, and C++)
NOVAAS	Node-RED solution, developed by NOVA School of Science and Technology
FA^{3}ST Service	Fraunhofer solution to provide reactive AAS

2.2 Digital Twin

Manufactories are shifting towards a smart manufacturing context whilst increased digitalization and connectivity are triggering greater interactions between physical and virtual spaces [5]. DT is the acting mirror of a physical object [6], which through high-fidelity virtual models emulates the physical object in a safe and digital environment [7] whilst enabling real-time bidirectional connection of the physical-digital spaces [6]. The concept of the DT was first introduced in 2002 by Grieves during his presentation on Product Lifecycle Management. Grieves [3] would, later on, propose a three-dimensional model of a DT composed by: i. the digital entity, ii. the physical entity, and iii. the communication between entities (or dimensions). The DT is a highly researched field resulting in a high density of DTs with different levels of maturity. Kritzinger et al. [8] proposed the classification of DTs into three subcategories: i. **Digital Model**; digital representation of a physical object, without a physical-digital connection; ii. **Digital Shadow**; characterised by the physical-digital connection where data will flow automatically from the physical object to the digital object, but manually from the digital to physical; iii. **Digital Twin**; data flow between the digital-physical is fully integrated and bidirectional. In some instances, the digital object might act upon the physical object. The DT can be used to generate additional value across all phases of the physical product lifecycle. Bridging the gap between the equipment's design phase and its respective operation [9]. Thus, DT can be used to facilitate and validate the design of different products and systems [10] resulting in a reduction of cost and lead time while improving the overall design stage through certification that the product to-be is within requirements and expectations [11]. Recently, the term Cognitive Digital Twin (CDT) has been emerging as a result of the fusion of semantic models with the concept of DT. Zheng et al. [12] compared multiple CDT definitions and defined the CDT as an autonomous and cognitive DT-based which "comprises a set of semantically interlinked digital models related to different lifecycle phases of the physical system including its subsystems and components, and evolves continuously with the physical system across the entire lifecycle". Within the scope of our research, [13] provides a literature review on how the CDT can support the different stages of smart product-service systems.

3 Semantic Asset Administration Shell

Bader et al. [14] defined SAAS as the union of the RDF of the AAS, Asset, Submodels, and Concept Descriptions. Our vision of a SAAS is aligned with this notion and addresses three main points: i. structure and deployment of AAS and the composing entities in a JSON serialisation, ii. JSON to RDF mapping, and iii. schema validation.

3.1 Deployment of the Asset Administration Shell

Machines are complex assets, composed of static and dynamic variables. Static variables are normally related to machine identification, while dynamic data is normally related to internal variables, such as transducers. Herewith, the proposed AAS is composed of one asset and three submodels: i. asset identification; ii. Sensors; and iii. Actuators. The asset references an "*assetIdentificationModel*" (i.e., the AssetIdentification submodel). The sensors submodel is composed of two "*SubmodelElementCollections*" where each collection corresponds to a sensor (i.e., temperature sensor and humidity sensor). Each of the "*SubmodelElementColletions*" is divided into three instantiations: i. value (e.g., reading of the sensor); ii. Timestamp; iii. Range (e.g., the minimum and maximum range of admissible values). For simplification purposes, the actuators and *assetIdentification* submodels are not expanded here. Collection of data from the asset was made through a python-based OPC UA server and client (https://github.com/FreeOpcUa/opcua-asyncio). Whereas the deployment of the described AAS was made within the OPC-UA client through the Eclipse BaSyx Python SDK (https://github.com/eclipse-basyx/basyx-python-sdk).

3.2 RML for mapping AAS into SAAS

The RDF Mapping Language allows the specification of mapping rules that transform semi-structured data (e.g., JSON) onto a semantically enriched graph, in RDF, by means of one or more domain ontologies. Based on the AAS information model depicted in Fig. 1, we developed a mapping ruleset to yield the SAAS as an RDF graph according to the constructs of the RAMI4.0 vocabulary (https://github.com/i40-Tools/RAMIOntology). Such a mapping allows the semantic integration of heterogeneous data streams from physical assets into a knowledge graph. In addition to the instantiation of a SAAS, each observation contained in a SAAS was modelled with the ontologies "*Sensors, Observations, Sample and Actuator*. (SOSA) (https://www.w3.org/TR/vocab-ssn/) and "*Quantities, Units, Dimensions and Types*" (QUDT) (https://qudt.org/) ontologies. The former contains constructs that allow the modelling of the observations measured by sensors. The latter allows for formalising the units of measurement provided by sensors. The observation instances are semantically enriched with information that allows one to identify the corresponding Asset and SubmodelElement. Such instances are independent from the SAAS instance and are generated whenever a new measurement is transmitted by an asset.

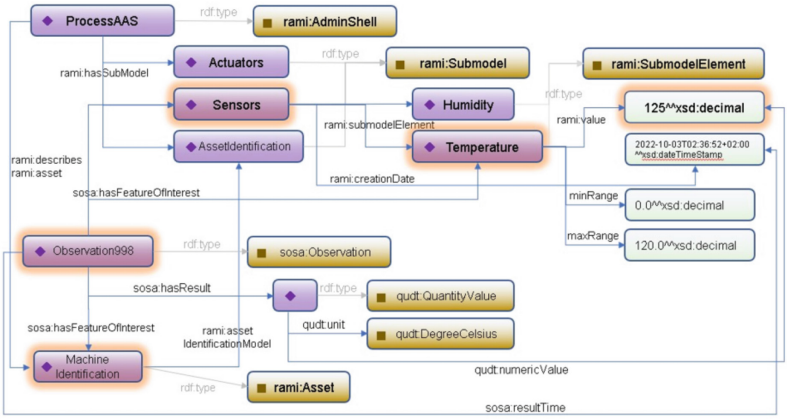

Fig. 1. Knowledge graph of instances of a SAAS and a Temperature observation. Orange glow denotes a discrepancy after SHACL validation.

3.3 SHACL for Validating a SAAS Instance

The Shapes Constraint Language (SHACL) allows modelling constraints for validating RDF graphs. Such constraints, i.e., rules, are semantically modelled as graphs themselves, which can be reused by various actors, thus decoupling the data validation layer from the application logic. One or more SHACL rulesets may be available in the Vocabulary Hub Component (VHC), as described in Section IV. In this proof of concept, we implemented a ruleset to ensure that a SAAS instance conforms to the AAS information model depicted in Fig. 1.a. The ruleset also allows reasoning over instances to infer abnormal readings of actuators and sensors. For instance, the Humidity and Temperature SubmodelElements provide the normal operational Range of each sensor. Whereas a value outside of said Range would constitute an anomaly.

4 SAAS Contribution for the Factories of the Future

The framework presented in Fig. 2 combines the concepts of the RAMI4.0 [1], smart factories framework [15], and the manufacturing data lifecycle [16]. We contribute to the literature by providing a reconstruction of the information layer. Here, it is introduced the use of a Semantic Translator (ST) which will take as input data serialised into AAS-compliant JSON and output a SAAS. Our notion of the VHC reflects an integration of a multitude of vocabularies. Hence, the mapping from JSON-to-RDF is made via RML whilst resorting to the use the previously presented vocabularies. The RDF graph yielded from the RML mapping is the SAAS instance, which must be validated against a set of SHACL rules persisted in the ST component. The validation is the last step prior to persisting the SAAS instance data into a graph database. The endpoints of such a database, e.g., SPARQL endpoints, support the microservices that relate to analytical tasks supported by the decision-making tools that relate to the Business layer. In sum, Fig. 2 presents a high-level model of our notion of an AAS-based CDT. Where each of the physical assets will have an “identification card” provided by the AAS, whereas

semantic interoperability is ensured through the ST component. The presented semantic approach enables standardization, enabling smart factories to streamline digitalisation on two fronts: i. resorting to the usage of established AAS submodel templates, and ii. common understanding within cross-enterprises data exchanges, easing the process of service delivery or even generating template models for servitization. In complex manufacturing systems, it is not viable to have monolithic information models, representing the entire system's DT, due to security, trust and privacy issues and massive data handling requirements. On the other hand, it is critical to developing modular and interoperable architectures that enable stakeholders to exchange and have access only to the information that is mandatory for their decision support. This vision requires the development of a new version of modular and CDTs of the different elements of these complex manufacturing systems, which can be plugged into a graph structure and represent the system at the level of detail and perspective demanded by a specific stakeholder. This graph will not only depict the system's past and present behaviour, but also identify and explain the reasons for specific behaviours whilst analysing patterns to predict the future.

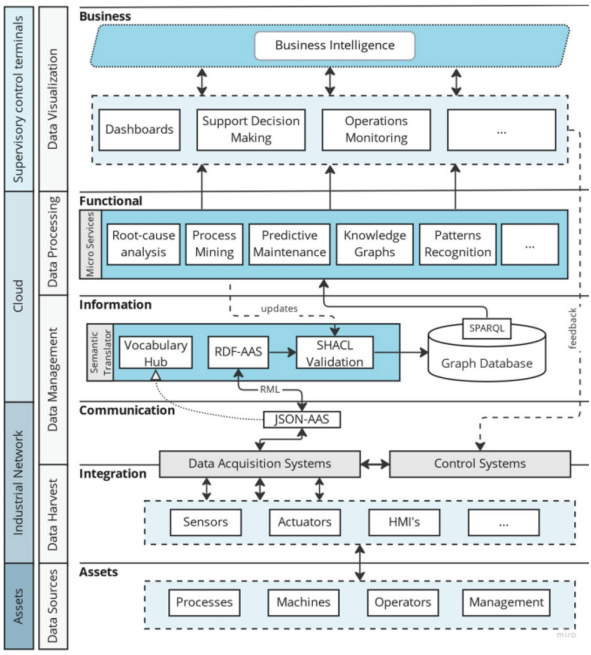

Fig. 2. Integration of the Semantic Asset Administration Shell with Smart Factories.

To demonstrate our approach, we illustrate how the SAAS of a simple industrial machine allows for knowledge discovery, through a graph based on the RDF data model in the context of a temperature anomaly, as illustrated in Fig. 1.b. Purple and dark-yellow rectangles represent resources such as instances and classes, respectively. Blue arrows indicate the connection between two resources. Prefixed elements, e.g., rami:,

indicate the namespace of an element, such as the RAMI4.0 vocabulary. The temperature observation is encased in the Temperature SubmodelElement within the Sensors submodel, which are mapped onto instances of rami:SubModel and rami:SubmodelElement, respectively. The Temperature SubmodelElement contains the sensor measurement (rami:value) at a given timestamp, and the range of allowed values for such a measurement, modelled by the min- and maxRange predicates which are not originally included in the current version of the RAMI4.0 vocabulary. However, this is a component of the AAS standard, and in that regard, an extension is proposed herein to adhere to the standard while providing us with a means to support the semantic validation with SHACL. The values for min- and maxRange predicates are targeted by the SHACL validator throughout the ST. A SHACL rule was implemented to flag instances of SubmodelElement for which such a value violates the normal operation range. The corresponding instance of sosa:Observation that violates the rule is also flagged. Knowledge-based tools can exploit the corresponding graph to trace the instances of sosa:hasFeatureOfInterest that were involved in the violation, which is indicated in Fig. 1. With an orange glow. To ensure further traceability, the Temperature data encased by the SubmodelElement was also mapped onto an instance of sosa:Observation, which also relates the measurement to the asset MachineIdentification and the Sensors submodel by using the sosa:hasFeatureOfInterest predicate. The properties sosa:resultTime, qudt:numericValue, and qudt:unit were mapped onto the values provided by the SAAS instance.

5 Conclusions and Future Work

When reviewing the previously stated research question, taking into consideration the research presented in this paper, four three conclusions can be drawn: i. **standardisation**, ii. **reutilization**, and iii. **autonomy**. Hence, through the deployment based on the AAS standard, common understanding across enterprises within Industrie 4.0 is ensured. This enables the generation of templates that can be used to streamline the implementation process and enable extensive reutilization. The use of ontologies enables the semantic description of heterogeneous data across assets in accordance with a set of constructs that are acknowledged by several actors. The presented semantic approach leverages the usage of the VHC to enable data integration, where the SHACL validation of knowledge graphs not only ensures data is well-formed but also enables to ensure traceability of faulty components that may blemish the efficiency of a manufacturing process. Furthermore, we do not perceive the SHACL validations to be static; they can be dynamically updated through empirical knowledge derived from the functional layer enabling. Moreover, in order to support industries in this growing need for digitalisation, we contribute to the literature through the proposition of a framework for AAS-based CDT. By linking the principles of the AAS with an ontological data representation based on standards, higher levels of modularity and scalability are achieved. Modular given the common understanding of the meaning of data granted through the use of standardised models and vocabularies, easing the process of servitization i.e., if data is simply understood, so is the process of delivery of digital data-driven services. Scalable in the sense that it supports the reuse of models or even services. As for future work, we identified the two

lines of action to improve our notion: ***i. Expand the AAS model and include submodel templates;*** The model's complexity was minimal, and it should be increased in future testing. IDTA already offers a series of AAS submodel templates that can be used in future implementations. ***ii. Ensure sovereignty and security across every data transaction;*** Leverage the use of data spaces initiatives, such as the International Data Spaces, to ensure data sovereignty and security are ensured across the entire value chain.

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Digital Twin Design and Evaluation for Dynamically Optimised Distribution Strategy in Food Supply Chains: An Exploratory Case Study

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Abstract. Up to 31% of food goods, especially fresh and perishable ones, are wasted during the transportation and storage. Products' innate susceptibility to spoilage, unexpected issues, and shifting conditions post-strategy commencement are among the manifold reasons for distribution strategy failure in the food supply chain (FSC). Dynamically optimised distribution (DOD) methods can help distribution strategies to adapt and respond to unforeseen changes in today's complex, connected and interdependent FSC. Building on Digital Twins (DTs) superior connectivity and actuation capabilities, this paper proposes a new DT-based method for DOD in the FSC, from DT design to modelling and evaluation in AnyLogic. Initial simulation results from a UK-based case study show that DT-enabled DOD could bring savings of more than £25,000 in direct costs and 150 tonnes of CO_2 per shipment in a typical 20-tonne transport refrigeration unit (TRU). Benefits are compounded by potential fuel savings of up 132 L per year and TRU due to DT-enabled DOD dynamic carrier re-routing capabilities.

Keywords: Digital Twins · Supply Chain · Food

1 Introduction

The latest data shows that around 2.5 billion tonnes of food is wasted worldwide each year, amounting to almost 40% of all food produced. This implies an increase (1.2 billion tonnes) that nearly doubles previous estimates (1.3 billion tonnes) of food loss and waste [1]. From this, transportation and storage of food products is a significant contributor, accounting for up to 31% of food waste [2]. This is particularly relevant for fresh and perishable goods due to the rapid deterioration of product quality, susceptibility to contamination with pathogenic microorganisms and spoilage. As a result, the development of dynamically optimised distribution (DOD) strategies is critical if these are to be reduced and a more sustainable food supply chain realised [3, 4].

Food supply chain (FSC) distribution strategy (DS) optimisation has been explored in several works [3]. However, studies tend to be limited to the pre-planning of the DS [3], thus limiting the ability to adapt and respond to unpredictable, shifting situations once

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distribution has begun. With FSCs evolving into complex, connected and interdependent "value webs" [4], the development of agile, resilient DS' capable of dynamically adapting and optimally responding to changes is paramount.

Digital Twins (DT) [4] offer the potential to underpin the solution to FSC DS challenge by bridging virtual models for operations management optimisation with relevant physical assets, entities, and processes. As shown in Fig. 1, the DT's *Sensing* data streams containing real-time information and knowledge from the *Physical Objects* are fed into the DT's *Virtual Models* to generate the decisions and actions to be performed on the physical system. Informed by real-time on the physical objects *Actuation* data streams continuously adapt and respond to changes in the physical realm [4].

While it is predicted that in the UK, the adoption of digital technology like DTs in the food industry could bring a potential $7bn value to over the next decade [5], barriers like shortage of expertise and resources (e.g., capital and time) are hindering the adoption of innovative technology and process engineering in the food sector [5]. This is particularly true for SMEs, which account for the majority of organisations in the FSC in the UK (97% [5]), as well as in many other countries.

All in all, novel DS solutions are required that can (i) adapt and respond unpredictable, shifting situations beyond the pre-planning stage (ii) combine both DS and digital technologies like DTs to enable the dynamically optimised distribution (DOD) capabilities in (i), and (iii) provide SMEs and food professionals with knowledge/resources (e.g., design and evaluation guides/tools) for digitalisation/DOD implementation.

Building on the DT framework presented on [4] and as an example of its implementation in DS, this paper proposes a new solution for DOD using DTs responsiveness and adaptiveness capabilities. Unlike state-of-the-art DS, the proposed solution provides both a design guide and evaluation tool for implementation in FSC DS, as may be relevant for FSC industrialists. Section 2 presents the proposed DT-based method for DOD in the FSC, from DT design considerations to modelling and performance evaluation of DT-enabled DOD using AnyLogic. This is illustrated in an example case study in Sect. 3, "Digital Twin-Enabled Dynamic Distribution of Beef in the UK". Finally, the main conclusions and suggestions for future work are drawn in Sect. 4.

2 DT-Enabled Dynamically Optimised Distribution in the FSC

This section discusses how Digital Twins (DTs) can be used to enable FSC dynamically optimised distribution (DOD), from DT's design and technological considerations, to how DT-enabled DOD can be modelled and performance evaluated using AnyLogic.

2.1 Digital Twins for Dynamically Optimised Distribution in the FSC

As shown in Fig. 1, *Sensing* data streams comprise real-time state data of the food products (*Physical Objects*). Smart packaging (SP) [4, 6] equipped with intelligent labels and sensors represent the next generation technology for food product monitoring for distribution in the FSC. Equipped with an array of sensors, SP can measure markers of freshness and/or identify the presence of harmful components in food, such as allergens, pathogens, and toxicants [6]. *Sensed Qualities* monitored can include environmental

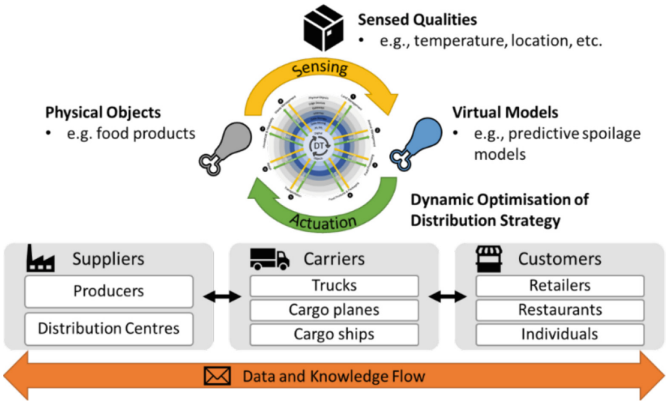


Fig. 1. Conceptual framework of Digital-Twin in [5] applied to Dynamic Optimisation of Distribution Strategy in the Food Supply Chain

conditions (e.g., temperature, humidity, etc.), position (GPS location) as well as those related to food product's freshness and safety (e.g., CO_2 concentration, pH, etc.) [4, 6].

Sensing data streams containing the *Sensed Qualities* of the food products are used to build their corresponding *Virtual Models*, namely to predict remaining shelf life, etc. This is particularly relevant for safety-critical food products like meat and fish, which are highly susceptible to microbial contamination and spoilage [7]. Different models (e.g., GroPIN model, SOPHY, etc.) can be used to predict bacterial growth and thus remaining shelf life of the food product [7]. With DT's frequent/real-time monitoring capabilities, tertiary models [7] can be built, accounting for the behavior, lag phase and growth rate based on the measured environmental and/or physicochemical factors.

With the insights and knowledge from food product *Virtual Models*, automated actuation can take place. *Actuation* data streams containing relevant actions guide the dynamic optimisation of the distribution strategy at every stage. With unifying DT models [4], FSC's key areas, processes, objects and technologies can be integrated, thus facilitating coordination between key players in the distribution stage: *Suppliers* (e.g., food producers, distribution centres, etc.), *Carriers* (e.g., trucks for land transportation, cargo planes for air transportation, cargo ships for sea transportation, etc.) and *Customers* (e.g., food retailers, restaurants, individual consumers, etc.).

2.2 DT-Enabled DOD in the FSC: Modelling in AnyLogic

By enabling communication and interaction, DTs connect all *Customers* (Fig. 2), *Suppliers* (Fig. 3) and *Carriers* (Fig. 4) [4], which become "agents" thanks to the DT's sensing and actuating capabilities [4]. This is reflected in the model proposed in this work, which combines discrete event simulation and agent-based modelling in AnyLogic to model interactions between agents and resources.

The Customer Agents

The state chart that governs the behaviour of the customer agents is shown in Fig. 2. At the beginning of the simulation, customers are in the *"normalWork"* state, which represents the customer operating as "normal" (i.e., with sufficient inventory).

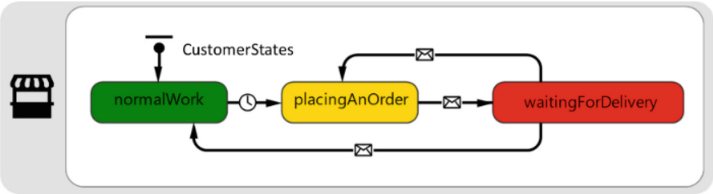


Fig. 2. Customer agent state chart modelled in AnyLogic

After some *timeout* (represented by the clock icon in Fig. 2), which corresponds to the mean time value between orders, the *Customer* agent transitions to the *"placingAnOrder"* state, representing the customer placing an order.

In the *"placingAnOrder"* state, an agent named *"Order"* is created (not shown). This agent only has one property, and it is equal to the index of the customer that created it. This agent is delivered to the *Supplier* agent (Fig. 3) upon creation, entering the process flow. Once it is completed, they are discarded. The customer remains in the *"placingAnOrder*" state until a *Carrier* agent (Fig. 4) has been loaded with a shipment and dispatched to the customer. When a carrier leaves the supplier, it delivers a *message* (shipment has left the supplier) to the *Customer* agent, triggering the transition of the latter into the *"watingForDelivery"* state. The *Customer* agent remains in this state until it receives another *message*, relating to the completion of the delivery. If a shipment has been successfully *delivered* and *unloaded*, a *message* is sent from the carrier, so the customer transitions back into the "*normalWork"* state. The exception to this is when the carrier arrives to the customer with a spoiled shipment. Here, a different message is sent, so the customer places another (replacing) order.

The Supplier Agents

Every supplier (Fig. 3) contains a process flow that governs the utilisation of the carrier fleet. The resource pool *"carriers"* represents the available fleet.

Once an order is placed, the *Order* agent is passed to the *Supplier* agent using the connections feature. This inserts the order into the *enter* block which triggers the *seize* block, which checks to see if there is an available carrier in the resource pool. If there are no available carriers, the process is stopped until one becomes available. An available carrier is seized and paired with the customer whose index is specified in the *Order* agent. This pairing process is established by a java action within the *seize* block, which also sets a variable *customerIndex* in the carrier agent equal to the index of the customer that placed the order.

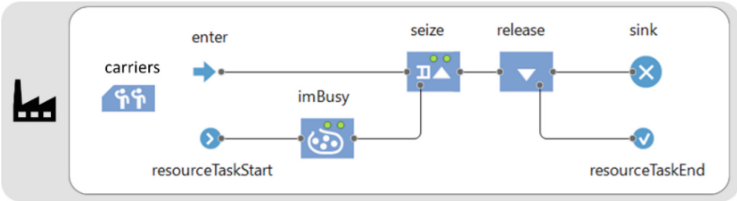


Fig. 3. Process flow created within Supplier agent in AnyLogic

The Carrier Agents

At the start of the simulation, a population of agents "*carriers*" (Fig. 4) is generated. The number of carriers in the population and their initial speed are defined and controlled by the parameters *numberCarriers* and *meanCarrierSpeed*, respectively. The variable *spoilageRange* represents the distance that a carrier can travel before its shipment would spoil. Using AnyLogic's Geographic Information System (GIS) functionality, the latitude and longitude for each carrier, *lastKnownLat* and *LastKnownLon*, respectively, are stored and used for updating *spoilageRange*.

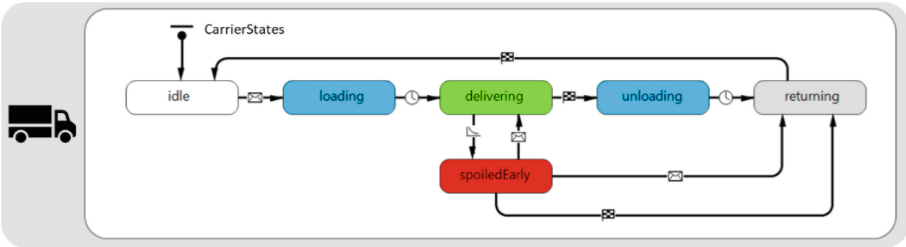


Fig. 4. Carrier agent state chart in AnyLogic

Instructed by the supplier, a *Carrier* agent transitions out of the "*idle*" state and is assigned to an *order* in the *seize* block. Thus, the carrier transitions into the "*loading*" state for a variable amount of time that represents the busyness of the supplier. Next, the carrier is instructed to move to the customer specified by the carrier's *customerIndex*. The carrier delivers a message to the customer, triggering the transition to the "*waitingForDelivery*" and "*delivering*" states for customer and carrier, respectively. The carrier moves into the "*unloading*" state at arrival at the customer. For successful (i.e., non-spoiled) shipment deliveries, the carrier delivers a message to the customer, so it transitions back to the "*normalWork*" state and the carrier moves to "*returning*" state, returning to the supplier and re-entering the "*idle*" state on arrival.

There is a possibility that the carrier can enter the *spoiledEarly* state whilst delivering. This transition is defined by the parameter *spoilageRate*, which can take on unique values for each carrier, if desired. Without access to DT's "real-time" feedback data on the food shipment's state, the carrier (like the other agents) does not know it has spoiled, so it continues its delivery. It is on arrival at the customer when the carrier transitions into the "*returning*" state, returning to the supplier and sending a message to the customer. This

will return to the state *placingAnOrder*, as the spoiled shipment cannot be accepted, and another must be sent.

DT-Enabled Dynamically Optimised Distribution Strategy

A Discrete Event Simulation and Agent Based Modelling hybrid approach was taken to model the Distribution Networks (DN). The flowchart in Fig. 5 shows the operation of the model, detailing the sequential operations that make up the delivery of one shipment to one customer for the non-DT and DT-enabled DN cases. In the latter, evolutionary algorithms are used to model the optimisation process (coloured red), for its final execution in AnyLogic.

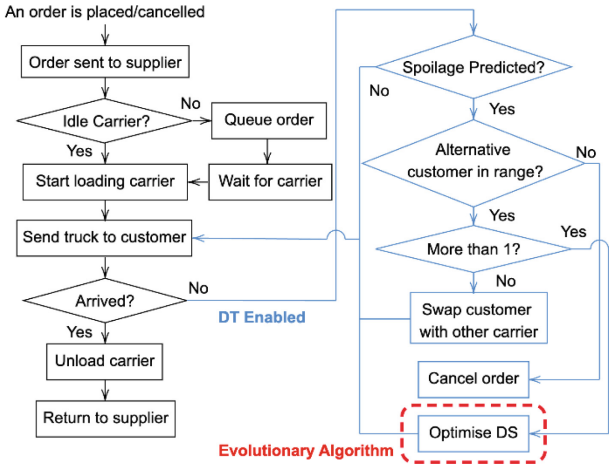


Fig. 5. Flowchart depicting the operation of the Distribution Networks model

The process begins when a customer places a new order or an existing order is cancelled due to spoilage, and it ends when the customer's order is either met or cancelled. The processes in blue represent all the actions and processes that are enabled because of the sensing, prediction and actuation capabilities provided by the DT.

When spoilage is predicted (i.e., carrier entering the *"spoiledEarly"* state) a dynamic event (*"checkForSwaps"*) checks if the carrier in *"spoiledEarly"* state could swap its destined customer with another carrier. To do so, *"checkForSwaps"* iterates through the customers in the "*placingAnOrder"* and "*waitingForDelivery"* state. These represent the customers with an outstanding order and hence offer an opportunity to swap shipments. Using inbuilt GIS methods, the distance to each customer can be calculated and compared to the *spoilageRange* value. If there is not a viable, alternative customer in range (i.e., the distance to the customer is higher than the remaining spoilage range), then the order has to be cancelled and the carrier returns to the supplier. Otherwise, carriers are rerouted to avoid shipment loss. Evolutionary algorithms are used when multiple options (i.e., multiple viable, alternative customers) exist.

2.3 DT-Enabled DOD in the FSC: Performance Evaluation in AnyLogic

Three key Performance Metrics (PM) are defined in this paper to quantify the effects in performance distribution for the non-DT and DT-enabled cases:

PM1 - Shipments wasted (P_w): ratio between the number of shipments wasted and the number of total shipments that left the supplier over the course of the simulation;

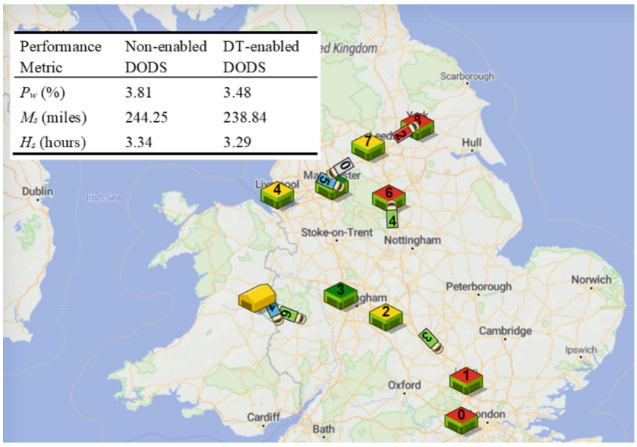
PM2 - Distance per successful delivery (M_s): calculated as the sum of all the miles travelled by the carriers divided by the number of unspoiled shipments arriving at a customer; and,

PM3 - Time customers spend waiting for a successfully delivered order (H_s), representing the time customers spent outside of the "*normalWork*" state. It is calculated as the total time customers spent in the "*placingAnOrder*" and the "*waitingForDelivery*" states divided the number of unspoiled shipments arriving at the retailers.

3 Case Study: DT-Enabled Dynamic Meat Distribution in UK

Meat products are safety-critical foods with high economic (e.g., retail price) and ecological footprints (e.g., water, fuel, CO_2 emissions, etc.) [4]. Costs are compounded by meat's susceptibility to spoilage, affecting quality and safety. With global consumption increasing by 12% by the end of the decade [4], meat is an ideal candidate for DOD.

With a damp climate and rolling grasslands, the UK is a major producer of meat with a high volume (around 75%) of domestic market [8]. As modelled in this simplified, exploratory case study (Fig. 6), Wales is UK's largest meat supplier [9] to UK's major cities [10] (e.g., London, Liverpool, Manchester, etc.), and thus centres for meat consumption. AnyLogic simulation parameters (Fig. 6) are chosen according to latest UK's available data [8] and as trade-off between model's plausibility and simplicity for simulation convergence considerations.



Performance Metric	Non-enabled DODS	DT-enabled DODS
P_w (%)	3.81	3.48
M_s (miles)	244.25	238.84
H_s (hours)	3.34	3.29

Key simulation constraints	Value
Number of customers (corresponding to UK's 10 most populated cities)	10
Number of carriers (*numberCarriers*)	4
Mean carrier speed (*meanCarrierSpeed*)	60MPH
spoilageRate range values	0-6 days
Mean order placement (related to *placingAnOrder*)	1 week
Mean simulation run time	179 weeks
Mean number of orders	2923

Fig. 6. AnyLogic simulation caption showing suppliers, carriers and retailers in the GIS map for the selected case study, including key simulation constraints and results for non-enabled and DT-enabled DOD

Shipments Wasted. Preliminary results show a reduction of 9% in P_w for the DT-enabled DOD case. The average retail price of beef steak in the UK is estimated at £14.16/kg [11]. The ecological footprint of 1 kg beef is estimated at 15,400 L of water and 85.2 kg CO_2 [12]. For a typical 20-tonne cargo payload Transport Refrigeration Unit (TRU), DT-enabled DOD could bring savings of more than £25,000 in direct costs and avoid the equivalent to more than 150 tonnes of CO_2 per TRU.

Distance Per Successful Delivery. UK TRUs thermal load approximate to 6,000 L of diesel per year [12]. By reducing M_s by 2.2%, DT-enabled DOD could save around 132 L of fuel per TRU per year in first order approximation.

Time Retailers Spend Waiting for a Successfully Delivered Order. DT-enabled DOD can also decrease H_s by 1.5%. This is particularly relevant for just-in-time food supply chains like in the UK, with vulnerabilities exposed by COVID-19 [13].

4 Conclusions and Future Work

Dynamically optimised distribution (DOD) can help food supply chains (FSCs) to adapt and respond to changes in today's complex, connected and interdependent "value webs". Building on the DT framework presented on [4] and as an example of its implementation, this paper proposes a new solution for DOD using DTs responsiveness and adaptiveness capabilities, from design to modelling and evaluation in AnyLogic. Initial simulation results from a UK case study show the potential of the proposed method to prevent significant economic and resource losses as well as associated CO_2 emissions.

Whilst applied to the FSC, the proposed DOD method is generalizable to other supply chains with stringent distribution requirements (e.g., cold chain). Future work will look at other applications and implementations of [4], such as further developments for the presented DOD solution, with modelling and simulation of more complex scenarios.

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Metadata Model Construction and Annotation Framework to Build Product Data Repository for Cloud Manufacturing

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Abstract. This paper presents a framework for automatically building a product data repository, overcoming the limitations of machine understanding and the time-consuming, costly nature of manual human annotation. In this study, we focus on Personal Protective Equipment (PPE), specifically respirator mask product categories, as a case study. First, we extract product specifications from the details and sub-details sections of product pages and build < attribute, attribute-values > metadata in dictionary form. Second, to process the data, we represent numerical data with a special token [NUM] and use hierarchical clustering based on Term Frequency-Inverse Document Frequency (TF-IDF) and cosine similarity for categorical data. Third, we propose an algorithm-based method to annotate product attributes and attribute values in product descriptions using the metadata, while minimizing human efforts. Additionally, we employ BIO tagging to extract location information for attribute values, streamlining the overall annotation process. This paper contributes to the field by presenting a method for automatically generating product-related datasets through an algorithm that enables the construction of metadata without any human intervention. This approach is a crucial step toward implementing a knowledge repository in a Cloud Manufacturing (CM) environment. Particularly, by addressing time and effort concerns in the dataset construction process, this method can significantly contribute to the creation of large-scale datasets.

Keywords: Attribute values extraction · Product data · Data integration · Graph database · Knowledge graph · Cloud manufacturing · Metadata model

1 Introduction

In the era of Industry 4.0, various models combining advanced IT technologies and manufacturing resources have been developed to provide manufacturers with more flexibility and agility. Manufacturing as a service (MaaS) is one of them and it often relies

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on Cloud Manufacturing (CM) technologies and shares manufacturing resources among participating members within the network. This effort has been highlighted recently to allow industries to capitalize on market opportunities during unexpected changes (e.g., pandemic) [1–3]. According to Rauschecker et al. [4], through the MaaS and CM technologies, Manufacturing Service Providers (MSPs) can decrease the downtime of their machine and increase manufacturing capacity. Manufacturing Service Consumers (MSCs), who purchase services from MSPs, do not need to have expensive manufacturing resources and manufacturing knowledge to put their concepts or designs into production, which may lower the business risk and threshold of starting a new business. What's more, MSPs and MSCs may create a positive connection through the cloud network and exchange positive feedback among them.

However, establishing such a manufacturing cloud network requires a tremendous amount of preparation work. Tao et al. [5] believe a knowledge repository is essential for successful cloud service to search and match suitable manufacturing functionalities to MSCs. Karl et al. [6] proposed an open online product marketplace framework providing an intelligent and systematic way to match product needs with product specifications and manufacturing capability. Mocko et al. [7] used the metadata of engineering behavioral models in the knowledge repository to find the desired model. To support such a system, MSPs need to digitalize their manufacturing functionalities and capabilities including capacities and form it into the digitalized knowledge repository. As Agrawal et al. [8] mentioned, a company usually requires a variety of suppliers that differ in the product category, schedule, and flexibility of production, which demands the main attributes of these products to be entered one by one and it is very time-consuming and often unrealistic.

In this paper, we propose a novel approach for automatically generating product-related datasets using an algorithm that creates metadata without human intervention. This method addresses time and effort concerns, promoting the development of large-scale datasets for CM environments. Our main contributions include the development of an automatic metadata generation algorithm, its applicability to various manufacturing domains, and data annotation automation, aiming to provide a scalable and efficient solution for comprehensive dataset construction in CM environments. The rest of this paper is organized as follows: Sect. 2.1 presents related research and compares it to the framework we propose. Section 2.2 describes the extraction of product data from web data. Section 2.3 describes the proposed metadata model algorithm for automatic metadata construction. Section 2.4 presents the product attribute value annotation algorithm based on the metadata model and the experimental results obtained using the algorithm. Finally, Sects. 3 and 4 summarize the research findings, outline the limitations of the results, and provide directions for future research, concluding the paper.

2 Metadata Model Construction and Annotation Framework

2.1 Related Methodology

Typically, product attribute tagging starts with proper classification to match the desired needs and target items, such as products [9]. Auto-classification of NAVER Shopping Product Categories is trained based on product-matching data directly verified by humans

at the monitoring center, which means that human manual work is involved in building the training data. OpenTag [10] is a tagging model proposed to solve the problem in product catalogs that often have missing values for many attributes of interest. Text data corresponding to the title, description, and bullet was collected from product pages targeting such as Dog Food, Camera, and Detergent on the Amazon website. Target attributes are brand, flavor, and size, approached using the BIOE tagging strategy. The B, I, O, and E mean the beginning, inside, outside, and end of an attribute, respectively. Another noticeable work in tagging is MAVE [11], which is a dataset constructed by creating product attribute value annotations based on the Amazon Review Dataset [12]. MAVE features 2.2 million products on Amazon pages, three million attribute value annotations across 1,257 unique categories, and a large volume of data. They proposed *Multi-source Attribute Value Extraction via Question Answering* (MAVEQA), which extracts multi-source (i.e., title, description, feature, price, and brand) from product pages and annotates product attribute values from multi-source. MAVE is a large-scale product attribute value extraction dataset. However, for target products such as masks, only two attributes are annotated. During the annotation process, categorical vocabularies are defined by human experts, presenting a limitation in generating a large number of attributes in terms of time and efforts. In this study, we propose a framework for extracting product attribute values and automatically constructing metadata based on web data, eliminating the need for human labor. For masks, we have generated a total of 58 attribute categories.

2.2 Product Data Extraction

We implemented the customized crawler using Python for extracting the data from Amazon.com public pages. We performed experiments in the target domain. In this work, we selected Personal Protective Equipment (PPE) and respirator masks. In crawler implementation, we used lxml[1] to collect static web pages quickly and Selenium[2] to respond to dynamic characteristics that change in real-time and control browser operation. Lxml is a package mainly used as an XML parser in Python. Selenium is a tool that can automate browser operations and simulate human interactions such as requesting a web page and receiving a response. The crawler sets at least one search keyword and collects product profile URLs from web pages generated from the search keyword. The crawler has an XPath for the location of this URL, and XPath serves as the language used to access the elements of the XML document. The structure of the data collected from product profiles is shown in Fig. 1. We collected data in comma-separated values (CSV) format, consisting of ASIN, URL, title, SRC, price, option, details, sub-details, description, and bullet. ASIN is Amazon Standard Identification Number, and ASIN made it possible to distinguish whether it is a duplicate product. URL stands for product profile address, and SRC indicates the image and video address in the product profile. The title is one that users can see in the product profile and the option is the product's option. The description consists of the *details*, *sub-details*, *description*, and *bullet of the products* and all can be used as data to understand the attributes of the product.

[1] https://lxml.de/.

[2] https://www.selenium.dev/.

2.3 Metadata Construction

Among the data collected from Amazon product pages, *details* and *sub-details* are the parts written by the product seller. Customers can grasp the product attributes through what the seller configured. However, product pages contain significant information, making it difficult for customers to compare product attributes easily. We built a product's < attribute, attribute-values > metadata to make it identifiable. In addition, we propose a method to annotate product attributes in raw data by utilizing the established metadata described in the next section. The procedure of metadata construction is as follows. First, we utilized product specification in details and sub-details data to build metadata and saved it in dictionary form, {key: value 1, value 2, value 3, ...}. We set the respirator mask as a keyword, extracted 420 product page data, saved each attribute as a key, and stored the value corresponding to the attribute as a value. We extracted a total of 66 product attributes, and the graph visualization of metadata using the NetworkX[3] library is shown in Fig. 2. In Fig. 2, the subgraph shows the entire product's main attributes, including Brand, Style, Material, Size, Color, and Product Dimensions. These key attributes can be used to build a product knowledge repository for future infrastructure implementation for a Cloud Manufacturing perspective.

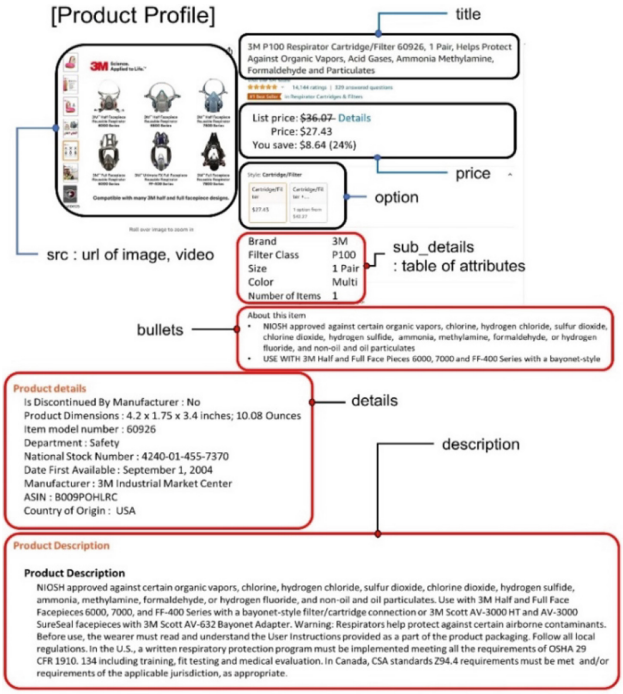

Fig. 1. An example of the product profile on the Amazon website. It consists of webpage metadata, including a product title, several sources, various product descriptions and other information.

[3] https://networkx.org/.

The stored *Specifications* S goes through the process of being separated into tokens by defined *splitters* sp. S is divided into data of numerical and categorical by sp. The numerical data is continuous characteristic data, and we use the special token [NUM] in the metadata construction model, which means that the token [NUM] is the numerical part. Algorithm 1 shows the pseudocode of metadata model construction. To preprocess the categorical data, we tokenized it using NLTK[4], one of the natural language processing libraries. And we used hierarchical clustering based on TF-IDF (Term Frequency-Inverse Document Frequency) and cosine similarity to classify the tokenized data into the same categories (attributes). The reason for doing this is to group attributes that are the same but differently expressed into the same attribute; for example, "Batteries", "Batteries required?", "Batteries included?" are clustered to the same attribute. Algorithm 2 shows the clustering process.

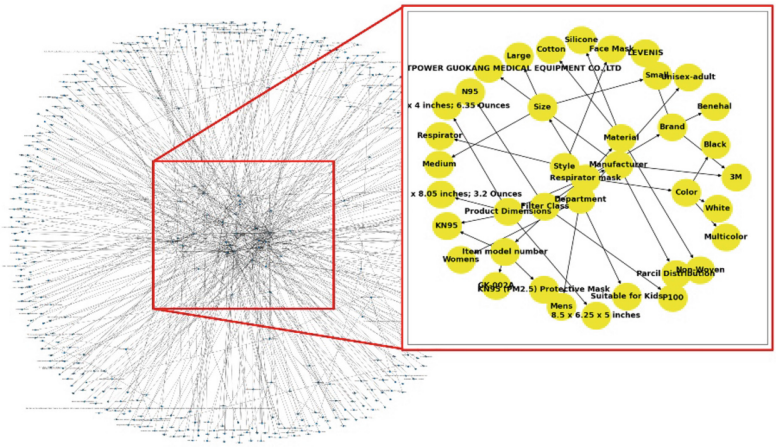

Fig. 2. A graph visualization of metadata configured based on product specifications. It comprises the product's main attributes (keys) and their corresponding values.

[4] https://www.nltk.org/.

Algorithm 1 Metadata Model Construction Algorithm

```
Input: Specifications S, splitters sp
                                        ▷ sp=punctuation, symbol, conjunction
Output: Metadata model M
        ▷ M = (A, V, E), where A is attribute nodes, V is value nodes, E is edges

Initialize empty M;
while each t ∈ S do                                          ▷ set M with S
    while each attribute, values in t do
        if attribute not in A of M then
            Add attribute to A;
            Split values with sp If values else value;
            For each value,
            if number in value then change to [NUM];
                while each value do
                    if value not in V of M then
                        Add value to V;
                        Add edge between attribute and value to E of M;
                    end if
                end while
            end if
        end if
    end while
end while
```

Algorithm 2 Attributes and Attribute-values Clustering

Input: attributes or attribute-values N of Metadata model M, tokenizer $T(n)$, word representation model $WRM(\omega)$, clustering model $CM(WR)$

Output: Categorized Metadata model M

```
while each n ∈ N do
    tokenized words W = T(n)
    while each ω ∈ W do
        word representation wr ∈ WR = WRM(ω)
    end while
    Fit and predict CM with WR
    Match result of CM to M
end while
```

2.4 Attribute Value Annotations

Most datasets are manually annotated in building a dataset, which is time-consuming and expensive to build large amounts of data. In this paper, we propose an algorithm-based method for annotating product attributes and attribute values in product descriptions by minimizing human efforts. First, the attribute values of the metadata built in Sect. 2.3 are embedded using TF-IDF. TF-IDF is a technique, in which, instead of counting the number of words, the frequency of a word is multiplied by the reciprocal of the number of documents that the word appears. We use the bulleted data in Fig. 1 as product description (raw) data. After tokenizing raw data with NLTK, it goes through lemmatization, which means converting each word into a lemma. The lemmatization ensures that the raw data are recognized as the same word, even if derived from the same lemma but written in different representations or written inadvertently as typos. Each token that goes through this process calculates its similarity to the attribute value in the embedded metadata. If the

similarity is higher than the threshold, it is considered equal to the attribute in metadata. Therefore, tokens connected as dependencies of the corresponding token are annotated as attributes. In addition, we can extract the location information of the beginning and end of attribute values using the BIO tagging technique. Algorithm 3 shows the overall process of attribute value annotations.

Algorithm 3 Attribute Value Annotations

Input: Dataset D, Metadata model M, tokenizer $T(d)$, threshold τ, word representation model $WRM(\omega)$
Output: annotations AN

```
Initialize AN;
while each d ∈ D do
    Initialize annotation an ∈ AN;
    tokenized words W = T(d)
    while each ω ∈ W do
        word representation wr ∈ WR = WRM(ω)
    end while
    while each a, v ∈ A, V of M do
        while each wr ∈ WR do
            if sim(v, wr) > τ then
                Extract ancestors and children wr with dependency
                Add attribute, attribute-value, token index to an
            end if
        end while
        Add an to AN
    end while
```

3 Results and Discussion

Table 1 compares MAVE [11] and our dataset in terms of their attributes and characteristics. As shown in Table 1, while the MAVE [11] dataset involves manual human annotation for the category classification task, our proposed method enables algorithmic category classification. Table 2 presents the results of annotating product description sentences using the metadata model constructed within our proposed framework. Upon inputting a sentence, the metadata model generates outputs for pid, begin, and end based on the attributes. The pid represents the category order, while begin and end signify the position of the corresponding attribute value in terms of tokens. In this research, annotation was performed solely through the algorithm, and the absence of a dataset annotated by humans with the same data makes it challenging to test the algorithm's performance. Additionally, a limitation exists in the fact that the metadata model was built using an algorithm rather than an expert, which can result in instances where the same word may appear under different attributes.

Table 1. Compared with MAVE dataset.

Dataset	Characteristic (modality)	Number of attributes (respirator)	Human efforts	
			Category classification	Annotation
MAVE [11]	Multi-source attribute value extraction (text)	2	Required	Not required
Ours	Automatic framework of product attribute values annotation (text)	58	Not required	Not required

Table 2. An example of a product description with annotations using the metadata model.

Source	**Text**
Description	PROPRIETARY COOL FLOW VALVE: Helps reduce heat and moisture. The exhalation value cover helps direct exhaled breath and moisture downward to reduce fogging of eyewear and grinding and welding shields
Attribute	**Values**
Brand	[{'value': 'breath', 'pid': 61, 'begin': 18, 'end': 18}]
Color	[{'value': 'VALVE', 'pid': 17, 'begin': 13, 'end': 13}]
Style	[{'value': 'cover', 'pid':57, 'begin': 14, 'end': 14}]

4 Conclusions

In this work, we proposed a scalable and efficient solution for building a product repository by developing an algorithm that constructs a metadata model and annotates attributes and attribute values. This work is a significant step towards implementing knowledge repositories in CM environments and can substantially contribute to the creation of large-scale datasets. The theoretical and practical contributions of this paper include the development of an algorithm for metadata construction and the demonstration of its applicability to various manufacturing domains. Furthermore, the automation of data annotation streamlines the overall process and addresses time and effort concerns. Our future work is implementing a knowledge graph by extracting attribute relationships from the product dataset, and a graph database can be built based on the knowledge graph. In addition, Graph Neural Network (GNN) can be used to develop a manufacturing search engine, recommendation system, and product tagging model based on missing value interpolation.

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Rx Product Marketplace Orchestrator: An Open Product Marketplace Orchestrator for Rapid-Response Across (Rx) Health and Medical Supply and Demand Chains - 70NANB22H011. We appreciate the comments and valuable insights from Dr. Jaemun Sim.

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Proposal for a Digital OEE Architecture with the Integration of Analysis Parameters of Machines of the Manufacturing Industry

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Abstract. Sudden and unexpected economic changes associated with market competition and short product life cycles have generated significant organizational challenges. Thus improvements in processes and product characteristics can directly interfere with their production capacity. To identify improvements in the process, it is fundamental to analyze how the process is developing and, based on that, make favourable decisions. Today, several companies analyze their data, but most of these are done by manually collected data, which brings much uncertainty and can delay the analysis and decision-making process. The present work aims to propose a digital architecture to calculate the OEE (Overall Equipment Effectiveness) for machines in the manufacturing industry. The relationship between the behaviour parameters of the machines allows for diagnosing critical factors for the production system, namely performance, availability, and quality. The machine parameters presented in a short period allow faster action by operators in cases of failures in the activity, and greater security in the planning of the production process, as well as in the development of products and maintenance schedules, directly impacting the production cost. The project's innovation is carried out through digital data modelling based on the ETL context with parameters derived from the behaviour of a machine, where they are dynamically processed and correlated in the Desktop software to illustrate the calculated OEE value.

Keywords: OEE · Industry4.0 · Architecture

1 Introduction

Organizations face significant challenges in the economic market due to competition worldwide and markets with high exchange rate instability and scarcity of products [1]. The challenge intensifies for organizations that maintain older production control systems and do not have control over their actual performance safely and efficiently [2].

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Such uncertainties lead companies to remodel their processes to more dynamic systems, which has led to significant changes in the routine activities of production processes, reflecting the great need for production in digitalized and more efficient contexts [3].

Other organizations that use manual data control in their process, which in addition to having a late result of the progress of the process, undergo several reworks to confirm the veracity of the information, as they are vulnerable to errors and calculation errors, as the measurement and analysis are done with human intervention, generating many uncertainties in the development of the process [1].

The primary tool used worldwide to quantify the productivity of a machine in the manufacturing industry is the OEE (Overall Equipment Effectiveness) to identify the efficiency of a machine [4]. The OEE analysis is structured from the multiplication of three pillars: availability, performance, and quality [4].

The availability pillar is related to the time parameters in which a machine is available for activity, accounting for the points at which it becomes unavailable due to maintenance or other downtimes [1]. The performance pillar is formed by the association of parameters between the actual and planned speed, while the quality pillar presents the number of parts produced within the requested quality standard and the quantity of production of parts not approved by the quality produced by the machine. [1].

The OEE is data used for more in-depth analysis of process losses, given that the machine has an important position in the production process; a machine that is stopped or with low efficiency entails losses for the entire process; considering this, the OEE calculation is a source of information about the current conditions of a machine, and it can help with more profound studies of losses, production losses [5].

The use of advanced digital technologies in the production environment provides more accurate processes, control, and remodeling for intelligent manufacturing, reflecting quality and value for the organization [6].

The advantages of using machine data more comprehensively are noticeable in the case presented by [7] where, from the OEE calculation, he built a process improvement system using machine learning techniques, collecting data in the form of sensors connected to CNC machines to collect more specific data of the process, seeking to identify the actual behaviour of the tools to portray the relationship between product quality and machine performance.

Industry 4.0 is driven by improving processes and systems, integrating production systems and data collection for production optimization [8]. The perspective of Industry 4.0 is to reformulate conventional manufacturing models into intelligent manufacturing models characterized by being agile and digitized, allowing the integration of data, people, and objects in real-time. [9].

With the implementation of Industry 4.0, several doubts ended up arising regarding its implementation, with that the authors [10] developed a research work regarding the connection between legacy systems and new technologies and concluded that it is beneficial in issues related to productivity and sustainability in addition to identifying the need for a connection structure between the different systems. They also complement the importance of the communication protocol, in this case, with MQTT being the most assertive due to its simplicity and open communication.

In this regard, the authors [11] used the SCADA system to design and integrate the OEE in real-time panels and even increased production analyses to track the process and increase execution visibility. The structure of the OEE architecture was carried out with the adaptation of sensors to create critical metrics for the OEE calculation. Although the demand for integrative models in industry 4.0 has increased, there is still no standardized digital model to work with models in a flexible, integral, and acting way from the beginning to the end of production because the advances presented are associated with products and processes of a specific production [5].

This article aims to present a digital architecture to structure data based on manufacturing machine activity parameters to account for OEE.

The proposed architecture of the solution aims to use software that makes it possible to work dynamically to account for and analyze the parameters of the production process for production control. For the construction of the architecture, the data will be simulated to represent the machine in activity. Due to the challenges of the industrial environment, the project is not focused on sensors. To adjust this limitation, the Docker Desktop application was used.

Docker Desktop is a software that is installed on the personal computer and serves to integrate applications in a container format, which offers a simple format and allows forwarding data to other applications such as databases and dashboards, choosing development languages, secure repository, allows creating environments and integrating them automatically [12].

The purpose of the database is to store a set of data, as well as to guarantee the integrity and security of this data and simultaneous access to the stored data [13].

The results reported by several works on the improvement of processes linked to applications related to Industry 4.0 instigated this research to seek technologies and apply them in the manufacturing context.

2 Methodology

Exploring new solutions, new models of control and analysis of already established production processes is a strategy that thrives in organizations to sustain and promote improvements in the most varied activities.

The methodology for the development of this study proposes a model contemplated in 3 phases, namely identification, development, and presentation of results [14].

In addition, the digital architecture is built within the ETL concept, subdivided into extraction, transformation, and data loading. Figure 1 below shows the architecture linked to its main stages and the resources used in each context.

The stages of the architecture address its three areas of action. The data structure addresses the time to collect and standardize the data, analyze needs, and difficulties, observe which data add value to the process, and build an adequate Dataset to go through the flow. Assemble the data stream and make it available for more complex analysis using Desktop software with applications on Node-RED and MySQL. Meanwhile, the third step addresses data correlation developed in Metabase. These steps are dependent on each other for the success of the architecture. Below are the phases of the methodology for building the digital architecture.

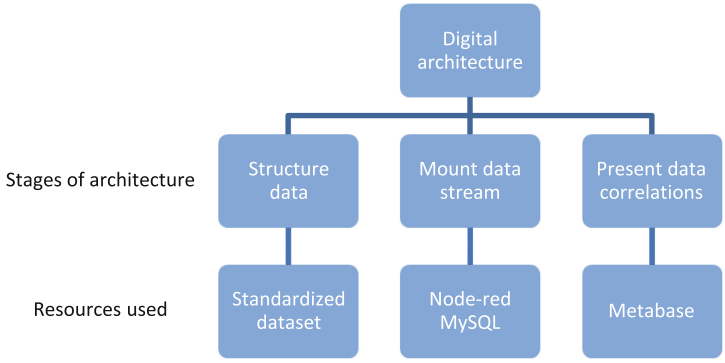

Fig. 1. Structure of the digital architecture and the resources used.

2.1 Identification

The first step in developing the digital architecture is to identify which scenario, which machine, which parameters are associated with the machine's activities and how the data is made available after collection on the machine.

This is because different parameters can be used to characterize each OEE pillar if they meet the requirements related to machine productivity, machine availability and quality of the parts produced. Also, parameters can come from more than one source and have different time ranges.

Availability is associated with machine parameters that inform how much time it spent working and remaining idle. Productivity is how the parameters developed concerning what was planned for that part and what was accomplished. In addition, quality is the ratio between the parts produced and the quality by the proportion of parts processed in the day.

One of the critical points for data collection that is reflected in the result of this architecture is the precise traceability of the data; that is, it is essential to classify each piece of information collected according to the machine from which the data originated, in addition to the accurate recording of time accompanied by data referring to the machine's action. Such action has a direct impact on the data collection phase.

Having identified the data that will be used to meet the three pillars, the following point is the development and structuring of this data in tables and storing them in a database to be worked on in the sequence.

2.2 Development

The digital architecture is built on ETL, extracting, transforming, and loading the data. This concept is applied to collect and make data available for analysis.

In this phase, the data processing and storage step takes place. To make the connection between the different sources, storage, processing and visualization of the data, the Docker Desktop application was used. Docker Desktop works as a container, which includes data structuring (Node-RED), database (MySQL) and dashboard (METABASE) with data analysis.

Node-RED is an open-source visual tool that connects IoT devices and applications, hardware, and web services. In Node-RED, the organization and processing of data happen to be worked on in the next step.

The Node-RED editor is adaptable to all browsers to favour the connection between flows, allowing this wide variety of nodes to be executed in just one click. These created flows are stored in JSON, which is easy to import and share with other members due to its online flow library [15].

Node-RED is composed of nodes, which read CSV files through them [15]. The existing nodes come from a library developed within the platform, which allows the creation of flows in an agile and less laborious way. The nodes represent each step necessary to structure the data and form a table forwarded to the database. In Fig. 2, it is possible to identify the flow of nodes present to structure the data.

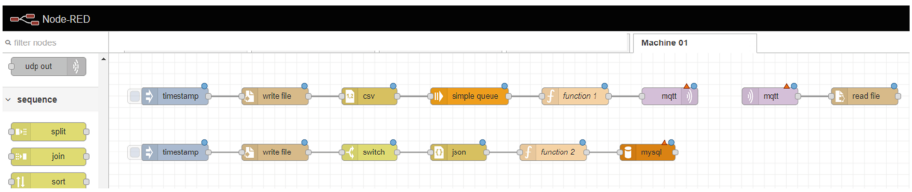

Fig. 2. Structure of the data architecture related to the applications used by Docker Desktop.

Figure 2 represents a path of nodes needed to ingest, structure and target the database from one of the data sources on a machine. Each machine has as many data sources as needed to meet the OEE pillars.

The nodes that make up the structure in the first line are: timestamp (or inject, which manually injects the message into the stream), write file (writes msg.payload to a file), CSV (converts between a CSV-formatted string and its JavaScript Object), simple queue (use this node to store incoming messages on the memory queue), function (a JavaScript function to run on messages received by the node), MQTT outbound (connects to an MQTT broker and publishes messages), MQTT in (connects to an MQTT broker and subscribes to messages from the specified topic) and reads a file (reads the contents of a file as a string or binary buffer).

The nodes that make up the second line are timestamp, write file, switch (forwards messages based on their property values or string position), JSON (converts between a JSON string and its JavaScript object representation), function two, and MySQL (allows immediate access to a MySQL database).

The general structure of the path is the same for each data source; what sets them apart is just the data collection nodes, the “function” nodes where the storage table is structured according to the original data from the source columns and the storage direction.

With this practicality, it is possible to meet a variety of data to be inserted in the architecture. Providing the opportunity to organize according to each need like every company, each process has its indicators highlighted according to its needs. The data, once structured, is forwarded to the MySQL database; it is later made available in

Metabase in table form; each selected data source, structured in Node-RED, becomes a table in Metabase.

The last node in Fig. 2 represents the MySQL database. MySQL is a database management system that uses the SQL language to organize information and is one of the most used and accessible databases. And then, the data is accessed in MySQL by Metabase.

2.3 Presentation

For the next step, the Dashboard (Metabase) is where the grouping and correlations will take place, with the presentation of graphs and other pertinent information about the machine.

The presentation is associated with Metabase, an open-source tool connected to Docker Desktop that allows data visualization and integration, combinations, and filtering between data for better visualization. Metabase also allows for more advanced programming and graphics that can be fed in real-time.

The most significant architectural challenge occurs at this stage, as it is where the grouping of data associated with techniques and concepts occurs in pursuit of the established objective, the grouping of data to measure the OEE and identify patterns, similarities and machine efficiency.

Thus, with the correlation of data according to each piece of equipment and each part, it is possible to correlate and calculate the three pillars of the OEE and arrive at its result.

After calculating and defining all the OEE pillars, the presentation still takes place in Metabase, where it is possible to develop a graphical interface and make the OEE of each machine visible to all users of the tool. In addition to OEE data, it is opportune to identify more detailed information about the number of parts with quality failure, the number of machine stops and the comparison between planned and executed.

3 Results

From these analyses, it is possible to understand the importance and contribution of this architecture to the reality of companies that work with legacy systems. The architecture allows obtaining information about the machine's behaviour during the production process from machine data and previously planned data about capacity and product design.

The other authors made significant contributions to data architecture and directed their work towards an entire process, such as the types of devices used to build the entire IoT model. Furthermore, this research is focused on the structuring and analysis of the OEE for machines and their particularities.

Data can be adjusted whenever possible. The architecture can be adjusted and replicated for other machine models. The data, after being standardized, can circulate through the architecture flow and reach the final objective.

Through architecture, it is possible to have greater clarity and security about the verified data more significant opportunity to analyze the essential issues for the process,

which can be more assertive. In decision-making, in addition to acting more quickly to correct the implications of the process.

The primary delivery is the calculation of the OEE digitally and the option to work with data clearly and safely, in addition to obtaining the calculation of the OEE in a short time interval, where the data presented on the face of the machine, based on performance, productivity and product quality, which represents the machine's overall efficiency rating.

4 Conclusion

Associating Industry 4.0 technologies with machine activity makes it possible to collect data and analyze the actual behaviour of the machine and its relationship with efficiency. It also opens doors to identify optimization situations in a process or product based on the log data issued by the analyzed machine.

Other studies on the subject sought to explore a broader architectural construction model for OEE analysis. However, no other works focused on transparency and dynamism in machine data processing were identified.

The OEE Digital architecture worked on structuring the data of Actuan-TES machines in a longtime production process, on presenting their accounting objectively and transparently as presented.

The architecture enables non-technical programming professionals to work with architecture and create data correlations quickly, clearly, and efficiently. So that it is possible to work the indicators in isolation, presenting greater assertiveness in identifying the indicators that impact OEE results.

The presented architecture allows several companies, in different actions, to process their data and develop and work their indicators to obtain greater control and systematization of their productions according to their objectives.

The architecture allows it to be replicated for machines with a legacy system or not in the same area of production. What differentiates this architecture's application is the choice of the parameters collected from the machine.

The parameters may vary depending on the model and technology of the machine on which the architecture is being executed. The digital architecture enables new horizons of action, data analysis opportunities, and decision-making on process capacity at a lower range than currently applied.

More studies will still be carried out to identify opportunities for this initial machine data to become consolidated information for decision-makers. This solution architecture will be validated in the manufacturing industry in the machining field.

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Digital Transition and Sustainable Development Goals: A Theoretical Reflection on the Impact of I4.0 Technologies

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Abstract. In a paradigm increasingly marked by the emergence and use of new technologies, economic flourishing is no longer enough to fill all of society's concerns. The three dimensions of sustainability are increasingly in people's consciousness. In parallel, the United Nations (UN) has launched a set of 17 sustainable development goals that aim to provide a more prosperous future for all societies. Future digital switchover projects should not be blind to this "sustainable" impact. In this sense and given that several works have already appeared that expose the technological benefits considering the 17 UN goals, this work aims to provide a systematization of the main impacts of the most popular emerging technologies on the SDG, to help in the planning of the digitalization processes. Predictive capability by Artificial Intelligence, the ability to connect and provide real-time data, achieved by the Internet of Things, and data security achieved by the Blockchain prove to be advantages in terms of sustainability and can be pillars of support for the digital transition.

Keywords: Digital Transition · Artificial Intelligence · IoT · Blockchain · SDG

1 Introduction and Theoretical Background

The fourth industrial revolution was first announced in 2011, and since then, has attracted the attention of business leaders and governments all around the world [1]. According to Müller et al. [2] the concept of industry 4.0 (I4.0) describes a set of technologies, which can be integrated into the products or along the entire value chain, creating a networking and digital information exchange between providers and clients.

Since the first industrial revolution, meeting the rising demand for consumption while minimizing unfavorable social and environmental effects. I4.0's sustainability effects and potential to support sustainable development are consistently receiving more attention [1].

At the economical level, the fourth industrial revolution can promote high-value outcomes, such as the increase in value creation, achieved by greater product and service

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customization [3, 4], or the decrease in delivery times. The reduction of overproduction and waste, as well as the decrease of product defects can lead to better productivity and efficiency indicators [3, 4]. Looking at the other two pillars of sustainability, environmental and social, the decrease of energy use, the natural resource conservation, or the development of new skills can be pointed out as potential benefits of the digital paradigm [3].

In the opposite direction, problems, such as the implementation costs, limitations at knowledge, or the time needed for implementation, arises [4]. Concerning the equipment two needs appear: one, to obtain new equipment, which will waste energy and new materials in its production, and the other one, to dispose of obsolete machines, which have to be eliminated or recycled, requiring more fuel consumption in transportation [5]. At a social level, the lack of skills by the employees to operate in this digital world can lead to problems such as unemployment [3] and functions with lower levels of qualifications will tend to disappear.

The problem of sustainability has gained attention from many generations, they valorize buying green products has grown among customers of all ages [6]. In this way, the number of "sustainable" questions related to environmental and social layers becomes a concern that organizations must think in their technology development projects. Being in main these dimensions, the United Nations (UN) developed, in 2015, seventeen Sustainable Development Goals (SDGs) with the aim of combat poverty and other forms of deficiency [7], which are: 1- "No poverty", 2- "Zero hunger", 3- "Good health and well-being", 4- "Quality education", 5- "Gender equality", 6- "Clean water and sanitation", 7- "Affordable and clean energy", 8- "Decent work and economic growth", 9- "Industry, innovation and infrastructure", 10- "Reduce inequalities", 11- "Sustainable cities and communities", 12- "Responsible consumption and production", 13- "Climate action", 14- "Life below water", 15- "Life on land", 16- "Peace, justice and strong institutions" and 17-"Partnerships for the goals" [8].

In the future, the impact assessment of projects introducing technologies at the SDGs level seems to be an important criterion for the success of projects. Several studies have matched emerging technologies with SDGs. In line with these concerns, how technologies can be used to impact society in a "sustainable" way, showing possible paths for digital transition projects. In methodological terms, first, the terms related to I4.0 technologies and SDGs were cross-referenced, and after a language filter (Portuguese and English), they were subjected to a content analysis. We proceeded to a categorization, in matrix form, of the technologies and each SDG, leaving in the relationship between their specific contribution. The paper starts with the presentation of the technology's contributions in line with SDGs and after that, a discussion and conclusion were made.

2 Reflection on the Role of I4.0 Technologies in Meeting the SDGs

According to the work by Dionisio et al. [9], 75% of the technologies cited in the literature related to SDGs refer to Blockchain, Internet of Things (IoT), Artificial Intelligence (AI), as well as, Autonomous Robots. As such and given the great relevance that these technologies have in the digital transition, the results presented below will be based on these technologies, i.e., AI, IoT, and Blockchain.

2.1 The Role of Artificial Intelligence (AI) in SDGs

The table (Table 1) summarizes the results, identifying for each objective the AI contribution, that will be explained in this section.

Table 1. Summary of AI contributions to SDGs.

SDG	AI contributions	SDG	AI contributions
1	Improves agriculture and disease detection in poor areas	8	Helps monitor the health status of employees
2	Facilitates harvest forecasting and environmental impacts	9	Can help in products customization
3	Helps in health services managing	11	Can help in infrastructure maintenance
4	Facilitates the student learning	12	Facilitate the perception of the exact quantities needed
6	Facilitates the management of water treatment plants and their distribution	13	Aid in the clothing industry minimizes resource consumption
7	Increase the efficiency of energy management, reducing the consumption of fossil fuels	17	Allows you to connect multiple data

Companies and academic initiatives like Google, Sustainability and AI Lab are making strides in the fight against poverty, improving farming, for example, aiding in the detection of diseases or forecasting crop yields, which impacts **SDG1** [10]. Predicting agricultural performance also has a positive impact on **SDG2** [11]. Sivakumar et al. [12] show other benefits of using AI in the food industry, namely in soil management and protecting farmers' health.

Many issues such as unemployment, poverty, air pollution, or prevention of infrastructure maintenance are thought to be solved by AI [9]. The processing of data by AI could also aid in the health of collaborators impacting **SDG1, SDG3, SDG8, and SDG11** [13]. AI can help raise educational standards for underprivileged children, for example, in adaptive learning strategies that use computer algorithms to promote engagement with the learner, impacting **SDG4** [10].

When discussing **SDG6**, the role of AI can be very preponderant, providing information about regions that have more water needs, offering a better water management [14]. Also, in 6th goal proposed by UN, AI mechanisms can optimize the processes in water treatment plants [15]. Digitalizing processes related to energy, allied to Machine Learning, contributing to increase energy efficiency or reduce fuel consumption, impacts positively **SDG7** [16]. Also about the 7th SDG, Wu et al. [17] refer that AI can improve adaptive energy management for renewable energy sources.

Sanchez-Segura et al. [18] present a system that uses AI and natural language processing techniques to analyze organizational semi-structured or unstructured data to uncover valuable hidden information, that could contribute to **SDG9**. AI also has a positive impact

on **SDG12** by allowing the consumer to see if the products are in the right condition and in the exact quantities [7]. Akram et al. [19] in their paper about technologies in fashion, discuss some benefits of AI, such as predicting fashion and recommending clothing by analyzing information available in social networking or monitoring the health state of a person by analyzing the data collected through sensors. These can be associated with **SDG3, SDG9, SDG12, and SDG13**.

Autonomous vehicles based on AI can optimize the route of vehicles (reducing the consumption of fuels) and identifies inefficient trips in the sea, facilitating the **SDG14** [10]. At a social level, the **SDG17** can be potentiated by the AI-driven DT, because this can connect people and data [20].

2.2 The Role of the Internet of Things (IoT) in SDGs

The table (Table 2) summarizes the results, identifying for each objective the IoT contribution, that will be explained in this section.

Table 2. Summary of IoT contributions to SDGs.

SDG	IOT contributions	SDG	IoT contributions
1	Allows real-time information about the food supply chain	8	Allows fostering innovation, increasing the process efficiency
2	Allows real-time information about the food supply chain	9	Facilitate the industrial innovation
3	Facilitates the monitoring of people's health status	12	Enables a more responsible production, through route optimization
6	Allows the monitoring of failures in the water supply network	13	Enables the reduction of gas emissions at the supply chain level
7	Increase energy efficiency and renewable energy consumption		

Ali & Govindan [21] in their work discusses the role of some technologies in the supply chain that could impact positively **SDG1 and SDG2**, namely, IoT, which could provide real-time information about the products. In the agricultural field, impacting **SDG2**, IoT is utilized to monitor weather conditions, manage water for the healthiest crops, and detect the moisture content of the soil [12]. Concerning **SDG6**, through IoT sensors that keep an eye on sewage lines, for example in the identification of pipeline leaks, businesses can deal with spills. In wastewater treatment, IoT can help in quality assurance for water storage, systematic management of water, or quality monitoring [15].

IoT when combined with other technologies such as Big Data, can increase energy efficiency and the use of clean energy, contributing to **SDG7** [22]. In the domain of **SDG9**, this technology combined with other technologies such as additive manufacturing can allow a material consumption reduction [22]. According to Vernier et al. [23], the IoT

can contribute to planning deliveries, managing energy, or optimizing routes reducing food waste in production and supply chains, contributing to **SDG12.** The IoT could also increase the efficiency of the processes, which can lead to more production capacity and higher levels of innovation, impacting positively **SDG8, SDG9, and SDG12** [20].

In the fashion industry, the IoT can contribute to monitoring people's health state and helps in supply chain management, which can impact **SDG3, SDG9, and SDG12** [19]. In the ambit of smart cities, some initiatives involving IoT have been made, leveraging **SDG5 and SDG16** [9].

2.3 The Role of Blockchain (BC) in the SDGs

The table (Table 3) summarizes the results, identifying for each objective the BC contribution, that will be explained in this section.

Table 3. Summary of BC contributions to SDGs.

SDG	BC contributions	SDG	BC contributions
1	Improve education, contributing to a decrease in poverty	8	Promote fair labor, free from abuse
2	Improve food safety at the supply chain level	9	Contributes to industrial innovation
3	Ensuring the security of patient data	11	Encourages recycling
4	Improving the educational system	12	Enables more responsible production
6	Ensures lower water consumption and better monitoring of water waste types	13	Improves the monitoring of trips and allows a better environment (through recycling)
7	Providing decentralized structures and energy accessible to all		

In the Dziatkovskii et al. [24] work, several positive impacts that teaching BC has on the various SDGs are discussed. This instruction can form more competent collaborators, eliminate poverty, and guarantee a better education system, which can contribute to **SDG1 and SDG4**. At the level of **SDG2**, this technology provides features such as data security or traceability of products along the food industry supply chains [9, 23], it can ensure a higher quality of products [7, 11] and increase the confidence by the various stakeholders [11, 12]. The role of BC in the **SDG3** is visible in patient information security at the medical industry level [9].

At the **SDG6** level, the BC will allow for easy trade of water between the various people and allow repairs in water supply networks to be done by pre-agreed suppliers [14]. The BC will also allow a reduction of water consumption in agriculture [11] and monitor the type of water waste that each person provides to facilitate the later efficient management of wastewater treatment plants [15]. At the **SDG7** level, the BC allows for more distributed energy [17] and decentralized energy trading structures [16].

In the eighth goal of UN, the BC can contribute in two ways, firstly in the storage of collaborator information that promotes fair labor, reducing contracting abuse [9], secondly, the utilization of this technology in financial transactions could guarantee its safety, fostering a better economic growth [24]. At **SDG9**, the BC, by enabling increased circularity in the fashion industry, contributes to innovation [19], impacting positively **SDG12, and SDG13**. At the level of **SDG11 and SDG13**, Caiado [25] talks about the possibility of BC to increase the predisposition of citizens to do their recycling. Also in 13 goals, the traveling gas emissions monitoring by BC is another improvement [9].

3 Discussion

This work presents the main contributions of each analyzed I4.0 technology. Concerning AI, it is visible that the great contribution settles on the prediction. The literature notes the same thing, referring AI as machine tasks that, if carried out by a person, would require intelligence [10]. IoT refers to a network of connected items, living things, or people who have the capability of transferring data over a network without the need for direct human or computer involvement [9], which goes in line with this work, where the big role of this technology is to connect the various points, providing real-time data sharing and monitoring. The AI, linked with IoT can make processes more flexible [25], which is not much supported in this work and could be considered in future works. Due to its many benefits, including security, transparency, disintermediation, decentralization, and speed, BC was chosen as one of the key technologies driving the Fourth Industrial Revolution [9]. The security that BC was revealed as the most relevant in this study, offering the possibility of covering a wide area of knowledge. Concerning the most covered SDGs, other studies show that technological advances can be very relevant in SDGs 2,4,7,9,12 and 13 [7], which is relatively in line with the findings of this study, changing only the 4 by the 6, however the necessity of learning these advances can impact the number 4. In this sense, **SDG2 and 7** have already been shown to be relevant, seeming to indicate that sustainability at this level has gone a long way than in others. In the selected articles, some of the UN goals are not directly covered. For example, in the case of **SDG15,** AI contributes, since, as can be seen in the results, it can reduce the consumption of fossil fuels and thus emit less CO_2.

After noticing the general contributions and with the goal of trying to systematize the contributions into possible parameters that can be used to evaluate future sustainable projects, one can have:

- Amount of errors minimized (using AI) and the positive impact these non-errors had on SDGs (number of objectives achieved);
- How much more data has been delivered securely (using IoT and BC) and what positive impact this data has had on SDGs (number of objectives achieved).

4 Conclusion

In summary, I4.0 and sustainability are two concepts with a lot of interconnection potential, and if in other industrial revolutions, sustainable development was sacrificed to value technological advancement, it is time to reverse this situation and let technology help

now in a more sustainable future. This work has the innovative character of presenting a synthesis of the contributions of technologies AI, IoT and BC, and culminating with two possible indicators that should be thought of in advance to perceive the viability of a project.

A limitation can be pointed to the great focus on the benefits, and in this way, as future work, it might be interesting to do something analogous but with the negative contributions of each technology or extend this study to other technologies.

The potential for research projects that aim to link these two terms is huge, and the next challenges are to try to understand the contribution of these technologies in SDGs not much discussed, or even to link potentials in known SDGs to achieve other goals.

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Framework for Simulation Applications Based on the Digital Twin Concept and SCOR Methodology

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Abstract. Business demand and scientific associations are studying related to applications of the Digital Twin simulations in the Supply Chain. This article analyzes technological breakthroughs regarding these concepts, research questions, and perspectives linked to the essence of the Digital Twin in the Supply Chain. The research method provided a literary review of qualitative approaches, presenting an overview of the researched domain, culminating in developing a framework for simulating applications based on the Digital Twin concept and SCOR Methodology. This model offers a vision and an approach that focuses on business processes within the Supply Chain, relating 4 phases of the chain in 5 different classes and 5-step behaviors with 36 inputs/outputs in the Supply Chain. The results of this research are related to better development of applications in the Supply Chain towards Digital Twin configurations, as companies demand better decision-making and performance due to the effects of the globalized digital transformation.

Keywords: Digital Transformation · Industry 4.0 · Digital Twin · Simulation · Supply Chain · SCOR Methodology

1 Introduction

The fourth industrial revolution was brought about by Information and Communication Technologies. Important elements of the Industry 4.0 concept are also interoperability and connectivity [1]. One of the principles of Industry 4.0 is to bring together advanced technologies, develop and promote an intelligent manufacturing environment, compete for long-term competitiveness, optimize resources to produce high-quality products, and find quick responses to diverse market demands and deadlines [2]. The combination of information technology and highly controllable computer-controlled machines is associated with this Industry [3]. Another important aspect is handling a large amount of data collected from processes, machines, and products [4]. Extensive software support based on decentralized and customized versions of Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) is becoming mandatory for the integration of manufacturing and business processes [5].

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The MES directly supports the implementation of production processes. This implementation supports business activities by optimizing production operations. MES, implemented in production, combines planning systems with industrial automation systems, controls the progress of production processes, and performs the characteristic functions of the Supervisory Control and Data Acquisition system. With the development of ERP, manufacturing companies' interest in integrating ERP and MES systems has grown [6]. Manufacturing systems are complex objects with many integrating factors and internal relationships. Integrating manufacturing software and Supply Chain (SC) is paramount to business growth. In the SC context, integrated information sharing is essential to ensure the process's proper functioning. According to [7], "internal integration improves external integration while directly and indirectly improving the company's performance. It is essential to strengthen internal and external business production guidelines to improve the execution of activities". Companies are simultaneously enabling real-time monitoring and tactical decision-making. Tests with simulation can be used to support the decision-making process. SC functions in MES are objects of study in this article concerning simulation within Digital Twin (DT).

Based on [8], DT consists of a virtual representation of a production system able to act in different simulation disciplines, characterized by the synchronization between the virtual and real system due to detected data and connected devices, mathematical models, and real-time data. DT has the simulation and computing capabilities to support industrial decision-making and potentially act directly on MES. Industry 4.0 manufacturing systems focus on discovering these capabilities to predict and optimize production systems at each stage of the lifecycle in real-time.

2 Literature Review

2.1 Research Questions

This article aims to map the basic contributing principles in the industrial field, considering a theoretical simulation study in the context of the Digital Twin linked to the Supply Chain. Assuming this general objective, the stages of conducting this research through questions were used to guide the Systematic Mapping Study.

RQ1 - What roles do Digital Twin simulation applications play in a Supply Chain in the Industry 4.0 scenario?

RQ2 - Where and how to integrate Digital Twin simulation applications in a Sup-ply Chain in the Industry 4.0 scenario?

RQ3 - What are the main challenges and barriers to applying Digital Twin simulations in a Supply Chain in the Industry 4.0 scenario?

2.2 Research Approach

String data collection was carried out in three stages based on research by concepts and associated terms using Scopus and Web of Science tools. In the first axis, articles were identified referring to "Manufacturing Execution System" ("Manufacturing Operation Management," "MES," and "MOM"). The second axis systematically identifies publications that review Industry 4.0. In the third axis, the concepts were "Simulation," "Digital Twin," and "Supply Chain." The revision strategies are shown in Fig. 1.

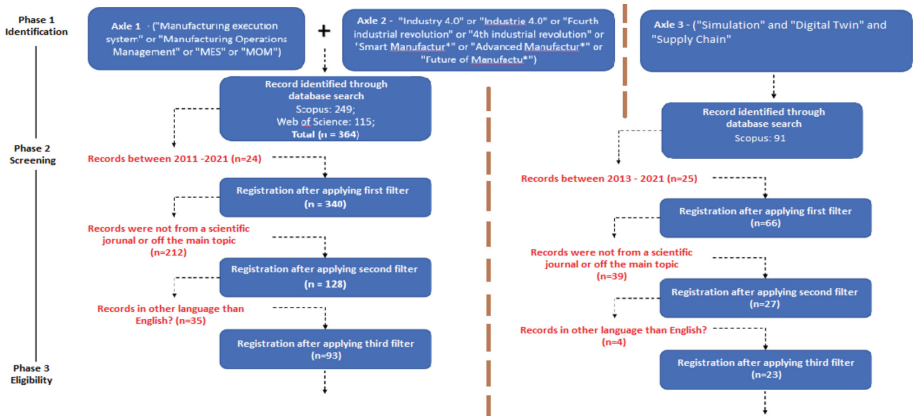

Fig. 1. Phase 1, 2 and 3 Flowchart of systematic reviews

At first, the established research strings were applied. Then, in the study selection process, inclusion and exclusion criteria were defined to filter articles for this study. Figure 1 represents the search strings and the filters applied in the screening and eligibility stages to qualify the search. The use inclusion criteria (IC) were: electronically available and found by the search string in all fields and period - studies published online from 2011 to 2021. Subsequently, the exclusion criteria (EC) were applied. Those criteria were as follows: studies not focused on MES/MOM (Axis 1), Industry 4.0 (Axis 2) and Simulation, DT and SC (Axis 3); not being an article (Registration in a book, magazine and the like were exclusion criteria); not written in English; duplicate work between re-search axis. Figure 1 shows a total of 455 articles. After applying all ECs, 116 articles were selected for this systematic mapping.

2.3 Qualitative Analysis

The sample size includes 116 articles used for detailed analysis, indicating that research has many case studies and other publications related to the topics under investigation. To guarantee eligibility and reduce this high number of articles, in reference to sampling axis 1 and 2, the Proknow-c method ([9]) was applied, consisting of the most important articles after the screening phase (n = 93), validated in four main repositories. Based on it, some folders were segmented. Repository A has articles according to the number of

citations (c > 5). These data represent recent articles and can be excluded. Repository P holds articles with less than 5 citations (c < 5); however, with authors who are also in repository A, ensuring current articles are also selected. As a result of validation in repository P, the article is directed to repository B. In articles from repositories A and B, their abstracts are read. The abstracts that meet research objectives are accredited to the C repository. Figure 2 represents steps and the Proknow-c method.

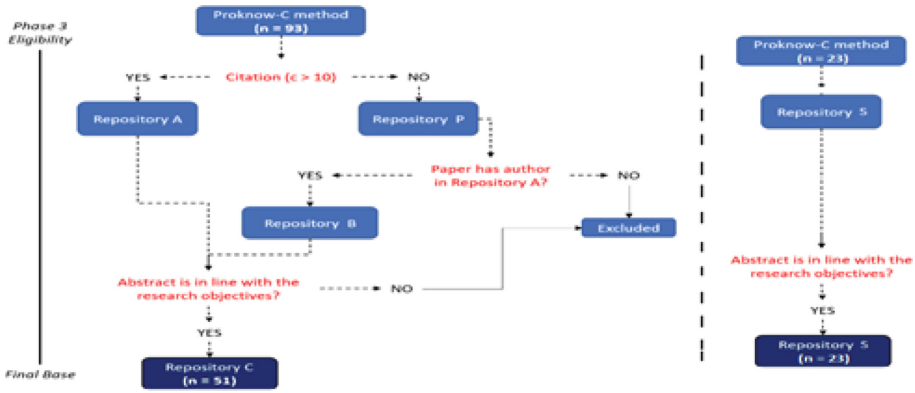

Fig. 2. Proknow-c method (Source: [9])

For axis 1 and 2, 51 articles were validated. For axis 3, 23 articles were validated. In total, 74 articles for reading in full considering the three axes of systematic mapping.

3 Literature Review

3.1 Concepts Based on Digital Twin

The DT is stimulating industry and research. DT consists of a virtual representation of a production system able to act in different simulation disciplines, characterized by the synchronization between the virtual and real system due to detected data and connected devices, mathematical models, and real-time data processing [8]. DT has the simulation and computing capabilities to support industrial decision-making and potentially act directly on MES. Nowadays, Digital Twin is considered by science one of the technological trends for the future. Digital Twin has become progressively more requested in academia and industrial spheres, mainly linked to simulation concepts and encouraged by the development of new technologies such as the Internet of Things, Big Data, and Artificial Intelligence [10].

3.2 Concepts Based on Simulation

Simulation is a process of experimentation through computational models representing a real system in detail. The simulation evaluates how an existing system behaves

when subjected to changes in its structure and environment. Simulation software is typically used to monitoring data, system models, simulation systems, production systems, and resources can be optimized in real-time [11]. Integrating different computational tools to simulate systems allows managers and designers to simulate production system performance [12].

Traditional simulation software has been used to check performance measures of complex systems through simulation experiments. Modern simulation software provides enhanced visualization functionality and interoperability with applications [13]. Modeling tools allow the analysis of product behavior, the performance of production lines, and the coordination of the multisite network, leading to the optimization of processes and industrial operations [14]. Optimization and agility can lead to semi-heterarchical control topologies in which structural elements that reflect reality (products, orders, resources) are interconnected and retrieve, in real-time, detailed information [15].

3.3 Integration of Digital Twin and Simulation in Supply Chain

MES is a resource structured and planned for manufacturing. It is a system that studies information from processes, coordinates productive activities, correlates, and interconnects planning and production [16]. MES's main objective is to assimilate real-time production data in manufacturing by supervising systems and business systems to produce management reports to enable decision-making and verify productive performance and planning. Simulation can be used to support the decision-making process for real-time dynamics. Modern simulation approach refers to DT creation. Industry 4.0 key enabling technologies are the foundation of this approach to simulate leveraging connectivity and interoperability in production systems to deliver real-time synchronization with the field [8]. DT runs synchronized simulations linked with other technologies. This simulation model is designed to read and overwrite production process equipment in real-time, in an automated manner, and synchronize simulation with its physical state. Simulation essences synchronized with MES generate a real DT.

DT can support the monitoring and improvement of production processes, optimizing them from the systemic structuring to virtualization of manufacturing equipment, integrating multiple dynamic simulations, monitoring a machine tool, monitoring product parameters during production, and developing a unique process, assembly process organization, and production line. Properly managing product and process data facilitates ordering digital models of needed components for the manufacturing process. These models are updated in real-time, analyzing and controlling conditions of materials and processes, allowing the development of simulations of different scenarios, which predict behaviors or failures, according to the most recent data obtained from Twin.

4 Framework

Connected technologies transform the way products are produced and enable quick prototyping and testing, adding connectivity to products and processes and evaluating the creation of products and services [17]. The development of digitalization is accompanied by digital transformation, which shows the integration of digital technologies during

business activities requires changes in technology, culture, and operations. Every step of the production process can be compiled to establish high-level digital simulations in the virtual and real world. The process will simulate and optimize the physical world's materials, products, and factories [18].

To structure and integrate DT, Simulation, and SC, a framework based on SCOR Methodology was developed at different levels of operational criteria. This study identifies concepts from 74 limited articles in the systematic mapping and recommends the most appropriate parameters for each stage of a SC. The objective and benefit of this structure are to identify perspectives linked to these concepts (Fig. 3).

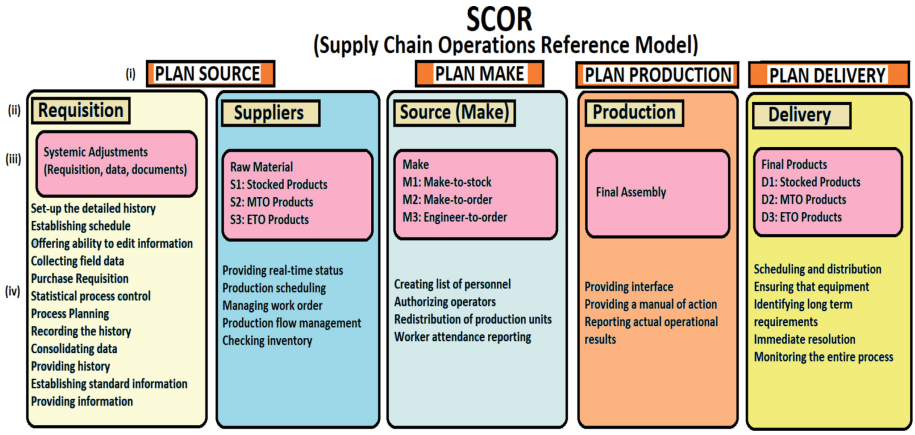

Fig. 3. SCOR Methodology Framework in Supply Chain

Four phases of the chain were represented (i) (Plan Source, Plan Make, Plan Production, and Plan Delivery) and were subdivided into five different classes (ii) (Requisition, Supplier Internal/External, Source Make, Production, and Delivery). Initially, at a general level, performances and behaviors were stipulated for each step (iii) (as an example, in Requisition, criteria's Purchase Requisition, data, and documents were defined). Soon after, specific parameters (iv) were stipulated for all classes involved.

The proposed framework has several advantages. It focuses only on data linked to Industry 4.0 and MES as a complete global view, on stages of the SCOR, and on a group of classes subdivided into general and specific criteria of data on Simulation and DT linked to processes and corresponding records. A descriptive and data-oriented diagnostic framework characteristic of the concepts under study was proposed as modeling. The objective is to identify future simulations with the support of DT in the SC to be implemented through this framework model evaluating performance criteria for processing. The framework used to structure simulations for strategic decision-making is evident, facilitated by the digitization of information.

Based on that, this systematic mapping study established a framework related to analysis criteria that could help with the research questions formulated. Regarding RQ1, as observed in the developed framework, several applications of DT simulation in different

business contexts are present in SC. The focus of these applications is strategic decision-making for SC integration. Regarding RQ2, the framework details specific criteria for each phase and proposes possibilities for improvement in different applications. Developing research and software to identify failures and procedural deviations is paramount for improving a business process.

About RQ3, several obstacles have been identified since the study environment is complex, considering that digital transformation is continuously growing. A challenge concerns interoperability between the applicability of DT simulations in the automation context. Another challenge is related to the adaptability of processes since SC is generally robust and difficult to change. In addition, advances in literary studies, software development, and suppliers for DT simulation applications have limitations, mainly linked to data encoding as an investigation to find solutions to optimize the systems.

5 Conclusions and Implications

This article analyzes concepts, research questions, and perspectives linked to the essence of DT in the SC. The research methodology applied in this work provided a comprehensive review of primary research studies on the concepts: Industry 4.0, MES, Simulation, DT, and SC, providing a literary review of qualitative approaches and an overview of the researched domain. This article presents a framework implementing systematic mapping based on the SCOR Methodology. The framework lists applications of DT simulations in SC, identifying phases, classes, performances, and behavior as well as specific criteria to integrate Industry 4.0 concepts, MES, and simulation. Developing a simulation model is an essential step to consider before implementing the framework in real work, analyzing data collection and processing parameters. This framework contributes to answering pre-formulated research questions (RQ1, RQ2 & RQ3). It seeks to study and develop DT-based simulation applications in SC, given the crucial roles that can be generated in the globalized context and integrating processes. In addition, further support in interoperability, growing social evolution, and digital transformations of processes with online data management.

The results of this research are related to better development of applications in the Supply Chain connected to Digital Twin configurations, as companies demand better decision-making and performance due to the effects of the globalized digital transformation. It contributes to the verification of performance improvement arising from the implementation of the framework while seeking the desired performance balance (e.g., technological investments and software development), contributing to the transformation of companies from their current status to future implementations.

For future works, it is proposed to continue implementing the framework in the analyzed line, allowing the deepening of software development to analyze data flow, viability, system reactivity to events, costs and improvements in performance in SC.

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Cybersecurity Challenges of Blockchain and Smart Contracts Technologies in IIoT

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Abstract. This paper aims at identifying the main challenges associated with the adoption of blockchain and smart contract technologies as potential solutions for cybersecurity in an Industrial Internet of Things environment. Initially, an introduction to IIoT, blockchain and smart contracts is made, highlighting their core concepts as well as explaining their characteristics and properties. Subsequently, based on a literature review, the various benefits and challenges for their implementation are identified. The latter are presented through a hierarchical approach that first categorizes them in architecture and privacy related challenges, with each category being further divided into more specific challenges to emphasize the complex nature of the problem. Some typical use cases are also mentioned to showcase the feasibility of these technologies. Finally, a conceptual framework for IIoT cybersecurity is proposed in terms of future work directions.

Keywords: Industrial Internet of Things (IIoT) · Smart Manufacturing · Blockchain · Smart Contracts · Cybersecurity

1 Introduction

The 4th Industrial Revolution, also referred to as Industry 4.0, aims to harness the advances in multiple fields, such as wireless connectivity and sensor technology, and to adopt innovative technologies, such as data analytics and digital twins, in order to leverage the increased communication capabilities and the increased availability of information that are enabled by them. These are expected to lead to a scale up of the required data exchange in manufacturing applications so that production processes can be monitored and optimized using a data-driven approach in almost real time. This ongoing revolution will connect equipment, people and data to achieve a new level of operational efficiency and productivity, thus delivering a significant step-change in the industry.

However, one of the major barriers for a more widespread adoption of the Industrial Internet of Things (IIoT) paradigm, is concerns over data security. This has led to an increasing amount of research interest, with various strategies being proposed as potential solutions. This paper focuses on the blockchain (BC) and smart contract (SC) technologies. While these technologies have been proposed by the current state-of-the-art as potential solutions for the cybersecurity issues in Internet of Things (IoT) in general

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[1–3], there is few published research that acknowledges the associated challenges in an IIoT environment [4].

Therefore, the aim of this paper is to offer an updated report on cybersecurity challenges that involve the application of BC and SC in IIoT. Section 2 provides a brief overview of the background on all three aforementioned technologies. Section 3 deals with the expected benefits when adopting BC for cybersecurity in IIoT, whereas Sect. 4 presents the security challenges that BC and SC technologies have to face when implemented in IIoT applications. Section 5 highlights some typical use cases that involve the application of BC and SC in smart manufacturing. Finally, Sect. 6 summarizes the main conclusions and describes the directions for future work, including a conceptual framework for IIoT cybersecurity.

2 Background

2.1 Industrial Internet of Things (IIoT)

IIoT is one of the five paradigms of Industry 4.0, together with Cyber-Physical production systems (CPPS), Enterprise architecture (EA), Enterprise Integration (EI) and Cloud manufacturing (CM) [5].

The term IIoT implies the usage of traditional IoT technologies in industrial environments [6, 7]. As a general term, IoT devices refer to consumer-based devices or systems, that are massively dispersed, deployed and interconnected and are mainly used for monitoring and controlling physical objects [8]. IIoT devices are massively deployed industrial devices that are interconnected with control and management platforms that offer remote sensing/actuation capabilities, in order to collectively improve the operational efficiency and productivity of industrial systems in context aware environments. As a result, their main focus is reliability and connectivity [9].

Obviously, in case of failure the consequences are more severe in IIoT devices, than in regular IoT ones [10], where a simple restart or data loss can be considered acceptable. In IIoT, a single failure can potentially influence the entire production system, even resulting in cease of operation.

Each IIoT system is composed of cyber systems and physical systems [8]. Cyber systems include control, networking and computing infrastructures that enable the operation, interconnection, and intelligence of the industrial systems. Physical systems include the manufacturing and automation systems that leverage industrial devices to undertake designated production and automation tasks.

In general, IIoT can be described as having a three-layer architecture, as shown in Fig. 1. Starting with the application layer, it consists of various industrial applications that include smart factories, smart plants and smart supply chains. Next, is the communication layer, where the integration of numerous different communication networks is taking place. This variety is necessary to support the interconnection of a considerable volume of sensors and actuators in smart industrial applications, as seen in the physical layer. Their purpose includes timely monitoring, accurate control, and efficient management.

Priorities in an IIoT network are not the same as in traditional Information Technology (IT) networks, since each network has different performance requirements, reliability requirements, operating systems and applications, risk management goals, security

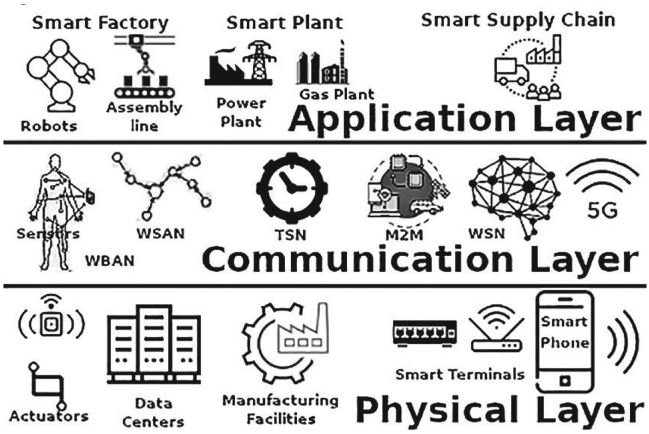

Fig. 1. IIoT layer architecture (adapted from [8]).

architectures and goals [11]. The main reasons most IIoT devices get compromised are [11] a) not implementing critical security updates or antivirus tools, b) usage of legacy hardware with limited and/or outdated support for security features, c) existence of multiple pathways through which cybersecurity threats can enter, bypassing existing cybersecurity measures and d) absence of physical and/or virtual isolation between unrelated networks.

2.2 Blockchain

In 2008 a white paper appeared under the alias Satoshi Nakamoto [12] that not only introduced BC technology, but also implemented it in a cryptocurrency named Bitcoin.

BC technology has realized an incredible growth rate in recent years. Freelance BC specialists saw demand grow as high as 6,000% within 2018 [13]. Current predictions call for an estimated 10% of the GDP will be stored on BC-related technology by 2025 and $176 billion of business to be value added by BC by 2025, surged to exceed $3.1 trillion by 2030 [13].

A BC is a distributed database that records transactions in a chronologically ordered list of blocks. Each block consists of a cryptographic hash of the preceding block, transactions and a timestamp for them, providing traceability and immutability. Transactions can describe any asset of value such as inventory, machinery, people, work, energy and money. A new block is consistently synchronized across the peer-to-peer (P2P) network by means of a consensus algorithm. This makes BC a cryptographic decentralized transaction and data management technology that a) allows the creation of a common information space of many different and independent participants that do not trust each other in complete manner [1], b) does not have a single point of failure [1] and c) does not require any third-party organization in the middle and eliminates the need for a central authority [14].

This reduces complexity, lowers costs and provides risk mitigation, all of which are measurable concepts in the industry and of critical importance [9–13].

BC manages to provide proof beyond contradiction that a set of transactions occurring between participants and the transfer of assets has been completed, by allowing entities to retrieve, validate, trace and verify all transactions, sequences and timing of actions taken, providing transparency, trust, traceability, responsiveness, reliability and consistency.

At its core, BC is based on three well-known and thoroughly tested technologies [15]:

1. **Public Key Infrastructure (PKI):** Since BC operates in an untrusted environment, PKI is used in order to establish a secure digital identity for every participant. This consists of a pair of keys (one public and one private) to be able to participate in the BC and enforces control of ownership over the objects managed by BC.
2. **Distributed P2P networks:** A P2P network is employed, in order to be able to scale up the network, to avoid single points of failure and to prevent a single or small group of players from taking over the network.
3. **Consensus mechanisms:** This allows all participants to agree on a single version of the true state without the need of a trusted third party.

A detailed description on the inner workings of BC technology is out of the scope of this paper. Interested readers can find further information on the basics of BC in [16–18].

Depending on the use of BC technology, several and different types exist. Their differences lie in how users interact with BC and how data is managed and/or accessed. BC can be distinguished in the following generic types, as shown in Table 1 [6].

The popularity of BC lies in its multiple properties that enable it to be an effective mechanism to address the issues involving IIoT, as already applied in IoT [19].

2.3 Smart Contracts

SCs are computerized transaction protocols used to execute complex and multi-step terms of a contract in order to enable the automatic exchange of values in a secure and transparent manner [9, 14]. In simple terms, a SC is a digitized form of a legal binding agreement, whose behavior is fully predictable [14, 15]. It consists of a set of rules, which the participating entities should agree on, and conditions causing the executions of those rules [20]. Agreements can be executed automatically when specific conditions are met, eliminating the need for a Trusted Third Party (TTP). This concept allows SCs to expand in totally different domains, more application areas and more general types of transactions and assets [14, 15]. The only limitations of this approach are "a necessity of the access to a common runtime environment for all SC objects and subjects, accurate mathematical description, and strict execution logic" [21].

One application area is BC, where SCs can reside on the chain and can be inspected by every network participant. A SC can be triggered by addressing a transaction to it; then it is executed automatically on every node of the network, according to the data provided when triggering the transaction [14].

Table 1. Generic types of Blockchain

According to	Generic Types		
	Blockchain	Examples	Notes
Access regulation	Public	Crypto-miners	Crypto-currency
	Private	Ripple payment protocol	
	Consortium or federated	Hyperledger-Fabric	Financial institutions, energy sector and insurance industry
Permissions	Permissionless	Cryptocurrency (Bitcoin, Ethereum, Litecoin, Monero, Zcash)	
	Permissioned	Monax and Multichain	
Incentives kind	Tokenized	Bitcoins for Bitcoin, Ether for Ethereum	
	Non-tokenized	Hyperledger-Fabric, RootStock	
Operation mode	Logic-oriented	Ethereum, Hyperledger-Fabric, NXT, Counterparty	
	Transaction-oriented	Cryptocurrency (Bitcoin, Monero, Ripple)	

SCs have the following properties [20]:

1. **Autonomy:** Participants consent on decisions and thus there is no need for intermediary and bias related to them.
2. **Trust:** Essential documents are present on a public ledger and thus cannot be destroyed or lost.
3. **Backup:** Presence of data on multiple nodes participating in the network makes the data safe.
4. **Savings:** SCs eliminate the need for a TTP and thus save money.

SC conditions are based on data taken from external services and are then stored into the BC or vice versa. Such services are referred to as oracles [6]. As an example, an oracle can inspect records to identify whether an asset has arrived and then write this information on the BC. Afterwards, the SC might trigger a conditional statement based on the read value and execute a block of code. Based on the type of information collected and on the interaction with the external world, there are different types of oracles [6]:

1. Software oracles: All data collected from web sources of the external world are handled by them; needed information is extracted and pushed into the SC.
2. Hardware oracles: Information is directly extracted from the physical world, e.g., RFID sensors. Their biggest challenge is reporting readings without sacrificing data security and guaranteeing their correspondence to a specific physical process.
3. Inbound oracles: Information from the external world that does not interact with the BC is inserted into the BC.
4. Outbound oracles: Information is sent from the BC to the external world.
5. Consensus-based oracles: Different oracles are combined to determine the future outcome of an event.

3 BC as a Solution

The benefits of using BC in securing IIoT can be summarized to the following [2, 6, 7, 15]:

- Increased IIoT security, since information published by a specific IIoT device is not forged or altered by malicious third parties (confidentiality and integrity).
- Increased system fault tolerance since the failure of some nodes will not disable the whole network (availability).
- Ability to provide public or semi-public access to IIoT data for regulatory reasons or in case there is a data transparency requirement by certain participants (e.g., governments, supervisors, stakeholders).
- Guaranteed data access, due to BC data being distributed among peers.
- Provision for a standardized and automated communication mechanism for multiple entities and persons as well as interaction that exhibits autonomous behaviour characteristics through SC.
- Vertical integration of networks that participate in a product's entire value chain. Therefore, when such a connectivity becomes automated, information can be collected and sent automatically from any of the multiple deployed systems to any of the relevant parts of the value chain (e.g. to the design team, to manufacturing department, to logistic operators etc.).
- Horizontal integration of networks that can connect manufacturers, suppliers and clients, for performing simple data transactions.

4 BC and SC Cybersecurity Challenges in IIoT

The main challenges that BC faces when implemented in Industry 4.0 environments can be divided in the following areas [21, 22]:

4.1 Architecture

Scalability [6, 19]: The selected architectures must be able to withstand the significant amount of generated traffic. Most of the centralized cloud-based architectures cannot efficiently cope with that.

Computational Resources [6, 23]: Most IIoT devices have very limited computational resources, mainly regarding memory and processing power, and as a result they struggle with modern secure PKI cryptography schemes, such as RSA (Rivest–Shamir–Adleman) [24].

Consensus Algorithm Selection [6]: The selection of consensus algorithm is essential for the proper implementation of BC and must be performed while considering the computational effort and energy needed for each algorithm. Moreover, this selection affects the cybersecurity attack surface of BC. For example, Proof-of-Work consensus algorithms deter denial-of-service (DoS) attacks and other service abuses; Proof-of-Stake consensus algorithms achieve distributed consensus in blockchain networks; Proof-of-Activity combines Proof-of-Work and Proof-of-Stake in order to ensure the genuineness of all BC transactions, as well as the user consensus on the exact status of the public ledger; Proof-of-Space is a piece of data used as proof for the reservation of a certain amount of memory or disk space; Proof-of-Personhood is a mechanism that binds physical entities to virtual identities in order to enable accountability while preserving anonymity; Practical Byzantine Fault Tolerance is a consensus algorithm designed to work efficiently in asynchronous systems and solve problems even when some of the network nodes fail to respond or respond with incorrect information; Proof-of-Burn ensures that all participating nodes come to an agreement about the true and valid state of a BC network in order to avoid the possibility of double-spending.

Energy Efficiency [6][1]: Selection of inefficient P2P protocols and computationally complex cryptographic algorithms have an impact on the energy consumption, especially in case of battery-operated devices.

Throughput and Latency [2, 6]: IIoT devices using BC produce large amounts of transactions that need to be processed, which is the typical situation in an industrial environment. Certain consensus algorithms used in BC have limitations regarding the number of transactions per second thus reducing throughput compared to traditional database systems. Similarly, BC requires an amount of time in order to add new blocks into the chain, which can significantly increase latency. As a result, the ability to provide real-time responses to events is negatively impacted.

BC Size [2, 6, 20]: The size of a BC increases every time an IIoT device performs a transaction. This implies the use of more powerful miners, as traditional resource-constraint IIoT devices are not able to manage even small blockchains. BC compression techniques along with mini-blockchains should be considered as alternative approaches.

Multi-chain Management [6]: In case multiple BCs need to be supported at the same time, solutions would have to be designed and implemented for this purpose.

Interoperability [2, 6, 23]: Most companies choose to create their own BC solutions. Nevertheless, interoperability among them is necessary in order to achieve a seamless integration. IEEE and several other entities are working on specific standards aimed at guaranteeing interoperability in diverse fields.

[1] See [25] for more details on using mining for smart contract validation.

Standardization [6, 23]: Heterogeneity among IIoT devices, and lack of standardization increase the complexity that needs to be addressed by the deployed cybersecurity measures.

Required Infrastructure [2, 6, 15]: BC technology requires the deployment of specific hardware infrastructure that is likely to generate high amounts of data traffic by P2P communications. This load needs to be supported by all involved devices in the infrastructure.

4.2 Security

Privacy [2, 6, 19, 23]: By default, all IIoT devices are identified either by their public key or their hash. As a result, their anonymity is not guaranteed in case this is required. Mixing techniques increase IIoT data privacy, but in some cases, they can be de-anonymized.

Integrity [6]: Incorrect or malicious data can alter essential parts of any industrial system. BC can provide data integrity service frameworks in order to avoid trusting third parties, but such a kind of system still has to evolve.

Identity [6]: If companies set identity providers to authorize access to IIoT devices and other participants, this also gives them the ability to block their access. Permissioned BC or multichains can be used for identity management and certification.

Accessibility Threats [23]: A legitimate user is denied access to data or services. Some examples include Denial of Service (DOS) attacks, modification attacks, dropping attacks, and appending attacks.

Anonymity Threats [2]: The real-world identity of a user is found by analyzing anonymous transactions and publicly available information.

Authentication and Access Control Threats: The adversary tries to authenticate as a legitimate user, in order to gain access to data.

Private Key Management [2]: This problem exists, since each user is responsible for his own private key, that must be generated and taken care of by the user himself, instead of a third-party. If a user loses the private key, it will be impossible to get access to the digital assets on BC.

5 Use Cases of BC and SC in IIoT

Use cases that involve BC and/or SC integration in an IIoT environment are still not commonplace but from the available literature it can be assumed that there is an increasing trend. This section reports some characteristic examples and briefly categorizes the main issues that are tackled.

In [26] an automated production platform consisting of four industrial robotic arms has been used as the testbed to deploy and test a BC-based solution to enhance data security. The relevant data involved sensor measurements such as ambient conditions,

operating times, failures etc. as well as services that are requested from the users that access management hubs, i.e. local terminals that collect and process the sensor data.

In [27] BC is used together with SC for increased transparency in collaborative manufacturing networks. The proposed framework assigns unique digital identifiers to the assembled products and their components, thus enabling higher supply chain visibility to all involved stakeholders (suppliers, manufacturers and customers).

A similar concept is presented in [28] where BC and SC are used to ensure trust between manufacturers and their clients during the implementation of remote monitoring services that rely on equipment operational data such as anomaly detection and predictive maintenance. The use case focuses on the proper design of such data-driven services as SC and their interactions with the BC. A simple cost-based validation is presented as well.

An interesting use case that combines BC and machine learning to enhance security and quality control in a smart manufacturing system is presented in [29]. The architecture of the proposed system involves four layers, namely an IoT sensor layer to capture real-time data about the products, a BC based layer to safely distribute the ledger that contains asset information including orders and quality data, a SC based layer to enable automated transactions in the system and a business layer to manage and control the various operations. Machine learning is used for efficient data analysis.

As can be concluded from the above use cases, there are three categories of main issues that BC and SC attempt to deal in an IIoT environment. These are: i) data sharing and security, ii) traceability and trust mechanisms and iii) system configuration and performance optimization.

6 Conclusions and Future Work

The detailed findings of this work are reported in Sects. 4, 5 and 6. However, they can be qualitatively summarized to the following points:

- BC can enable IIoT systems to perform decentralized transactions and information exchanges signed and timestamped within a trusted framework.
- SCs can enhance BC protocols by enabling the deployment of executable code that runs inside the BC itself and eliminate the need for intermediaries, thus saving time and conflicts.
- For the time being, encryption methods used by BC are cybersecurity solid and cannot be broken, thus making BC one of the best solutions for IIoT devices, also due to its other characteristics mentioned in this paper. However, the wide application of cryptographic algorithms may introduce unknown backdoors or vulnerabilities.
- IIoT in its full concept has not yet gained widespread adoption across all sectors so there is still time to adjust regarding cybersecurity issues. Failure to properly address these issues could have a severe negative impact on all involved stakeholders.

The future plans of the authors include the creation of a trusted mechanism, along the guidelines of the NIST Cybersecurity Framework [30], that shall combine BC with SCs. Initially it shall act as a supervisor and monitoring system and later on evolve to an active defense tool. Its core functions, as seen in Fig. 2 are: Identify, Prevent, Detect,

Respond, Recover and Predict. This trusted mechanism is expected to be developed as part of the Prevent, Detect, Respond and Recover core functions of the framework. In this context, BC shall act as a data encryption mechanism while SCs will mainly be employed to automatically execute mitigation actions as well as recovering actions for any affected services and/or capabilities.

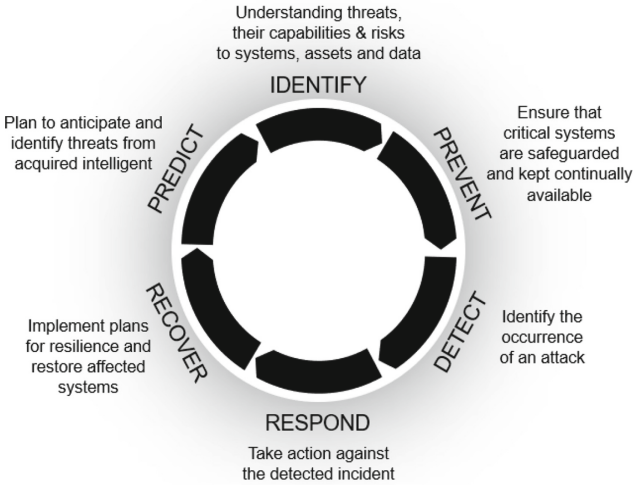

Fig. 2. IIoT cybersecurity conceptual framework.

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Cyber Security Culture as a Resilience-Promoting Factor for Human-Centered Machine Learning and Zero-Defect Manufacturing Environments

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Abstract. Humans have often been perceived as a leading cause of error in Zero-defect manufacturing (ZDM) processes. There is thus a reduction of human interventions in the deployment of industry 4.0 (I4.0) technologies used for ZDM such as Machine Learning (ML). However, as manufacturing (e.g., I4.0 context) is often placed within a socio-technological context involving the co-integration of humans and technology, the manufacturing processes are now more vulnerable to cyber risk and threats. System vulnerabilities also derive from limitations associated with ML. This paper highlights three challenges associated with ML: explainability, data privacy, and security for ZDM. We argue that due to the high level of data complexity and lack of flexibility in ML models, humans play a critical role in ZDM decision-making. The paper explores the concept of security culture as an enabler for transformative resilience and zero-defect manufacturing and contributes to rethinking the human-centered approach in ZDM. The paper stresses a need to enhance contextual and empirical understanding of transformative resilience and security culture in ML/ZDM environments to better address adverse events such as cyber threat situations.

Keywords: Zero-defect Manufacturing · Machine Learning · Cyber Security · Human-centered Manufacturing · Security Culture

1 Introduction

1.1 Industry 5.0 and Human-Centered Manufacturing

Technologies e.g., Machine learning (ML) have reduced human intervention, as humans are perceived as a leading cause of error [1]. Similarly, within the cyber security domain, 95% of cyber-attacks are argued to derive from human-related errors [2]. As technology may be adapted to humans, they might acquire an inadequate knowledge base (e.g., explainability and faulty decisions) [3]. This could lead to incorrect use, as well as harm information confidentiality, integrity, and availability [4]. Moreover, humans in Zero-defect Manufacturing (ZDM) may acquire various constraints (e.g., knowledge, time,

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cognitive constraints, etc.) that may negatively impact their decision-making. Vulnerabilities in technology may thus facilitate cyber security risks [5]. Hence, humans' lack of awareness and knowledge might result in organizations becoming more vulnerable to threats such as cyber-attacks [3]. This is especially true in relation to adverse events such as the COVID-19 crisis or the ongoing Russian war against Ukraine, which has made cyber resilience an international policy priority [6]. Cyber resilience is thus about an organization´s ability to recover and adapt after an adverse event, involving preparedness for known and unknown threats [7, 8]. According to the European Commission's science for policy report [9], the COVID-19 crisis has been a warning sign in that we are never completely safe from unforeseen events and that such events make the world vulnerable. The crisis has provided a need and thus an opportunity to progress through adaption and transformation. Rather than "bouncing back" to a pre-crisis state, the concept of "transformative resilience" has been proposed to argue for the development of policies and interventions to "bounce forward" toward more sustainable solutions from a social, economic, and environmental perspective [9]. This may involve strengthening people and enhancing their creativity and commitment needed to handle such situations. Similarly, the concept of "resilience-promoting factors" emerges from Fisher et al., [10] who define it as those "variables representing characteristics and features of the self or one's environment that provide a protective or ameliorative function in the event that adversity occurs". They add that these factors infer the possibility of risk. As security practices usually are highly technocentric, information security attacks are becoming more successful [11]. Therefore, the most essential foundation for resilience in organizations is argued to be a security culture [12]. Hence, we argue that a security culture may be viewed as a resilience-promoting factor (e.g., [10]).

As industry 4.0 (I4.0) emphasizes digitalization and AI-driven technologies for production efficiency, the central principles of Industry 5.0 (I5.0) are sustainability, human-centricity, and resilience [13]. From this view, we argue that manufacturing processes of the future will become more human-centric. Human-centered manufacturing places worker needs and well-being at the center of the manufacturing process [14]. Consequently, we explore security culture as a human-centered precondition for transformative resilience towards ZDM. Thus, we examine the value of involving humans in the ZDM decision loop; viewing them as a resource rather than a threat in the operationalization of ML for ZDM. We further explore the concept of security culture as a mechanism for the development of transformative resilience to better address adverse events (e.g., cyber threats). Hence, the research question "*In what way may the interplay between transformative resilience and security culture concepts enable robust ML/ZDM?*". As such, we present a new way of thinking about ZDM, and propose that this could be an area that requires further empirical research.

Under these circumstances, our argument and thus the scientific contribution of this paper is that we provide a better understanding of transformative resilience as an outcome of how humans actively engage with ML in ZDM. Hence, we argue why transformative resilience is important to better be able to address adverse events such as a cyber threat situation (e.g., a defect), that may slow down or harm the manufacturing process (e.g., increasing vulnerability). Additionally, our contribution highlights the

reasons and thus importance of developing a cyber security culture for ZDM to enable a safe and transparent foundation for transformative resilience.

This paper is organized as follows. In the next section, the concepts I4.0, ZDM and ML, and ML challenges are explained. Further, we address cyber security as a critical aspect in relation to these concepts, presenting transformative resilience and security culture as new human-centric dimensions for ZDM. Finally, the method, discussion, concluding remarks, and suggestions for further research are presented.

2 Theory

2.1 Industry 4.0 and Zero-Defect Manufacturing (ZDM)

I4.0 has mainly centered on technology and the techno-centric approach in relation to industrial automation, predicting errors, identifying defects and defects causes, etc. From this view, humans have to a larger extent followed technology and not the other way around to adapt to human needs and ways of working [15]. The recent transition to I5.0 draws on the socio-technical systems approach where issues of human and technology reconciliation are heavily emphasized [16].

In the background though, the pursuit of both I4.0 and I5.0 saw the rapid advancement of technologies such as AI, ML, and industrial internet of things (IIoT) for production automation and the emergence of the ZDM concept to minimize the effects of traditional quality improvement methods targeting zero defects. Psarommatis et al., [17] have argued that the combination of advanced digital technologies with ZDM will become the new benchmark for companies working towards sustainable and resilient manufacturing.

I4.0 technologies have in the past been seen to support ZDM. The industrial application of ML in particular helps in defects management, e.g., defect detections, logging imperfections, or conducting root cause analyses [17]. Quality defects are costly and may ruin an organization's reputation. They also involve a waste of resources and time.

Zero-defect Manufacturing has been defined as a target-based approach where the goal is to decrease and mitigate failures within manufacturing processes and 'to do things right the first time' [17].

The augmentation of I4.0 technologies such as ML with ZDM has made it possible to reduce the costs often associated with defective products, and reduced inspection points throughout the manufacturing process, guaranteeing that no defective product is delivered to the customer [17].

Defects represent characteristics of products that do not conform to their quality standard [18]. Many proponents of ZDM and I4.0 have argued that most defects in manufacturing are due to human mistakes or errors hence the arguments for ML [1]. However, an alternative view offered by proponents of I5.0 is that ZDM needs the co-existence of humans and technology because of the inflexibility technology offers compared to humans. Using the example of a human operator in the production process, Oliveira et al., [19] argue that humans are the most important drivers of flexibility in manufacturing environments irrespective of how advanced automation systems are or how much artificial systems offer. Wan and Leirmo [20] argue that a "common pitfall on the journey towards ZDM is to implement cutting-edge technology, thinking that it will eliminate defects without prioritizing the role of humans in the manufacturing system".

In the next subsections, we examine the implications of the view from Pasquale et al., [1] where technologies such as ML have reduced human intervention because humans are viewed as a leading cause of error. Further on, we argue for the significance of human centricity applicable to the security aspect of ZDM and as a mechanism to enhance transformative resilience.

2.2 Why Resilience Matters

According to Psarommatis et al., [17] the combination of ZDM and I4.0 technologies such as ML increase not just flexibility in the production system but also resilience. According to Holling [21], resilience is an ecological concept describing a natural system's ability to continue functioning when facing an adverse event (e.g., shock). Resilience thus refers to "positive adaptation within the context of significant adversity" [22]. It involves an analysis following a "setback event" and emphasizes positive adaptation to such an event. A non-resilient response thus involves reintegration loss (e.g., lack of motivation, risk aversion) [23].

A framework to describe resilience was developed by Fisher et al., [10] and included: adversity triggers, resilience outcomes, resilience mechanisms, and resilience-promoting factors. Powley et al., [24] built further on this framework and included novelty and thus the accumulation of knowledge as part of resilience-promoting factors. An adversity trigger may relate to an unforeseen event such as a type of threat [25]. The novelty aspect is thus related to the rarity of events impacting "the perception of relevance and probability that leads to larger impact" [26]. Hence, it constitutes available knowledge on triggers. Hence, with low novelty regarding triggers, performance is brought back or recovered by resilience to its initial level of "bounce back" (e.g., recovery resilience) [27].

However, with higher novelty profiles (involving human understanding and response required to adapt to the change associated with triggers), adaptive and transformative resilience (reaching higher levels of performance) is possible. Transformative resilience thus involves the ability to "bounce beyond" the original novelty level [23]. This major novelty profile requires knowledge of which organizational functioning and outcome are transformed. Building on March [28], transformative resilience involves exploration and thus the ability to take risks, search, play, experiment, innovate, be flexible, and discover [24]. However, there is little research on team resilience, involving the link between individual-level behaviors and organizational-level processes [23]. Moreover, transformative resilience is a context-dependent concept. Hence, the significance e.g., of a specific focus and capacity may vary [29]. As such, we explore the concept of security culture related to manufacturing as a human-centered precondition for transformative resilience for ML towards ZDM.

2.3 Challenges of Machine Learning (ML) in ZDM

As argued earlier, ML is one of the key I4.0 technologies where ZDM offers a lot of promise. ML is a subfield of AI where machines perform computational algorithms that

turn empirical data into usable models and make predictions with minimal human intervention [30]. Usually, ML comprises two categories: supervised ML and unsupervised ML were later no human interventions.

Because ML models generally learn from data fed into them to identify patterns and automatically make predictions, they are well suited for ZDM including quality improvement projects where traditional methods in manufacturing are used.

The literature has many examples where many ML techniques have been applied to manufacturing operations to gain more insight into frequently occurring problems, or to help investigate possible system errors and explore reasons for various issues [3]. Studies (e.g., [31]) suggest that ML models may also address operational planning, and environmental and social sustainability because they provide supply chain visualization and traceability solutions, analyzing data based on risk. This makes it easier to increase productivity, product quality, reduce rework and costs, and enhance the transparency of the production process [30].

And yet unsupervised ML models have unique challenges but the biggest of all is the enormous volumes of data required to enhance decision quality. Wuest et al., [30] note that because of these limitations including the availability, quality, and composition of the manufacturing data, the performance of ML algorithms tends to not be good enough.

Perhaps the most important study which directly associates ML challenges to ZDM application is that of Papageorgiou et al. [3]. In their study of ML methods for root cause analysis, they identified 6 challenges, namely (1) explainability, where the black box nature of AI/ML models is difficult to comprehend by humans; (2) quality of training, where the lack and scarcity of adequate and suitable sources of data to train AI/ML models is cited; (3) standardization and interoperability, where companies use different architectures and protocol, which makes collaboration difficult; (4) data privacy, where access to private databases to train AI/ML is a challenge, (5) data security, where industrial applications demand more secure transactions that the current complexity of AI/ML models can't guarantee; and (6) the emergence of new technologies which may make integration with AI/ML difficult.

In this paper, we elected to focus on explainability and security in this case including both data privacy and data security from the challenges cited by Papageorgiou et al. [3]. These three challenges from the study directly underscore the human-centric perspective that is the core of the paper.

Explainability of AI models, sometimes described as XAI, is about making AI-model outputs understandable to humans for decision-making [32]. The argument developed by Papageorgiou et al. [3] is that due to the high complexity, and ambiguity including the inexplicit learning methods they employ, these models are difficult for human comprehension or more specifically for ZDM, humans may fail to establish the cause-and-effect relationship. According to Mugurusi and Oluka [32] augmenting the AI/ML decision loops with humans and using them as a basis for decisions. In some cases, AI systems may thus produce the wrong results in individual cases. Data privacy is significant in this matter because e.g., root cause analysis towards ZDM requires datasets from different production stages that could potentially expose sensitive information about the industrial provider. Hence, there is a security issue because the industrial environment requires secure transactions. The security aspect is therefore very important in relation to ZDM,

to prevent the leakage of sensitive or confidential information. Moreover, data integrity is necessary to prevent corruption and information loss which may lead to production downtime, defective products or even threaten the security and safety of employees and users [33]. AI and "smart" algorithms are already being used today to improve IT security for detecting malware and blocking "illogical" access attempts. But as it may fail to recognize complex threats, humans are an important factor in terms of recognizing and exposing attacks.

2.4 The Cyber Security Context

In the cyber security domain, human error is the most frequent cause of adverse incidents and thus a serious threat to the industry at large [34]. Moreover, as manufacturing is often placed within a socio-technological context (exchanging information between systems, people, and other organizations), confidentiality may be broken, disclosing information in unapproved ways [35]. Organizations not considering socio-technical factors may therefore not be able to respond properly or defend themselves from threats as they are lacking understanding of what is identified as a threat, and the impact of attacks [36]. Threats may be external (e.g., a hacker) or insider threats (e.g., an employee) who intentionally or unintentionally misuse organizational information or information systems [37]. Or it can be contextual factors like unfamiliar tasks (performed rapidly), not understanding the consequences of actions, tasks given insufficient attention, lacking supervision, and complex tasks that require high levels of understanding [38]. Hence, one of the reasons the human aspect is important regarding information security is due to unintended errors associated with using technologies [39]. As the manufacturing setting becomes more complex and unpredictable (e.g., crises) there is a need for higher levels of understanding and skills [39]. Creating a cyber security culture could thus be one way to enhance transformative resilience.

2.5 Cyber Security Culture

A security culture is the collection of shared values and mindsets in organizations facilitating different ways of thinking, feeling, and action on expectations of how employees should go about security [12]. Consequently, it is key to limit information leakage and provide effective information sharing [40]. A security culture involves trust (in terms of aligning security practice with everyday routines/not assuming malicious behavior) [41], creating security awareness and knowledge of security procedures to such an extent that it becomes a part of employees' work identity. Moreover, it involves understanding own vulnerabilities, risks, what is identified as a threat, and the impact of attacks [36].

Regarding risk, there exist disagreements on whether regulations are efficient mitigation tools as humans are perceived as the weakest link. Hence, securing system design involves understanding what makes it insecure [42]. Not trusting and constraining humans by assuming malicious behavior might thus impact responsible behavior negatively, facilitating "non-complacency", and a culture of mistrust [34]. Creating a culture where humans willingly share cybersecurity responsibility, might thus result in early detection and prevention of threats in ML/ZDM environments [34]. Equally important,

the sense of community, involvement and open communication might enhance motivation to follow security requirements [43]. Furthermore, human needs and limitations should be given attention regarding system design [34]. This involves integrating humans in the decision-making and development of technologies (e.g., machine learning). Enhanced transparency and understanding across disciplines within the manufacturing process may thus make it easier to make better decisions.

In this paper, we further examine the role of security culture to mediate the relationship between human-centered ML/ZDM and transformative resilience.

3 Method

A conceptual approach has been adopted in this paper. The theory on ZDM is not well developed as it is a very recent concept even if there are notable applications in industry [17, 44]. The absence of descriptive or even exploratory models to allow the formulation of hypotheses and propositions that can be tested against reality can be detrimental to theory building [45]. Typically, the adoption of conceptual methods in this study of ZDM should remedy such inconsistency.

Conceptual research methods infer among other things, the development of an initial scheme of a few explored situations of interest, either quantitatively and/or qualitatively in order to simplify/classify/conceptualize/taxonomize the elements associated with those situations [46]. Besides their theory-building properties, Meredith [45] argued that conceptual methods increase the external validity of research conclusions and lead to a better balance between theory-building and theory-testing research.

The arguments made earlier, and the basis of our forthcoming discussion is based on three major important studies which include that of Powell et al., [44], Psarommatis et al., [17], and Caiazzo et al., [47]. Among these three formative literature reviews on ZDM, only Psarommatis et al., [17] cite a finite relationship between technology and AI/ML when the three ZDM strategies (i.e., detection, repair, prediction, and prevention) are analyzed. Powell et al., [44] recognize that AL/ML, Big data, IIoT, and extended reality will become key enabling technologies for ZDM in the future. Caiazzo et al., [47] believe that as smart factories become common, ZDM will exploit I4.0 for data acquisition and storage, automatic signal processing, data mining, and knowledge discovery for diagnosis and prognosis, monitoring of process parameters, online predictive maintenance, and re-configuration and re-organization of production. Seamless integration of humans and technology into ZDM contributes to better data-driven flexibility hence resilient production systems [3]. Oliveira et al., [19] believe the human worker represents a key driver for flexibility in manufacturing environments with high levels of automation irrespective of how flexible these systems are.

4 Discussion and Concluding Remarks

4.1 Security Culture as a Human-Centered Precondition for Transformative Resilience in ML/ZDM Environments

Building on the arguments of e.g., Pasquale et al., [1]; Oliveira et al., [19]; Lu et al., [14]; Wan and Leirmo [20] and thus the importance of involving humans in the manufacturing system, we suggest a new way of thinking about ZDM. As such, we emphasize

the security aspect of using ML for ZDM, by including the concepts of *security culture* and *transformative resilience*. Our argument derives from the importance of involving humans related to technology development and uses for ZDM. For example, in times of e.g., crisis and uncertainty, the manufacturing systems and networks involving technologies may become more vulnerable to threats, due to rapid changes. This enhances the need for new learning, flexible decision-making, and adaptation. Moreover, with the manufacturing setting becoming more complex and unpredictable, we need higher levels of understanding, and skills (e.g., [38]). In this sense, ML and ZDM involve a change in the way humans understand, use, and adapt to technologies, as well as how they make decisions.

In addition to humans following and thus working in accordance with technologies such as ML, ML needs to be more understandable to humans (involving learning from ML) in the process of decision-making. Hence, as technologies such as ML require learning over time to make good decisions, ML may only be useful up to a certain level providing only basic knowledge (Fig. 1) in the absence of human involvement. Hence, if something happens e.g., a cyber threat, it may only be possible to "bounce back" to the original novelty level [23]. In the same way, humans must understand ML to contribute to new learning and thus higher levels of novelty [24] in relation to making the best decisions for ZDM. However, facing an adverse event/trigger such as a cyber threat situation requires flexible decision-making and creative ways of thinking (contributing to new or enhanced learning). Humans, as they are often left out and viewed as a threat, may due to their more flexible and playful nature [28] provide higher levels of novelty in such situations, given the right preconditions. As such transformative resilience means that problems may be solved at a higher level, making it possible to "bounce beyond" the original novelty level [44].

Under those circumstances, our argument and thus the scientific contribution of this paper is that we view transformative resilience as an enabler for humans to actively engage with ML for ZDM. Hence, we argue that transformative resilience is important to better be address adverse events such as cyber threats (e.g., a defect), that may slow down and harm the manufacturing process. Additionally, our contribution highlights the importance of developing a security culture for zero defects to enable a safe and transparent foundation for transformative resilience. For example, as a security culture values trust, awareness, involvement, and open communication, it may lower the threshold for admitting mistakes (e.g., insider threats), facilitating better opportunities to correct the mistakes made and understand own vulnerabilities. An enhanced understanding of one's vulnerabilities and risks might thus make it easier to respond properly to threats. Moreover, involving humans and cooperating across organizational levels in relation to ML, could facilitate understanding, meaning creation, positive emotions, clarity, and a sense of relevance. Hence, empowering and encouraging humans to embrace change and adopt technologies. As the European Commission stresses the importance of adaption and transformation in relation to staying safe from adverse events (e.g., crises), we stress emphasizing the values consistent with a security culture as a highly relevant and sustainable (human-centered) intervention to enhance transformative resilience towards engagement and new learning in relation to ML towards ZDM. This means that managers and/or engineers should take a holistic perspective in creating technology and quality

standards that resonate with the operators. Conversely, engineers need to understand the needs of the operators to make technical changes. As such, using ML for quality inspection to predict and detect defects along with the involvement of human capabilities.

Rather than viewing humans as a threat in relation to ML and ZDM, we argue that humans should be viewed as a resource that can drive flexibility thus making better decisions (transformative resilience), given the right preconditions (e.g., security culture). In Fig. 1 we illustrate the reflexive impact of having humans in the loop. Humans bring a unique understanding of ZDM processes at the tacit knowledge level that even advanced deep learning and ML models lack. This knowledge is cognitively flexible and has been described by Willingham [48] as flexible knowledge. It is this kind of knowledge that provides manufacturing firms these bounce back and bound forward capabilities when technologies have blackbox challenges. Consequently, our contribution suggests a human-centric understanding of ML/ZDM environments by considering security culture as a resilience-promoting factor for transformative resilience in organizations. Thus, we propose a new way for industrial organizations to think about and approach ZDM.

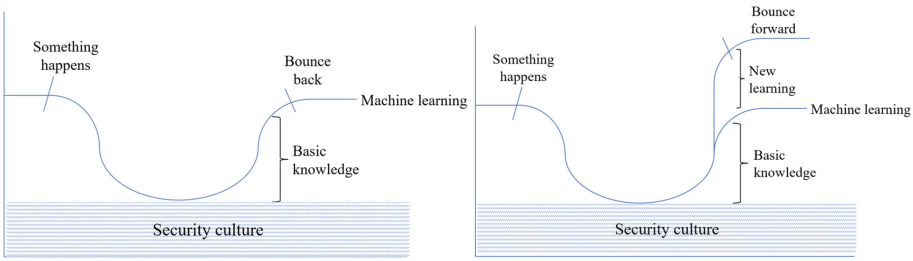

Fig. 1. The mechanics of transformative resilience in ML/ZDM environments

4.2 Further Research

From a human perspective to secure system design, Bella et al., [42] we need to understand what makes it insecure. Hence, we argue that empirical research is needed. This may relate to qualitative methods on enhancing insight into what type of threats are associated with ML (or other AI technologies) and ZDM, and how this may be addressed from a human and organizational industry perspective. As such, management challenges in relation to the use of ML related to ZDM, involving decision-making, could be emphasized, as well as the barriers and possibilities of implementing ML. For example, identifying vulnerable areas, understanding what type of AI technology organizations use, in relation to what stages or areas in the manufacturing process they use them, type of information exchanged between what systems and people, etc. Under those circumstances, it is essential to know employees' needs and understanding of the ML technologies, and how engineers, managers, and operators cooperate in relation to developing these technologies for different parts of the manufacturing process. As such, exploring what factors may make it easier in relation to facilitating a safe, transparent, and resilient work environment (security culture) that involves and empower workers. Consequently,

there is a need for a contextual and empirical understanding of what security culture and transformative resilience are in relation to ML towards ZDM to better address adverse events such as a cyber threat situation.

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The Effect of Digitalization and Human-Centric on Companies' Production Performances

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Abstract. Industry 5.0 is the inclusion of humans in the production line. This is because human is now considered a prerequisite for any industry to enhance production performances. However, most of the technological enablers still do not consider the human factor in the production system and only a few articles expose the impact of human-centric approaches and digitalization on production performance. Therefore, this study applied a questionnaire-based survey approach to map out the level of digitalization and human-centric in companies of different sizes and identify the impact on production flexibility and throughput performances on the production systems. The survey was conducted using Google Forms. One of the key findings is the level of digitalization should go hand in hand with human centricity. Both the production performances of product throughput and process flexibility have an S-shape tendency where a high level of human-centric can have a positive impact on both production performances. Respondents from different sizes of enterprises in different regions of the world and job nature can have a different perception of both the degree of human-centric and digitalization. Companies should consider different human roles like managers and engineers in the human-centric framework to enhance human-centric in a more holistic approach.

Keywords: Human-centric · Digitalization · Industry 5.0 · Survey · Performance

1 Introduction

From the first Industrial revolution to the fourth, the implementation of automation and machines has increased steadily. This results in production performance improvements such as productivity and quality. One of the reasons is that machines can outlast humans in long-lasting repetitive work, with higher manufacturing speed and accuracy [1]. With the increasing deployment of advanced digital technologies such as artificial intelligence (AI), complex processes are transferred from humans to machines [2].

Till today, humans, particularly operators, are not completely removed from shopfloor despite the using machines and technological tools in production. On the

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contrary, they are often included in the activities such as the decision-making process, material handling and assembly due to their flexibility and their cognitive and motor skills that machines cannot imitate economically yet [3]. Automation technologies and digital transformation promise increased productivity and profits to companies, but there is an imbalance or mismatch between the automation level and human capabilities such as human-machine collaboration, and human-machine interface [4].

Industry 5.0 is to solve the mismatch issue between manufacturing and human-social needs which leads to three focus areas of human-centricity, sustainability, and resiliency [5]. After the EU commission published a report on Industry 5.0 in 2021 [6], there is an increase in published work focusing particularly on human-centric in the manufacturing sector to reduce waste and improve overall product quality [7]. Although there is no single definition of a human-centric approach, it denotes a similar concept which is to put focus on humans themselves [7]. Human-centric approaches are not only applied in manufacturing, sectors such as energy [2] and maritime [8] are also shifting their attention towards a better human-machine collaboration to increase their performances.

Although the human component in Industry 5.0 receives high focus due to its better knowledge transfers and flexible capabilities, various literature reviews on human-centric approaches highlight that production systems are still not prioritizing human needs (ergonomics, etc.) and most of the technological enablers still do not consider the human factor in the manufacturing processes and production system to achieve high production performance [9–11]. Currently, only a few articles expose the effect of human-centric approaches and digitalization on production performance. Most of these studies are based on empirical data such as single or multiple case studies and can only demonstrate the impact of human-centric approaches and digital technologies on performance only on a small scale.

This study is to map out the level of digitalization and human-centric of the production systems of various companies as well as to identify the impact on production flexibility and throughput performances. Therefore, this study focuses to answer the following research questions (RQ):

1) What is the relationship between different levels of human-centric and digitalization in companies?
2) What human-centric approaches could companies consider along with digitalization development to improve product throughput and process flexibility performances?

2 Theoretical Background

While Industry 4.0 focuses on digitalization and automation, Industry 5.0 re-introduce humans (e.g. operators) back to the shop floor to increase the process efficiency of production [5]. In the conference [5], the authors categorized the definition of Industry 5.0 from three different perspectives namely EU proposal-based, intelligent cutting-edge technology-based and human-machine collaboration-based. From the EU proposal perspective, Industry 5.0 is, for example, placing a premium on workers' well-being throughout the manufacturing process and leverages new technologies beyond development and employment [12]. From the human-machine collaboration perspective, Industry 5.0 focuses on building a synergy between the human workforce and machine to

improve process efficiency and designing a human-centric solution which enables human work to rejoin the automated process [13]. Although there is no set definition, Industry 5.0 aims to combine the strengths and capabilities of autonomous decision-making of both humans and technologies to increase production performance [14].

Currently, most published literature on human-centric in Industry 5.0 focuses to increase the collaboration of humans with autonomous technologies in production systems that improve production performance (such as flexibility) and human-centricity (such as reducing fatigue levels among workers). Perizzini and Pellicciari [15] present a novel human-centric factory model that considers crucial aspects (such as ageing workers, and digital technologies) to design factories and improve performance. The study by Kong et al. [16] developed a human–cyber-physical symbiosis and so support real-time, trusting, and dynamic interaction among operators, machines and production system. Pinzon et al. [17] introduce a holistic framework for a human-centric approach and cyber-physical systems to improve operational and social sustainability-related performance impacts. Further, Wanasinghe et al. [18] introduce a human-centric digital transformational framework for the oil and gas industry to deploy existing digital technologies to enhance their workers' health, safety, and working conditions. Dengler et al. [19] develop a system of machine learning to detect errors and present the information in an understandable format to operators to have a colligative decision-making process. Canas et al. [20] suggest to incorporate augmented reality in learning mythology can change which can improve the education and training for operators to work in an industry 4.0 environment.

Human-centric manufacturing is now considered a prerequisite for any industry to enhance flexibility, agility, and robustness [21, 22]. The outcomes of human and autonomous technologies collaboration will be a highly effective manufacturing process with added value, thriving trusted autonomy, and decreased waste and expenses [23]. To the best of our knowledge, there are no studies that have investigated, on a large scale, the level of digitalization and human-centric approach in manufacturing companies and identified their impact on product throughput and process flexibility performance.

3 Methodology

This study applied a questionnaire-based survey approach to answering the RQs. The global survey was conducted online mode using Google Forms and the respondents' answers were collected over a timeframe of 6 months. The questionnaire contains 38 closed questions in total with nominal (e.g., choose the company size) and ordinal scales (e.g., rate the human-centric approach in the company). A 5-scale Likert (e.g., "very low, low, medium, high to very high") is used in the questionnaire. To ensure the reliability and validity of the questionnaire, the questionnaire was screened among several critics on web-based questionnaires and sent to experts for pilot testing. The revised and enhanced online questionnaire link (refer to appendix) was sent to 432 subject matter experts. The sampling criteria of the respondents were that they must be working, practicing, or involved in projects focusing on digital manufacturing and must be working in the manufacturing or service sector.

A total of 120 respondents participated in the survey. The result has a response rate of (31%), which is acceptable in the survey research methodology [12]. The respondents

in this survey are located in Asia (29%), Africa (14%), North America (11%), South America, (10%) and Europe (36%) and are working in small (15%), medium-sized (24%) and large enterprises (61%). Most of the respondents are working with production and quality management, have more than 10 years of experience within this field, and identify as top- or middle management.

This study reflects a minor part of the survey results [29]. Nineteen closed questions were included and analyzed to answer the RQs. To map the digitalization level, product throughput and process flexibility performance, several questions were asked. This approach reduces the bias and increases the validity of the survey. To test reliability, Cronbach's alpha coefficient was calculated for each of the summated scales. All the summated scales have values above the recommended threshold of 0.6 [24]. The reliability statistics of this survey has a Cronbach's Alpha of 0.927, and so, deemed reliable for further analysis.

4 Results

In this section, the survey results are presented and visualized in a whisker and box diagram. The survey results are showing five different human-centric levels ranging from very low to medium to very high and their results on digitalization level, product throughput time performance and process flexibility performance.

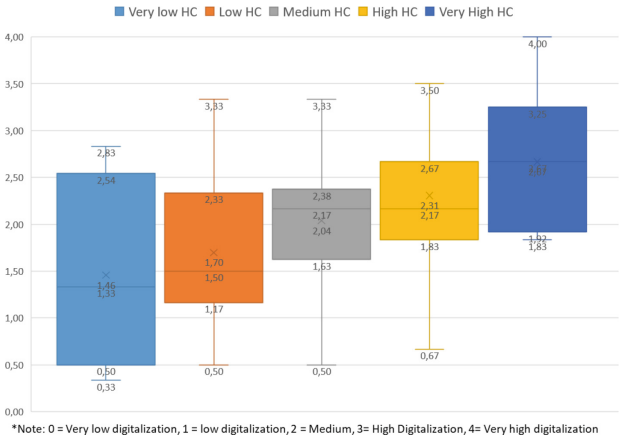

Fig. 1. Digitalization level in production systems with different human-centric approaches

Figure 2 shows the results of the human-centric approach on product throughput performance, while Fig. 3 presents the results on process flexibility performance. The performance dimensions are an average of five different questions relating to applying strategies, methods, and tools distinguished by companies with different levels of human-centric approaches. Both the production performances of product throughput and process flexibility have an S-shape tendency.

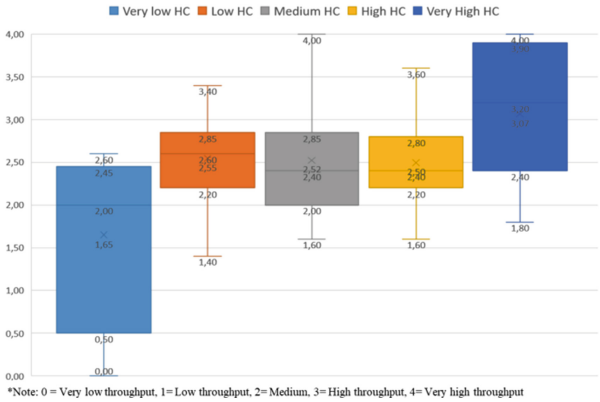

Fig. 2. Human-centric approaches impacting product throughput performance

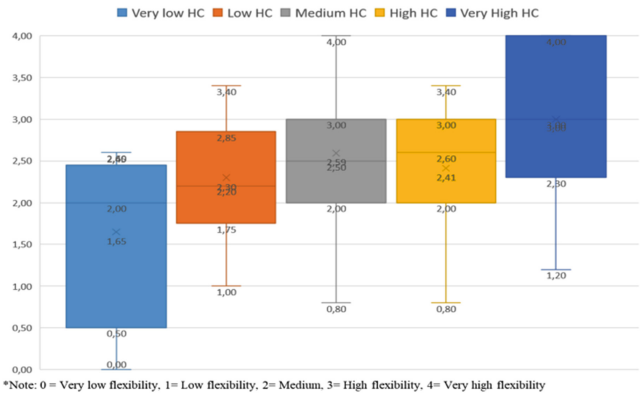

Fig. 3. Human-centric approaches impacting process flexibility performance

In Fig. 2, companies which responded to very low human-centric (mean = 1,65), have a medium throughput performance compared to companies from low to very human-centric where they all have high throughput performances. The impact on throughput performances is small for companies with low to high human-centric as compared to companies with very low and very high human-centric. Figure 3, companies which responded to very low (mean = 1,65) and low human-centric (mean = 2,30) have a medium flexibility performance, while companies which responded ranging from medium to very human-centric have a higher flexibility performance. Similarly, there is a huge difference between companies with very low and very high human-centric approaches companies when it comes to the impact on product throughput and process flexibility performance.

5 Discussion and Conclusion

In highly digitized production lines, human roles on the shop floor are often substituted by robots and automation [25]. However, the types of human activities that are involved in the production, depending on the level of digitalization. For example, in a production line with a high degree of digitalization where the operators are cooperating closely with robots in the same workspace, companies should focus on developing higher skills activities for operators to work on shopfloor such as day-to-day robot maintenance and learning basic programming knowledge [7]. It is crucial to align the degree of human-centric approach with the level of digitization, as depicted in Fig. 1, to achieve improved production outcomes in terms of product throughput and process flexibility.

Human involvement is crucial during uncertain events in the production line [26]. Given the evident benefits of human-robot collaboration in manufacturing systems [26, 27], it is crucial to adopt a human-centric approach when deploying robots during the early design stage to enhance product output and process flexibility, as depicted in Fig. 2 and 3. However, implementing a human-centered approach in conjunction with industrial robots presents significant challenges in task planning [26]. A challenge is to efficiently allocate tasks and assembly operations to human operators or robots, taking into account the strengths and limitations of both.

Human-centric should always be one of the focus points to elevate into Industry 5.0. It is also important to note that human-centric goes beyond just the operators. Although operators have direct contact on the shop floor, both managers and engineers have roles to play [7]. Managers play a role in advancing the level of a human-centric approach in production. For example, managers, especially in large companies, should facilitate a feedback channel from the operators to understand the needs and challenges faced by them because often some of the decision-making is beyond their control [28].

This study provided new insight into what should be developed and focused on, in parallel with the level of digitalization of companies. The results show that there is a huge impact on both product throughput and process flexibility between companies with very low and very high human-centric approaches companies. One limitation of the questionnaire is the different perceptions and understanding of both the degree of human-centric and digitalization by the respondents from different sizes of enterprises in different regions of the world. We included, therefore, several questions to map a performance dimension to reduce bias. Further, the job nature of the respondents with different knowledge of digitalization can also have an impact on the results.

Nonetheless, this survey provided a new viewpoint on where the industry should position humans when it comes to introducing new technology. The level of human-centric of a company goes hand in hand with the level of digitalization which supports the Industry 5.0 perspective - human involvement in manufacturing. Future research should consider different roles of humans like managers and engineers in the human-centric framework to enhance human-centric in a more holistic approach.

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Appendix

Link to the survey and questionnaire: https://forms.office.com/r/AumEsRnPvE.

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Human Factors

Cognitive Ergonomics in Industry 5.0

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Abstract. Industry 5.0 is a concept that represents a human-centered, resilient, and sustainable manufacturing system. With the increase in the importance of the human role within the system, there is a need to adapt standard ergonomic methods to ensure safety within the work environment. The human-centered approach extends the limits of work safety to well-being principles while the new digital technologies which seek human interaction demand enhanced cognitive functions. In this paper, the principles of cognitive ergonomics will be presented as their current use in manufacturing. Due to digitalization, the human operators' role demands changes to the principles of Industry 5.0 ergonomics. The novel framework of cognitive ergonomics implementation in Industry 5.0 will be presented based on a literature review. Results will be used in a future work to implement the novel and innovative digital production and process planning system in the local stove manufacturing company.

Keywords: Industry 5.0 · Ergonomics · cognitive ergonomics · human factors · production optimization

1 Introduction

Digitalization by principles of Industry 4.0 after a decade has yet to achieve as many goals as planned. Moreover, there is almost no evidence of complete manufacturing company digitalization and many theoretical settings available in the literature [1]. Digitalization mainly occurred in large companies and market leaders, who have implemented Industry 4.0 only partially. In contrast, most companies accepted specific segments of Industry 4.0 due to natural technology development and increased availability [2]. The COVID-19 pandemic made digitalization slightly faster due to the need for remote work, so many companies now implement certain Industry 4.0 tools [3]. Those are primarily online communication tools, but also some have used the opportunity to update and digitize their manufacturing planning and control systems. With the constant disruptions in the market and high level of uncertainty, the need for digital technologies implementation remains, as well as the flexibility and modularity of manufacturing and other processes in the company. As the well-known barriers to Industry 4.0 implementation remain present [4], now, with the continuous disruptions in the market, the European Union presented

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a concept that would overcome the barriers of Industry 4.0 and remain a key driver in the economic and societal transitions. It is a vision of industry which „aims beyond efficiency and productivity as the sole goals and reinforces the role and the contribution of industry to society". Called Industry 5.0, it places a human in the center of the production process. It uses new technologies to "provide prosperity beyond jobs and growth while respecting the production limits of the planet." Industry 5.0 is an upgrade of Industry 4.0 with the goal to enable a transition to a human-centric, sustainable, and resilient European industry [5].

Industry 4.0 has partially neglected a human role in the system [6], and has encouraged the substitution of a human worker (machine operator) with a robot, which has, in the end, lead to the one of the biggest barriers in its implementation, which is a resistance of a human workers to change. Therefore, the human-centered system of Industry 5.0 is presented which sets worker in the center of the system whose wellbeing and safety is a highest priority: "It empowers workers, addresses the evolving skills and training needs of employees. It increases the competitiveness of industry and helps attract the best talents." [5] Industry 5.0 not only modifies the company, but also influences the society including the preservation of resources, climate changes and social stability [7]. The most common differences between the Industry 4.0 and 5.0 are shown in Table 1.

Table 1. Industry 4.0 and 5.0 characteristics [3, 5–7]

Industry 4.0	Industry 5.0
Manpower distanced from factories	Return of manpower to factories
Focus on connection machines	Focused on delivering customer experience
Smart products	Interactive products
Intelligent supply chain	Responsive and distributed supply chain
Cyber physical systems	Cognitive cyber physical systems

Human centricity demands better work conditions for every worker but also takes into consideration their motivation and satisfaction level. Therefore, also the traditional ergonomic methods need a modification, but also the more intensive use and implementation within the organization, not only in the traditional form but also in form of cognitive ergonomics and well-being, which is why in the following chapters the literature review will be given, based on which the framework of cognitive ergonomics in Industry 5.0 will be presented.

2 Traditional (Physical) and Cognitive Ergonomics

Ergonomics is focused on a mechanical feature of the human body and its improvements to avoid the occurrence of possible safety issues [8]. Many methods are available to measure human posture and movements which result in the value showing the level of risk for the worker [9]. Traditional ergonomics, therefore, deals with the quality of human

work where the health and safety of workers go along with workplace improvement in which the ergonomic aspects of it enable higher productivity. Human in the workplace environment is observed to acknowledge short-term aspects, such as fatigue and soreness, or long-term aspects, such as strain, injuries, or disabilities. Increasing work speed, reach zones or power are goals of classical ergonomics, which increases work productivity while decreasing the possibilities of human injury and illnesses to improve product quality. By Taylor's work principles [9], the tasks are specified and designed in a detail while human works by standardized instructions on how the work should be performed. Posture, force, velocity and acceleration, repetition, duration, recovery time, heavy dynamic exertion, segmental vibration, environmental characteristics, heat stress, cold stress, whole body vibration, lighting, and noise are characteristics of a workplace environment that directly influences workers' health, safety, and productivity [10]. In this process, the impact of the human mind was overseen. Work affects the mind and vice versa, both with short- and long-term effects [11]. Therefore, cognitive ergonomics is a complementary view of work to classical ergonomics and its combination leads to positive impacts on workers' health and motivation. Cognitive ergonomics is developed from cognitive psychology. By its definition "Cognitive ergonomics (or software ergonomics) is a part of human/computer interaction study concerned with computers as support-or for that matter hindrance-of human thinking. It is a highly interdisciplinary field, where representatives of computer science, cognitive psychology, and other areas meet in a mutual exchange of ideas and research results." [12]. Unlike cognitive psychology which aims to understand the nature of human cognition, cognitive ergonomics describes how human cognition affects work and is affected by work. The quality of work depends on the workers' understanding of the situation, its goals, means, and constraints. The challenges occurred when the human capacity for learning and adaptation started to be insufficient to meet the technological demands and the capacity for processing information was decisive for the capacity of the input-output relations. Cognitive ergonomics deals with cooperative work, user interface design, modeling of users and systems, problem-solving, learning, and system design. In cognitive ergonomics, risks refer to those aspects of the working conditions that may lead to unwanted outcomes [13]. Therefore, cognitive ergonomics needs to develop methods that can produce a comprehensive qualitative analysis of the risk conditions. Human-centered manufacturing systems demand the extension of traditional ergonomics, in form of cognitive ergonomics and principles of well-being. Here cognitive ergonomics is needed to create a motivational workspace, now with a challenge of collaboration of humans and machines, often nowadays collaborative robots.

2.1 Related Works

The Web of Science, as the most relevant scientific database, was browsed by terms "cognitive ergonomics" AND "industry 4.0/5.0" for the papers published field of engineering (mechanical, industrial, multidisciplinary to acknowledge the current findings of the use of cognitive ergonomics in the manufacturing industry.

The Industry 4.0 concept was presented in 2011; therefore, the most relevant and interesting work from then to the present (January 2023) was browsed for this paper. Cognitive ergonomics and its use in the industry appeared in the literature in the late'80s,

as it was the beginning of the increased use of computers [11]. Human-computer interaction was a common research topic, emphasizing computer interface design. In the search period (2011–2023), researchers mainly related cognitive ergonomics to lean management, whose principles are recognized as a stressor in the work environment [14] and could worsen workers' Quality of Work Life (QWL) [15]. With the use of cognitive ergonomics task-based approach, problem detection before its occurrence in the production system is enabled [16]. In Industry 4.0, the tasks of the Operator 4.0 range from learning new tasks to solving complex problems and initiating changes [17], which is why it is crucial to have a strategy for cognitive automation that can also identify the needed competencies of humans so that the initial learning curve can be reduced [18]. Human behavior can also be captured from their motion [19], while specific patterns reveal a cognitive load or attention span disruption. Digital Human Modeling is the core of Ergonomics 4.0 which can accelerate the decision-making and adaptation processes. Predicting human performance and motivation remains a challenge, while a quantification model of the human capability in managing complex tasks characterized by a set of physical, organizational, and cognitive factors is one of the possible future solutions [20, 21]. Cognitive ergonomics is also a good tool in product development and design, enabling a better user experience and higher productivity [22]. Remote workers tend to have a lower perceived workload than local workers, but mental demand was deemed higher while performance was rated lower [23]. This can be correlated to operator 5.0 and their use of the new gadgets, designed by cognitive ergonomics principles and affordance-based design approach, which reduces cognitive friction [24]. Assessment of the Cognitive work analyses can provide sustainability, yet there is a need for new methods to address the human factors challenges [25, 26].

In conclusion, ergonomics is a traditional discipline, while cognitive ergonomics was presented mainly to study human-computer(machine) relations. The researchers have acknowledged the importance of ergonomics in the digital manufacturing system by Industry 4.0/5.0 principles but didn't present a clear framework of ergonomics' role and position within the manufacturing system to improve the quality of work and workers' work conditions, motivation, happiness, and productivity which will be defined in the next chapter.

3 Cognitive Ergonomics in Industry 5.0

Cognitive ergonomics is an essential part of Industry 5.0. In coexistence with traditional (physical) ergonomics and well-being, it can achieve its full potential to create a resilient, sustainable, human-centered manufacturing system. Based on the previously presented literature review, the framework of cognitive ergonomics in Industry 5.0 is shown in Fig. 1. Traditional (physical) ergonomics enables digital human modeling by workers' anthropometric values and avoidance of possible injuries during work activities. The workplace environment is also being modified and ergonomically adapted to workers to ensure safe conditions so physical work can be performed smoothly. Since physical work impacts the mind and vice versa, with the different digital characteristics, tools, and methods of Industry 4.0, cognitive ergonomics is crucial in modifying workers' behavior. The principles of cognitive ergonomics are rooted in cognitive psychology and neuroscience,

with a high level of the subjectivity of a worker present in every aspect. Principles of cognitive ergonomics led to workload optimization and decision-making process optimization, while the workplace should follow the cognitive experience design in software and hardware. On the other hand, well-being completes the circle of human-centered design, which enhances workers' soft skills, life-long learning, social connections, and environmental awareness (green technologies), which leads to human happiness and personal growth. These three segments combined enable the healthy and motivated worker, which is highly skilled and able to collaborate with robots and other machines and use digital technologies or augmented reality in everyday activities.

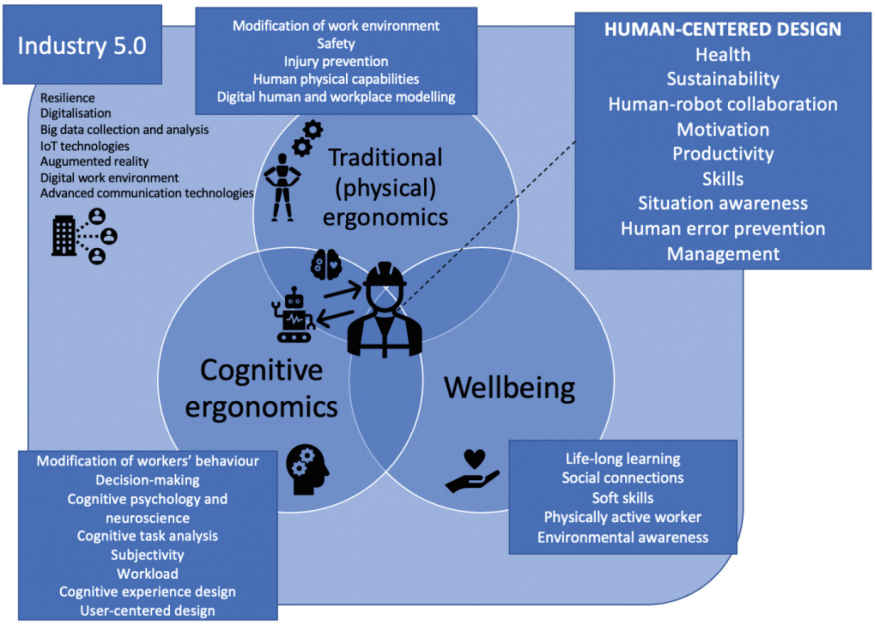

Fig. 1. Cognitive ergonomics in Industry 5.0 framework

This kind of worker is always aware of the current situation, able to manage activities in the dynamic environment to prevent errors, optimize the work and increase productivity. Every modification of the current manufacturing system by the Industry 5.0 principles should consider those three segments as a need for human-centricity, sustainability, and resilience.

The literature proposes several methods for measuring the cognitive load of a worker and motivation level, although only partially accurate because of human individuality and subjectivity. Cognitive load can be measured while the work is in process or as a simulation of a work-study case as a workplace modeling and optimization. Technologies such as smart glasses, which track eye movement, pupil dilation, and blink rate, can be very useful in measuring human concentration and motivation. EEG and cardiovascular metrics can reveal a worker's vital signs and be used as a correlation to cognitive behavior functions. Subjective but also relevant information about the cognitive load and

motivation of the worker can be recognized from verbal reporting and self-rating on a Likert scale. The worker evaluates emotions, load, stress level, and motivation, which can be used to optimize the workplace and the processes, along with the quantitative results of measuring vital signs. The development of e-learning methods and the use of augmented reality enables the worker to achieve the needed skills and knowledge for work in the Industry 5.0 environment. The goal is to reduce the learning curve and achieve the lifelong learning concept to minimize the stress, which negatively affects the cognitive load of a worker, therefore, also on motivation and productivity.

4 Conclusion

Industry 5.0 is a strategy for a human-centered, sustainable, and resilient manufacturing system. This requires the modification of many aspects of the manufacturing and organizational processes but also raises the importance of traditional ergonomics which now must be extended, not only to ensure the better physical health and safety of the human worker but also to ensure the happiness and motivation which also impacts productivity. Cognitive ergonomics deals with processes related to the human mind and how it affects human attention, behavior, health, productivity, learning, etc. It is complementary to traditional ergonomics and should be considered in every modification of the workplace environment. Another essential aspect of cognitive ergonomics is the learning possibilities of a worker, which must be aimed at decreasing the learning curve for several reasons. One is the sufficiency of the trained workforce on the market; therefore, the fluctuation can be high for manual work positions, and the unskilled and uneducated worker must be adapted to a workplace in the shortest amount of time. Another is the need for new skills and knowledge due to the principles of Industry 5.0, its new hardware and software tools, which every human within the production system must adapt to and learn to use. With traditional and cognitive ergonomics, the principles of well-being are now of high importance, which enables the satisfaction of the worker and enables personal growth, awareness of its surroundings, and responsibility for sustainable development. This is how the human-centered system can be designed to ensure a sustainable and resilient manufacturing system. As for future work, the results will be used to implement the new, innovative manufacturing technologies of shaping, welding, grinding, and applying a protective coating in the local stove manufacturing company as well as the development of a model for balancing routine and undemanding tasks with more complex tasks such as problem-solving (specifying work equipment that enables learning and innovative processes in the organization); recognition of participatory processes that improve efficiency by combining the human, organizational and technological components of work.

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Worker in the Context of Industry 5.0: Literature Review and Mains Research Drivers

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Abstract. The evolution from Industry 4.0 moves to Industry 5.0 and Society 5.0, which will transform the way industries operate through digital technologies, appreciation of the human, and sustainability. With this, there is a need for research on the worker and Industry 5.0. This paper aims to identify the main themes driving research on the worker inserted in the context of Industry 5.0. As methodology, a systematic literature review was performed in the Scopus database, obtaining a portfolio of 298 articles, which were identified as the following main areas in the articles: System, Data, Technologies, Production, Process, Human, Work, obtaining for each area, research driving themes.

Keywords: industry 5.0 · worker · research drivers

1 Introduction

The Fourth Industrial Revolution, called Industry 4.0 or smart factories began in 2011 with a conference in Germany presenting a form of technological development from the integration of digital technologies [6]. From the technological development, thinking about the social side, the concept of Society 5.0 emerged, inducing the humanization of technology to help people [2], aiming at a sustainable future. To integrate and solve challenges arising from Industry 4.0, Industry

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5.0 is defined by human-centric manufacturing and symbiosis of man-machine, putting the well-being of workers at the center of production processes [15].

According to Mckinsey [19] the digital transformation supported by the concepts of Industry 4.0 and 5.0 can assist humanity in more difficult times where pandemics such as Covid-19 emerge. This is also visualized in the European Commission's [9] report on how Industry 5.0 has the potential to build resilience in manufacturing through innovation, government, and industrial partnership to improve people's lives, the workforce [14], driving force behind innovation and the digital revolution has to come from people. Industry 5.0 has the potential to promote harmony between factories and employees, also providing seamless proximity between workers and robots with wearable technologies [10] allowing for greener environments for circular manufacturing [9]. Thus, the goal behind the digital transformation associated with the concept of Society 5.0 in which the process is no longer only the focus of implementing digital technology, but rather the improvement of people's lives, aiming for a sustainable future [28].

In this way, the objective behind the digital transformation as a whole is renewed, now it is necessary to integrate what already exists in the empowering worker's perspective in 4.0 industry [20] with the 5.0 society, thus generating an industry 5.0 focused on the perspective centered on the human being [7]. Thus, the evolutionary process of industry 4.0 to the present day can be characterized as digital transformation [16], in which works on industry 5.0 can already be found in the literature. Becoming a way of synthesizing digital technology and human beings in a symbiosis that improves the performance of both and does not generate waste [17,18] or digital waste generated by miss use of worker's skills [20].

Having this in mind, this paper identifies and discusses the main themes driving research on the worker inserted in the context of Industry 5.0. To achieve the objective of this article, a systematic literature review, and the analysis of the main themes that guide researchers using the NVIVO software version 12 will be carried out. It is expected, from the analysis of these themes, a better understanding of the trends in research about the worker in the context of Industry 5.0.

The rest of the paper is organized as follows: Sect. 2 presents the Materials and Methods. Section 3 discusses the results of the systematic literature review, and also the discussion about the main research topics about workers inserted in the context of Industry 5.0. Finally, Sect. 4 rounds up the paper with the conclusions and points out the future work.

2 Materials and Methods

The first step is the problem formulation, following the main objective of this article which is analyzing the research themes that involve the worker in the context of industry 5.0. For that the research question was developed: What are the main research themes involving the worker in the context of Industry 5.0? The second step to achieve this objective is providing a content analysis supported by the software Nvivo 12.

Then the last step is the result discussion and analysis. The search started with the combination of the group of keywords that represent "Industry 5.0" and "Work". Because it has some variations, Boolean indexes "AND" were used to connect the identified groups and "OR" for synonyms between groups. The research has a time cut of 2018 because in this year scholars began to disseminate the term Society 5.0, giving rise to Industry 5.0 later. The complete research protocol is described in Table 1. 1.

Table 1. Research Protocol

Search Term (Title, Abstract or Keywords)	**Group 1 (Industry 5.0)** ("Industr* 5.0" OR "Fifth Industrial Revolution" OR "5th Industrial Revolution" OR "Human-centric manufacturing" OR "Human-cyber-physical" OR "Society 5.0") **Group 2 (Work)** ("Work*" OR "Employ*" OR "Operator")
Search Strategy	AND among groups
Publication Type	Research Paper, Review Paper and Conference Paper (Considering classification of the database)
Language	English
Search Period	2018-2023

With the application of the research protocol, 330 articles were found in the Scopus database, being a base of great relevance for studies related to manufacturing, industry 4.0, and industry 5.0 [6]. To map all relevant research themes involving the objective theme of this research. However, 32 articles were not available for access as such they were removed from the analysis according to the exclusion criteria. With this exclusion a final portfolio of 298 articles that were used for the analysis.

Considering workers in the context of industry 5.0, automatic research was conducted using NVIVO software, version 12, the algorithm helps to identify the main themes and subtopics involving workers in the context of Industry 5.0 in the portfolio and separated into nodes for analysis. This allows for identifying the direction of research for this topic, directing future research.

3 Themes and Research Drivers

When analyzing the number of publications by year, an increase in publications over the years can be seen: in 2018, 7 articles, in 2019, 20 articles, in 2019, 40 articles, in 2021, 84 articles and in 2022, 143 articles. There are already publications on the themes of this article in 2023: 4 articles. The publication rate of the theme workers in industry 5.0 is increasing within the years analyzed. This makes it important to map the main research areas involving workers and industry 5.0 and future research trends. Figure 1 shows the main journals that are publishing the theme.

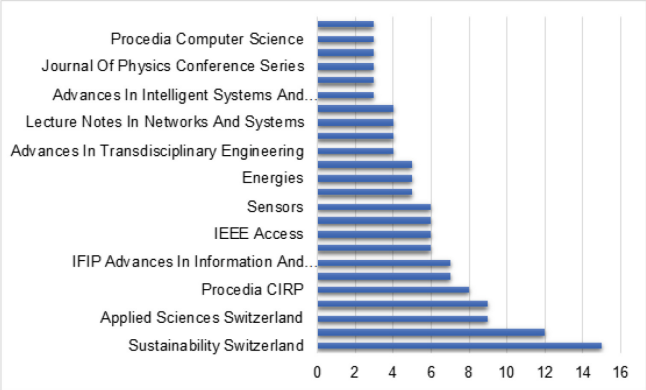

Fig. 1. Main Journals

To help identify the directions in the portfolio, NVIVO software version 12 and its automated coding capabilities were used, the main areas of the review are shown in Table 2.

System: which refers to what are the main research trends in cyber-physical systems that somehow interact with workers. Also in this code, there were mapped other types of information systems that involve industry 5.0 its complexity, and smart systems in which workers' jobs will be inserted. Examples such as human-in-loop systems that support each other in the production process, where people and technology interact more intensely and efficiently in Industry 5.0.
Data: This research driver refers to the big data immersed in the context of industry 5.0 workers, data collection, and analysis for real-time information and decision-making. In this context, it is important to note that workers will need to be able to handle and organize data processing and storage, keeping in mind that data needs to be secure and avoid data overload. This can create a hybrid work environment associating the real and virtual, aided by technologies such as digital twins and artificial intelligence.

Technology: represents the evolution of digital technologies in the context of industry 5.0 to improve communication between worker and machine and further the blockchain for data security and protection and wearable technologies to improve human perception and movements for work improvement. People need to be supported in physically intensive or dangerous tasks by cobots, while they need to control process and cope with high cognitive load tasks

Production: aims to show how the production process is influenced by workers in the context of industry 5.0. Emerging themes such as mass production and product quality, design, and customization show how the nature of the industry 4.0 production philosophy is still preserved in industry 5.0. This is a challenge for industry 5.0 which will still need to focus on mass production and customization with a focus on worker safety and quality.

Table 2. Areas of research and Research fields

Main Areas	Keywords	Research Drivers	Authors
System	Cyber-physical; Physical; Complex; Smart manufactuting; Intelligent; Production.	-The importance of 5.0 industrial systems interacting with and influencing workers; -Research on digital, Complex and intelligent systems in industry 5.0; -Preparation and changes of the production system for industry 5.0.	[11,12,21]
Data	Big Data; Collection; Analytics; Sensor; Processing; Exchange; Storage.	-Role of big data in the context of Industry 5.0; -Research on sensors that help establish interconnectivity; -Data management.	[3,13,22]
Technology	Advanced; Digital; Enabling; Emerging; Innovation; Development; Communication; Smart, Blockchain; Change.	-Impact of digital technologies in industry 5.0; -Main innovations that occur from the concepts of Industry 5.0; -Communication and security technologies;	[1,4,10, 23]
Production	Process; Lines; Systems; Mass production; Quality; Design; Customized products.	-Industry 4.0 changes on mass customization in face of Industry 5.0. -Main challenges for quality and design for Industry 5.0; -Adaptation of workers in production systems in Industry 5.0.	[8,24,25]
Process	Production; Manufacturing; Learning; Design; Decision-making; data.	-Main areas in production for Industry 5.0; -Learning process and design for Industry 5.0; -Data management and decision making for the process;	[8,25,26]
Human	Factors; Workers; Operators; Resources; Intelligence; Beings; Intervention;	-Humans and workers in the context of Industry 5.0: ethics, behaviour, competences, labour and legal rights, ways of working and changing social standards; -Future Intelligence and Skills and necessities for health for workers; -Impact of the acceptance of technology in the face of Industry 5.0.	[21,28,30]
Work	Human workers; Working environment; Future Work; Working conditions.	-Future upgrades for Workers and Benefits in Industry 5.0; -Evolution of work in Industry 5.0; -Technology of Worker and Industry 5.0 Symbiosis;	[5,27,29]

Process: aims to show how industry 5.0 is operating. The main trends are manufacturing and production in general, but there are also trends for learning, design, education, business, data, innovation, natural language, and decision-making. This shows how industry 5.0 can cover more areas than industry 4.0 and implies that future industry 5.0 workers will need to upgrade their skills to meet these needs for developing new processes, avoiding waste, and adding value to the overall process.

Human: research trends are perceived for Human factors, Human workers, Human operators, and Human resources, showing the synergy between humans and digital technology and research on human needs, body care and mental health, capabilities, skills, and training. A future framework of new work profiles that reconciles people and machines is needed to increase production efficiency and reduce possible unemployment.

Work: the main themes are the future of work in industry 5.0 and how it will evolve. The main research trends are the improvement of working conditions, the working model and environment, and how human workers are immersed in this change. Future job upgrading and workers' experiences are key factors to guide the change to thrive in the industry.

To summarize, workers in the scheme of industry 5.0 will have to be prepared for changes in the workplace and how these jobs will handle digital technology. Primarily workers will be needed to work with a large amount of data generated by Big Data and there is a worry about how these data can be processed and turned in adding value to the process in contrast to adding waste. Workers will need to develop competencies to understand the digital system failures and breakpoints to be able to adapt the technology to the real needs and not the opposite of being adaptable to the technology.

4 Conclusions

The objective of this article was achieved with the help of a systematic literature review assisted by an automatic search in a portfolio of 298 articles, resulting in 7 areas containing one of them guiding research themes about the worker inserted in the context of Industry 5.0. The main themes indicate that it will be necessary that workers develop skills to work together with machines in production projects, and process large amounts of data from Big Data to understand the whole production system. Another trend of industry 5.0 is to maintain the philosophy of customization and mass quality with high productivity and for this it will be necessary to include the worker in its production system, allowing the adaptation of these systems to the worker. Finally, it also points to a trend in the interaction of technologies with workers in an environment of symbiosis to strengthen and improve human work full-time. The codification of the guiding research themes presented in this article may stimulate research in the area, improving the quality of life of workers, and stimulating the qualification and adaptation to new models of work and jobs consciously and sustainably. In addition, this article points out that the implementation of industry 5.0 in line

with the guidelines of society 5.0, placing the worker as the protagonist of the process, can add value in their operations to reduce waste, allowing an increase in competitiveness in organizations and improvement of processes. To conclude, suggestions for future work can be pointed out as trying to identify in each of the 9 main areas involving workers in Industry 5.0 what are the specific challenges in the context of digital transformation. With this, researchers can try to address the other areas of knowledge pointed out in the bibliometric review and investigate with the help of case studies in the practical environment

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The Well-Being of Workers in Lean Manufacturing Work Environments

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Abstract. Lean philosophy has been widely introduced in many manufacturing and service industries, allowing for increased operational gains and creating a relationship between the work environment and the workers' well-being. This study aims to understand the relationship between Lean and workers' well-being on a shop floor. A questionnaire based on the Job Demands-Resources (JD-R) model was conducted in an industrial company in Brazil, and a total of 165 responses were collected. Through an exploratory factor analysis (EFA), eight factors were identified (soft Lean practices, Lean training, the pace of work, small group problem solving, interdependencies, problem-solving work demands, engagement and exhaustion). Posteriorly, a cluster analysis allowed us to identify 3 distinct groups in the sample, cluster 1 – includes those employees with a high level of engagement and exhaustion: cluster 2 – employees with a moderate level of engagement and exhaustion; and cluster 3 – employees with a low level of engagement and exhaustion. Additionally, using multiple linear regression analysis, it can be concluded that soft Lean practices (0.46) and the pace of work (−0.23) are the variables that most influence the engagement, and the same can be observed regarding exhaustion, where soft Lean practices (−0.36) and pace of work (0.40) also present statistically significant results.

Keywords: Lean Manufacturing · work environment · employees' well-being · occupational health

1 Introduction

The current globalized and dynamic environment forces organizations to review their production systems. In this scenario, Lean is essential in increasing organizations' performance [1]. In recent years, several studies on Lean Manufacturing have been published [2–5].

A relationship that has more recently begun to be explored is the relationship between Lean implementation and worker well-being; for example, early research conducted in Lean environments revealed that some of the demands of work, such as high work pressure, emotional demands and role ambiguity could lead to weariness, exhaustion,

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and health problems [6, 7]. Although these early studies have produced a long list of possible consequences for the well-being of workers, knowledge on the topic still needs to be improved as indicated by recent research [8].

Although implementing Lean usually translates into operational gains, these gains in productive performance can be hampered by work characteristics and the work environment itself [9]. Parker [10] and Jackson & Mullarkey [10] argue that implementing Lean Manufacturing negatively affects some work characteristics, such as work autonomy, worker participation in analysis and decision-making. On the other hand, Seppala & Klemora [12] argue that some workers demonstrated satisfaction with the work environment after implementing Lean.

Some authors present Lean as a socio-technical system [13–15], which, consequently, opened the door to discussions about the human dimension (soft skills) and their interactions with the technical dimension (hard skills). However, some authors argue that there is still a need to do more research on the human dimension in the Lean environment, especially regarding the impact on worker well-being [16, 17].

In conclusion, the well-being of workers is an essential factor in Lean management, but empirical evidence still needs to be provided to support the relationship between these two concepts [5]. Considering this scenario, understanding Lean's relationship with workers' well-being can add value to work environments and increase organizational gains.

Therefore, knowing the relevance of employees' well-being in organizations, it is important to assess how employees answer to using Lean. The research objective of this study is to investigate the relationship between Lean and the well-being of workers. For this, a review of the literature review was conducted and an empirical study was designed. Subsequently, through statistical analysis of the data obtained through a questionnaire, we present and discuss the results that analyze workers' perceptions about their well-being in a work environment with Lean implemented.

2 Lean Manufacturing and Its Relationship with the Human Dimension

Since the publication of the work by Womack et al. [18], the Lean concept has evolved continuously. Hines et al. [18] argue that the distinction between Lean thinking at the strategic and operational levels is crucial to understand Lean, Alves et al. [20] suggest that the success and sustainability of the Lean transformation are linked to the existence of an organizational culture focused on a collaborative environment that adds value to the company's deliverables. Bhamu & Sangwan [21] argue that the successful adoption of Lean in any company depends on how well the organization started implementing this philosophy (technical skills and social skills). Psomas & Antony [22] complement this view by mentioning that several studies indicate that both the time of implementation (how Lean is introduced to workers) and the post-implementation context (e.g., a hostile environment with stressed workers or a context with high engagement levels) are essential to achieve the expected results.

2.1 Worker's Well-Being: The JD-R Model

According to Bamber et al. [23], the well-being of workers is related to happiness in the work environment, occupational health and good relationships. Several studies in the last decades have demonstrated that work characteristics can impact the well-being of workers [6, 7]. The JD-R model proposed by Demerouti et al. [24] is usually used to explain how the organizational environment impacts employee well-being and performance. The model integrates earlier models of work motivation and job stress, such as the two-factor theory [25], the job characteristics [26], demand–control [27], and effort-reward imbalance models. This model is widely used in Lean research contexts [8, 28, 29].

Since the seminal work in 2001, the model has taken hundreds of empirical studies to mature and has become highly popular among researchers. The following points can explain the reasons and assumptions for that popularity: i) the JD-R model assumes that employees' health and well-being result from a balance between positive (resources) and negative (demands) job characteristics. The model does not restrict itself to specific job demands or job resources. The JD-R model describes the existence of two distinct psychological processes that are present and co-occur in all professional environments: burnout and motivation; ii) the JD-R model is very flexible and can be tailored to a much wider variety of work settings (e.g., manufacturing, transport or academia); iii) the JD-R model is heuristic in nature and represents a way of thinking about how job (and personal) characteristics may influence employee health, well-being and motivation. This implies that even if the two studies show no overlap in terms of the study concepts, they could still be based on and test the same assumptions of the JD-R model.

Job demands are job aspects that require sustained effort and are, therefore, associated with physiological and psychological costs [24, 31]. Job demands include work pressure, heavy workload, role ambiguity, and job insecurity. Job resources refer to aspects of the job that help reach work-related goals, reduce job demands and the associated costs, and stimulate personal growth and development [24]. Examples of job resources are regular feedback, training, mentoring, coaching, and career development opportunities.

The current version of the JD-R model, which inspires many researchers, proposes that high job demands lead to strain and health impairment (the health impairment process), and that high resources lead to increased motivation and higher productivity (the motivational process) [8]. Managers use the JD-R model to predict employee engagement and employee burnout.

2.2 Connection Between the Work Environment, Lean Manufacturing, and Worker Well-Being

In 1996, Jackson & Martin [32] hypothesized that management practices associated with Just In Time (JIT) impact the nature of work and that the content of work, in turn, influences psychological outcomes. In 2012, Hasle, Bojesen, Jensen & Bramming [9] demonstrated that the characteristics of the Lean philosophy were divided between context, implementation, and practices, whereas the characteristics of work design were rewritten according to the work environment and the perception of worker well-being within the work environment with the Lean philosophy implemented. In 2013, Longoni,

Pagell, Johnston & Veltri [33], carried out a complete study of the effects of Lean both on worker health and safety and on the performance generated in this work environment, claiming that measuring Lean as just a technical practice, without analyzing the human resources, can lead to insufficient conclusions for the topic. In 2018, Huo & Boxall [28] related job characteristics and problem-solving tasks in a Lean environment to analyze which factors influence worker engagement and exhaustion and how these factors interact with each other. The job characteristics studied were: the pace of work, dependence between tasks and worker autonomy in problem-solving tasks. The authors' findings suggest that the impact of Lean on workers' well-being depends on how the manager enables workers to be involved in decision-making.

In 2019, Beraldin, Danese & Romano [8] investigated the relationship between JIT workloads, soft Lean practices (SLPs) and problem-solving demands to analyze whether they jointly influence worker well-being regarding engagement and exhaustion (the authors did not study the relationship between engagement and exhaustion). The study examined whether soft Lean practices could significantly impact worker engagement when exposed to more demanding conditions related to JIT and problem-solving activities. This is because soft Lean practices provide adequate resources to properly carry out work activities under more intense conditions. The authors conclude that soft Lean practices act as resources to increase engagement and reduce exhaustion. Still, on the other hand, just-in-time demands act as an obstacle, reducing engagement and increasing exhaustion. To validate the results obtained previously, it is necessary to replicate the model in different contexts from those already studied – as has been proposed by Beraldin, Danese & Romano [8] for future studies.

3 Methodology

The literature review allowed us to identify the factors that influence the well-being of workers in the Lean work environment. It is therefore proposed to replicate the study developed by Beraldin, Danese & Romano [8] in a new context (a Brazilian multinational industrial company that has been implementing Lean Manufacturing for years).

Data was collected from shop floor workers in a single location, involving workers from different functional areas such as production, maintenance, and industrial processes. This approach provided the necessary variability to investigate the topic, avoiding the effects of possible doubts that could compromise the study's validity. The questionnaire used was the same that Beraldin, Danese & Romano [8].

The constructs were translated into Portuguese and were pre-tested and validated with the company's quality manager to verify if all questions were easy to interpret. Minor adaptations were made to facilitate the understanding of the issue for the target audience. For each item of the constructs, respondents indicated their level of agreement on a seven-point Likert scale, ranging from 1 (strongly disagree) to 7 (strongly agree). Survey data was collected in April 2021, and no responses were discarded due to missing values.

4 Results

This section's main objective is to present the study's results resulting from the statistical analysis of the data collected through the application of the questionnaire to the shop floor workers. First, a characterization of the sample profile is made using descriptive statistics. In the second phase, an analysis of the main results of the investigation is carried out.

4.1 Sample Characterization

The final sample includes 165 respondents. Regarding gender, the distribution of responses was not balanced, with only 7.3% female and 92.7% male. Regarding the age of workers, 18.2% of workers are under 30 years old, 29.7% are between 31 and 40 years old, 38.2% are between 41 and 50 years old, and 13.9% are over 50 years old.

4.2 Data Analysis

Exploratory Factor Analysis
Due to the exploratory nature of this study, it was decided to carry out an exploratory factor analysis (EFA) using the SPSS software (Version 28). The final solution was obtained by applying the principal components method, using the varimax rotation method, with items with coefficients lower than 0.45 being suppressed. To verify if the sample was adequate, the KMO and Bartlett test was used; both presented values that allowed us to conclude that the factor analysis was adequate for the sample [34]. Table 1 shows all the factors that resulted from the EFA, the average for each factor and corresponding Cronbach's alpha values ($\alpha > 0.70$).

Table 1. Exploratory Factor Analysis results

Factor	Designation	Average	Cronbach Alpha (α)
1	Soft Lean Practices (SPL) – 19 items	5,62	0,96
2	Exhaustion (Ex) – 4 items	2,97	0,88
3	Lean Training (LT) – 3 items	4,80	0,91
4	Pace of Work (PW) – 3 items	4,18	0,90
5	Small Group Problem Solving (SGPS) – 3 items	5,34	0,82
6	Interdependencies (ID) – 4 items	5,00	0,77
7	Problem-solving work demands (PSWD) – 4 items	5,13	0,70
8	Engagement (Eng) – 3 items	2,32	0,72

Cluster Analysis
The cluster analysis was based on the factors resulting from the EFA. The cluster analysis

was conducted using hierarchical analysis and Ward's method, resulting in 3 clusters. Before analyzing the workers' perceptions, the Tukey HSD test was performed to verify if there were similarities between the clusters within each factor and if no similarities were perceived. As mentioned before, the three distinct clusters present different levels of engagement and exhaustion. With the conclusion of the cluster analysis, we proceeded to characterize and evaluate the factors already presented that most influence the workers well-being (or not) in a work environment with Lean implemented.

Cluster 1 includes the employees who demonstrate the highest levels of engagement and exhaustion in relation to the other clusters. It was found that factor 1 – Soft Lean practices (average of 6.36) and factor 5 – Small Group Problem Solving (average of 6.33) are the factors with the highest values. Other factors that present moderate values are factors 3 – Lean Training and 5 – Interdependencies, with averages of 6.01 and 6.02, respectively. The factor - Pace of Work - has the lowest value (average of 4.61).

Cluster 2 presents more moderate results in all factors compared to the other clusters. The highest perceived value is in factor 5 – Interdependencies (average of 5.04), with two other factors with very similar results, factor 1 – Soft Lean practices and factor 6 – Problem-Solving Work Demands (averages of 4.92 and 4.91, respectively). The factor with the lowest value is factor 3 – Lean Training (average of 3.79).

Cluster 3 has the lowest level of engagement and exhaustion compared to the other clusters. It is possible to notice that factors 1 and 5 – Soft Lean Practices and Small Group Problem Solving also present high values for this cluster (averages of 6.06 and 5.79, respectively), but there are two factors with values much smaller when compared to the other clusters, being factors 6 – Interdependencies (average of 3.44) and 4 – Pace of Work (average of 3.28).

Table 2. Impact of each factor on each cluster

Clusters	Average of SPL	Average of LT	Average of PW	Average of SGPS	Average of ID	Average of PSWD
1	6,36	6.01	4,61	6,33	6,02	5,75
2	4,92	3,79	4,31	4,49	5,04	4,91
3	6,06	5,33	3,28	5,79	3,44	4,71

Table 2 presents the average values of workers' perception of each construct in the different clusters. Finally, a Kruskal-Wallis test was performed to confirm whether the cluster results were statistically different. The test showed that the sample means of each factor are different between the clusters. Furthermore, the null hypothesis is rejected for all the variables.

Multiple Linear Regression

Multiple linear regression was performed to verify how the factors extracted from the EFA influence employee engagement and exhaustion levels. When analyzing the results of the multiple linear regression of the engagement variable, the R^2 indicates that the independent variables can explain 20.40% of the variance. Regarding the exhaustion

variable, R^2 indicates that the independent variables can explain 34.00% of the variance. The Soft Lean practices and the Pace of Work are the only statistically significant factors. When analyzing the standardized coefficients, it can be concluded that Soft Lean practices (0.46) and the Pace of Work (−0.23) significantly contribute to engagement, and the same can be observed about exhaustion, where Soft Lean practices (−0.36) and Pace of work (0.40) also present statistically significant results.

5 Discussion

The EFA resulted in the identification of 8 factors, and the cluster analysis identified 3 clusters: cluster 1 being constituted by 51 workers (30.9%), cluster 2 by 79 workers (47.9%) and cluster 3 by 35 workers (21.2%). With the results obtained, each cluster was characterized: cluster 1 – includes workers with levels of engagement and exhaustion, cluster 2 – includes workers with moderate levels of engagement and exhaustion and cluster 3 – includes workers with lower levels of engagement and exhaustion. As most workers are in cluster 2 and cluster 1, this indicates that the majority of the workers of this multinational have moderate to high levels of engagement and exhaustion. This diagnosis aligns with the results presented in the study by Hopp [35], indicating that Soft Lean practices are perceived differently among different groups of workers. It should be highlighted that cluster 1 has a greater number of workers with higher academic qualifications. There seems to be some relationship between educational level and perceived levels of engagement and exhaustion. The Lean training to which workers are exposed in cluster 1 appears to be more adjusted to their needs than in workers in the other clusters (2 and 3). There seems to be some need to better adjust Lean training according to the target group.

In cluster 3, two characteristics stand out: more than half of this cluster corresponds to workers over 40 years of age and with more than 20 years of work experience. That is a possible negative correlation between age, working time, and the worker's engagement level and exhaustion. This confirms what Giardelli et al. [36] emphasized, that the more age and years of experience in the company, the lower the engagement and exhaustion. Considering the JD-R model, the relationship between resources (Lean Soft practices, Small Group Problem Solving and Lean Training) and demands (Interdependencies, Pace of Work, Problem-solving Work Demands) is unexpected. Therefore, it recommends reducing demands, especially interdependencies, and maintaining and/or further increasing resources, especially Lean Training.

6 Conclusions

With the analyzes presented, the study demonstrates the existence of a relationship between the well-being of workers and the use of soft Lean practices at work, but this does not occur equally over time with all workers since, for longer-lived workers, the level of engagement tends to decrease [36]. This research can be used as a reference for companies that want to reach higher levels of performance using Lean without negatively affecting other aspects, such as the well-being of workers, making its implementation sustainable.

The implementation and support of Lean is both a technical and operational task. This result converges with the JD-R model [31], which argues that resources available directly influence workers' engagement and that work demands influence exhaustion. Therefore, it is essential to monitor the level of employee engagement and exhaustion and diagnose in advance if they are adequate to the objectives of the Lean methodology.

This study complements the study by Beraldin, Danese & Romano [8], which has as a limitation the collection of data in a single manufacturing company, bringing to the literature the diagnosis in another context, and with this, directing future research to the topic studied. This relationship has not been reviewed by Beraldin, Danese & Romano [8]. The diagnosis to the organization studied tells us that the demands are much higher than expected for the workers' well-being. There is a need to mitigate lean demands (e.g., through more training and identifying which tasks could lead workers to feel exhausted and less engaged - the elimination of those tasks can be achieved through the introduction of technological tools, especially for the most physically demanding jobs). In future studies, it is intended to intervene in a practical way in the variables that unbalance the relationship between the demands and the resources arising from lean management to result in greater commitment and less exhaustion on the part of the workers involved.

Some limitations to this research can be identified: we did not address all the characteristics of the company's work environment, and the sample size is limited. Despite the limitations, we were able to contribute to increasing knowledge in lean manufacturing and well-being, as well as carrying out a diagnosis of the organization in question to make it more sustainable.

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Human in the Data-Driven Zero Defect Manufacturing Loop: Case Examples from Manufacturing Companies

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Abstract. Data-driven Zero Defect Manufacturing (ZDM) system gathers and organizes data from different sources, integrating and analyzing the data using different tools, with the purpose to react on potential quality issues before they happen with adequate levels of data accuracy and precision. This paper discusses the role of humans in the data driven ZDM loop, considering the context of four manufacturing companies, from the EU H2020 project DAT4Zero which has also funded this study. These companies represent distinct manufacturing environments, each with specific industrial challenges and requirements, which were studied to map, analyze, and exemplify the potential role of humans in the data driven ZDM framework in real manufacturing environments.

Keywords: Zero defect manufacturing · Human in the loop · Quality control

1 Introduction

Zero Defect Manufacturing (ZDM) is among the application areas with high potential to benefit from digitalization through the application of enabling technologies, smart products, and smart processes in manufacturing [1]. Among others, in-line data gathering, data monitoring, and advanced data analytics tools and methodologies offer many new opportunities to ZDM [2]. However, digitalization doesn't equate with the elimination of the human element from the manufacturing shopfloor. On contrary, the skilled workforce (e.g., operators, engineers) remains a critical resource for activities requiring flexibility, customization, and uniqueness, namely identifying the root causes of problems, solving them, and driving continuous improvement efforts [3]. With the recent Industry 5.0 report of EU commission [4], human-centric manufacturing is now even more emphasized. Human-centricity implies that the skilled and flexible workforce will play a key role in decision making [3], collaborating with the systems.

The literature has reached some maturity with regards to digitally enhancing the human abilities, skills, and roles in manufacturing by utilization of enabling technologies

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over the past decade Nevertheless, the role of humans in ZDM hasn't received much attention, and is considerably under-researched, requiring further exploration [5–7]. While the human aspect is largely neglected, manufacturing quality is in fact largely impacted by the human-in-the-loop [6], especially with their knowledge, flexibility, and resilience capabilities to handle the unexpected events (e.g., delays, disturbances). This paper aims to contribute to narrowing the current gap on investigating and understanding the human role in ZDM and discusses the role of humans in emerging data-driven ZDM paradigms. The study was conducted as part of an ongoing EU H2020 project, designated DAT4Zero, that focuses on developing a digitally enhanced quality management system. Case studies are presented to illustrate the human role in the digitally enhanced ZDM loop.

2 Methodology

As the researchers have been involved in the DAT4Zero project use cases actively, this study applies action research methodology, analysing and evaluating the change, and reporting the outcomes [8]. Several distinct use case companies have been part of the project with the common aim to develop a digitally enhanced quality management system, but with various types of contexts, requirements, interest, and hence involvement of humans in the processes. During the project, the researchers have conducted site visits and online meetings, planned, and coordinated the activities, identified the requirements, as well as contributed defining and testing the solutions. Collected data was transcribed, analysed, and visualized through appropriate diagrams and flowcharts, and further validated by the use case partners.

3 Data-Driven Zero Defect Manufacturing

ZDM paradigm aims to avoid or eliminate defects through a set of strategies, tools, resources, and control rules [6]. Psarommatis et al. [5] categorizes four ZDM strategies; detection, repair, prevention, and prediction. While detection and repair strategies focus on eliminating the defects caused by products and process parameters, prevention and prediction strategies go beyond by focusing on avoidance of defects before they may happen. These latter strategies take a proactive approach to predict defects according to process and product conditions and avoid the occurrence and propagation of deviations in conditions (e.g., product dimensions, machine parameters) along the process chain [9]. According to [6], ZDM strategies may focus single or multi-stage processes, can be product, process, or people-centric, and may address strategic (e.g., supply chain design), tactical (e.g., quality inspection methods) and operational (e.g., product and process deviations) level effects and decisions.

Enabling technologies offer a myriad of opportunities to advance ZDM and create a digitally enhanced data-driven ZDM paradigm as summarized in the literature reviews of [6] and [5]. As a starting point of data driven ZDM, detection of product and/or process deviations as well as their correlation with defects can be further advanced with implementation of sensors, IoT, that can enable continuous collection of data from equipment, processes, and products. Such continuous data acquisition enables advanced analysis of

process through big data and AI-based or simulation-based algorithms, providing more precise description of links between process/product deviations and defects. With such data-driven knowledge, process conditions can be monitored, and defects can be predicted. Consequently, data driven ZDM consists of continuous ***data acquisition*** from processes and products through sensors and IoT, ***management of acquired data*** from various sources through advanced ICT solutions, ***data analysis and modelling*** to describe and predict causal or logical links between deviations and defects through advanced algorithms and tools (e.g. simulation), and finally ***decision making*** as a feedback control on deviations to avoid defects.

4 Human in the Data-Driven ZDM Loop

The advance of ZDM cannot be fully achieved solely by integration of digital technologies to create data-driven control loops. The human component should be considered too in order to obtain new insights and improvements in manufacturing quality [5], as well as to overcome the shortcomings of the human abilities in defect detection, especially in human-driven quality inspection [10]. In Industry 4.0, as with the previous industrial revolutions, the focus has been on the emerging technologies. However, with Industry 5.0, the focus is on the role the human operator has in manufacturing and consequently it is important to consider how humans may contribute to the advancement of data-driven ZDM. This can be done mainly in two ways: (i) by providing contributions to one or several stages of data acquisition, management, analysis, and modeling and (ii) by taking decision making roles as empowered humans.

4.1 Human as a Contributor to Data Acquisition and Analysis for ZDM

Humans can help capturing and yielding more data from the shop floor in addition to what is accessible by means of information systems that support processes, machines, and robots. This can be achieved by their knowledge [11], or by the help of data capture technologies. For example, the operators can provide the knowledge and complex information about failures, which are difficult to detect with sensors [12]. Direct sensing of data can be achieved by sensorized AR wearable devices that can acquire information automatically as discussed in [13]. The role and contribution of humans in data analysis and modeling largely rely on their experience and knowledge to provide critical insights that otherwise could not be captured by digital tools. For example, engineers and managers may provide contributions to analysis and modeling of ZDM strategies [7]. With the help of explainable AI algorithms and reinforcement learning, humans can also contribute to re-designing the collaboration processes between humans and algorithms to improve the quality. For example, operators can teach the robot new paths to carry out quality inspection through ML [14].

4.2 Empowered Humans in Decision Making for ZDM

The decision-making autonomy of humans can be empowered by digital technologies, along with their abilities to make effective and flexible decisions [15]. Humans with

their respective roles influence or make ZDM-related decisions at strategic, tactical, and operational levels. When it comes to strategic level decisions, managers play a significant role in defining the ZDM vision and achieving what the customers want [7]. At the tactical level, humans can decide the quality aspects of an automated control system. At this level, the engineers take part to avoid systematic errors and identifying the root causes of defects, as well as investigates how to incorporate digital tools to improve the efficiency of quality control [7]. At the operational level, digital technologies can especially support and empower the operators in quality control and verification tasks. Augmented Reality (AR) in combination with process mining and machine learning technologies provides significant opportunities to assist operators in quality verification. Besides sensing, capturing data from processes, and analyzing the data retrospectively, it can assist operators in work performance by digital instructions, as well as provide automated quality verification functionalities, as shown in [13].

5 Case Examples from DAT4Zero Project

To better illustrate concrete cases of how human operators can be embedded into ZDM production cycles, we present case examples from the DAT4.Zero (D4Z) project. The D4Z project is a Horizon2020 project (https://dat4zero.eu/) aims to develop a digitally enhanced quality management system. D4Z builds on data acquisition, management, analysis, and modeling/utilization layers. The data acquisition and management layers generate, gather, and organize the data from shop floor resources, processes, and products, through distributed multi-sensor networks, and data integration technologies. The data analysis and modeling layers processes, simulates, and utilizes the data to support developing strategies, making effective decisions, and feedforward control mechanisms to contribute towards the achievement of ZDM in smart factories and their ecosystems. Several distinct industrial pilot companies are involved to develop and demonstrate this data-driven quality management system as discussed in below sections, along with aspects of human in the data-driven ZDM loop.

5.1 Case Example 1 – ENKI

Brief Case Description. ENKI is a producer of one-of-a-kind customized micro-intravascular catheters, high value single-use products that find applications in oncology, angiology, angiography, angioplasty. The products have extremely tight tolerances on the diameters of the microtubes and hence strict quality control requirements in the processes to avoid defects and waste. The critical processes to monitor and control include the extrusion of the tubes, and assembly.

The D4Z System and Loop. The data driven ZDM system should firstly acquire data about the parameters of the extrusion process (e.g., temperature of the cooling bath, inner diameters of the tubes, hoppers parameters) and assembly processes important for quality monitoring and control. This is achieved by sensors; however, the accuracy of inline measurements is a challenge and should be ensured. The data is then managed and analyzed by analytical methods to form, track, and understand the insights of the fault causes and conditions, coupled with an automated fault detection system. This will allow developing efficient mitigation and control strategies.

Humans in the Data-Driven ZDM Loop and Decision Making. Operators form efficient mitigation strategies with the help of decision support tools such as fault analysis system dashboards for understanding and labelling fault situations and causes. The dashboards results are generated by transparent machine learning methods to help the operators form new knowledge during use and to allow the users to build trust in the underlying decisions made by algorithms. Tools that are transparent and accountable will play a key role in efficient adaptation of AI-based systems in environments with many empirical based decisions, where operators are responsible for production issues. The operators also detect and report defects in the fault detection system, allowing utilization of their tacit knowledge and experience. Further, the catheter is manually assembled by the operator who is capable to detect and solve autonomously most of the quality issues encountered. The operator conducts visual inspection on a sample of the catheter tubes to detect a wide variety of production defects, including black spots, crooked markings, among others. But human capabilities are limited and due to the nature of the task, errors resulting to misclassification may occur. In DAT4.Zero, operators use a Head Mounted Display (HMD) that provides overlay of digital information over what is physically perceived. The software leverages the camera inputs of the HMD to extract images that are digitally magnified to improve the visual inspection. However, the HMD have additional sensors beyond cameras, namely depth camera, accelerometer, gyroscope, magnetometer, four cameras and a 5-channel audio microphone array. The use of sensor rich device supports the acquisition of numerous additional data streams related to the workflow that assist in establishing a comprehensive work context. As such, the operator is empowered to acquire seamlessly all data in the data-driven ZDM loop for analysis and traceability of the processes, as well as to detect and categorize defects, and to generate inspection reports.

5.2 Case Example 2 - DENTSPLY

Case Description. Dentsply develops and produces high-precision gears for dental applications with components only a few millimeters in size and extremely strict tolerances of a few micrometers, hence high-quality requirements. One of the main quality goals is to reduce the noise created by dental rotary tools with head shaft and chuck as the major contributor components, as this is highly valued by the costumer and user. The critical manufacturing processes include the micro-grinding and micro-milling of the metal components, as well as the assembly of parts to the final product.

The D4Z System and Loop. The data-driven ZDM system aims to integrating and utilizing the data on geometrical product parameters combined with integration of new sensors with focus on process data, in order to investigate and analyze the potential correlations between product and process parameters, and hence identifying anomalies and optimizing the quality control loops for production and assembly with better predictability and visualization of correlations.

Humans in the Data Driven ZDM Loop and Decision Making. The production processes highly involve human operators, especially in managing the machines, offline measurement operations, and the transportation of parts between processes. One operator usually manages 2–3 machines simultaneously and performs off-line inspection

methods next to the machining processes. The product process correlations should be made available to operators, engineers, and management roles to support decision making from strategic to operational levels. In the assembly area, the product variety increases the complexity of the assembly as the operator must use and check the different information for deciding consecutive assembling steps. This requires that the operators need to know many assembling processes, which means an increased probability of errors taking place, ultimately requiring rework. The visualization of the information for decision making processes is key for a "smart operator" to improve productivity, reduce failures and increase sustainability. The main goal of the solution is to reduce the challenges derived from high complexity by digitally enhancing the operator with context driven visualisation of information for improved decision-making during assembling. Mixed reality HMD again can play a critical role here to empower the operator in decision making as well as acquiring more information from processes.

5.3 Case Example 3 – BENTELER

Case Description. BENTELER Automotive Raufoss AS (BAR) is a producer of aluminium structural components and chassis parts, supplied to the car manufacturers. Quality defects are usually a result of issues appear in combination of manufacturing processes including extrusion of aluminum profiles, forming, punching, cutting and machining processes to make a final component before assembly. Critical characteristics and tolerances of the products are monitored at quality gates of production stages to assure the quality of the product at the end of the long value chain.

The D4Z System and Loop. The data-driven ZDM system in this case also aim for developing an inline measurement and adjustment system through utilization of data from processes and products, as a supplement to the quality gates. Data utilization include acquiring data about critical parameters (e.g., positional and dimensional accuracies), managing the data, analyzing and modeling the data to estimate the deviations and improve the process control. By improving the inline process control, critical process parameters (e.g., cooling, temperature) can be adjusted and optimized to avoid defects (e.g., profile twist, geometrical deviations). Additionally, machine learning and Big Data applications are implemented to analyze the historical data and training the algorithms for predicting the product deviations during machining as well as adjusting the processes to avoid the occurrence of defects.

Humans in the Data Driven ZDM Loop and Decision Making. Humans are mainly involved in the decision-making process with their tacit knowledge and experience in this use case. While the dimensional controls of the product are made and reported by a measuring machine, technicians and operators evaluate the results of the reports and take corrective actions. Furthermore, operators have a significant role in forming the fault mitigation strategies in a data driven ZDM loop. In this context, the operator's decision-making ability is empowered by digital tools such as user-oriented dashboards that can provide deeper understanding and classification of fault conditions and fault causes, as well as propose optimal control strategy for fault mitigation. When it comes to providing input to the data acquirement and analysis in the data driven ZDM loop, the

knowledge and experience of technicians and operators about process states and faults can be captured and formalized by additional labelling and comment tools.

5.4 Case Example 4 - FERSA

Case Description. FERSA Bearings designs, develops, manufactures, and distributes high-quality bearing solutions to customers from various sectors such as commercial vehicles, automotive, and agricultural vehicles. The overall quality requirements of the bearings include high precision tight geometrical tolerances, excellent surface quality, and minimum friction. The main production processes include machining of the inner and outer rings, washing, assembling of rings with rollers and cages, and quality controls, including dimensions (e.g., height, outer and inner dimensions).

The D4Z System and Loop. The data-driven ZDM system in this use case aim to avoid the following main defects: wavering raceways and burning due to vibrations and extreme temperature, leading to cracks; waviness harmonic and twist due to dimensional deviations, leading to lost oil and scrap of the part; and dimensional mismatch between inner and outer ring, leading to issues at the assembly stage. The data-driven ZDM strategies incorporate in line data acquisition from machines and processes to identify detailed process parameters such as dimensions of the products (e.g., raceway dimension) and machine controls (e.g., driver speed, driver temperature) through sensors (e.g., accelerators, temperature sensors, watt meter). Managed by the data management solutions (e.g., edge platform, datalake), the data is analyzed to identify and model the correlations between the process parameters and defects. For example, vibration analysis provides a feedback mechanism to identify the failure situation.

Humans in the Data Driven ZDM Loop and Decision Making. The operators makes the process adjustment decisions, which can be empowered by the analysis tools described above. The results of the analysis guide deeper understanding of process status, which can be provided as feedback to make predictive ZDM strategies/policies via visual decision support tools (e.g., dashboard). The operators are hence notified about the anomalies before leading to defects such as burns and out-of-tolerance twists.

6 Conclusion

Case studies indicate that combining the best of capabilities of humans and technology is not only a better way to advance ZDM, but also perhaps necessary. A two-way engagement where human and digital tools complement each other's abilities towards common ZDM goals. With their flexibility and tacit knowledge humans can provide considerable contributions to the data-driven ZDM loop, especially when empowered by technology which should complement the human requirements and expectations, rather than the other way around. Naturally, workstations with manual processes such as seen in assembly operations, require more human intervention and empowerment. Future research studies should generate more knowledge on the human role in ZDM and investigate this topic more extensively.

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Human Factors in the Design of Advanced Quality Inspection Systems in the Era of Zero-Defect Manufacturing

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Abstract. Manufacturing companies around the world are under constant pressure to perform effectively and sustainably. Incidental processes, such as Quality Inspection (QI), are needed to achieve Zero-Defects Manufacturing (ZDM). This study aimed to identify the Human Factors and Ergonomics (HF&E) in the design of advanced automation, QI systems, and ZDM through selected papers and empirical observations. Our presented model is built around the six main dimensions, i.e., top management, manager (project owner), designers, engineers (internal and suppliers), and operators. The commitment of top management, the openness of the manager, the design-friendly nature of the technological system, and the constant updating of knowledge by engineers are important for the success of ZDM. Researchers need to be familiar with cognitive and organisational human factors to align theory with specific cases. Operators face physical and cognitive challenges, and their environment and health must be considered for their successful contribution to the design of advanced QI systems.

Keywords: Zero-Defect Manufacturing (ZDM) · Quality Inspection (QI) · Human Factors and Ergonomics (HF&E)

1 Introduction

Manufacturing companies around the world are under constant pressure to perform as effectively and as sustainable as possible. The current manufacturing landscape is a highly competitive and rapidly evolving business environment [1]. Manufacturing companies should update their strategy to account for the needs of many regional markets in the context of global competition to maintain the rates of existing market share rates and also to approach new markets [2]. Traditional mass producers of goods such as automobiles and CNC machines are moving closer to embracing the Mass Customisation (MC) paradigm in order to maintain their responsiveness and competitive advantages [3]. Serving consumer demands is MC's main priority [4]. But this customer-focused economy also includes traits such as unstable product demand, quick time to market,

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and short life cycles. However, providing customised solutions becomes a means for manufacturing companies to move away from hardware-centric and towards solution-centric [5].

Based on current market needs, manufacturers have encountered a critical challenge that they had never encountered before. The variety of items produced by the manufacturers leaves no time for production optimisation, which was taking place up to this point [6]. As a result, there are many defective parts that are scrapped, recycled or repaired if possible [7]. MC strategy could make the production process unprofitable because it increases the price of the finished products and uses more resources such as energy. In light of the contemporary market and environmental situations, many manufacturing enterprises focus on true sustainability—that is, social, economic and environmental sustainability—in order to survive [8, 9]. Today, the idea of a smart industry is gradually moving away from a technology-driven solution and toward a value-driven one. Human-centricity, sustainability, and resilience serve as the foundation for this value [10]. Modern manufacturing businesses must strike a balance between providing competitive jobs and new goods with innovative materials and customisable alternatives while minimising their environmental imprint. In order to fulfil these qualities, the implementation of the philosophy of Zero-Defect Manufacturing (ZDM) and of enhanced automation for a number of quality control procedures [9, 11]. The ZDM philosophy, also viewed as an emerging paradigm in the domain of quality assurance, attempts to completely eradicate defects in production using all the potential of Industry 4.0 technologies [12, 13]. However, the challenging objective of zero faults requires the fusion of digital technologies with human components, including Industry 4.0 enabling technologies and smart factories [13].

Given that human behaviour has a substantial impact on manufacturing quality [14], the human-centric ZDM method could produce new insights and improvements in quality [9, 11]. Unlike Lean manufacturing and Lean safety that aim to identify and reduce waste in processes [15] and have been criticised for increasing stress or removing human intervention, HF/E focuses on the application of human factors information to the design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable, and effective human use [16]. Numerous studies show that incorporating humans into the production process can boost efficiency, despite the beliefs of recent years that humans should be removed from the production environment to minimise human errors [17]. Businesses must also invest in knowledge and skills if they want to remain competitive, although innovative technology is crucial [18, 19]. Along with correction and compensation, the nurturing of human resources has been added as a third crucial policy under ZDM [20]. However, implementing human-centric methods to ZDM in production systems could be argued is hampered by organisational, psychological, and technological hurdles. The route towards ZDM is made more bearable by acknowledging the varied challenges faced by the different roles, even though these barriers may take different forms for those human jobs in the manufacturing sector [21]. Technology should be used to support people, not the other way around, according to Industry 5.0 [10]. Synergy effects between man and machine will move the industry closer to the ZDM vision by considering people's demands in the development and adoption of new technology.

To our knowledge, a model for estimating human factors in the design of advanced QI systems is missing. Thus, the purpose of this article is to (i) examine human design factors on advanced automation, QI systems, and ZDM, and (ii) propose a model which could be used to estimate such challenges. This paper is structured as follows. Section 2 explains the theoretical background for the creation of this work. Section 3 introduces the theoretical model for estimating the impact of the HF/E on advanced QI systems. Section 4 summarises the scientific and practitioner contribution of the article and presents future steps towards ZDM.

2 Theoretical Background

Historically, QI standards have been left to company interpretation. ISO 17020 and Juran [22] provide simple steps on how QI should be performed, these are (i) interpretation of specification, (ii) measurement of the quality of the characteristic, (iii) comparison between (i) 'interpretation of specification' and (ii) 'measurement', (iv) judgement on conformance, (v) process of conforming items, (vi) disposition of nonconforming items, and (vii) record of obtained data. Furthermore, the Automotive Industry Action Group (AIAG) [23] states that the collection of instruments or gauges, standards, operations, methods, fixtures, software, personnel, environment, and assumptions used to quantify a unit of measure or assess the characteristic of the feature being measured should be included in the consideration. Azamfirei et al. [24] considered both the frameworks and current literature on digital transformation and proposed a multi-layer QI system framework for Industry 4.0. In it, 'resources', 'actions', and 'data' are described. Humans interplay in such framework as operators, engineers, and designers of the specifications, measurement equipment, and quality evaluation. In addition, the commitment of top management is vital for the success of ZDM and its techniques [13]. When dealing with HF/E, the following three factors need to be considered i.e., physical, cognitive, and organisational [16]. Physical, cognitive, and organisational factors as well as challenges change depending on the level of automation the quality system may present [25, 26].

2.1 Physical Ergonomics

Physical ergonomics refers to the physical load and its potential effect on the human body when performing activities [16], in this case the QI actions mentioned above. The most debated subject in physical support in QI involve (i) collaborative robotics (cobots) for joined work and QI, and (ii) in-line lightweight metrology equipment such as Articulated Arm Coordinate Measuring Machine (AACMM).

2.2 Cognitive Ergonomics

Cognitive ergonomics refers to the study, evaluation and design of tasks, tools, environment, and system in conjunction with their interaction with humans and their abilities [16]. Today's challenging time with increasing speed of change, uncertainty, and complexity require new ways of thinking and acting. Good actions can be taken only if we can make good decisions [27]. Stallard et al. [28] estimated visual inspection error for

metal-castings given different training and judgement types, environmental and human factors. Their model included 'human capabilities' (fatigue, health, judgement error, training error), 'environmental impact' (work atmosphere, lightning, noise), and 'defect density'. Since humans are in constant contact with automation for QI, ironies of automation need to be considered as they drastically affect human cognition [29]. The most debated subjects in the field of QI involve (i) human stress [14, 30], (ii) tasks design and human stubbornness, (iii) human-machine interface of in-line inspection tools, (iv) environment consideration, (v) decision-support systems.

2.3 Organisational Ergonomics

Organisational ergonomics refers to the optimisation of social technical systems that include organisational structures, policies, and processes [16]. Relevant topics include quality management, resource management, communications, organisational culture, teamwork, and participative projects, among others. Organisational core values are the basis for the successful implementation of practices [31]. Access to core values is often hindered by stress which, if it is perceived to be too demanding, makes the frontal association areas of the brain shut down. At a manager level, studies shown that high levels of brain integration are related to higher moral reasoning as well as superior performance. At an operator level, in Azamfirei et al. [26] the performance of the manufacturing system was drastically affected by undocumented human interference in the system as operators were stressed in maintaining a level of quality and productivity. Thus, brain integration can be seen as a basis for all kinds of quality management to be successful [14].

3 Proposed Mode

Our interpretation of the literature, together with empirical observations in the field of semi- and fully automated in-line QI, let us create six dimensions of HF/E in the design of advanced QI systems, i.e. (i) top management, (ii) manager (project owner), (iii) designers, (iv) engineers (internal and suppliers), (v) researchers, and (vi) operators, see Fig. 1.

3.1 Top Manager

The commitment of top management is vital for the exit of ZDM and its tools, such as advanced QI systems [13]. Their commitment should be at all stages of implementation, from university-industry collaboration, education, system design, and deployment.

3.2 Manager

Managers are the main responsible for the design of advanced QI systems in collaboration with different entities, such as designers, operators, researchers and internal and external engineers. The openness of the manager is vital for the success of the project. As described in Azamfirei et al. [26], when a pre-existing paradigm is questioned, such

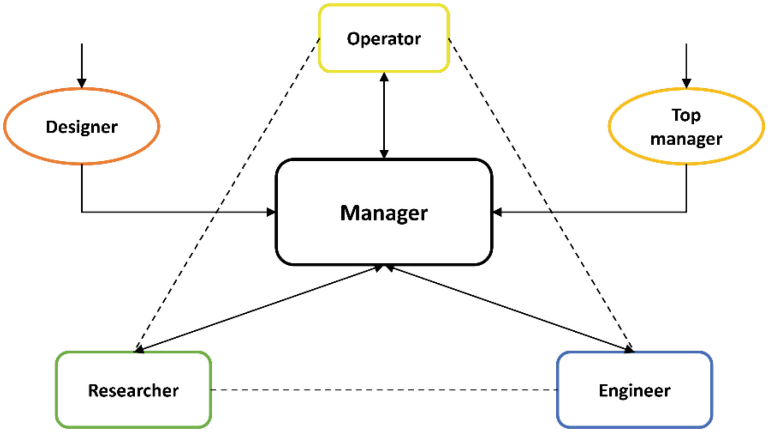

Fig. 1. Proposed integrated model for estimating human factors in the design of advanced QI systems.

as Industry 4.0 and ZDM, managers can experience challenges and paradoxes. It is argued that it is due to the managers being 'stuck' within previous production paradigm in terms of techniques, beliefs, and values. In the case of ZDM, the standardisation of the term in CEN/CENELC-CWA-17918 [32] is still taking place, and some local managers still mistake modern ZDM from 'zero-defect' movement inside Six-Sigma. In our model, we value the maturity of the paradigm and the familiarity of the manager with the requirements and values. Furthermore, management stress is considered. We believe university-industry collaboration and co-creation could ease with such challenges.

3.3 Designer

Designers are responsible for the study, research and develop of ideas for new products and the systems used to make them. Nevertheless, certain organisation might separate 'product design' from 'system design'. Their understanding of the needs and state-of-the-art technologies can be jeopardised by the reality that no system is perfect or free of uncertainties. Certain design parameters can place a level of stress that might hinder the physical and cognitive load. The increased level of customisation together with their corresponding adjustment of processes will require designers to be closer in the loop and have a deeper understanding on the physical, cognitive, and organisation factors.

3.4 Engineer

This category covers both internal engineers and suppliers. They are responsible for the creation of the technological system and its guidelines. Physical ergonomics apply when designing systems that will accommodate the needs of the operators. Cognitive and organisational HF/E apply to this category. The system design must be user-friendly and intuitive for its correct purpose. Additionally, engineers must constantly update their knowledge as technology and paradigms change. Such adaptation may lead to paradoxes, memory fatigue, and stress. Additionally, the correct communication channel is

important for them to receive the right information. Though engineers do not actively participate in organisational ergonomics, their creation will be part of a socio-technological system, thus a holistic picture is needed in co-creating with managers, operators, and researchers.

3.5 Researchers

Researchers represent in this model the source of new knowledge in the changing fields. Researchers may lack a true perception of the state of the manufacturing companies and the use of technology. Their familiarity with cognitive and organisational HF/E is important for the adjustment of theory to specific cases.

3.6 Operators

Operators are challenged by all three HF/E in modern manufacturing systems. They are physically challenged by repetitive, dull and dangerous tasks in an unfriendly environment. The environmental impact and health need to be considered and "calibrated". Not all operators present the same training, judgement and health. Cognitively the stress can shut down their ability to learn and process companies values such as 'zero-defect'. Such shut down can also affect their capability to follow quality instructions. Such physical and cognitive challenges need to be overcome for operators to successfully contribute to the design of advanced QI systems where they will be part of.

4 Conclusions

The purpose of this article is to (i) examine human factors in the design of advanced automation, QI systems, and ZDM, and (ii) propose a model which could be used to estimate such challenges. Selected papers in the field of QI, ZDM, and HF/E were interpreted and used against empirical observations in the design of semi- and fully automated in-line QI systems. To our knowledge, an integrated model of the cause and effect of HF/E in the design of advanced QI systems is missing. Our presented model is built around the six main dimensions that influence the design of advanced QI systems, i.e., top management, manager (project owner), designers, engineers (internal and suppliers), and operators. HF/E affect all the dimensions described and its effect must be measured at the same time to understand the efficiency of the designed QI system. ZDM will require full commitment of the top management to operators for its implementation. Future work will imply computerisation of the proposed model and simulation of different scenarios. Furthermore, questions arise with respect to the exploitation of data for ZDM in terms of safety and privacy, which should be further investigated.

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An Artificial Neural Network Architecture to Classify Workers' Operations in Manual Production Processes

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Abstract. The recent Industry 4.0 paradigm is disruptively changing the manufacturing landscape. Where fully automated settings are not feasible or economically viable, Industrial Internet of Things sensors are gaining traction due to their flexibility and affordable costs. In such a scenario emerges crescent attention to digitizing the human factor. Based on this, this manuscript proposes an integrated digital architecture in which a radio-frequency-based indoor positioning system is adopted to anonymously tag human operators. The highly unbalanced spatio-temporal dataset is fed into a recurrent neural network architecture that classifies without overfitting the manual picking/deposit activities in products' stocking areas of a real and low standardized manufacturing job shop with a performance of 0.93.

Keywords: indoor positioning · manual manufacturing processes · neural network · Operator 4.0 · Industrial Internet of Things · Long Short Term Memory

1 Introduction

During the last years, manufacturing companies have massively embraced the Industry 4.0 paradigm to address data-driven decision-making process rather than relying on industrial supervisors' experience. While modern manufacturing processes are increasingly automated, human workers still play a pivotal role in such environments [1]. Therefore, operators are assisted by Industrial Internet of Things (IIoT) sensors to fully digitize such complex and low-standardized environments. Romero et al. [2] define this human-centric and digital approach as Operator 4.0. Benefitting from this, not only in-plant performances may be quantitatively improved but the working conditions as well. For instance, motion capture technologies and Radio Frequency Identification sensors to track workers' activities during task executions [3,4]. Over the latest years, among the

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positioning digital architectures, Ultrawide-Band (UWB) based indoor positioning systems (IPS) gained a lot of interest due to its promising accuracies in indoor manufacturing systems [5,6]. To achieve a performing process monitoring, digital data is a necessary condition but not sufficient one to monitor and improve in-plant operations. Therefore, deep learning architectures widen their application in manufacturing environments as well [7]. However, no application targets the classification of workers' activities from their spatio-temporal trajectories. In such a scenario, this manuscript proposes an integrated IIoT architecture in which workers' trajectories are gathered by an UWB-based IPS network and automatically fed into an artificial neural network (NN) architecture, long short-term memory-based (LSTM). The proposed architecture classifies operator picking/deposit activities with an F1-score equal to 0.93. As a measure of performance, the F1-score is calculated from the precision and recall of the test dataset. This manuscript is organized as follows. Section 2 outlines the adoption in manufacturing environments of IIoT sensors along with deep learning applications to enhance decision-making processes. The original proposal of this work is the digital IIoT architecture (Sect. 3), validated in a real manufacturing job shop (Sect. 4). Section 5 presents the promising results obtained to classify tagged workers' activities. Finally, Sect. 6 ends this work by outlining the conclusions and further research opportunities.

2 Literature Review

As key enabling approaches of digital transformation, IIoT technologies are rapidly changing manual manufacturing environments. Therefore, data acquired from physical objects are mined by algorithms to develop targeted key performing indicators (KPIs) and monitor processes' efficiency [8]. In such a scenario, IPS represents an opportunity to enhance the visibility of low-standardized productive cycles by dynamically tracking whichever industrial entity. For instance, Darányi et. al. [9] exploited UWB-based spatio-temporal data to assess utilization ratios of shared industrial tools along with their layout geometrical positions. Indeed, while industrial plant supervisors may effectively detect bottlenecks, industrial workers may spend considerably less time searching for assets. A similar target is achieved by tagging materials to develop an UWB-based value stream map [10]. However, there are few applications aimed at equipping human workers with positioning wearables in the process monitoring research area [11]. While IIoT wearables are contributing to digitizing modern industrial settings, deep learning applications are widening their applications to further enhance the manufacturing decision-making process [8]. In particular, recurrent NN aimed at classifying time-series data represents one of the most adopted approaches. A stark example is to leverage LSTM-based NN to predict industrial machines' faults. Consequently, operating costs and downtimes may be reduced [12]. However, while Antonucci et. al. [13] shows the advantages of adopting a NN architecture to predict human motion patterns upon spatio-temporal trajectories, there are no applications in manufacturing environments. With respect to the current trend and limitations, this manuscript proposes in the following Section an

integrated digital IIoT architecture to classify through an artificial LSTM-based NN architecture the operator picking/deposit activities of UWB-based tagged workers in job shop storage areas.

3 Digital IIoT Architecture

To adequately classify the spatio-temporal trajectories of workers, an UWB-based IPS represents the adopted IIoT hardware originally developed through Decavawe modules and is composed of two main components (Fig. 1).

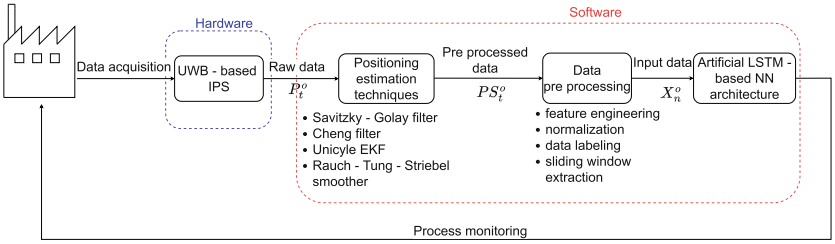


Fig. 1. Conceptual data flow diagram of the developed digital IIoT architecture

On the one hand, the compact and wearable tags, worn by workers on the preferred upper arm, are based on Decawave DWM1001 SoM which integrates a compliant UWB transceiver and a low-power nRF52 microcontroller (Fig. 3 (a)). On the other hand, six anchors (ANs), Raspberry PI 3 based connected to a DWM1001, represent the reference infrastructure of the manufacturing job-shop for the moving industrial resources. The reference network triangulates using the Time Difference of Arrival geometric method the unknown positions of moving tagged operators. Finally, the MQTT protocol enables to remotely access to the IIoT network server. Based on this, Fig. 1 provides a conceptual framework of the developed algorithms to quantitatively predict the manual operations performed by workers during the shift. Since manufacturing job shops are typically noisy environments, the first step of the proposed architecture aims at increasing the consistency of the acquired positioning data. Indeed, $P_t^o = (x_t^o, y_t^o, ts_t^o)$ represents the 2D indoor position bundled with its respective timestamp, assumed by a generic $\boldsymbol{o}$-th worker during the $\boldsymbol{t}$-th timeframe. Upon these parameters, the velocity and orientation over consecutive time frames are trivially evaluated (e.g., v_t^o and θ_t^o). The v_t^o are processed by a Savitzky-Golay filter, which uses the least squares method to fit a discrete set of points to a polynomial curve of degree $\boldsymbol{d}$. Despite this noise reduction, positioning data may still have spikes. Therefore, the Cheng filter eliminates from the spatial dataset any P_t^o whether the absolute deviation of its respective v_t^o and the median absolute deviation of velocities of the $\boldsymbol{o}$-th worker is greater that the expected walking speed of workers. Subsequently, the positioning dataset is further improved with a unicycle extended Kalman filter (EKF) [14]. The last positioning estimation method

adopted is the Rauch-Tung-Striebel (RTS) smoother which performs a backward estimation of the positioning trajectories. After this first step, for clarity, the resulting spatio-temporal dataset is labelled as PS_t^o. Before discussing the functioning of the proposed artificial NN, the PS_t^o follows a pre-processing stage to improve the following learning capabilities (Fig. 1). First, features engineering methods may be adopted to increase the input features of the dataset. For instance, b_t^o is a binary parameter equal to 1 whether the $\boldsymbol{o}$-th worker during the $\boldsymbol{t}$-th timeframe belongs to a particular region of the manufacturing job shop. Therefore, $I_t^o = (x_t^o, y_t^o, ts_t^o, b_t^o)$ represents the set of independent parameters at the $\boldsymbol{t}$-th timeframe. The entire set of input features are normalized and assigned a binary label (L_t^o) according to the available video-based ground truth. In detail, L_t^o is equal to 1 whether the underlying I_t^o is part of picking/deposit trajectory, 0 otherwise. Finally, the last pre-processing method is to divide the entire data set into floating time windows of fixed size J and assign to the last feature the known L_t^o.

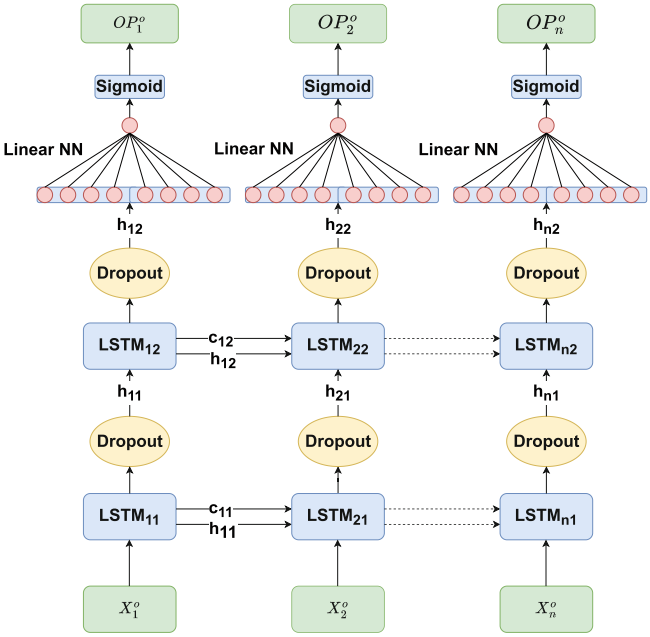


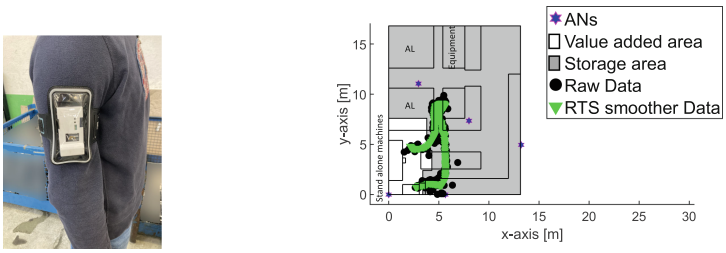
Fig. 2. Developed artificial LSTM-based NN architecture.

The last step of the digital architecture is to feed the dataset into the artificial LSTM-based NN architecture. As depicted in Fig. 2, the implemented artificial NN architecture consist of 2 stacked LSTM cells connected to a linear NN and a Sigmoid activation function. The data set to be processed is divided into N input matrices X that store J I_t^o. During the forward propagation, X_n^o, the previous

hidden state ($h_{n-1,1}$) and the previous memory cell ($c_{n-1,1}$) are fed into the first LSTM cell ($LSTM_{n,1}$) to compute $h_{n,1}$ and $c_{n,1}$. In particular, $h_{n,1}$ is passed to $LSTM_{n,2}$ as input. To avoid overfitting during the training stage, the LSTM cells have dropout capabilities. Indeed, a fixed ratio of randomly chosen neurons are not considered within the training dataset. Then the resulting $h_{n,2}$ is passed to the linear NN that has as many neurons as the size of the final hidden state. The resulting output is processed by a Sigmoid function to provide the binary class probability (OP_n^o) and conclude the forward propagation process. At this point, the back propagation process is triggered to minimize the training error given by the comparison between OP_n^o and the related L_n^o. The first step is to calculate the Binary Cross Entropy Loss (BCE Loss) to define the distance between the output probability and the expected value. To minimize the training error, the NN architecture computes the gradient of the loss function and updates the weights. Indeed, the Adaptive Moment Estimation algorithm reaches the local minima through an adaptive learning rate for each iteration. Finally, this forward and back propagation process is performed on the entire training set for a fixed number of epochs to achieve a sub-optimal BCE Loss.

4 Case Study

The aforementioned digital IIoT architecture is validated in a manual manufacturing job shop that performs manual machining operations for the automotive sector. To achieve a successful experimental campaign, it was explained to final users the clear purpose of this analysis, and involved workers signed a non-binding GDPR module To be consistent with privacy requirements. The target of the experimental campaign is to classify the manual picking/deposit activities occurred in storage areas of such manufacturing job shop. To achieve this purpose, six ANs are displaced at know positions in the ceiling to acquire the spatio-temporal positions of anonymously tagged human workers over the shift (Fig. 3 (b)).



(a) (b)

Fig. 3. Monitored job shop (a) Tag worn by a worker (b) Layout.

In addition, based on the digital architecture requirements, the manufacturing job shop is divided into two areas. On one hand, the value-added area host

two stand-alone machines where workers manually load materials to be manufactured by two automatic lathes (AL). Subsequently to this preprogrammed machining, workers unload finished goods from the stand-alone machines to end the manual productive process in the deburring and rectification workbenches. On the other hand, the storage area groups stock-keeping units where workers pick/deposit finished or raw materials. This scenario is represented by the green spatio-temporal trajectory depicted in Fig. 3 (b). This data represents the input for the data pre-processing stage depicted in Fig. 1.

5 Results

The proposed artificial NN architecture is trained using a number of epochs, a floating window and batch sizes equal to 150, 128 and 64, respectively. The latter parameter determines the number of inputs X_n after which the network updates the weights. Subsequently, a cross-validation of dropout $= \{0.3, 0.5\}$, hidden size $= \{64, 128, 256\}$ and learning rate $= \{0.001, 0.0001, 0.00001\}$ are evaluated in order to find the optimal hyperparameter trade-off. This approach guarantees stability and convergence at a low value of BCE loss, without requiring high computational efforts. After 150 epochs, a dropout of 0.5, hidden size equal to 64 and a learning rate of 0.00001 represent the optimal hyperparameters configuration resulting in a BCE loss equal to 0.0514. Once the artificial NN architecture is trained and validated, the output provided by the network has to be converted into a binary value. To achieve this purpose, it is necessary to set an optimal decision threshold (DT) in the Sigmoid function. This analysis is performed through a class probability ranging from 0.45 to 0.64. Since the dataset is fairly unbalanced, the F1-score represents the parameter to be optimized. In particular, the picking/deposit activities account for 8% of the entire dataset. The optimal DT of the Sigmoid function is equal to 0.6. This DT provides an F1-score for the Class 0 and Class 1 equal to 0.99 and 0.93, respectively (Fig. 4 (a) and (b)).

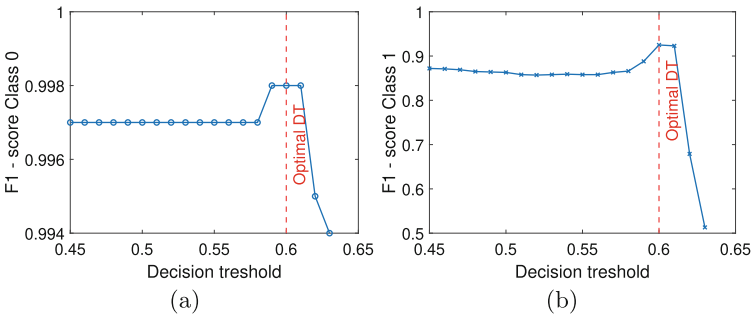
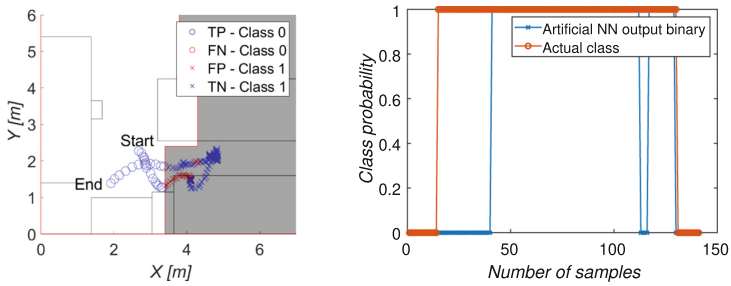


Fig. 4. Optimal DT analysis (a) F1-score class 0 (b) F1-score class 1

To further discuss the performances of the proposed artificial NN architecture, it is relevant to analyze the returned values of precision and recall for both classes in the test set. Considering the 638 instances belonging to Class 1, the NN architecture returns 84 false positives (FP), 554 true negatives (TN), and 6 false negatives (FN). Therefore, the resulting precision and recall are equal to 0.87 and 0.99, respectively. This optimal DT of the Sigmoid function achieves the lowest amount of FP and FN and thus avoiding over and underestimating picking/deposit activities in workers' trajectories. Figure 5 shows the promising local performances of the developed artificial NN on different viewpoints. While Fig. 5 (a) suggests that misclassification errors (e.g., FP) are mainly localized in the boundaries of the value-added area of the manufacturing layout, Fig. 5 (b) shows that the network has a small delay in recognizing picking/deposit activities. To conclude, given the promising performances, the proposed digital IIoT architecture enhances the visibility of low-standardized and unpredictable manual manufacturing settings. Benefitting from such validation campaign, this quantitative approach may be adopted at the end of the working shift to achieve a performing process monitoring by analyzing different KPIs (Fig. 1). For instance, industrial plant supervisors may evaluate the distribution of picking/deposit activities in the storage area and consequently evaluate the distances travelled by tagged human workers to if necessary balance the workload. Therefore, the efficiency of the manufacturing job shop and the social sustainability of workers may be consistently improved.



(a) (b)

Fig. 5. Local performance of the architecture (a) Trajectory of a manual picking/deposit activity (b) Comparison between actual and returned classes

6 Conclusions and Further Research

Exploiting the benefits to digitize the human factor in low-standardized manufacturing environments, this manuscript proposes an artificial LSTM-based NN to classify UWB-based workers picking/deposit trajectories. Benefitting from a hyperparameter and DT optimization, this NN architecture, hardly adopted to achieve this purpose, is distinguished by an F1-score to classify picking/deposit

activities equal to 0.93. Further research opportunities should leverage this validated digital IIoT architecture to monitor the manufacturing job shop through strategic KPIs. In addition, further manufacturing activities should be considered to achieve a multiclass classification of the monitored process.

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The Leadership Role in Fostering an Innovation Culture

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Abstract. Achieving Innovation is a complex challenge, involving or depending on several factors or causes. It is recognised as being crucial to economic growth, creating new industries and tackling societal challenges. There are several tools to measure innovation management but assessing innovation rests a challenge, as current valuation tools still blend results and process indicators. This study is an exploratory and descriptive study of a quantitative nature. It was carried out, in March-April 2021, to companies in the North of Portugal. Data were collected through a questionnaire. The results seem to indicate the main areas affecting innovation culture from the employees' perspective, as well as the relevance of the leadership role in the paradigm shift.

Keywords: Innovation · Innovation Culture · Leadership · Strategy · Values

1 Introduction

Innovation is a complex challenge, involving or depending on several factors or causes. Schumpeter presented it in 1911 [1], as a creative force of capitalism. Since then, the concept evolved and nowadays the basis of innovative transformations is linked with knowledge and entrepreneurial capacity [2], contemplating the process and outcome dimensions [3]. The innovation process encompasses some factors among which leadership [4], internal innovation capacity [5], networks and relationships [6], strategy [7], technology management [8], and culture [9] seem to be the most critical. Culture reflects the adequacy between the company culture and the dynamics of change inherent to innovation. Leadership, the features, and style to stimulate innovation, and strategy, the formation and implementation of the organisation's strategic guidelines [10]. Innovation is created by people and organizations, and for people and organizations, the role of social relations is of primary consequence, bearing in mind that economic relations are submerged and are designed by the previous [11].

It is recognised that innovation is fundamental to economic growth, creating new industries and tackling societal challenges [12]. The Innovation Scoring, (COTEC), the IMP3rove – European Innovation Management Academy (A.T. Kearney GmbH and APRE), the PwC's Strategy& (PwC), and the SPRING Singapore (the Singapore

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Ministry of Trade and Industry Agency) are some of the management innovation tools that we can already find and use. Nevertheless, assessing innovation rests a challenge, as current valuation tools still blend results and process indicators [13]. Also, innovation culture is not contemplated in its plenitude, which undermines the holistic view of innovation [14]. The existing research is a major quantitative approach, and a deeper understanding of the phenomenon is required [15].

This study focuses its research on the relevance of the leadership role in fostering an innovation culture and is composed of four sections. It begins with a literature review, followed by a presentation of the used research methodology. It analyses and comments on the obtained results and, finally, presents the conclusions and suggests directions for future research work.

2 Literature Review

2.1 Innovation and Innovation Strategy

Innovation is the achievement of a new or significantly enhanced product (good or service), process, new marketing method, or a new organizational method in business practices, workplace corporation or outdoor relationships [16]. It progresses across the innovative effort that is established within society and the economy, dynamically involving a panoply of actors [17]. Traditionally defined into four types, innovation is associated with product/service, process, marketing, organization, and business models [12]. However, innovation is not ordinary, almost haphazard to be found in about all organizations [18], and this raises practical questions. Challenged with the topic of managing the "action of innovation" it is crucial to discover a model for action that contemplates the ways and means, as well as the pursued aims due to its impact on the nature of performance [19]. Differentiation seems to be efficient for companies to obtain competitive advantages [20]. Change must be an opening to new solutions and value-added, even if the results are not continually visible and not possible to measure and quantify. In the end, whatever the innovation, it involves a dive into the unknowable [21]. And this intangibility requires the design of tools that help managers monitor the results of their investment since the degree of uncertainty and risk is reduced with a well-defined innovation strategy [22]. Organizations' choice about developing new products or technologies is to respond agilely to rapid market changes [23], while exploiting new opportunities and existing capabilities [24] is related to innovation strategy. Organizations are required to develop various strategies to exploit new opportunities and exploit existing capabilities simultaneously [24], as well as capitalize and equalise mutually exploratory and exploitative innovations to get prime performance [25].

Outlining the innovation strategy objectives organizations want to achieve to gain a competitive advantage [26], the difficulty of implementing the innovation strategy is greater than its design [27]. And, according to the literature, one way to overcome this impasse can be by combining their norms and shared values with the requirement of the strategy [28]. In other words, the effective and efficient implementation of an innovation strategy depends on the match between the innovation strategy and organizational culture [29]. However, many organizations still face the difficult challenges of managing the organizational culture to enable the successful implementation of the innovation strategy

[30]. In this sense, the management of organisational culture should be managed to facilitate the implementation of the innovation strategy [31].

2.2 Innovation Culture

Organizational culture is a framework of usual norms, beliefs, and values that command how organizations consider individuals [32], driving them to choices and decisions [33]. It is related to the norms that members of an organization recognise as their workplace environment, and these norms guide how members act, behave, react, and adapt to accomplish organizational goals [34]. Organizational culture is the mode in that organizational members cooperate between themselves and other stakeholders, being used to differentiate organizations [35] while positively contributing to corporate governance and management [36]. The origin of the organizational culture can come from different sources among which are included the beliefs and assumptions of the founders, and the learning experience of the members of the organization [37]. Founders have the chance to centred strategy and direction at an early stage of the organization [38] and the business strategy and direction are mostly constructed on their operational expectations [39]. Founders may impose their personal experiences and culture on their workers and associates [40]. The learning experience is an additional font of organizational culture, which is a result of the social tendencies and the dynamics of the business environment. Members of the organization may adopt some attributes from the community as well as from the business environment [41].

Innovation culture signifies the shared common assumptions, beliefs and values of organisational members that could enable the product innovation process. It is linked with an organisational culture or climate that incites the employees' innovation capability, allows risk, and supports personal development and growth [42]. It has features that can be observed from five viewpoints: leaders and managers, teams, individuals, environment, and organization [14]. Innovative organizations need people who believe can change the world, can encourage creativity, and can implement teams [43]. Innovative teams play better when generating ideas and disseminating them, trusting each other, helping each other, communicating and can freely think [44]. Individual innovation is the "engagement in innovative behaviours", which involves behaviours correlated to the innovation process [45]. It is primarily an individual decision, attributable to the individual's tendencies and goal orientations. Innovative leaders find innovative individuals and encourage staff creativity [46] [47]. Innovative external relations usually have a variety of internal/external contact points, a giving view of the external environment, a high facility and multiplicity of contacts and ease and quickness of forming collaborations [14].

For the current research, two models were used: i) the ETOILe model, which stands for External links, Team, Organization, Individuals and Leaders [2] and ii) the six Building blocks of innovation, which stands for Values, Behaviours, Climate, Resources, Processes, and Success [48]. Figure 1 presents a set of areas and factors that can enhance or inhibit innovation culture. Leadership is in the centre as it has a *fulcrum* role.

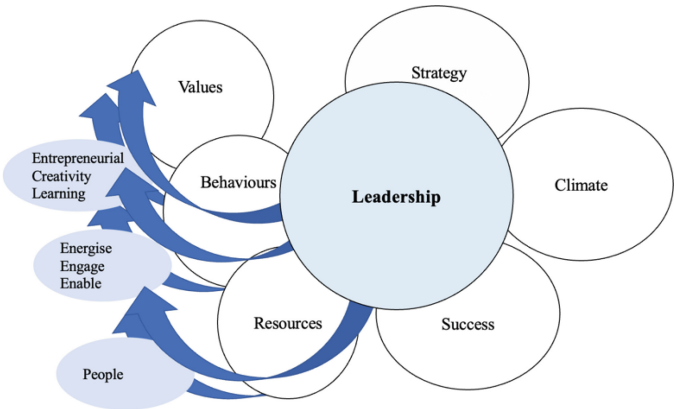

Fig. 1. Areas and factors of innovation culture (own elaboration)

3 Methodology

In companies, there is a recurring problem which is, on the one hand, knowing how to deal with people and, on the other hand, ensuring that the culture is innovative. The result is that, among other things, people are not motivated, do not help each other and are afraid to take risks. In the medium and long term, companies begin to lose competitiveness and, in the limit, disappear from the market. The innovation culture is a complex issue and the methodology to be adopted must consider the company itself, as well as its organizational culture. This study is intended to answer the main question: "How can leadership promote and enhance an innovation culture in an organization?". This requires clear and measurable goals. As a general objective, it is intended to "Understand what main areas influence innovation culture". As specific objectives, it is intended to identify what people value and how behave, how the company look at its resources and communicates its strategy, and how is perceived the organizational climate as well as the success, both from the internal and external perspectives.

To answer the research objectives quantitative research was applied, in March-April 2021, to companies in the North of Portugal. Data were collected through a questionnaire, online, sent by students from the 1st year of the Integrated Systems of Management Master of IPCA, the Polytechnic Institute of Cávado and Ave, based in Portugal.

The questionnaire was built by the researcher considering the literature review and her professional experience. Two models were used: i) the ETOILe model, which stands for External links, Team, Organization, Individuals and Leaders [2] and ii) the six Building blocks of innovation, which stands for Values, Behaviours, Climate, Resources, Processes, and Success [48]. The questionnaire was divided into several variables (including their dimensions) and each of them contained affirmations. Respondents should indicate their level of agreement through a Likert Scale from 1 to 5, being 1 "totally disagree" and 5 "totally agree". The statements were oriented to evaluate the factors perceived by the workers in the following selected variables/dimensions: i) Values (13 statements); ii) Behaviours (13 statements); iii) Strategy (7 statements); iv) Resources (3 statements); v) Climate (12 statements) and vi) Success (7 statements). Questionnaires were sent to the

companies where the students worked and each student gathered 5 answers, for a total of 95 answers. Students were almost from the Quality and Safety Department and tried to reach highly qualified people from different Departments, to get a broader perspective of the theme. This decision was taken because all workers have the potential to add value to the organization in the medium and long term [49].

4 Discussion and Results

The questionnaire was sent to 95 employees from 19 private companies. The response rate was 100%. Statistically examining the answer, 36 questions with high agreement were found (for this it was used the average criterion higher than 3,75 on a 1 to 5 Likert Scale). Regarding Leadership relevance, it is concluded that the main factors that would lead the innovation culture in a company are presented in Table 1.

Table 1. Full set of components proposed for evaluating innovation culture.

Building Blocks	Factors	Survey Questions	Average
Values	Entrepreneurial	We want to explore opportunities and create solutions	4,5
		We desire and tolerate ambiguity when seeking new opportunities	4,1
		When we identify new opportunities we quickly try to put them into practice	4,1
	Creativity	We stimulate new ways of thinking and solutions from distinct angles.	4,3
		Our workplace offers us the freedom to pursue new opportunities.	4,7
		We want to be spontaneous and not anxious to joke at ourselves.	4,6
	Learning	We are good at asking questions in the pursuit of the unknown.	4,4
		We are constantly experimenting with our innovation efforts.	4,1
		We are not afraid to fail, and we treat failure as a learning opportunity.	4,2
Behaviours	Energize	Our leaders inspire us with a vision for the future and communication of opportunities for the organizatio	4,7
		Our leaders often challenge us to think and act entrepreneurially.	4,6
		Our leaders model the right innovation behaviours for others to follow.	4,6
	Engage	Our leaders dedicate time to coach and deliver feedback on our innovation efforts.	4,0
		In our organization, people at all levels proactively take initiative to innovate.	3,8
		Our leaders provide support to project team members during both successes and failures.	4,0
	Enable	Our leaders use suitable influence strategies to help us pilot around organizational blockages.	4,2
		Our leaders can modify and change the course of action when needed.	4,5
		Our leaders persist in following opportunities even in adversity.	3,8
Strategy	Communication	The organisation has a clear and shared innovation strategy, involving employees in its definition.	3,9
		The innovation strategy translates into an action plan with quantitative objectives and targets.	3,9
		The organization has a marketing strategy that supports and values innovation activity	3,8
		The organization monitorizes the external environment, which it uses to define and implement its strategy	4,0
Resources	People	We have committed leaders who are willing to be champions of innovation.	4,3
		We have access to innovation experts who can support our projects.	4,4
		We have the internal talent to succeed in our innovation projects.	4,5
Climate	Collaboration	We have a community that tells a common language about innovation.	3,8
		We appreciate, respect, and leverage the differences that exist within our community.	3,8
		We work well together in teams to capture opportunities.	4,2
	Safety	We are coherent in actually doing the things that we say we value.	4,6
		We question decisions and actions that are inconsistent with our values.	3,8
		We can freely voice our opinions, even about unconventional or controversial ideas.	3,8
Success	External	Our customers think of us as an innovative organization.	3,9
		Our innovation efforts have led us to better financial performance than others in our industry.	3,8
		Our customers think of us as an innovative organization.	4,1
	Entreprise	I am satisfied with my level of participation in our innovation initiatives.	4,0
		We reward people for joining in potentially risky opportunities, nevertheless of the outcome.	4,6

5 Conclusions and Future Research Work

The present study aimed to add knowledge about the main areas that influence innovation culture and how leadership can have a crucial role in fostering innovation culture. Innovation to succeed is crucial but needs an environment where it can flourish, happen, and grow. The study reinforces special attention to entrepreneurial mindset, creativity, and encouragement of continuous learning, as well as communication, collaboration, safety, and success, at both internal and external levels. People are at the centre of the paradigm-changing, being leadership one of the central elements, as it can design and influence organizational culture and strategy, as well as behaviours, through energising, engaging, and enabling, while being willing to champion innovation.

The main limitations are the number and convenience of the sample. Regarding future research, it is expected to test this Framework in an organization and design a tool to evaluate and monitor innovation culture.

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Sustainability

An Exploratory Study on the Implementation of Social Sustainability Practices in Portuguese Industries

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Abstract. Given the growing concern for social sustainability, companies have adopted practices to address stakeholders' pressures and take responsibility for their suppliers. Although the social dimension of sustainability generates interest in academic and industrial communities, most published papers focus their research on emerging economies. This paper aims to address the degree of implementation of social sustainability practices - basic and advanced - in companies located in Portugal. The development of a survey allowed the collection of 142 answers. The findings show that both basic and advanced practices have a reduced level of implementation in the Portuguese industrial context. Regarding basic social sustainability practices, Portuguese industries should stimulate collaboration with their suppliers. At the level of advanced sustainability practices, there is a need to improve the involvement of NGOs and community groups in supply chains. Furthermore, the Kruskal-Wallis test shows that the companies' size influences the implementation level of social sustainability practices.

Keywords: Social Sustainability · Social Sustainability Practices · Supply Chain · Industrial Companies

1 Introduction

Nowadays, companies operate in complex supply chains with multiple suppliers that are dispersed geographically [1, 2]. Technological progress allows stakeholders information access, so issues such as poor working conditions related to health and safety are easily reported [3]. Thus, in response to a growing concern with social sustainability, stakeholders are pressuring companies to adopt practices that reduce and eliminate social issues in their supply chains [4, 5].

The current state of the art shows a growing interest in social sustainability, although the research focuses mainly on emerging economies [4, 6, 7]. Given the importance of extending research to other contexts, this paper aims to analyze the level of implementation of social sustainability practices in Portuguese industries. Although Portugal is one of the most sustainable countries in the world, the sustainable development goals are far from being achieved, as is the case of decent work and economic growth, which

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is lower than the other countries in the eurozone [8, 9]. Then, it is worth answering the following research question:

- What is the level of social sustainability practices implementation in Portuguese industrial companies?

For this purpose, the data collected from a survey addressed to Portuguese companies are analyzed.

This paper consists of five sections. Section 2 presents a brief theoretical basis with the main concepts related to the research. The methodology adopted is described in Sect. 3. Section 4 presents the results and discussion, and Sect. 5 concludes with the answer to the research question. This last section also mentions the contributions and limitations of the work and suggestions for future research.

2 Theoretical Background

2.1 Social Sustainability in Supply Chains

The concept of sustainability incorporates three dimensions - social, economic, and environmental - referring to the notion of the triple bottom line developed by Elkington [10]. In the actual context, characterized by globalization, companies are increasingly part of complex supply chains [1, 2]. Therefore, a company's sustainability depends on its suppliers' sustainability, so it is necessary to bring the topic of sustainability into the supply chains [11, 12].

Sustainable supply chain management is related to management flows/materials and inter-company cooperation, considering the three pillars of sustainability [13]. Nevertheless, in the literature, it is found that sustainability is often limited to environmental improvements, so the social dimension is neglected and requires additional research [7, 14].

Although there is no unique definition for social sustainability, and this notion is permutable with the concept of Corporate Social Responsibility (CSR), the social sustainability pillar includes all issues related to the safety and health of employees [15]. A more recent conceptualization explains social sustainability as all aspects related to products/processes that affect the health, safety, and well-being of people in supply chains [16]. Hence, a socially sustainable supply chain follows ethical values, encourages initiatives in local communities, and blames its members for the negative impacts of their activities [17, 18].

2.2 Social Sustainability Practices

Social sustainability practices relate to the effort to promote socially responsible behavior [19]. In this regard, Awaysheh and Klassen explain that social practices are managerial practices that influence how a company contributes to the protection and development of people [3].

According to Klassen and Vereecke, social sustainability practices can be classified into monitoring practices, relating to evaluating the performance of the focal company and the other elements of the supply chain, and collaborative practices, aimed at

coordinating the focal company with suppliers and stakeholders [20]. From the resource-based view (RBV), there are two categories for classifying socially sustainable practices: process-based and market-based, later known as basic and advanced social sustainability practices, respectively [4, 14].

Basic social sustainability practices focus on issues related to the health and safety of workers in supply chains. Thus, include monitoring suppliers (compliance with codes of conduct and performing audits) and implementation management systems certifications, such as SA8000 and OHSAS 18001, now renamed ISO 45001 [14]. Lastly, advanced social sustainability practices center on new products or processes development and the redefinition of the supply chain (a strategy that looks for the involvement of Non-Governmental Organizations – NGOs – and community groups).

3 Methodology

3.1 Survey Development

The strategy used to study the current level of implementation of social sustainability practices in Portuguese industrial companies was the development of a survey.

First, a literature review was conducted to support the development of the survey. Thus, using the LimeSurvey platform, a pilot survey was conducted and shared with three professionals and two researchers to detect potential errors or interpretation problems that could later compromise the participants' answers. Based on the suggestions received, some questions were reformulated.

The definitive version of the survey has three sections, adapted from different earlier works: Basic Social Sustainability Practices (BSSP), Advanced Social Sustainability Practices (ASSP), and General Information. Each section related to social sustainability practices - BSSP and ASSP - holds seven statements, adapted from the work of Croom and other authors, and are evaluated using a 5-point Likert scale [21]. The Appendix presents the statements included in these sections (Table 5).

Finally, the general information section has five questions that characterize the industry (sector of economic activity and size) and the participant (gender, position, and years of experience) [5, 7]. Relating to the industries' sector of economic activity, participants named it according to the divisions (10 to 33) of Section C (Manufacturing Industries) of the Portuguese Classification of Economic Activities, Revision 3, known as CAE REV. 3.

3.2 Data Collection, Response Rate, and Non-response Bias

Initially, an email was sent to a sample of Portuguese industrial companies requesting their participation in the study. This sample was randomly selected from the Bureau Van Dijk database, from which 2202 companies were contacted. In addition, when not complete answers were received, and to increase the response rate, a reminder was sent in the middle of the data collection process, which occurred between May 31 and July 31, 2022. A total of 322 responses were collected (14,62%), but only 142 were usable (6,45%), standing for the completed questionnaires.

The comparison of early and late responses assessed the existence of non-response bias. Since there were no significant differences in the mean values of the several items, this is not a concern.

4 Results and Discussion

4.1 Descriptive Statistics

As shown in Table 1, most of the responses were from the three main divisions of the manufacturing industry sector, which is consistent with the Portuguese reality [22]. Furthermore, 95.07% of the sample is small and medium-sized enterprises (SMEs), which are representative of the Portuguese context. In Portugal, 99.50% of manufacturing industries have fewer than 249 employees [23].

Table 1. Sample characteristics

Number of employees	**N**	**%**
<10	4	2.82
10–49	76	53.52
50–249	55	38.73
250–499	4	2.82
>500	3	2.11
Total	142	100
Economic Activity (CAE REV. 3)	**N**	**%**
32 – Other manufacturing activities	26	18.31
10 – Manufacture of food products	19	13.38
25 – Manufacture of fabricated metal products, except machinery and equipment	18	12.68
13 – Manufacture of textiles	17	11.97
22 – Manufacture of rubber and plastic products	13	9.15
24 – Manufacture of basic metals	11	7.75
14 – Manufacture of wearing apparel	6	4.23
15 – Manufacture of leather and related products	4	2.82
16 – Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	4	2.82
29 – Manufacture of motor vehicles, trailers, and semi-trailers	4	2.82
17 – Manufacture of paper and paper products	3	2.11
20 – Manufacture of chemical products and artificial fibers, except pharmaceutical products	3	2.11
31 – Manufacture of furniture	3	2.11
28 – Manufacture of machinery and equipment n.e.c	3	2.11
27 – Manufacture of electrical equipment	2	1.41
11 – Manufacture of beverages	2	1.41
18 – Printing and reproduction of recorded media	1	0.70
19 – Manufacture of coke and refined petroleum products	1	0.70
23 – Manufacture of other non-metallic mineral products	1	0.70
30 – Manufacture of other transport equipment	1	0.70
Total	142	100

It should also mention that respondents had adequate knowledge to take part in the study since the most frequent positions were managers (27.46%), operations directors (19.72%), and quality managers (19.01%). Additionally, 59.15% of the participants had worked for more than ten years in their current company.

4.2 Social Sustainability Practices

In Table 2, it is possible to characterize the state of implementation of socially sustainable practices in Portuguese industries.

Table 2. Descriptive Statistics and Cronbach's Alpha

Construct	Items	Mean	Standard Deviation	Mean of the Construct	Cronbach's Alpha
BSSP	BSSP1	3.45	1.18	3.09	0.90
	BSSP2	3.02	1.21		
	BSSP3	3.08	1.17		
	BSSP4	3.90	1.16		
	BSSP5	2.94	1.24		
	BSSP6	2.37	1.13		
	BSSP7	2.85	1.27		
ASSP	ASSP1	3.20	1.19	3.13	0.95
	ASSP2	3.20	1.16		
	ASSP3	3.20	1.19		
	ASSP4	3.11	1.12		
	ASSP5	2.80	1.13		
	ASSP6	3.23	1.16		
	ASSP7	3.16	1.14		

The mean value of the constructs writes down a reduced implementation level of social sustainability practices in the Portuguese industrial context. This is consistent with earlier studies, which reveal that companies in other developed countries (Ireland and the United States) also have a reduced level of implementation of these practices [14, 21]. Furthermore, the results are consistent with Picasso and other authors, who prove a lower level of socially responsible initiatives in manufacturing plants based in Western countries, such as Portugal, compared to manufacturing in Eastern countries [24].

At the level of basic sustainability practices, item BSSP4 stands out as the item with the highest mean value ($\overline{x} = 3.90$). This practice is used in Portuguese industries to verify health and safety conditions related to their employees. On the other hand, it appears that the items related to collaboration with suppliers (BSSP5, BSSP6, and BSSP7) have

a mean value below 3. Therefore, Portuguese industries should incentivize collaboration in their supply chains.

In terms of advanced sustainability practices, it seems difficult to single out a particular item because of its high mean value, given that all of them have similar values, which are close to 3. The fact that advanced social sustainability practices require more resources and a better capacity for innovation may justify these results [4, 13, 20]. Item ASSP5 can be highlighted in the ASSP construct by its lower value ($\bar{x} = 2.80$). Thus, considering the statement that corresponds to it, it is inferred that Portuguese industries should promote a better involvement of NGOs and community groups in their supply chains.

For a better view of the Portuguese industrial context, the mean values of constructs were analyzed in two distinct ways: by the main divisions of economic activity (Table 3) and the industry dimension (Table 4).

As shown in Table 3, for a significance level of 5%, the null hypothesis of the Kruskal-Wallis test is accepted. Consequently, there are no statistically significant differences in the mean values of these constructs according to economic activity. So, it contradicts the idea that the implementation of social practices differs according to the activity sector where a company works [25].

Table 3. Mean values of constructs by the economic activity and Kruskal-Wallis test

	Group 1 **Other manufacturing activities** ***(N = 26)***		**Group 2** **Manufacture of food products** ***(N = 19)***		**Group 3** **Manufacture of fabricated metal products, except machinery and equipment** ***(N = 18)***		**Kruskal-Wallis test**
	$\bar{x}$	**SE**	$\bar{x}$	**SE**	$\bar{x}$	**SE**	**Sig.**
BSSP	3.49	0.90	3.08	1.12	2.77	0.97	0.08
ASSP	3.42	0.94	3.03	1.12	2.91	0.92	0.07

$\bar{x}$ = Mean; SE = Standard Error

Finally, in Table 4, the non-parametric Kruskal-Wallis test shows that the size of the industries influences the BSSP and ASSP mean values, which is consistent with the literature that states that typically larger companies have more resources (human and financial) needed to implement social sustainability practices [14, 25].

Table 4. Mean values of constructs by the dimension of industry and Kruskal-Wallis test

	Group 1 **Micro** *(N = 4)*		**Group 2** **Small** *(N = 76)*		**Group 3** **Medium** *(N = 55)*		**Group 4** **Large** *(N = 7)*		**Kruskal-Wallis test**
	$\bar{x}$	**SE**	$\bar{x}$	**SE**	$\bar{x}$	**SE**	$\bar{x}$	**SE**	**Sig.**
BSSP	3.60	0.28	2.83	1.02	3.33	1.07	3.37	1.05	0.04
ASSP	3.35	0.47	2.90	1.11	3.43	0.94	3.57	0.93	0.01

$\bar{x}$ = Mean; SE = Standard Error

5 Conclusion

The main goal of this paper is to analyze the level of implementation of social sustainability practices in Portuguese industrial companies. After examining data from 142 companies, the answer to the research question is that the current implementation level of social sustainability practices is reduced, which is consistent with the reality of industries found in other countries, as is the case in Ireland and the United States [14, 21].

Additionally, the Kruskal-Wallis test verified that the adoption of social sustainability practices did not present significant differences in the three main economic activities of the manufacturing sector. In contrast, the industry's size influences the adoption level of these practices. This result can be justified by the fact that companies with different dimensions have different resources needed for social sustainability practices' implementation [3, 4, 25].

This study contributes to the literature by exploring social sustainability in contexts different from emerging economies. It also identifies basic and advanced practices that companies should implement.

The limitations include that the data collected were cross-sectional and from several industries. Furthermore, the questionnaire was only addressed to the companies and not to their suppliers, so it was impossible to capture both perspectives: buyer and supplier. Thus, using dyadic variables and replicating this research in different countries are suggestions for future work.

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Appendix

Table 5. Constructs related to Social Sustainability Practices

Basic Social Sustainability Practices (BSSP)	**Source**
BSSP1. You monitored your key supplier's compliance with your health and safety requirements	[21]
BSSP2. You sent health and safety questionnaires to your key supplier to monitor their compliance	
BSSP3. You monitored your key supplier's commitment to health and safety improvement goals	
BSSP4. You conducted audits of the health and safety of their employees	
BSSP5. You introduced employee health and safety compliance and auditing systems with your key supplier	
BSSP6. You helped your key supplier obtain OHSAS 18001 certification, SA8000, or other management system certification	
BSSP7. You developed an ethical code of conduct system with your key supplier	
Advanced Social Sustainability Practices (ASSP)	
ASSP1. Your company developed new products/processes with your key supplier that reduced health risks for consumers	
ASSP2. Your company developed new products/processes with your key supplier that benefited workers throughout the supply chain	
ASSP3. Your company developed new products/processes with your key supplier that reduced health and safety hazards for employees	
ASSP4. Your company developed new products/processes with your key supplier that provided fair margins to all your suppliers	
ASSP5. Your company has changed its supply chain strategy to bring non-governmental organizations and community groups into the supply chain	
ASSP6. Your company has changed its supply chain strategy to minimize negative impacts on communities around your supply chain operations	
ASSP7. Your company has changed its supply chain strategy to focus on fair trade throughout the supply chain	

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Exploring Socially Sustainable, Smart Manufacturing – Building Bridges Over Troubled Waters

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Abstract. Contemporary manufacturing organizations formulate strategies towards smart manufacturing. However, strategies often merely regard technological improvements of working processes and activities and pay limited attention to human-centric perspectives. This study addresses the complex phenomenon of reaching socially sustainable smart manufacturing by exploring the human-centric perspectives in the eras of Industry 4.0 and Industry 5.0. Data were collected through an explorative qualitative case study with focus groups applying the history wall approach to document informants' choices of activities that impact digitalization. To investigate informants' interpretations and experiences of digital initiatives and prospects, the history wall approach was coupled with the analytical lens of the co-workership wheel, with its four conceptual pairs: trust and openness, community spirit and cooperation, engagement and meaningfulness, responsibility, and initiative. A total of 17 informants from different organizational levels at a case company participated. Activities, impacting digitalization, brought forward were grouped into technology, organization, and external impact. Results showed that human-centric and intangible perspectives surfaced as prerequisites when navigating industrial digitalization. Further, digital initiatives and prospects risk drowning in re-occurring organizational changes making successful implementation difficult. Thus, organizations cannot rely solely on technology, but must consider activities related to organizational aspects and impacts from the external environment, when introducing digital initiatives. Intrinsically, recognition of the co-workership concept, emphasizing human-centricity, can support the foundation necessary for bridging the gap towards socially sustainable smart manufacturing and strengthening the emerging I5.0 research.

Keywords: Social Sustainability · Smart Manufacturing · Human-Centric · Co-workership · Industrial Digitalization · Industry 5.0/4.0

1 Introduction

Smart manufacturing has emerged as key within industrial digitalization, encompassing profound changes in manufacturing industries through digital technologies as part of Industry 4.0 (I4.0). Complementary to I4.0, Industry 5.0 (I5.0) has arisen, emphasizing

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socially sustainable aspects of smart manufacturing, including human-centric perspectives. Smart manufacturing embraces a plurality of core technologies, methodologies, and trends aided towards increased process efficiency, value creation, and competitiveness [1]. I4.0 technologies include e.g., the internet of things, robotics, and big data analytics, often related to artificial intelligence (AI) [2]. Today, manufacturing organizations formulate strategies towards smart manufacturing. However, the breadth and depth of strategies for implementing and enabling I4.0 technologies vary substantially across many technologies [1, 3]. Strategies often merely regard technological solutions and improvements of working processes and activities and overlook the human-technology nexus [4]. As a response, a more human-centric perspective has arisen, emphasizing challenges to balance the considerable one-sided emphasis on technology when striving towards smart manufacturing [5–7]. Human interaction, critical thinking, and interpretation are argued essentially when facing challenges of industrial digitalization [8]. The human-centric perspective emphasizes the need to acknowledge human strengths and competencies to reach sought efficiency of smart manufacturing. Talents, skills, diversity, and empowerment are of importance. Hence, the emerging value-driven concept of I5.0 aims to complement the technology-driven I4.0 [6]. It is accentuated that I5.0 focuses on a sustainable and resilient manufacturing industry through human-centric perspectives [5], contributing to sustainable development beyond the profit-centered productivity of I4.0 [9]. Socially sustainable smart manufacturing is hence argued hard to reach without considering the human strengths and competencies. Thus, research is encouraged to apply a human-centric perspective when studying industrial digitalization [3, 8–10]. In this sense, the human-technology nexus of smart manufacturing refers to the necessity of encompassing both human and technology for successful implementation of I4.0 technologies towards an elevated digitalization level. It is important to understand the human-technology nexus when striving towards a socially sustainable smart manufacturing [6, 11]. To explore the human-centric perspectives this study applied co-workership, a concept aiding understanding of organizational change based on employees' initiatives and prospects [12]. Herein the term co-worker refers to all employees and is viewed as an autonomous actor of the collective structure in a manufacturing organization. The concept of co-workership has given positive results for development initiatives in organizations, e.g., in the health care sector [13] encouraging employees to participate in the development process. This paper applies the co-workership wheel in the manufacturing sector, to study the development of socially sustainable smart manufacturing.

The research builds on previous work by [3] to further contribute to the exploration of co-workership in the manufacturing sector, strengthening the emerging I5.0 research. The co-workership wheel is a theoretical framework of four conceptual pairs [13]. The first pair, *trust and openness*, is about relationships and the perceived trust within all functional relationships illustrated as a core ability, mainly manifested through open dialogues among managers and workers, workers and workers, or workers and employees in general [13]. The second pair, *community spirit and cooperation*, signifies that effective cooperation should transcend organizational borders, regardless of organizational structures or hierarchy, professional roles, functions, or other barriers, and community spirit is the encouragement of learning with colleagues and by colleagues [13]. The third pair, *engagement and meaningfulness*, emphasis that beyond commitment to work

itself, constructive co-workership requires commitment to the organization, influencing engagement and meaningfulness of work [13]. The fourth pair, *responsibility and initiative*, highlights that responsibility strengthens initiative actions within an organization and may engage employees in organizational visions [13]. The co-workership wheel describes conditions necessary for constructive co-workership, and when these conditions exist, they feedback a development process, e.g., during organizational change. In this study, the motivation and usage of the co-workership wheel reflect the interest in employees' perspectives when navigating digital initiatives to reach a socially sustainable smart manufacturing.

This study addresses the complex phenomenon of socially sustainable smart manufacturing by exploring the human-centric perspectives in the eras of I4.0 and I5.0. Following this, the research question asked is: *How can the movement towards smart manufacturing be understood through employees' interpretations of digital initiatives and prospects?*

2 Method and Analysis

2.1 Case Description

The Case Company (CC) is a large Swedish manufacturing company operating in the global energy sector. CC produces and performs maintenance of high-quality, heavy, and large-sized components with cutting-edge technology. CC has a hierarchical organizational structure level supported by centralized business functions. The case is part of an ongoing longitudinal study (2019–2023) on the human-technology nexus. Previous research has demonstrated that initiatives of industrial digitalization are scattered across disparate units at CC with varying digitalization levels and different mindsets toward smart manufacturing [3, 4]. The case focuses on a manufacturing unit at CC with a high degree of work that requires advanced, but manual expertise, e.g., welding operations. This unit at CC is in the early phases of adopting I4.0 technologies.

2.2 Data Collection

This qualitative case study explored how socially sustainable smart manufacturing can be understood through employees' interpretations of digital initiatives and prospects. The case incorporated three focus groups, (see Table 1), with 17 informants from different job functions to encompass the entire organization: shop floor operators; shop floor team leaders; support functions including one manager. As such the range of functions can give different perspectives of digital initiatives [3, 4]. The phenomenon studied is elusive, thus requiring a sampling technique that allows finding hidden, hard-to-reach, and groups of informants with disparate views [14]. Purposive sampling [15] was applied to capture informants' different perceptions related to the research question. CC supported sampling informants from other functions, considering a range of gender, employed time, and work tasks.

The focus groups were designed to engage informants by collectively formulating their understanding of activities perceived as having a direct effect on the prospects of

Table 1. Overview of focus groups informants.

Functions categorization	Focus group name	Informant IDs	Duration (hours)
Shop floor team leaders	A	T1, T2, T3, T4, T5	1.6
Shop floor operators	B	O1, O2, O3, O4, O5, O6	1.5
Support functions and one informant from the management team (M1)	C	S1, S2, S3, S4, S5, M1	1.9
	Tot. 3 focus groups	Tot. 17 informants	Tot. 5.0 h

moving towards smart manufacturing from both present and retroactive perspectives, inspired by the history wall approach [16]. Focus groups were run in a workshop format to jointly create a history wall, i.e., a visual representation of activities in the organization over time [17]. Initially, informants were asked to consider what activities had occurred, either directed towards increased digitalization or perceived as influencing the prospects of digital initiatives since 2015. The reason for choosing the year 2015 was based on previous simulation project [18] and interview studies [3, 4] with CC indicated that from 2015 and forward, several digital initiatives, development projects, as well as organizational changes took place. During the 1.5–2-h sessions, informants sat in a half circle around a table and wrote activities on a long rolled-out paper that all informants could reach and write on, i.e., a history wall, stretching between 2015– 2022, overlooking informants' interpreted activities (see Fig. 1).

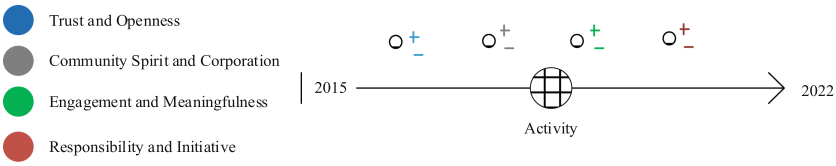

Fig. 1. History wall – interpretated activities.

The focus group leader, one of the researchers, circled the table. The other researchers focused on notetaking and video and audio recording (with informed signed consent), occasionally breaking in with follow-up questions. Next, informants overviewed the marked activities in rounds, each round focusing on one of the four conceptual pairs (see Fig. 1). The informants considered initiatives and prospects for each activity, marking their positive interpretations with a plus sign (+) or their negative interpretations with a minus sign (−). Different colors were used for each conceptual pair (blue, black, green, red) (see Fig. 1). Thus, the data collection combines the focus group format of the history wall with the conceptual pairs of the co-workership wheel.

2.3 Analysis

The analytical process consisted of four steps. Firstly, researchers rolled out all three history walls and counted the activities for each focus group. The total number of activities for the three focus groups was 66, and examples of activities are: advanced planning system; management execution systems; re-occurring change of top management; computers; padlets; digital flow boards; 3D measurement software; lean coordinator; lack of IT support staff; new light in factory shop floor; 3D printing; digital screens to support shop floor operators; structural re-organizations; lack of communication; keeping competence; training new staff; automated storage. Next, activities were coded for each history wall to formulate initial categories: digital; machines; software; change of management; employee turnover; structural organizational changes; culture and values; ergonomic; new contracts/products; market demand; Covid-19 pandemic. The multidisciplinary research group enriched the analysis with perspectives from production systems, informatics, and management, contributing to a multifaceted understanding of industrial digitalization. Thirdly, the initial categories were refined and grouped into three final categories: *Technology*; *Organization*; *External impact* (see Table 2).

Table 2. The number of activities for the three focus groups were distributed across categories.

Focus group name	Number of activities	Number of activities across categories
A	26	Tech. (14); Org. (7); Ext. impact (5)
B	15	Tech. (6); Org. (8); Ext. impact (1)
C	25	Tech. (14); Org. (8); Ext. impact (3)
Tot. no. = 3	Tot. no. = 66	Tot. Tech. (34); Org. (23); Ext. impact (9)

Lastly, to illustrate the distribution and amount of the plus signs (+) or minus signs (−), the final categories were placed in relation to the four conceptual pairs (see Table 3).

Table 3. Distribution of positive and negative reactions to the activities on the history wall.

Final categories	Trust and openness	Community spirit and cooperation	Engagement and meaning-fulness	Responsibil-ity and initiative	Tot. Per category
Technology	(−) = 15 (+) = 49	(−) = 19 (+) = 6	(−) = 2 (+) = 12	(−) = 7 (+) = 26	(−) = 43 (+) = 93

(*continued*)

Table 3. (*continued*)

Final categories	Trust and openness	Community spirit and cooperation	Engagement and meaning-fulness	Responsibil-ity and initiative	Tot. Per category
Organization	(−) = 11 (+) = 1	(−) = 11 (+) = 1	(−) = 5 (+) = 6	(−) = 17 (+) = 16	(−) = 62 (+) = 32
External impact	(−) = 13 (+) = 5	(−) = 8 (+) = 0	(−) = 1 (+) = 2	(−) = 2 (+) = 5	(−) = 24 (+) = 12
Total per conceptual pair	(−) = 52 (+) = 58	(−) = 35 (+) = 6	(−) = 6 (+) = 21	(−) = 26 (+) = 44	

3 Findings and Discussion

The findings (see Table 3) recognize that the total number of positive reactions was 134 and the total number of negative reactions were 126, i.e., a slight overweight of positives. The category *Technology* generated the largest number of reactions (where the majority 93 (of 136) reactions were positive), followed by *Organization* (where the majority 62 (of 94) reactions were negative), and finally, *External impact* (where the majority 24 (of 36) reactions were negative). It is not surprising that *Technology* generates the largest number of reactions as informants were asked to reflect on digital initiatives and prospects. Interestingly there were many positive reactions within the category of *Technology*, this in contradiction to previous studies of CC having shown fragmented views on digital initiatives [3, 4]. Re-occurring structural organizational changes, e.g., employee turnovers, along with several management team changes, took place during the seven-year period studied. This may explain the number of negative reactions in the category *Organization*. Revealing that the informants experience the organizational aspects as challenging when simultaneously facing digital initiatives and prospects. Activities illustrated in the history walls often stretched over several years, such as long-term product investments with limited operationalization. Regarding *External impact,* most reactions were negative, referring mainly to unexpected changes in the market demand overturning long-term strategies, or the impact of the Covid-19 pandemic. However, *External impact* generated limited reactions relative to the other two categories, one explanation possibly being that the Covid-19 restrictions in Sweden, compared to other parts of the world, were less strict.

The analysis thereafter, one at a time, considered each of the conceptual pairs of the co-workership wheel (see Table 3). Regarding *Trust and Openness,* the findings show a slight majority of total positive reactions. However, studying the distribution across categories, the positive reactions relate to *Technology*. Whereas both *Organization* and *External impact* have relatively large numbers of negative reactions. Those findings recognize the importance of relationships, trust, and open dialogues among all employees to strengthen co-workership related to external and internal challenges [13]. Overall, the second conceptual pair, *Community Spirit and Cooperation*, shows a high degree of negative reactions. One explanation could be that informants tend to illustrate activities

as single events in small teams not really related to overall change strategies or effective cooperation across work groups and organizational levels. This indicates that CC has a hierarchical organizational structure with borders that hinder and discourage learning and knowledge exchange among CC employees. The pair *Engagement and Meaningfulness* has a clear overweight of positive reactions as informants stressed that they are engaged and committed in their individual work tasks, but call for a stronger holistic context with an engagement and meaningfulness throughout the entire organization, referring to the good old times. The final pair *Responsibility and Initiative* has a majority of positive reactions compared to negative. This finding highlights that employees consider that they initiate and take responsibility for implementation and drive of activities, especially within respective function groups.

The findings and how the conceptual pairs of co-workership support the movement from the organizational capabilities and traits to socially sustainable smart manufacturing can be explained in the metaphor of a bridge. The bridge stretches across troubled waters, which is an analogy for the different activities, categorized into *Technology*, *Organization* and *External impact*, that may both hinder or drive industrial digitalization forward. The troubled waters (activities) express an unrest in the organization, making it difficult to clearly distinguish how disparate activities affect the movement towards socially sustainable smart manufacturing. Here the analytical lens of co-workership with its four conceptual pairs has assisted in making the unruly and muddy waters more translucent and thus, the activities tangible. As such the metaphorical bridge is being built up by pillars of the four co-workership conceptual pairs *Trust and Openness, Community Spirit and Cooperation, Engagement and meaningfulness, and Responsibility and Initiative* - pillars that are important for the foundation to reach socially sustainable smart manufacturing.

4 Conclusion

The phenomenon of socially sustainable smart manufacturing has been studied by exploring the human-centric perspectives in the eras of I4.0 and I5.0. Data were collected through an explorative qualitative case study with focus groups applying the history wall approach coupled with the concept of co-workership as an analytical lens, to reveal informants' choices of activities and their interpretations and experiences towards digital initiatives and prospects. Investigating how informants from different organizational levels collectively formulated their present understandings and retroactive experiences of activities towards smart manufacturing. As such, the human-centric and intangible perspectives of moving towards smart manufacturing surfaced, contributing to I5.0 research through a deeper understanding of employee interpretations. The approach brought out informants' thoughts and facilitated their sharing and discussion of ideas, searching and finding consensus to move forward. The informants expressed that the method was appreciated. This emphasizes the fruitfulness of combining the history wall approach with the analytical lens of co-workership with its four conceptual pairs, including human-centric perspectives, as a contribution to method. Findings show that digital initiatives and prospects risk drowning in re-occurring organizational changes and thus are difficult to implement throughout the whole organization. Meaning that organizations navigating

industrial digitalization during the eras of I4.0 and I5.0 cannot rely solely on potential technological leverage, but must also address organizational aspects and impacts from the external environment. Hence, the need for human-centric foundations is here argued as a prerequisite when embarking on novel digital initiatives. As such, awareness of the co-workership wheel, with its four conceptual pairs, stressing human-centric perspectives can thus function as pillars and lay the foundation for the bridge towards socially sustainable smart manufacturing.

Future studies are encouraged to cover multiple cases as one limitation may be the single case study and the number of conducted focus group sessions so far. Future research is encouraged to further explore and deepen understanding of human-centric perspectives of the ever-shifting horizon of smart manufacturing to strengthen the emerging I5.0 research.

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A Survey on Current Practices, Strategies and Research Needs for Circular Manufacturing of Plastics

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Abstract. Advances in manufacturing technology made plastics comparatively inexpensive, light, mouldable and durable. The great success of plastics comes along with a strong negative environmental impact and their accumulation in landfills and leakage into the natural environment is now recognized as a global environmental crisis. The circular economy approach to plastics provides a feasible solution to the prevailing linear system and aims to raise the proportion of plastic that is reused or recycled back into the system. The transition towards a circular economy, cannot be achieved solely through changes within the waste-handling system but must be combined with changes in other parts of the value chain, including the design, the manufacturing, etc. Plastic manufacturing companies need support in the transition. Therefore, this study aims to provide knowledge to plastics companies to move from linear towards circular manufacturing processes. We conduct a systematic literature review examining current practices and research needs in circularity within the plastics industry. This study contributes to the literature by mapping circularity strategies in plastics, explaining innovative circular plastic materials, and highlighting current circular manufacturing technologies such as additive manufacturing and the chemical transformation of waste plastics into various value-added chemical feedstocks, which can replace petrochemicals. Additionally, circular pathways are illustrated to support practitioners in identifying their current position in the value chain and understanding pathways to increase circularity. One of the key conclusions is that circular plastic value chains are still deficient in the implementation of R-strategies (such as rethinking, reducing, reusing, etc.) besides recycling.

Keywords: Circular Manufacturing · Plastics · Literature review

1 Introduction

Advances in manufacturing technology made plastics comparatively inexpensive, light, mouldable and durable [1]. As a result, plastics are a ubiquitous part of modern life and their application area is wide-ranging (e.g., in industrial processes for medicine, high-performance plastics in electronics, etc.). The development of synthetic polymers enables to achieve the desired performance properties of plastics at the lowest cost.

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Thereby, plastics manufacturing processes for commodity polymers use today optimized formulations that include small-molecule additives and co-monomers, combined with tailored polymerization conditions and end-use component production.

However, the great success of plastics comes along with a strong negative environmental impact and their accumulation in landfills and leakage into the natural environment is now recognized as a global environmental crisis [2, 3]. The linear value chain of plastics is one of the primary current sources of CO_2 emissions and environmental pollution. Most of the plastics on a global scale are used only once in industrial processes, products and packaging, etc. and only a small part is reused or recycled [4]. For instance, in Europe, 31% of all plastic waste is sent to landfill, while 39% is incinerated [5]. The linear supply chain is still quite applied in Europe. While the rate of landfilling is decreasing, incineration rates are increasing. The monetary insensitive and strict regulations have not pivoted the plastics industry towards recycling or reuse.

With the increasing awareness of the circular economy, companies are rethinking their business models and using it as a competitive advantage. The circular economy of plastics is a viable alternative to the existing linear system, wherein the plastics are produced, used and disposed of. The purpose of the circular economy is to increase the number of plastics that are reused or recycled back into the system [6]. The transition towards a circular economy, therefore, cannot be achieved solely through changes within the waste-handling system but must be combined with changes in other parts of the value chain, including the design, the manufacturing, etc.

Plastic manufacturing companies need support in the transition. There is a need to investigate the plastics value chain to move from linear to circular. While many studies focus on waste management improving recycling and recovery of plastics waste [7], this study aims to provide knowledge to plastics companies to move linear towards circular manufacturing processes. To achieve the aim of the study, we conduct a systematic literature review (SLR) and examine the following research questions:

1. What are the materials and technologies supporting circular manufacturing of plastics?
2. What are the pathways and stages involved in circular manufacturing of plastics?

2 Method

An SLR was conducted to answer the research questions. The SLR is a review of clearly formulated questions that uses a systematic and evidence-based approach to identifying, selecting, and analyzing secondary data. This approach differs from other review methods because of its transparency, inclusivity, and explanatory and heuristic nature. The main objective of the SLR is to facilitate theory development, align existing research, and uncover areas where additional research is needed [8].

The literature on the circular manufacturing of plastics is fragmented. The SLR is an adequate approach to organizing and unifying knowledge within this field. To be as comprehensive, combinations of generic keyword (and their variants) strings such as "circularity", "manufacturing, "plastics" are used as search criteria in the Title, Keywords and Abstract. The literature search was primarily carried out on ScienceDirect and Web of Science during the time period of October 2022. Google Scholar was used as a

backup to verify that recent articles were not missed. After retrieving the articles from the databases, duplicates were removed, resulting in 498 articles. An essential part of any SLR is establishing inclusion and exclusion criteria to ensure objective reasoning in the choice of literature. Articles from the past decade were included in the review as circular economy is a recent research topic, reducing the original number of 498 articles to 391 after excluding 107. Conference proceedings, professional journals, book chapters, and doctoral dissertations were excluded because significant research would have appeared in refereed academic journals, further reducing the number to 203 after excluding 188 articles. All 203 remaining article titles and abstracts were screened manually and those only vaguely related to circularity, manufacturing, or plastics were excluded, reducing the number to 60 after removing 143 articles. The remaining articles underwent full-text screening to confirm their relevance to circular manufacturing of plastics, resulting in 44 articles after excluding 16. Three highly relevant articles cited multiple times in the 44 articles but not previously identified were added, bringing the total number of articles included in the final review to 47.

3 Material for Circularity

For a material to be considered circular, it must undergo a full life cycle before being reclaimed. The life cycle of plastic products can range from a few days for packaging materials to several years or decades for consumer or industrial products. Plastics are categorized into three groups: elastomers, thermoplastics, and thermosets. The differences stem from the molecular structure of the materials, with thermoplastics being uncrosslinked, while vulcanized rubber and thermosets are crosslinked. The latter is also the main component in composites, and windmill blade cases are discussed in some articles with a focus on the effect of the original product design on the recovery and reuse of composite products [9], and case studies regarding the reuse of materials in additive manufacturing [10]. According to Hildebrandt et al. [11], durable products made of thermosets are more likely to be destined for energy recovery because of the limited recycling options available for this material.

Within the different groups of thermoplastic materials, the are several types of plastics, and only the main types are categorized for recycling. The thermoplastic materials discussed in this study are polyethylene terephthalates (PET), polypropylene (PP), low density (LD) polyethylene (PE), high density (HD) PE, polystyrene (PS), expanded polystyrene (EPS), and acrylonitrile butadiene styrene (ABS), and these are typical volume plastics used in packaging application. Engineering plastics like polyamides (PA), polycarbonate (PC), and polyoxymethylene (POM) are not commonly seen discussed in the reviewed articles. 2 of 47 articles discuss the use of recycling elastomers from end-of-life tire rubber granulate (TRG) in new tires and new products. A study by H. Monteiro et al. [12] shows that recycled TRG has a positive effect on primary energy and carbon emissions, and that supply chain processes, and material production have much higher impacts than the manufacturing of the new products. Bio-plastics and biodegradable plastics are common themes in several articles. Plastic materials from bio-based feedstock can replace fossil-based materials of the same group e.g., PET and PE. These materials can be recycled in the same way. The study by Rybaczewska-Błażejowska

et al. [13] shows that recycled PET (rPET) demonstrates the best environmental profile compared to both fossil-based and bio-based PET in all impact categories. Some plastic groups such as polylactic acid (PLA) can only be produced from bio-based feedstocks and are biodegradable under specific conditions.

4 Manufacturing Technologies for Circularity

Advances in technology and processes have increased the circularity of materials. The major current recycling process is dominated by mechanical recycling which sorts and degrades plastics during the process [14]. A large challenge and so barrier is still the quality of the waste material [15]. An empirical study from Swedish manufacturers shows that a high amount of plastics ends up in combustible waste. To reduce this share innovative decontamination technologies for post-consumer waste are needed. The study highlights the importance to reduce the number of varieties of undesired additives used in plastic manufacturing which complicates the sorting process.

An alternative to mechanical is the chemical recycling of plastic waste, and it is seen as a valuable solution enabling the production of feedstock to replace petrochemicals [14]. The chemical recycling process enables the production of higher-quality recycled plastics than mechanical recycling, by depolymerizing polymer chains back to reusable monomers [16]. One of the main challenges is the separation and purification of mixed plastic wastes and multi-component metal-plastic [14]. Mixed fractions of plastics and plastics contaminated with organics are critical in regard to waste management due to the lack of possibilities to be sorted and cleaned to their pure form. Hydrothermal treatment is a prospective solution, which has only been scarcely investigated, but with promising results in processing high-density plastics in order to produce high-value chemical components and recover monomeric constituents [17].

The advances in manufacturing technologies support the circularity of plastics. 12% of the studies introduce additive manufacturing (AM) to reuse plastic waste and produce new products. One example is the use of recycled composite for glass-fiber-reinforced polymers, which is still an open issue regards to end-of-life management [10]. Romani et al. [10] provide promising results regards to tensile test, with the use of mechanically recycled wind blades glass fibers for AM application as an alternative to virgin glass fiber. The degradation of mechanical properties can increase with the number of recycling cycles [18]. 6% of the reviewed studies focus on injection moulding as a prosing path to circular manufacturing. The developments in injection moulding try to maximize the share of recycled plastic materials [19]. A study by Huang et al. [20] shows promising results with the recycling of injection moulded polypropylene material in the sector for renewable energy technologies.

5 Circular Manufacturing Assessment

An effective approach to evaluate circularity strategies in the manufacturing value chain is based on the R-Strategy framework [21]. The findings from the SLR indicate that manufacturing companies are primarily focusing on recycling strategies (as shown in

Fig. 1a, 62.7%). Other R-strategies such as refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, and repurpose are still not widely used, and only a few studies have provided empirical data demonstrating the advantages and decision support in transitioning towards circularity.

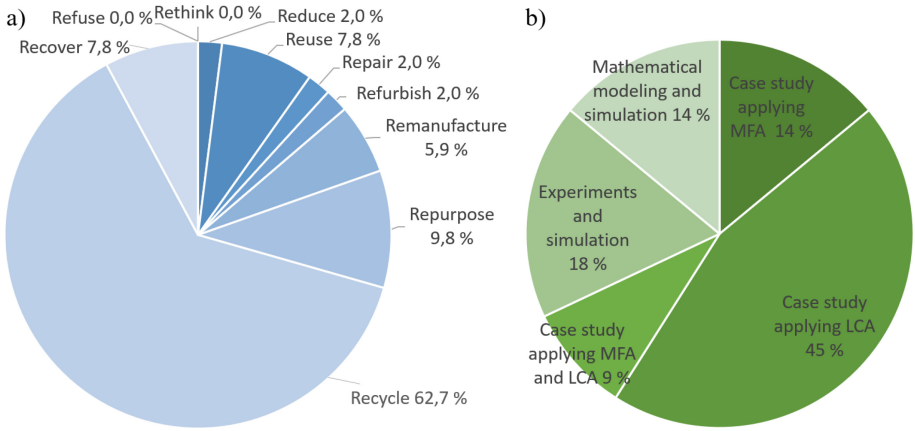

Fig. 1. a) Identified R-strategies, b) Identified circular assessment methods.

Joustra et al. [9] investigate the effect of the original product design on the recovery and reuse of composite products for wind turbine blades as case material. The study highlights the importance and necessity of including circularity aspects in the design phase to enable multiple lifecycles of the composite materials. Moraga et al. [22] examine the use of circular elastomeric materials and analyse different R-strategies (energy recovery, recycling, refurbishing, and reuse) that can reduce the loss of materials and environmental footprint in electronics. The scenarios with cycles of refurbishment and reuse showed improved resource efficiency compared to recycling scenarios. Di et al. [23] highlight the importance and benefits of separating and developing homogenous waste streams. The US has currently still a mixed waste collection system compared to the European countries. European countries have more comprehensive, effective, and separated waste collection systems with up to nine different waste flows that enable to apply of more different R-strategies. The SLR results show that case studies with material flow analysis (MFA) and/or life cycle assessment (LCA), and experiments/mathematical modelling with simulations are the main methods to assess the circularity of products and materials (as shown in Fig. 1b).

Based on the examined research study, we identified the pathways and stages for circular manufacturing of plastics (as shown in Fig. 2). Empirical studies show that advanced manufacturing technologies can effectively utilize recycled materials to produce high-quality products with multiple life cycles. Innovative technologies and methods can also aid in identifying circularity potential in end-of-life and waste management stages, promoting remanufacturing, repurposing, refurbishing, repairing, and reusing strategies. Further, it enables the creation of homogenous waste streams, which enhances the value and quality of secondary materials. By incorporating R-strategies into various

stages of the value chain, circularity of products can be increased and material extraction, landfill, and incineration reduced. The framework allows practitioners to determine the extent to which they apply these pathways and their dependency on material extraction and open loop cycles. By analyzing their current practices, practitioners can identify opportunities to improve material efficiency and increase circularity by closing cycles.

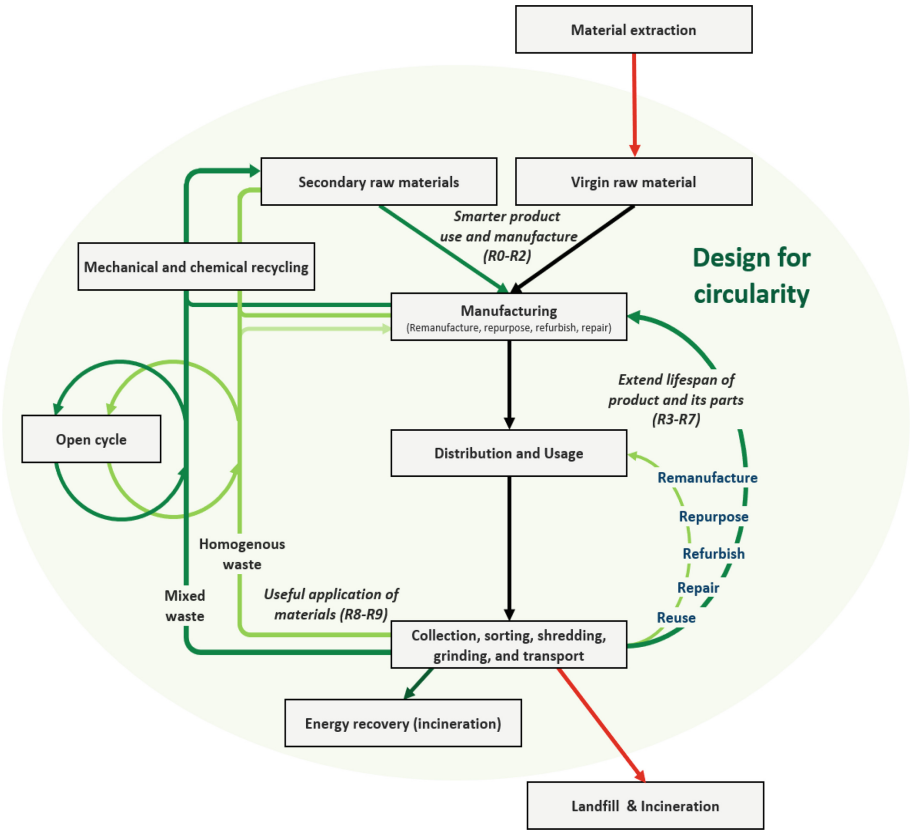

Fig. 2. Pathways and stages in circular manufacturing of plastics.

6 Conclusion

The plastic value chain has primarily focused on improving waste management and recycling processes in recent decades, while other R-strategies aimed at increasing the lifespan of products, parts, and materials have seen limited implementation. Many manufacturers still struggle to transition their value chain from linear to circular. This study confirms, as in several other studies from different industries [24], that some manufacturing companies have started to change their value chain towards circular business models and have seen an improvement in their sustainable performance. These studies

have typically focused on specific plastic compositions and niche industries. The lessons learned and technologies applied in empirical studies can enhance the implementation of the circular economy and drive progress towards circular manufacturing. Nevertheless, one of the conclusions of this study is that there is a challenge in generalizing these approaches and applying them to other plastic value chains. The framework presented in this study aims to bridge the gap and assist manufacturers in determining their circularity and their proportion of open/closed loop cycles, and helps determine which value stream partners or networks need to be established or strengthened to close cycles and extend product and material lifecycles.

However, this study has some limitations. The plastic manufacturing industry is comprised of numerous small and diverse companies, and their efforts towards circularity may not be thoroughly documented in research papers. Additionally, there is a possibility of overlooking relevant papers due to the use of keywords and filters. Furthermore, the length constraints of this paper have resulted in only highlighting certain aspects of circular manufacturing in the plastic industry. For instance, the design for circularity in plastics received limited attention. The metrics used in the framework to measure the circularity of different paths could also be refined. Future studies should evaluate the applicability of the introduced framework for manufacturing companies, assess its impact on sustainable performance, and enhance the framework as required.

The SLR aided in identifying future research needs for various pathways. Future studies should develop methods to make plastic products more easily recyclable through the use of mono-material solutions, materials that have an established recycling route and to better measure materials' life cycle performance to increase the life cycles of plastic products. Moreover, a significant challenge for manufacturing technologies such as AM and injection molding is the unpredictable nature of the properties of recycled materials used. Hence, there is a requirement for more research on improved separation methods to guarantee sufficient quality in both mechanical and chemical recycling. Finally, companies require assistance in implementing and utilizing R-strategies that go beyond just recycling and recovery. Further studies should aim to offer techniques and recommendations for utilizing R-strategies to gain a competitive edge.

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Barriers to the Circular Economy in the Plastics Industry: A Systematic Literature Review

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Abstract. Despite the high economic importance of the plastic industry worldwide and the capacity of plastic to be recycled multiple times due to its ability to preserve its value and properties, the plastic recycling sector still needs to be developed and more cohesive. Thus, there is a need to understand what is hindering plastic recycling. To that end, this paper presents a systematic literature review of the barriers to implementing the circular economy principles in plastic industries, investigating 30 articles retrieved from the SCOPUS database and published between 2008 and 2022. The systematic literature review identified forty-one barriers clustered into seven categories: social, organisational, economic, supply chain, technological and informational, institutional, and market barriers. This study aids practitioners and managers in identifying the main barriers that may be hindering the adoption of circular economy practices within their businesses.

Keywords: Circular Economy · Plastics Industry · Challenges · Systematic Literature Review

1 Introduction

The world is being subjected to extreme changes. The massive increase in the world population, expected to reach 9.2 billion by 2040 [1, 2], will inevitably lead to extreme increases in the demand for natural resources [2, 3]. At the same time, greenhouse gas emissions, the leading cause of climate change, continue to rise [2–5].

Plastics are highly durable and non-biodegradable materials made from petroleum by-products, with a lifetime varying from hundreds to thousands of years. Their adaptable nature makes them crucial materials, prompting their high demand and use worldwide [6]. However, the widespread use of plastic causes problematic pollution, affecting different ecosystem components [6, 7]. In fact, despite the high economic importance of the plastic industry worldwide and the capacity of plastic to be recycled multiple times due to its ability to preserve its value and properties, the plastic recycling sector still needs to be developed and more cohesive [8].

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The transition to a Circular Economy (CE) can help to improve the recycling of plastics by proposing a novel means to transform the traditional linear "take-make-use-disposal" system into a circular system [3, 4] and with the circular practices and the circular flow of products and materials, preventing the depletion of natural resources and the creation of waste [9]. The fundamental principle of the CE is the concept of circular loops of resources, waste streams, and energy and the minimisation of energy and raw materials inputs in the manufacturing system [9]. However, many barriers hinder the plastic industry's development and implementation of circular principles [6, 8, 10]. Previous studies on the transition to a CE in the plastics industry have generally discussed the challenges and barriers in very particular regions (e.g., single countries like in [6]), from a particular stakeholder perspective (e.g., post-consumer perspective like in [9, 10]) and using case studies as the preferred research methodology (as in [11–13] and [14]). Moreover, CE implementation barriers in different industries may differ depending on the various value chain actors and the diverse range of waste management and resource recovery practices [15]. Therefore, identifying the plastic industry-specific barriers is necessary to overcome the obstacles to CE adoption. The plastic industries need to understand which barriers prevent them from implementing CE practices to build robust strategies to overcome these obstacles and enable the transition towards a CE [16].

To close the gap previously presented, this study aims to identify the main barriers to CE implementation in the plastic industry through a systematic literature review (SLR). Hence, this study addresses the following research question: *Which barriers hinder the implementation of circular economy principles in plastic industries?*

The remainder of this paper is structured as follows: Sect. 2 describes how the SLR has been conducted; Sect. 3 presents the results and discussion, identifying and categorising the barriers to the CE implementation in the plastics industry; and Sect. 4 provides the main remarks, limitations and avenues for future work.

2 Methods

An SLR methodology was performed to understand which barriers hinder implementing principles in the plastics industry. The guidelines presented by Denyer and Tranfield [17] were adopted to achieve a replicable and transparent SLR. The authors define an SLR as a three-stage approach consisting of (1) planning, (2) conducting and (3) reporting the results of the review. With that in mind, the review began by identifying relevant, peer-reviewed literature regarding the issue under study. Scopus was used to search relevant literature because it is considered the most widespread database on different scientific fields [18] and the most extensive searchable citation and abstract source of literature continually expanded and updated [19]. A structured keyword search was performed with the keywords ('circular economy' AND 'barriers'). The keywords were searched for in the Article Title, Abstract, and Keywords of the papers. The language of the documents was restricted to English. The search was performed in March 2022, resulting in 634 preliminary results. From these, only articles from journals in the 1st and 2nd scientific journal quartiles were chosen to reduce the number of papers selected. Afterwards, the paper's title and abstract were screened, and 86 articles were considered related to the study of the barriers of CE in plastic industries. After reading the introduction and

conclusion sections, only 30 papers were deemed relevant for studying the barriers to CE. The article selection process is shown in Fig. 1.

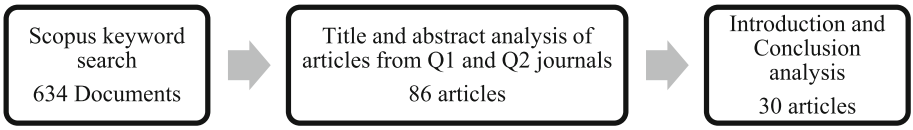

Fig. 1. Article selection process.

3 Results and Discussion

Practitioners and scholars have attributed the slow progress in CE adoption to various barriers. These barriers can take several forms. The SLR identified 41 CE barriers: four social, seven organisational, seven economic, five supply chain, six institutional, eight technological and informational, and four market barriers. The categories of the barriers were selected based on the works of [4, 20, 21] and [22] since the combination of the categories used in these works allows to use broader categories that are not too restrictive. The CE barriers in the plastic industry, identified through the SLR, are presented in Tables 1,2,3,4, 5 6 and 7.

Table 1. Social barriers.

Barrier	References
Lack of consumer awareness and interest	[3–7, 9, 11, 12, 14, 21–30]
Customer acceptance and demand for recycled products	[4, 13, 21, 22, 24, 26–31]
Price-conscious buyers/Insufficient market demand	[11, 12, 14, 16, 21, 24, 26, 31]
Missing public education campaigns	[25, 32]

Regarding the social barriers, there needs to be more consumer awareness of the CE concept, principles, and benefits, despite the increase in CE activities by the government and companies worldwide. Besides, the consumers' perception of the quality and safety of recycled/refurbished products is generally negative. The lack of willingness to buy recycled/refurbished products makes CE implementation more difficult. Additionally, some consumers perceive CE products as costly and may be unwilling to acquire them due to the perceived absence of tangible benefits. Lastly, public campaigns are needed to educate the public regarding the label information and the recycling guidelines.

There is a hesitant company culture regarding organisational barriers. CE is still a niche discussion in organisations, and the current company culture still favours the linear model, which prevents CE thinking. Linear business model structures and thinking are still prevalent in most companies. Moreover, there needs better leadership and management inside organisations, to more interest in CE. There is a lack of knowledge about the

Table 2. Organisational barriers.

Barrier	References
Hesitant company culture	[4–6, 12–14, 16, 20, 21, 27–30, 33–35]
Lack of management support	[3, 4, 11, 13, 22, 26–28]
Operating in a linear system	[5, 20, 22]
Lack of information and knowledge	[14, 21, 27, 33–35]
Administrative burden	[2, 14, 33]
Risks associated with the transition to CE	[6, 14, 21, 22, 26, 31]
Perception of CE as a cost and not an investment	[11, 16]

Table 3. Economic barriers.

Barrier	References
Low prices of virgin material	[4, 5, 10, 13, 16, 22, 23, 25, 27, 29, 30, 32, 34]
High up-front investment costs	[2, 4, 5, 9, 11, 14, 20–24, 26–30, 33, 34]
Long-term economic return	[3, 4, 12, 22, 23, 27, 28, 34]
Lack of funding	[2, 5, 12, 13, 15, 16, 21–23, 30, 32, 35]
High cost of CE practices	[2, 14, 26, 27]
Lack of economies of scale	[32, 34]
High production costs of recycled material	[12, 24, 25, 32]

Table 4. Supply chain-related barriers.

Barrier	References
Lack of collaboration and coordination among the supply chain members	[3, 5, 8, 12–14, 16, 20, 21, 23, 26, 29, 31, 33–35]
Inconsistency in the flow of supply	[9, 12, 13, 20, 23, 24, 26, 29]
Challenging product tracking and traceability	[26, 31, 34, 35]
Complex reverse-logistics structure	[12, 13, 21, 34]
Inelastic supply of waste	[29]

term "circular economy" and a poor exchange of information between companies and decision-makers. Monitoring and reporting data is an enormous administrative burden and a high cost to companies. When transitioning to a CE, the risk and responsibility for product outsourcing, damages, repair, maintenance, regulations, and human factors

Table 5. Institutional barriers.

Barrier	References
Lack of adequate legislation and government support	[2–8, 11–14, 20–24, 26, 28–30, 32, 33]
Limited circular procurement	[5, 13, 16, 34]
Lack of industry incentives for more sustainable activities	[3, 6, 21, 22, 27, 28, 30–32]
Lack of a standard system for performance assessment, data collection, calculation, and submission and punishment	[9, 14, 16, 21, 22, 27, 28, 30, 31, 34]
Rigid safety requirements	[6, 11, 32]
Lack of environmental laws and regulations	[14, 22, 27]

Table 6. Technological and informational barriers.

Barrier	References
Low-quality recycled materials	[5, 6, 8, 10, 12, 24, 29, 32, 34]
Disregarding the end-of-life phase in the current product design	[5, 21, 29, 30]
Lack of technical and technological personnel expertise	[2, 12–14, 16, 21, 22, 26, 28, 30, 33–35]
Complexity of products	[4, 20, 26, 29, 31]
Lack of appropriate and advanced technology	[6, 7, 11, 13, 16, 20, 21, 23, 27, 30, 32, 35]
Lack of standardisation	[5, 7, 26–28, 31]
Absence of adequate CE infrastructure	[28, 34]
Lack of collecting, sorting, and recycling capability	[6, 10, 11, 24, 34]

remain with the manufacturer, increasing operating and financial costs. In addition, the CE is still highly perceived as a cost instead of a prospect inside the organisations.

Regarding the economic barriers, the major problem seems to lie in the significant up-front investments that companies need to make since moving from a linear to a circular business model requires changes in almost all value chain activities, with long-term economic returns and benefits that many manufacturers, collectors, and recyclers have difficulties in recognising. Additionally, there seems to be no incentive to invest in this transition when one realises the price of recycled materials is much higher than that of virgin materials. There needs to be more funding for implementing circular models, training employees to implement circular principles, engaging in R&D to promote circular practices, and day-to-day circular operations to hinder the transition to a CE.

Furthermore, the operations cost of primary materials is much lower when compared to the production costs of recycled goods.

Supply chain barriers are related to the need for more collaboration and coordination among the supply chain members that hinder the recycling, remanufacturing, collection, and reuse of all the by-products throughout the chain. Additionally, the uncertainty in the reused/recycled material/product flow needs to be addressed in managing and planning the value chain activities. Furthermore, tracking and tracing recycled products' life cycles and material flow is complex. The procurement process of used goods from customers to the industry represents complex flows. This critical factor in reverse logistics should be overcome for the successful circular supply chain management. To conclude, recycled materials rely on previous utilisation models and have an inelastic supply, which does not facilitate the transition to a CE.

One institutional barrier identified is inadequate legislation and local authorities' support. Furthermore, there is a lack of supportive public procurement policies since the government does not regulate in favour of CE and, in some cases, even handles against it. The economic incentives for "greener" activities are essential for investment in sustainable practices, but they are still lacking. The lack of a standard system for performance assessment, data collection, calculation, submission and punishment hinder the transition to a CE. Moreover, the existing safety conditions for highly technical products, hazardous elements, and material issues are very rigid. The government regulations and environmental rules on energy requirements, carbon emissions, and ecological problems are not clear enough.

Regarding the technological and informational barriers, there is a problem with the low quality and durability of recycled materials; compared to virgin ones. There are also problems with product design, disregarding the end-of-life phase. The need for more technical workforces and technological innovations is another obstacle. Advanced technical personnel skills and technology are needed to convert from a linear to a circular economy. Besides, the complexity of the recycled products makes it difficult to recover and reuse the products/components effectively and efficiently Moreover, there is a need for more appropriate and advanced technology to ensure product durability, efficiency, quality, and product design for ideal life cycle scenarios. There needs to be more standards and frameworks regarding processes, materials, and activities associated with CE principles. Another barrier is the restricted access to infrastructure to employ CE in manufacturing industries and limited access to facilities to dispose of/recycle materials and circular design products. Moreover, more infrastructures and technologies must be used to collect, classify, and separate components.

Concerning the market-related barriers, the main problem is consumers' low demand for recycled materials/products. Product cannibalisation, with products with a longer lifecycle limiting the sales of new ones and restricting a company's revenue stream, is also a problem. The vulnerable markets for recycled plastics (depending on oil price and recycled plastics availability) are also referred to in the literature, and the final market-related barrier to the transition to a CE is the fact that the plastic sector has limited resilience to market shocks.

Table 7. Market-related barriers.

Barrier	References
Low demand for recycled materials	[8, 32]
Product cannibalisation	[13, 26, 31]
Market vulnerability	[6, 10, 11]
Limited sector resilience	[6]

4 Conclusions

Practitioners and scholars have attributed the slow progress in CE adoption to various barriers that have increasingly been investigated in recent years [2]. To facilitate the quicker acceptance of CE principles, it is essential to identify the barriers that make their implementation difficult [23]. Hence, this SLR identified 41 barriers to implementing a CE in the plastics industry, grouped into seven categories: social, organisational, economic, supply chain, technological and informational, institutional, and market barriers. This study aids practitioners and managers in identifying the main barriers that may be hindering the adoption of CE practices within their businesses.

This literature has some limitations, mainly due to its qualitative nature. The classification of the material is inevitably impacted by researcher bias, even if the research methodology was detailed to generate a transparent review. The article selection process is another source of bias. The selection of articles only published in 1st and 2nd scientific journal quartiles and in the English language may have left out some relevant publications, especially grey literature that may have offered an important contribution to the problem.

Since the barriers to implementing a CE do not have equal importance, and some are interconnected, future studies need to develop an evaluation framework capable of prioritising these barriers to identify the ones most urgent to overcome to ease the transition to a CE in the plastics industry. Another avenue of future work will be identifying mitigation strategies to overcome the most pressing barriers by establishing the relation between the identified barriers and possible coping strategies.

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The Perception of Sustainability in an Ethernet Network Cable: A Qualitative Analysis Using the AHP Method

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Abstract. Sustainability has been gaining focus in recent years in companies of different segments and sizes in order to create competitive advantages and differentiation in the market to maximize profit and opportunities. Sustainable innovation corroborates this concept in order to create products that have the theme of sustainability in their development. However, in markets where the source of raw material comes from commodity products, this practice is not trivial. Thus, in an attempt to differentiate itself from competitors, a company developed a product with a "sustainable" vision, using polymer originating from ethanol (sugarcane). However, is this perception of sustainability transmitted to customers, partners and society? Therefore, this study uses the AHP multicriteria decision-making method to quantify the qualitative analyzes carried out. The results indicate that the sustainability message is transmitted, but at different levels (percentage of confirmation), and therefore, it is suggested that improvements/focuses be implemented in the marketing informational materials.

Keywords: Sustainability · Sustainable product · Multicriteria decision · AHP · Ethernet networks

1 Introduction

Sustainability and innovation are distinct areas of study, but with very close synergy. According to Adams *et al.* [1], Sustainability-Oriented Innovation (SOI) involves making intentional changes in the organization, whether in philosophy, values, products, processes, or methodologies, with the aim of creating and/or realizing social and environmental value and generating financial returns. Therefore, sustainability can be considered the cradle of organizational and technological innovations [2], as being "ecologically correct" can lead to reduced costs for processes and/or consumption of inputs in some cases.

With this ideology in mind, some companies have created products with a sustainable bias, as they convey a concern for the environmental and/or social sphere. Moreover, competitive advantages could be achieved by developing sustainable actions [3].

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Such considerations corroborate the concept of the Triple Bottom Line (TBL), as products should not only bring profitability to companies, but also concern themselves with the needs of the planet [4]. In other words, companies should seek financial returns (economic dimension), but taking into consideration impacts in other dimensions (environmental and social dimensions), in this way, it can also be understood as concerns under the light of 3Ps (Profit, People and Planet) [5].

In this context, similar to the TBL concept, ESG (Environmental, Social & Governance) metrics have become sources of competitive advantages for companies, being even a topic of study on the relationship between these indicators and sustainable product development [6]. Therefore, considering the TBL concept and the ESG appeal, companies have developed products that try to convey this vision.

One of the ways to evaluate if something is being carried out as planned is by using Multicriteria Decision-Making (MCDM) methods. This methodology is tool for improving the comprehensibility and robustness of the evaluation system, making the result of the analysis, and its interpretation more reliable [7].

Therefore, the present paper aims to analyze the perception of a sustainable product in an item whose main components (raw materials) come from commodity market. To do so, a MCDM method will be applied since there are conflict criteria being used in the assessment under the light of the TBL concept. The expected result will be an evaluation of how the message has been conveyed to the external audience of the organization and, if necessary, recommend improvement actions.

To assist the reader in structuring this article, the document is segmented as follows: Sect. 2 consists of a brief literature review and contextualization of the problem. Next section (#3) aims to present the research methodology and the format of the question form. Section 4 is dedicated to the interpretive analysis of the results and a brief discussion of them. Finally, the last section (numbered as 5) includes the conclusion of the research and suggestions for future work.

2 Literature Review and Contextualization

2.1 Sustainable Innovation

As presented by Cillo *et al.* [8], sustainable innovation consists of renewals and/or improvements of products, services, technological or organizational processes not only aiming for better economic performance (*i.e.,* profitability), but also better environmental and social performance having the ability to generate good impacts from the social and environmental point of view.

As commented, sustainability and innovation have a high synergy, since in current times, competitive differentiation is sought through sustainable and/or innovative development [9]. However, in the commodity market, innovation and sustainability is not a trivial task, as there are many barriers to differentiation.

In the context of this paper, the analysis of the perception of sustainability will be given under an Ethernet network cable – which can be considered a product that comes from a commodity market, since both copper and plastic (polymer) are items with this characteristic.

2.2 Evaluation Criteria

Regardless of the MCDM method selected to perform the analysis, it is necessary to define the evaluation criteria that will be used. In general, these criteria are conflicting with each other and, therefore, a multicriteria tool is needed for better decision-making assertiveness [10].

In this article, we chose to seek criteria (indicators) related to the TBL dimensions that are consistent with the context of application, *i.e.*, in the copper cabling industry. The criteria were taken from academic literature [11–13], consisting of: environmental dimension (*i.e.,* durability, raw materials, and ecological), economic dimension (*i.e.,* costs, quality, and innovation), and social dimension (*i.e.,* public perception, safety, and ESG policy).

Regarding the alternatives, in order to simplify the evaluation by the interviewee, this lowest level of analysis consists of answering an objective question (*i.e., 'yes/no'*), but with a certain degree of subjectivity, since the scales can range from $\{-9; 9\}$ (also known as the Saaty scale of nine positions).

2.3 Multicriteria Decision-Making Method – The AHP Method

The AHP method, developed by Saaty in the 1970s [14], is one of the most classic and popular analytical techniques for analyzing complex problems in decision-making. It consists of a family of procedures that uses the pair-wise comparison of criteria by asking how important one criterion is in relation to another, being a simple, intuitive and flexible way for decision makers to analyze the problem [15]. It breaks down the main problem into different levels and groups of analysis, as presented in the Fig. 1, which shows the hierarchical structure used to schematize the questions and approach of this assessment.

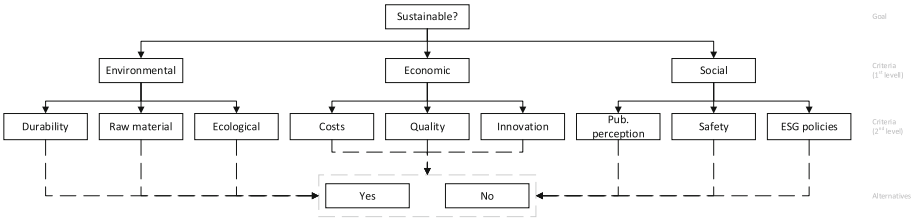

Fig. 1. AHP hierarchical structure used to analyze the perception of sustainability.

Note that there are three macro groups (environmental, economic and social – identified as "criteria (1st level)") with three indicators in each group (identified as "criteria (2nd level)"). As can be observed, the problem consists of a multicriteria analysis, where some of these may be conflicting with each other. Additionally, this structure allows visibility on which levels (criteria) are most relevant for isolated analysis, thus allowing the creation of improvement actions that only target that criterion (or group of criteria) temporarily.

In terms of questions, the AHP method breaks them in some level of analysis, for example:

- 1st level: What is the degree of preference for the following macro indicators (environmental, economic and social)?
- 2nd level: What is the degree of preference for the following criteria (durability, raw-material and ecological)?
- 3rd level: [for the durability box question] because the product is made of ethanol-based polyethylene, do you think that the durability superior to the traditional product (polyethylene extracted from petroleum)?

2.4 Ethernet Cabling

Currently, communication networks have grown exponentially, especially when considering IoT (Internet of Things) devices being connected to the network [16]. Whether in industry or in an office, the demand for Ethernet cabling has gained prominence.

Ethernet refers to a type of communication protocol defined by the IEEE-802.3 standard that can transmit data both in optical and metallic twisted-pair cabling, being considered the most common type of communication in companies and industries [17]. Figure 2 presents the main components of the twisted-pair metallic cable for Ethernet networks.

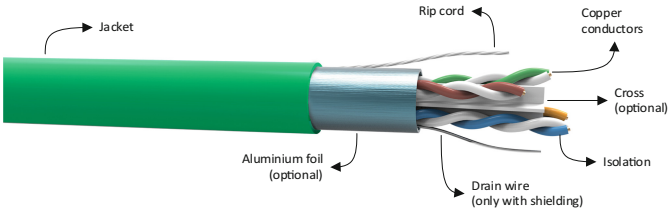

Fig. 2. Main components of a metallic twisted-pair cable for Ethernet networks.

With a view to sustainable innovation, the company developed a different jacket material than traditional one. The polymer used in the external jacket of the cable is derived from ethanol, that is, it comes from sugarcane – a renewable energy source. Therefore, it is based on this external cover material that the company's marketing department uses the "green/sustainable appeal". Thus, as mentioned, the main objective of this article is to evaluate the perception of sustainability that this product transmits to customer and users.

3 Methodology

In terms of the format used to approach the interviewee, we chose to present three slides that refer to the "green cable", as shown in Fig. 3. These are the information that are presented to customers and potential users of this product – for confidentiality purposes, the company logo was removed from images.

Based on this provided information, two people were asked to respond to the questionnaire provided. In terms of the respondents, it was deliberately chosen one person

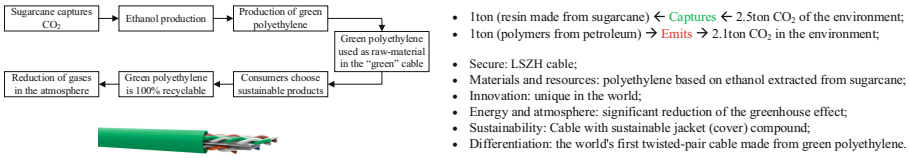

Fig. 3. Advertising material created/available by the company's marketing team.

from within the company and another from outside the company, referred to as the internal evaluator and external evaluator, respectively.

For knowledge purposes, the cable is manufactured by a specialized company in the production of Ethernet cabling located in Brazil, being one of the references to the worldwide cabling market.

4 Results and Discussions

Based on the questionnaire completed by the evaluators, the information was entered into the software for analysis. As discussed previously, the AHP method operates under the concept of hierarchy. Therefore, in the first level of analysis, there was an effort to determine indirectly, which macro group has the greatest relevance during the evaluations.

As shown in Table 1, the results obtained for this level indicate what the evaluators understand by priority considering their own evaluation in terms of environmental, economic and social spheres.

Table 1. Degree of importance of macro criteria (criteria level 1) and consistency ratio (CR).

Evaluator	Level 1			
	Environmental	Economic	Social	CR
Internal	0.47059	0.05882	0.47059	0.00000
External	0.58155	0.10945	0.30900	0.00355

As can be observed, the CR (consistency ratio) metric was below 0.10 – a metric considered ideal by the AHP method. It is an important metric in AHP because inconsistent judgments can lead to inaccurate or unreliable decision-making. In addition, interesting insights can be extracted from this preliminary analysis, among them:

- As per the internal evaluator, the environmental and social spheres have the same relevance, meaning that the criteria under these groups will have the same impact in the final evaluation;
- For the external evaluator, there is a greater preference for the environmental dimension (~58%), followed by the social (~31%), and finally, the economic one (~11%); in practice, the social indicators will have an impact, approximately, three-times higher compared to the economic indicators, and the environmental indicators will have a weight close to five-times higher than the economic indicators.

As observed, there is an apparent preference for environmental and social concerns. The next step was to evaluate the criteria in their subgroups in order to identify their weights and contributions to the final result. Based on the responses obtained, the consolidated results of this stage are presented in Table 2.

As seen from the perspective of each subgroup, the criterion that stands out for both evaluators is the *'innovation'* aspect. As mentioned before, innovation in products with commodity raw materials is not trivial. However, as this metric falls under the economic dimension, which has low importance for both evaluators, it will have little influence on the consolidated and final result.

As for the environmental dimension, the internal evaluator understands that the raw material is the most relevant and therefore it is assumed that there is a confirmation bias, since the message conveyed is of a "green product" with raw material from ethanol, which is considered a renewable energy source. For the external evaluator, durability is the most relevant factor, so she wants to compare the durability of a traditional product between a "sustainable" one.

Table 2. Degree of importance of the criteria present in level 2 and their consistency ratio (CR).

Evaluator	**Level 2 – Environmental**			
	Durability	**Ecological**	**Raw material**	**CR**
Internal	0.09242	0.42317	0.48441	0.01759
External	0.64064	0.29256	0.06680	0.09609
Evaluator	**Level 2 – Economic**			
	Costs	**Innovation**	**Quality**	**CR**
Internal	0.07692	0.61538	0.30770	0.00
External	0.23849	0.62501	0.13650	0.01759
Evaluator	**Level 2 – Social**			
	Public perception	**ESG policies**	**Safety**	**CR**
Internal	0.20984	0.54995	0.24021	0.01759
External	0.6267	0.27969	0.09361	0.08247

In terms of the social dimension, the internal evaluator understands that the relationship with ESG policies is more important – since this set of metrics (ESG) has gained prominence in the market as a whole. Unlike the external evaluator, who understands that public perception of this product is more important, that is, how much it is sustainable under a society view and its real benefits.

The above analysis of criteria weight and relevance lead to a specific goal, which is to evaluate how sustainable the product in question is under a subgroup of assessment. Since the last level of evaluation consists of objective questions weighted, we chose to present the consolidated result of the AHP method, which is displayed in Table 3.

As can be observed, for both interviewees, the evaluated product transmits the feeling of a sustainable item based on the shared information. However, the extent to which

Table 3. Consolidated result of the perception of sustainability in the Ethernet cable.

Evaluator	Result	
	Yes	No
Internal	0.7934	0.2066
External	0.5580	0.4420

this represents for each one differs significantly. For the internal evaluator, due to the confirmation bias and being "closer" to the company's day-to-day operations, it was possible to obtain a value close to 80% that YES, the product is sustainable. As for the external evaluator, this perception was more balanced, giving a positive result (YES) of approximately 56%. This indicates that there were doubts about the shared marketing material or the product itself, for this evaluator, it does not represent an item with strong synergy with sustainability.

Therefore, despite both results being positive, it is recommended to review how and what information to present in the marketing communication, which is shared with potential customers. The partial results (presented in Table 1 and Table 2) can indicate which dimension of TBL needs prioritization with the informational marketing content.

5 Conclusion and Discussion

The aim of this work was to evaluate the perception of sustainability that a product transmits with the help of the AHP method. To do this, it was necessary to contextualize the object of study (metallic twisted-pair Ethernet cable) and identify criteria that are consistent with the analysis from the perspective of the TBL dimensions.

With this in hand, it was requested that evaluators answer a questionnaire to analyze of their responses. The consolidated result indicates that the product and marketing communication convey the perception of sustainability, however, under different perspectives for each interviewee.

In sum, for the internal evaluator, a confirmation bias was expected, as the evaluator is in daily contact with this product and communicating the message to customers and partners. As for the external evaluator, despite the favorable result for the perception of sustainability, the level found was more balanced, showing that possible improvements can be made – in terms of promotional material and/or in the product itself. Thus, the marketing department could act in a targeted manner based on the partial responses found, focusing on those that have the greatest relevance for each evaluator.

As limitations of the research include that the evaluation was conducted with only two people, one internal and one external to the organization. Additionally, the number of criteria and their types (measures) could be different based on what each company is looking to identify as improvement gaps.

Based on the limitations presented, as future works: 1) it is suggested that the research be extended to more people in order to have a wider comprehensive perception, prioritizing respondents external to the company in order to avoid confirmation bias; 2) it is

also proposed to adapt the criteria, in terms of quantity and/or variations, based on what the company is looking to identify (confirmation of strong points, or identification of improvement areas).

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Comparison of Wire Arc Additive Manufacturing and Subtractive Manufacturing Approaches from an Environmental and Economic Perspective

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Abstract. Wire arc additive manufacturing (WAAM) is a metal AM process that uses metal wire as feedstock and an electric arc to melt the feedstock wire. WAAM has gained attention in the industry due to its benefits like better material efficiency and higher deposition rates. However, WAAM needs post-processing operations like machining due to its poor surface finish. Therefore, the sustainability potential of WAAM can't be presumed and needs to be proven quantitatively. Fewer studies that conduct an environmental or economic assessment of WAAM are present and do not comprehensively study the effect of post-processing on WAAM's performance. Therefore, the main objective of this study is to carry out an integrated and quantitative environmental and economic assessment of the WAAM process, including the effect of its post-processing operation. A case study of a product: a marine propeller made by WAAM and CNC milling technologies is presented. It is observed that the WAAM approach causes a 60% lower environmental impact compared to CNC milling. However, the WAAM approach is found to be slightly more cost-efficient (by 7%) than CNC milling. The effect of post-processing on WAAM's environmental and economic performance is also studied. WAAM is found to be more economical and ecological than CNC milling when the post-processing machining allowance of 4 mm or lower is left across the surface area of the propeller considered. This study can be helpful to AM practitioners in understanding the factors affecting WAAM's sustainability and in decision-making on sustainable process selection.

Keywords: Life Cycle Costing · Life Cycle Assessment · Propeller · Wire Arc Additive Manufacturing · CNC milling

1 Introduction

By depositing material in consecutive layers, additive manufacturing (AM) builds a component instead of material removal by conventional subtractive manufacturing technologies. This results in advantages such as the capability to produce complex geometries,

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mass customization, shorter lead times, and waste minimization, among others [1]. As a new additive manufacturing technique, Wire Arc Additive Manufacturing (WAAM) utilizes metal wires as raw materials, which are melted in an electric arc, and deposited layer by layer to construct a given shape. It is categorized as Direct Energy Deposition (DED). When WAAM is used in place of conventional subtractive methods, more material can be saved, and lead times can be shortened [2]. WAAM is more appropriate for building large and medium components than laser-based AM due to its higher deposition rate [3]. Due to its advantages over subtractive technologies, WAAM is a promising sustainable manufacturing process. However, WAAM products have poor dimensional accuracy and surface finish, and hence require further post-processing such as machining operations [4].

Some studies observed that WAAM is a material and energy-efficient alternative compared to subtractive manufacturing processes [5–7]. Bekker and Verlinden [5] carried computed the environmental impacts of WAAM, green sand casting, and CNC milling approaches for manufacturing a 1 kg stainless steel product. The environmental impact of WAAM and green sand casting was comparable but CNC milling caused an impact nearly 1.5 times higher than WAAM. However, this study did not include the post-processing operations required for finishing the WAAM part. Campatelli et al. [6] observed that an integrated WAAM-finish machining approach compared to a pure machining approach can lead to around 60% material savings and 34% energy savings in fabricating a structural steel airfoil. The width of the WAAM-built airfoil was maintained at 6.8 mm, leaving sufficient allowance for finish machining to the final maximum width of 3 mm. Priarone et al. [7] carried out a cumulative energy and cost assessment of an aluminum frame, titanium bracket, and steel beam using WAAM and machining approaches. WAAM was seen to be more energy-efficient than the machining approach for all 3 products. However, for steel beam WAAM was found to be significantly expensive due to its higher manufacturing time, in contrast with aluminium and titanium parts. Based on the above studies, it is realized that:

- Studies carrying out environmental and/or economic assessments of WAAM are fewer in number.
- Additionally, these are case studies involving specific products and their results can not be extended to other products with different materials, geometries, and processing conditions.
- Therefore, there is a need to evaluate and compare the environmental and economic performance of WAAM with conventional technologies by including more products with different geometries under different conditions.
- WAAM has a material saving potential but needs a finish machining allowance due to its lower surface accuracy. The finish machining adds to the environmental impact and production costs of WAAM. Therefore, it simply can't be assumed that WAAM is environmentally sustainable and economical. Its sustainability potential needs to be assessed quantitatively for different products, including the effect of post-processing operations.

Therefore, the main aim of this study is to conduct a comparative ecological and economic assessment of a product manufactured by WAAM and CNC milling approaches. A marine propeller made up of low-carbon high-strength steel (ER70) is considered

as the product in this study. Additionally, this study examines the effect of the post-processing machining allowance on WAAM's material utilization, environmental footprint and cost, and suggests the range of machining allowance for which WAAM is more sustainable environmentally and economically than the CNC milling process. This article is structured as follows: Sect. 2 describes the methodology employed in this paper to conduct an integrated ecological and economic assessment of a product, Sect. 3 explains the propeller part considered in the study, and environmental and economic data are associated with WAAM and CNC milling. In Sect. 4, the environmental burdens, and production costs of the propeller fabricated by additive and subtractive approaches are presented. The effect of material utilization on WAAM's environmental and economic behavior and limitations are also discussed here. Finally, the conclusions and directions for forthcoming work are discussed in Sect. 5.

2 Methodology

Life Cycle Assessment (LCA) is a popular methodology that computes the environmental burdens of a product over its lifecycle. The framework for LCA is defined by ISO 14044:2006 standard [8]. Life Cycle Costing (LCC) is used to evaluate the costs associated with a product's partial or full life cycle. Using an LCC assessment, decisions can be made to minimize the product cost without compromising any stakeholder's expectations [9]. This study performs a simultaneous environmental and economic assessment of a WAAM-built product using LCA and LCC procedures, respectively. This integrated LCA and LCC assessment is performed in the following steps: A clear goal and scope of the study are well-defined in the first step. The scope here refers to the life cycle stage(s) that need to be considered in the assessment. The second step involves the collection of environmental inventory data such as raw material, energy, shielding gas, post-processing wastes, and economic inventory that includes the costs associated with these resources consumed during the fabrication of products. The third stage encompasses the calculation of environmental impact and total cost based on the inventories gathered in the second step. Ultimately, in the last step, the outcomes are analyzed thoroughly and major contributors to environmental impact and cost are recognized. Furthermore, suggestions for improvement of economic and environmental performance are also derived in this phase. This methodology can be applied to other additive and subtractive manufacturing methods, as well.

3 Case Study

In this section, a case study assessing the environmental impacts and production costs associated with manufacturing a propeller by WAAM and conventional manufacturing (CM) processes is presented. A four-blade propeller (see Fig. 1) composed of ER70 steel is considered in this case study. The propeller has an outer diameter of 100 mm and a height of 30 mm. The central rotating hub has an outer diameter of 30 mm and an internal diameter of 15 mm. The thickness of the blades is 3 mm. This propeller has a volume of 26.15 cm^3 and a surface area of 159.13 cm^2. Considering the density of steel as 7.8 g/cm^3, the propeller weighs 204 g.

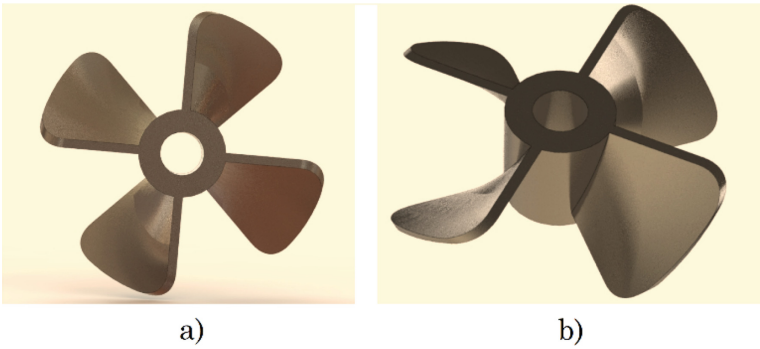

Fig. 1. a) The top view and b) isometric view of the four-blade propeller considered

3.1 Goal and Scope Definition

The main goal of this study is to compare the environmental impacts and costs in the production of a propeller using WAAM and conventional subtractive manufacturing technologies. The scope of this assessment is limited to cradle-to-gate i.e., raw material and manufacturing phases of the propeller. This includes extraction of raw materials, their transformation into feedstock materials, production of the propeller, and subsequent post-processing like finish machining to obtain the desired dimensions (see Fig. 2) The environmental and economic assessment is performed for manufacturing one propeller.

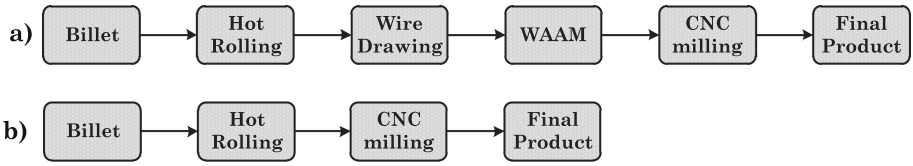

Fig. 2. System boundaries considered for a) WAAM b) Conventional Manufacturing

3.2 Life Cycle Inventory Assessment

For the WAAM process, the feedstock wire acts as the raw material. The wire is produced from a steel billet which is subjected to hot rolling and wire drawing. The life cycle inventory (LCI) data for steel billet, hot rolling, and wire drawing are obtained from the Ecoinvent database [10]. According to the Ecoinvent database, hot rolling and wire drawing processes have material efficiencies of 95% and 96% respectively. A feedstock wire of 1 mm diameter is used in WAAM. The final product weighs 204 g. Due to the poor dimensional accuracy and surface waviness of as-built WAAM products, they often require post-processing operations such as CNC machining to achieve the required dimensions and surface finish. Therefore, to accommodate the material removed during post-processing, an additional material allowance across the surface area of the WAAM-built product needs to be considered. In a previous study by the authors [11], a WAAM-built steel wall with a final thickness of 3 mm requires a machining allowance of 1.85 mm

across its surface area. Based on this study, a sufficient machining allowance of a uniform depth of 2 mm across the propeller's surface area is considered. This results in an additional material requirement of 31.8 cm^3 (or 248 g) along with the final part volume. Therefore, the total material required for the WAAM process is 58 cm^3 or 453 g. The WAAM process takes 15 min to print the part based on the tool path simulation in the commercial slicer Prusa 3D. The wire feed speed of 3 m/min, travel speed of 360 mm/min, and a layer height of 1.3 mm is used. The printing process consumes 0.507 kWh of energy. The part is allowed to be cooled in the air for 2 min after printing each layer. The resulting cooling time is 40 min. Additionally, a shielding gas mixture of composition Ar 82% + CO_2 18% is used at a 16 l/min flow rate during the printing phase to protect the molten material from the atmosphere. The post-processing CNC milling is performed using a 4 teeth 10 mm carbide endmill of diameter 10mm in two stages: semi-finishing followed by finishing. For semi-finishing, a cutting velocity (V_c) = 71 m/min, feed per tooth (f_z) 0.09 mm, and depth of cut (d) equal to 0.5 mm while for finishing, V_c = 71 m/min; f_z = 0.09 mm and d = 0.1 mm were considered based on the tool-maker's recommendations [12]. This postprocessing takes 3 h 43 min based on toolpath simulation in SolidWorks CAM and consumes 2.91 kWh of electricity. The detailed inventories of the WAAM process are enlisted in Table 1.

Table 1. Life Cycle Inventory for WAAM approach

Inventory	Amount	Reference
Steel billet	0.491 kg	Ecoinvent
WAAM		
Steel wire	0.453 kg	Calculated based on CAD model
Electricity (wire drawing)	0.063 kWh	Ecoinvent
Electricity	0.507 kWh	Measured
Shielding gas	0.24 m^3	Calculated
CNC milling		
Carbide endmill Ø10 mm	81 g	Measured
Material wastes	0.249 kg	Calculated based on 2 mm machining allowance
Electricity	2.91 kWh	Measured
Cutting fluid	4.13 kg	Ecoinvent

For the conventional manufacturing (CM) approach, the CNC milling process is considered. A cylindrical bar of diameter 102 mm and height 32 mm is used as the raw material. Steel billet is the starting material in this case, similar to WAAM, which is hot rolled into a cylindrical bar. The cylindrical bar is then milled to the final propeller geometry in 3 operations in the following: roughing, semi-finishing, and finishing using a 10 mm carbide endmill with 4 cutting teeth. The following cutting parameters are considered based on the tool manufacturer's recommendation [12]: for roughing (V_c = 93 m/min; fz = 0.09 mm, d = 2.5 mm); semi-finishing (V_c = 71 m/min; f_z = 0.09 mm,

d = 0.5 mm); and finishing (V_c = 71 m/min; f_z = 0.09 mm, d = 0.1 mm). The total machining process lasts for 6 h 5 min based on toolpath simulation in SolidWorks CAM and consumes 4.65 kWh of electricity. The LCI for the CM approach is listed in Table 2.

Table 2. Life Cycle Inventory for CM approach

Inventory	Amount	Reference
Steel billet	2.13 kg	Ecoinvent
CNC milling		
Carbide endmill Ø10 mm	81 g	Measured
Steel bar	2.02 kg	Calculated based on CAD model
Material wastes	1.814 kg	
Electricity	4.65 kWh	Measured
Cutting fluid	30.25 kg	Ecoinvent

3.3 Economic Inventory Assessment

To calculate the life cycle costs associated with WAAM and CM approaches, a cost model with a scope limited to cradle-to-gate has been developed by the authors [11]. In this cradle-to-gate cost model, the following costs are considered:

(i) Machine cost ($C_{machine}$) is the cost of the machine tool used during the process.
(ii) Material cost ($C_{material}$) i.e., the cost of the raw material consumed during the process.
(iii) Consumables cost ($C_{consumables}$) i.e., the cost of electricity and/or shielding gas, cutting fluid, and cutting tools consumed during the process.
(iv) Post-processing cost ($C_{post\text{-}processing}$) i.e., the cost incurred due to post-processing operations involved in WAAM. It comprises the price of the machine, consumables, and labour associated with the post-processing operations.
(v) Labour cost (C_{labour}) i.e., the cost of the operator involved in the execution of different activities involved in the process.

The WAAM setup consists of a KUKA industrial robot, CITOWAVE III 520 welding machine, welding torch, control system, exhaust system, protective fence, and computer interface. For CNC machining, HAAS UMC 750 5-axis CNC machine is considered. The WAAM and CNC milling machines are presumed to be utilized for 3 shifts of 8 h per day, 250 working days per annum, and a depreciation period of 7 years. The machines are considered to be available for 80% of the total time. The acquiring cost of WAAM and CNC machine systems are 300,000 € and 150,000 €, respectively based on the manufacturers' quotations. Additionally, maintenance and tooling costs of 3% and 2%, correspondingly are considered each year. Therefore, the machine costs for WAAM and CNC milling machines are 12 €/hr and 6 €/hr, respectively. The steel wire

used in WAAM costs 16 €/kg, and the steel bar for CNC milling costs 5 €/kg, based on their vendor quotations. The endmill cost is included in the tooling cost for the CNC machine. The cost of electricity is 0.13 €/kWh according to the Eurostat electricity prices for Portugal [13]. The shielding gas used in WAAM costs 2.3 €/m^3, according to its supplier quotation. The labour cost considered in this study is 15 €/h [14].

4 Results

Based on the LCI data collected above, an environmental impact assessment was performed in the LCA software SimaPro 9.2. Using ReCiPe 2016 Endpoint (Hierarchist) methodology. The environmental burdens of the WAAM and CM approach expressed in milli-points (mPts) are presented in Fig. 3. WAAM causes a 2.5 times lower impact than the CM approach. This can be mainly attributed to the material savings exhibited by WAAM. WAAM consumes approximately 4.5 times lower raw material than CM. The raw material is the major environmental hotspot for both approaches. It is responsible for nearly 51% and 81% of the total environmental impacts of WAAM and CM, respectively. Another significant contributor to WAAM's environmental impact is the energy consumed in its post-processing which accounts for 31% of its total impact. About 19% of the total impact of CM is caused by its energy consumption.

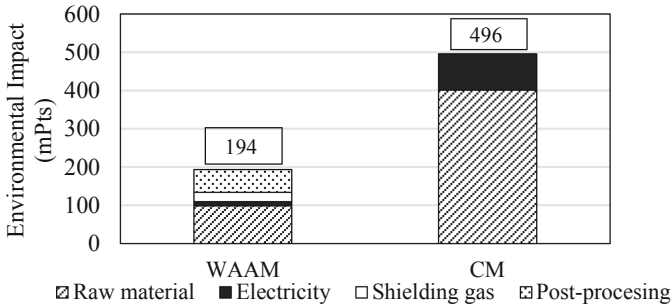

Fig. 3. Environmental impact comparison between WAAM and conventional manufacturing

The results of the economic assessment are displayed in Fig. 4. WAAM has a slightly lower cost (~7%) than the CM approach. This is mainly due to the higher post-processing cost associated with WAAM which accounts for roughly two-thirds of its production cost. It is noteworthy to see that although WAAM requires significantly lesser material than CM, its material cost is comparable to that of CM. The raw material cost for WAAM (16 €/kg) is about 3 times more expensive than CM (5 €/kg).

4.1 Influence of the Machining Allowance on WAAM's Performance

From the results of this study, it is evident that material consumption is the major environmental hotspot for the WAAM process. WAAM shows better material efficiency than its conventional counterpart resulting in lower environmental impact. Additionally,

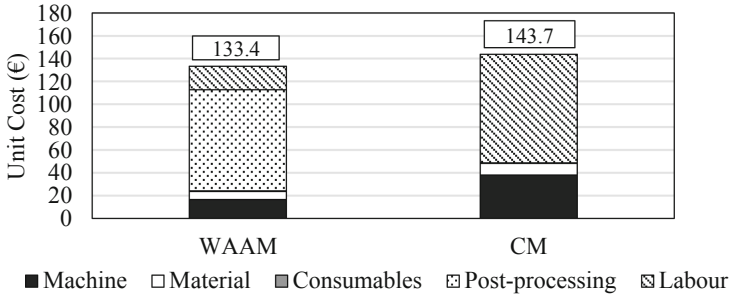

Fig. 4. Unit cost comparison between WAAM and conventional manufacturing

the amount of material consumed also affects the process times which in turn influences machine, material, consumables, labour, and post-processing costs. The machining allowance considered for WAAM products affects the material efficacy of the WAAM process. In this case study, a machining allowance of a uniform depth of 2 mm across the product's surface area is considered. This results in a material efficiency of 45% for WAAM, while the CM approach exhibits a material efficiency of 10%. In this section, the effect of machining allowance on WAAM's material efficiency, environmental impact, and production cost is studied. As the machining allowance is varied from 1 mm to 5 mm, WAAM's material efficiency decreases from 65% to 23% (see Fig. 5). Consequently, the environmental impact of WAAM increases from 123 mPts to 340 mPts (refer Fig. 6) and the cost increases from 125 € to 150 € (see Fig. 7). WAAM is seen to be a more environmentally friendly option for all values of machining allowances ranging from 1mm to 5 mm, while it is more cost-efficient only when its machining allowance is lower than 4 mm (implying material efficiencies higher than 28% for WAAM).

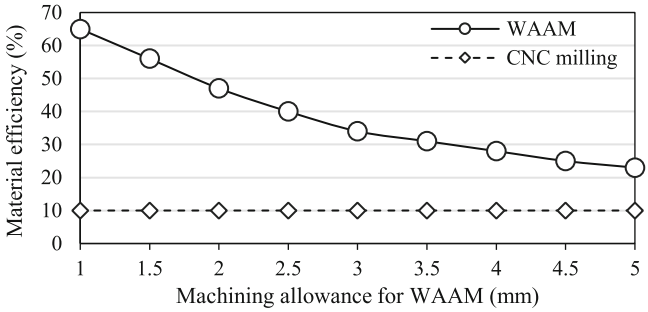

Fig. 5. The relationship between material efficiency and machining allowances for WAAM

4.2 Limitations of This Study

The following limitations were realized while conducting this study:

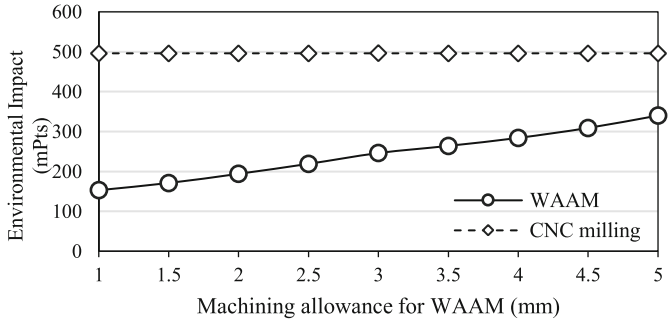

Fig. 6. The effect of WAAM machining allowance on its environmental impact

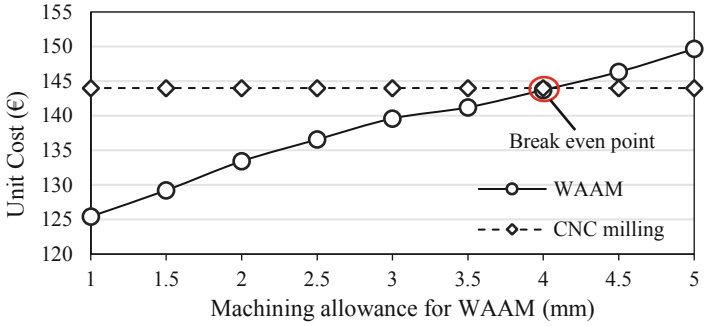

Fig. 7. The effect of WAAM machining allowance on its unit production cost

- The LCI data related to the raw material (steel billet, bar, and wire) production could not be collected experimentally and hence, are taken from the existing Ecoinvent database. It must be noted that the results of the LCA study are sensitive to the accuracy of these inventory data.
- This study does not take into account the effect of cutting tool wear on the environment due to a lack of information related to its exact material composition. The manufacturing of carbide-cutting tools is a resource and energy-intensive process and thus, its environmental impacts need to be considered.
- This study also excludes the effect of cutting tool life on the cost of the CNC machining process due to the unavailability of experimental data required to predict tool wear. Based on the tool life, more than one cutting tool can be required which can affect the economics of machining processes.

5 Conclusions

This study carries out a comparative cradle-to-gate ecological and economic assessment of a steel propeller manufactured by additive WAAM and subtractive approaches. This study also investigates the effect of post-processing i.e. machining operation for WAAM and suggests a range of machining allowances for which WAAM is a more ecological

and economical option. Based on the results of this study, the following conclusions are drawn:

- The results indicate that WAAM is a more ecological and economical process than CM due to its better material utilization in fabricating the given product.
- Raw material production is the main contributor to the environmental footprint for both approaches.
- The post-processing stage accounts for the majority of the WAAM production cost, while for the CM approach labour cost accounts for the bulk of its production cost due to longer processing time.
- The effect of machining allowance on the economic and environmental performance of WAAM is also studied. For a variation of machining allowance between 1 mm and 5 mm, WAAM is seen to be the most environmentally efficient process but is observed to be the most cost-efficient process only for allowances less than 4 mm.

Future works should involve diverse product geometries, materials, and cradle-to-grave system boundaries. Moreover, the effect of cutting tool material and its wear on the environment and the economics of CNC machining need to be considered. WAAM process is more advantageous as it utilizes raw material in the form of wire and can build complex parts in lesser time while subtractive approaches require billets of discrete dimensions as raw material. Owing to this, the WAAM approach can facilitate better stock management when used for production on an industrial scale. The environmental and economic performance of WAAM is expected to improve further with technological innovations enabling better dimensional accuracy, lower surface waviness, cleaner energy, lower material and machine costs, and improved process automation, among others.

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Manufacturing Process Level Framework for Green Strategies KPIs: The Welding Process Case

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Abstract. Increased global temperature has dictated the need to reduce carbon emissions in the manufacturing sector, while it is expected to both improve sustainability and maintain the quality of manufacturing processes. Green strategies, such as Zero Defect Manufacturing, Circular Economy and Sustainability have been proposed, with different key performance indicators (KPIs) with unidentified relationship between those KPIs and process parameters. Up to now, no study has identified this relationship, or tried to combine different green strategies and KPIs. This study aims to investigate the impact of specific process parameters (process power & speed) for the case of welding on KPIs for Zero Defect Manufacturing (defect rate), Circular Economy (energy consumption) and Sustainability (carbon footprint). The methodological approach was based on previously published framework, while a specific case study was used to showcase the complexity of relationship between the process parameters and the relevant KPIs. The main outcome of this study is the non-linear relationship shown in most cases, such as in the case of the impact of power and speed on the defect rate and on the carbon footprint. In addition, KPIs from one green strategy could be applicable to the other, via defining the link between quality of welding, energy consumption and carbon emissions. The latter could be used to define a holistic strategy incorporating different strategies and KPIs for improving sustainability in manufacturing.

Keywords: KPIs · Green Strategies · Zero Defect Manufacturing · Circular Economy · Sustainability · Welding

1 Introduction

According to EU statistics, industry is the second largest contributor to carbon emissions, second only to the energy sector [1]. Carbon footprint reduction of industrial processes is essential in order for manufacturing to align with Green Deal. A variety of green strategies have been proposed and developed to support green transition, such as zero defect manufacturing, circularity and sustainability.

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There are several different green strategies that are applied in the industrial or other settings, with the most commonly used being zero defect manufacturing, circular economy and sustainability. Other green strategies are lean manufacturing, green manufacturing, Industry 5.0, some indirectly or other indirectly focusing on resources efficiency. In order to determine the implementation progress of the green strategies, certain key performance indicators (KPIs) have been proposed. KPIs are used to define goals, provide information to as to the progress of the implementation, but also to determine intermediate goals and milestones. KPIs can be either qualitative or quantitative parameters.

In literature, several papers have discussed about KPIs regarding sustainability [2–4], circular economy [5] and zero defect manufacturing in manufacturing [6]. All these approaches bare in common that they focus only in one green strategy, rather than exploiting the cases where multiple green strategies can be applied in manufacturing. In the latter cases, some KPIs may be applicable to multiple green strategies, hitting in this way two birds with one stone.

The aim of the current work is to apply a qualitative approach to determine similarities and differences among the KPIs of different green strategies for the case of welding process.

2 Materials and Methods

A qualitative comparison framework was developed [7], focusing on determining the correlation between different KPIs of the most used green strategies (zero defect manufacturing, circular economy and sustainability). The schematic representation of the framework can be viewed in Fig. 1, with the main steps listed in bullet points:

- Identify the manufacturing process
- Define materials and products as input and output parameters
- Determine the parameters that will be used in the process
- Select the relevant KPIs from a pool of KPIs for Zero Defect Manufacturing, Circular Economy and Sustainability (left hand side of Fig. 1)
- The selection of KPIs will also have an impact on the selection of process parameters
- Define the relationship between process parameters and relevant KPIs
- Assess whether the different KPIs once paired have good correlation
- Fuse more than one green strategies by taking into account more diverse KPIs and extra data beyond life cycle analysis.

To determine the applicability of the already discussed framework, an example of welding process was selected [8], which is described in the next section with more details. Additional information regarding the defect rate were extracted from the literature, assuming a 30% of probability rise when the minimum reference value was found 15% [9].

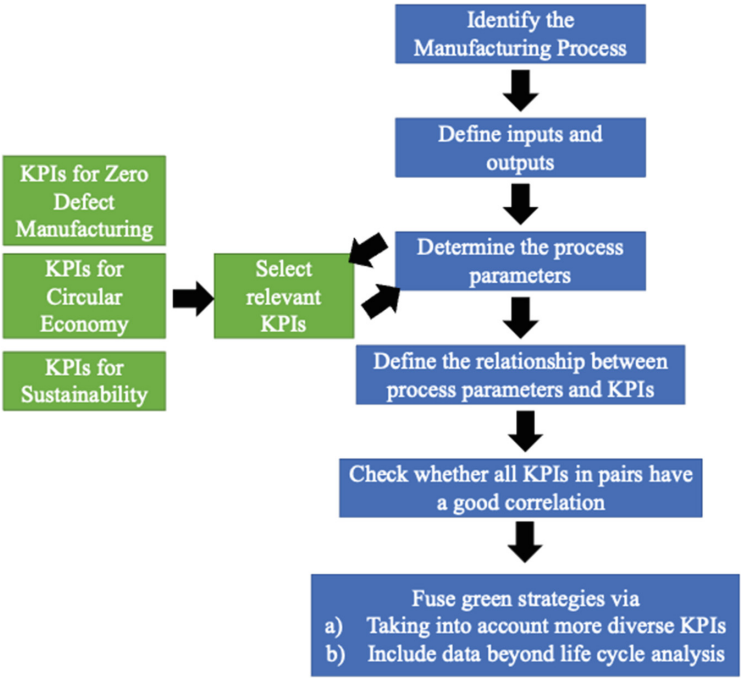

Fig. 1. Qualitative framework approach for comparing KPIs from different green strategies (Adopted and adapted from [7])

3 Case Study

The case study was based on data from previous work [8]. The case study focuses on laser welding of Aluminium (45 mm × 45 mm × 0.4 mm) over NiCu alloy (45 mm × 45 mm × 0.2 mm) using laser power of 1.2, 1.4 or 1.6 kW. The speed was 12 m/min for 40 mm (0.2 s).

The input parameters chosen were the welding power and the process speed. These parameters affect defect rate for Zero Defect Manufacturing, energy consumption for Circular Economy, and carbon footprint for Sustainability (Fig. 2).

The pairs created are listed below:

- Power and defect rate (Fig. 3)
- Process speed and defect rate (Fig. 3)
- Power and energy consumption (Fig. 4)
- Process speed and energy consumption (Fig. 4)
- Power and carbon footprint (Fig. 5)
- Process speed and carbon footprint (Fig. 5)

A life cycle analysis was performed, to calculate carbon footprint using SimaPro, the rest of the calculations were based on theoretical calculations.

As it can be seen from the Figures above, the relationship between process parameters and KPIs is not always monotonic and simple. Linear behaviour was only seen in the

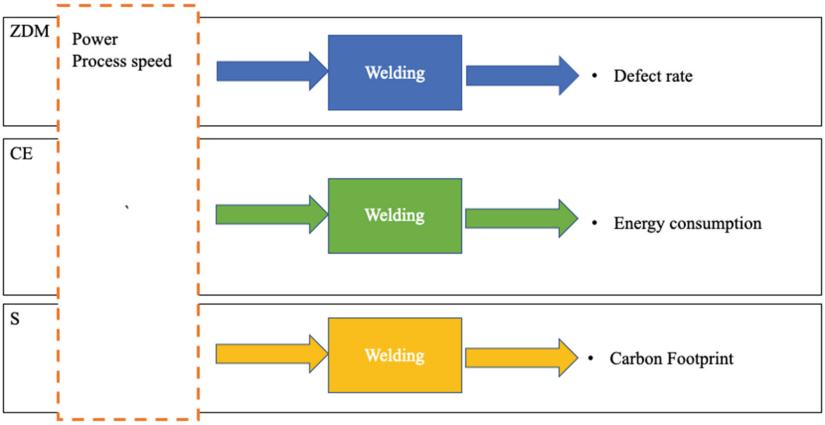

Fig. 2. Process parameters (left side) are linked with the KPIs they affect per green strategy (right side)(ZDM for Zero Defect Manufacturing, CE for Circular Economy and S for Sustainability).

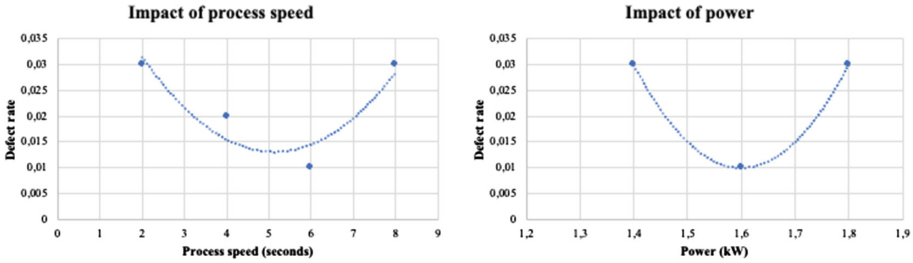

Fig. 3. Impact of process speed (left figure) and impact of power (right figure) on the defect rate for Zero Defect Manufacturing.

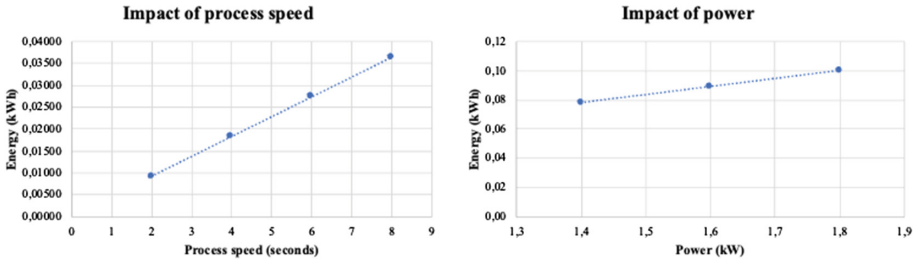

Fig. 4. Impact of process speed (left figure) and impact of power (right figure) on the energy consumption for Circular Economy.

case of Circular Economy, for the impact from both process speed and power (Fig. 4). The rest were polynomial, second degree in Fig. 3 and right Fig. 5 or third degree in left Fig. 5.

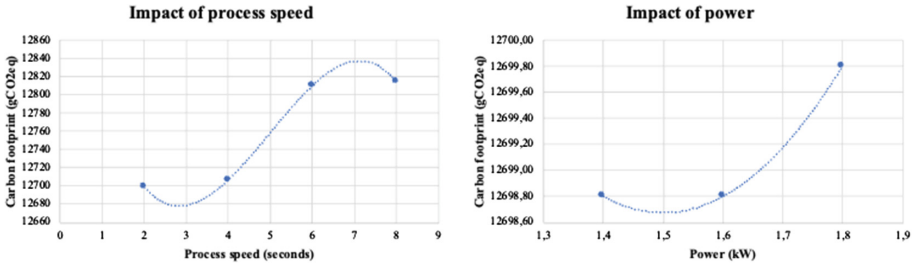

Fig. 5. Impact of process speed (left figure) and power (right) on the carbon footprint for Sustainability.

In details:

1. For the case of Zero Defect Manufacturing, the defect rate is influenced by power and process speed in a non-linear relationship. Indeed, for extreme values, the defect rate increases. For lower power values, the welding is incomplete while for higher power values, there is over-melting hence the welding is of poor quality [10]. The reverse happens for process speed; for slower welding processes with the same power, there is over-melting hence the quality of the welding is poor [11]. For faster welding processes, there is not enough time to perform the welding properly. Therefore an optimum set of parameters for both power and process speed is required in order to minimize the defect rate (Fig. 3).
2. For Circular Economy, the relationship between process parameters and energy consumption is linear; the more power or the higher process speed, then the higher the energy consumption (Fig. 4). This means that for circularity reasons, the aim is to decrease the values for power and process speed in order to decrease energy consumption and save consumptions.
3. Regarding Sustainability, the KPI that was examined was carbon footprint and the relevant process parameters were process speed and power (Fig. 5). The relationship was polynomial, either second or third degree, but the range of values was relatively small. This was because of the different steps included for the carbon footprint calculation; carbon footprint for materials production and carbon footprint for energy consumption at welding process level.

4 Discussion

The relationship between process parameters and KPIs is not always monotonic either because of the selection of values of the process parameters or due to the inclusion of other depending parameters. This is obvious in the case of carbon footprint, where energy related carbon emissions and material production related emissions were taken into consideration for its calculation. Therefore, a change in the energy related carbon emissions does not always lead to the same change in the value of carbon footprint.

Zero Defect Manufacturing aims to reduce the number of defected products via optimizing process parameters. It was shown that for extreme values of power and process speed (either low or high values), the defect rate increases. Therefore, there is

need for defining a critical value for the welding process speed, that acts as a boundary for good/poor welding quality. Above the critical value of the welding speed, then humping is observed, while below the critical value the welding process is of good quality [11]. In terms of the relationship between power and defect rate, welding power is linked to the strength required for welding which acts as an additional criterion [10]. Maculotti *et al.*(2022) have suggested that the defect rates are increasing when the values for process parameters are outside a certain range [9]. This phenomenon is recurring throughout literature [12], even in the case of additive manufacturing [13], with a high complexity which further increases when the quality of the process is linked to more than one factors [14]. Defect rate is directly associated with Zero Defect Manufacturing, but its impact can be seen in Circular Economy and Sustainability approaches. The higher the defect rate, the more energy will be consumed to perform a specific number of good quality welding works (Fig. 6). The higher the number of welding applications, the higher the carbon emissions, not only because of carbon emissions due to energy consumption, but also because more materials will be required to be produced for the welding.

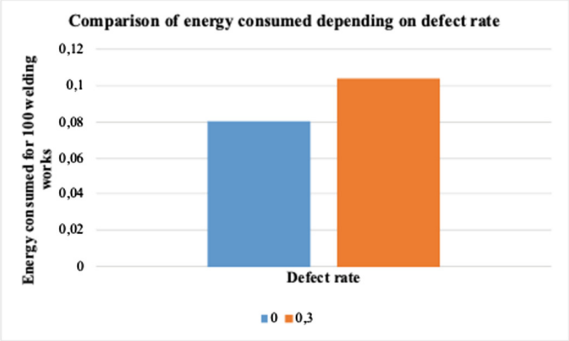

Fig. 6. Comparison of energy consumption for 100 welding works when there is no defect rate (blue) or when there is 30% defect rate.

Energy consumption for the welding was found to be linearly depended on the process speed and power of the welding. Therefore, in order to reduce energy consumption and align with Circular Economy via preserving resources such as energy, a parametric study is needed. Now in terms of the impact of energy with the other two green strategies, extreme values of energy consumption [9] are linked to the quality of welding via the depth of penetration, while energy consumption is linked to carbon emissions for the case of Sustainability. For the Zero Defect Manufacturing, low energy is linked to incomplete welding, while high energy is linked to over-melting. In both cases, the welding is of poor quality and the defect rate will be increased. In the case of Sustainability, energy consumption is part of the calculation of the carbon footprint. Increasing energy consumption will lead to increased carbon footprint, but only slightly, because for the carbon footprint calculation other steps are also taken into consideration; in this case, these steps are carbon emissions during material production.

Carbon footprint is the KPI for Sustainability affected by process speed and the relationship is more complex than linear, because of carbon emissions via different

steps. Overall, the impact of process speed and power on the carbon footprint is not great, because the process step is only a fraction of the calculation. The carbon footprint as KPI cannot be used for Zero Defect Manufacturing or Circular Economy, because it is not clearly linked with these green strategies conceptually. However, carbon footprint of processes and productions may have an indirect effect, as maintaining a certain value for carbon emissions or even trying to reduce it involves re-designing of processes and production lines to ensure a good quality, to reduce defects rate and to minimize energy consumption.

Overall, it is possible to combine KPIs from different green strategies, but the impact of the input process parameters is not straight forward. The approach presented here provides a first insight on the relationship between KPI and process parameters among different green strategies, showing that same KPIs can be used from different green strategies. The main limitation of the current study is that the selection of KPIs is not straightforward, since sometimes there are other parameters to be taken into consideration. These parameters are usually costs associated with the selection of KPIs, or linked to qualitative KPIs that are equally important for green strategies, especially for their social impact.

5 Conclusions

Different green strategies have different KPIs to fulfill to determine their applicability in manufacturing. These KPIs are affected by the selection of process parameters, in a non-linear fashion the majority of the cases. In addition, KPIs from one strategy can influence KPIs in other strategies indirectly, demanding thus a hierarchical stratification and unification of KPIs to merge different green strategies into one holistic strategy for improving sustainability and energy efficiency in manufacturing, while decreasing carbon emissions. Future work should focus on the unification of green strategies via a hierarchical approach and framework, but also expanding to other KPIs, green strategies and manufacturing processes.

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Drivers and Barriers of Residual Agroforestry Biomass Valorization: A Bibliometric Analysis

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Abstract. Residual agroforestry biomass, a byproduct of agricultural and forestry practices, can be used as feedstock in various industries, including bioenergy, pharmaceuticals, and cosmetics. In addition to its potential to contribute to the bio-circular economy, it can also help to reduce fuel loads in forests and mitigate the risk of forest fires. This study conducts a bibliometric analysis to identify the current state-of-the-art on drivers and barriers to the valorization of residual agroforestry biomass. A total of 194 articles from Scopus and Web of Science were analyzed using VOS viewer and R programming tool biblioshiny. The results revealed that only 4% of the articles focused specifically on residual agroforestry biomass, with the majority of them centered on the use of biomass for bioenergy production. The most influential authors, top-cited papers, and top journals in the field were also identified. This study represents the first step towards a more comprehensive systematic review of the literature on residual agroforestry biomass valorization.

Keywords: Drivers · Barriers · Supply chain · Residual Biomass · Agroforestry

1 Introduction

Residual agroforestry biomass refers to the organic matter left over after crop and forest product harvesting, as well as after forest maintenance activities [1]. The removal of this biomass from forests and agroforestry systems can significantly reduce the risk of forest fires by decreasing fuel loads [4]. In the summer of 2022 alone wildfires destroyed over 30,000 hectares of land in Portugal [2], affecting economic and social activities as well as the environment [3]. A strong market for residual agroforestry biomass could reduce fuel loads [5] and enable the use of plant residues as feedstock to produce energy,

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biofuels, food supplementation, biobased polymers, medication, and other products. It can reduce dependency on geographically distant suppliers and hence reduce the cost of production. The viability of using residual agroforestry biomass as a feedstock has so far been limited due to its low monetary value [6], as it poses challenges in its collection, transportation, processing, and its utilization.

Several literature reviews have examined biomass from agriculture and forestry [7]. Some have focused on specific aspects such as energy conversion processes [8] or analytical models for the biomass supply chain [10]. These reviews have revealed various topical issues within the emerging research literature [11]. However, only a few have specifically looked at residual agroforestry biomass and its value. This paper aims to provide a comprehensive understanding of the developments in the field of residual agroforestry biomass valorization using a bibliometric analysis approach. This approach involves analyzing co-authorship patterns, keyword co-occurrences, and citations [12]. By focusing on co-authorship patterns, the study can reveal collaboration networks between authors and countries. Analyzing keyword co-occurrences can help identify trends and hot topics in the field. Examining citations can reveal which works are most influential in shaping the direction of research. It's application in residual agroforestry biomass research is relatively new. This paper is organized into four sections. Section 2 describes the research process. Section 3 presents the bibliometric analysis and co-occurrences key-word analysis, and Conclusions are presented in Sect. 4.

2 Research Process

Since an initial search using the keywords "drivers and barriers" "valorization of residual agroforestry biomass" yielded limited results, the search keywords were changed to "drivers and barriers and biomass" in the title and abstract of the documents. This modified search produced 117 studies on Scopus and 163 studies on the Web of Science. The documents from the two databases were combined and 86 duplicate studies were removed, resulting in a sample with 194 documents inclusive of 3 early access articles and 1 early access review. The annual growth of the studies between 1998–2022 was 11.62%. The annual growth rate (AGR) was determined using the Eq. 1:

$$AGR = [(Ending\ Value/Beginning\ Value)^{1/n} - 1] \times 100 \quad (1)$$

where, "Ending value" is the number of articles published in 2022 (i.e., 14 articles), "Beginning value" is the number of articles published in 1998 (i.e., 1 article), and n is the total time period (i.e., 24 years). Due to space constraints, the database with the 194 documents can be accessed through the online index at the following https://doi.org/10.6084/m9.figshare.22213666.v1. Table 1 gives an overview of the data used for the bibliometric analysis.

It was found that 25% (i.e., 48 articles) on this topic were published in the 10 journals shown in Table 2. For each journal, Table 2 shows the H-index (which is a metric proposed by American physicist JE Hirsch to evaluate the impact and effectiveness of a researcher's published work). Also, for the papers in the sample the "Total Citations" (TC) (i.e., the number of citations received by papers published in each journal), and the "Number of Publication" (NP) related to the drivers and barriers of biomass. Six out of these 10

Table 1. Overview of data used for analysis

Description	Results	Description	Results
Main information about data		**Authors collaboration**	
Timespan	1998:2022	Single-authored docs	10
Sources (Journals, Books, etc.)	134	Co-Authors per Doc	4.48
Documents (1998–2022) Early access documents (2023)	190 4	International co-authorships %	17.89
AGR %	11.62	**Document (sample = 194)**	
Document Average Age	6.82	articles	138
Average citations per doc	23.66	proceedings paper	7
References	13330	book	1
Document contents		book chapter	9
Keywords Plus (ID)	1763	conference paper	8
Author's Keywords (DE)	727	editorial	1
Authors		erratum	1
Authors	812	Review	25
Authors of single-authored docs	10	Early access articles and reviews	4

journals focus on energy or bioenergy. Articles publish in journals like "Coral Reefs" and 'Deep-sea research part ii: topical studies in oceanography' which are not directly related to agroforestry biomass, were also included in the analysis because provided valuable insights into the drivers, barriers, and challenges of implementing of biomass as feedstock in various industries.

Table 2. Top 10 Journals most frequent in the database

Element	H_index	TC	NP	PY_start
Renewable and sustainable energy reviews	9	637	9	2011
Plos one	6	277	7	2014
Biomass & bioenergy	5	104	5	2013
Coral reefs	5	228	7	2008
Biomass and bioenergy	4	139	4	1999
Energy policy	4	714	4	2007
Energies	3	23	4	2019
Renewable energy	3	26	4	2014

(*continued*)

Table 2. (*continued*)

Element	H_index	TC	NP	PY_start
Deep-sea research part ii: topical studies in oceanography	2	50	2	2011
Ecology	2	24	2	2017

Notes: TC-Total Citations, NP-Number of Publications, PY_Start—year of first publication

Based on Table 2 "Energy policy" has the highest TC value of 714, which indicates that studies published in it have been highly cited in other publications. "Renewable and sustainable energy reviews", "Plos one", and "Coral reefs" have published the highest number of papers (NP = 9, 7, and 7 respectively). The publication year of the journals varies from 1999 to 2019 and 9 of the 10 journals have been publishing papers for five years and more.

3 Bibliometric Analysis

Bibliometric analysis is a mathematical and statistical method for evaluating and categorizing publication patterns on a specific topic, as well as author communication [13]. In this analysis, VOS viewer and Biblioshiny were used. The study focused on three areas: i) evaluating the most popular authors and countries through co-authorship analysis, ii) identifying themes and topics covered through keyword co-occurrences analysis, and iii) determining the most frequently cited works in the sample through citation analysis.

3.1 Co-authorship

The co-authorship analysis was performed in order to identify top contributors and better understand author collaboration in the study of agroforestry biomass drivers and barriers. Biblioshiny was used to conduct an in-depth analysis of the author-coauthor relationship in in the dataset.

Co-authorship Analysis Based on Authors. The analysis showed that 812 authors were involved in the writing of the 194 documents in the database. 94% wrote only one article, 40 wrote at least two, and five wrote at least three, with two writing four. Faaij A. wrote five articles. Table 3 lists top authors and their contributions, including fractionalized articles and contributing countries, between 2006–2021.

Some authors like Alt C. or Adams P., despite the low number of articles in the sample, made it to the list because of their high rate of fractionalized articles. Fractionalized articles are articles that are divided by the number of authors to account for their individual contribution. For example, if an article has four authors, each author is assigned 0.25 of the articles. This is done to avoid overestimating the productivity and impact of researchers who co-author many papers [13].

Authorship Based on Countries. In nearly 50 countries, researchers studied the drivers and barriers of biomass valorization. According to Table 3, the United States had 93 articles, Australia had 80, and the United Kingdom had 48. 17.89% percent of the studies

Table 3. Top 10 authors and countries

Authors	Articles (Nº)	Articles Fractionalized	Country	Articles
Faaij A	5	1.42	USA	93
Junginger M	4	1.08	Australia	80
Wilson S	4	0.78	UK	48
Brainard R	3	0.67	China	29
Graham N	3	0.62	Brazil	19
Kamp L	3	1.33	India	18
Mumby P	3	0.75	Germany	17
Taylor B	3	0.62	Netherlands	17
Adams P	2	0.36	Switzerland	11
Alt C	2	0.34	Sweden	9

Note: The author column and country column do not correspond to each other and are not interrelated

had international co-authorship, with an average of 4.48 co-authors per document. Apart from the researchers listed in Table 3, Portuguese researchers contributed to five articles and were among the top 22 contributors.

3.2 Co-occurrences Based on Keywords

The keywords used in the texts were identified using the bibliometric tool biblioshiny. The top twenty keywords and their occurrences in research document abstracts were analyzed in three ways: i) Identifying key themes, ii) comparing word frequency, and iii) investigating word associations. This method provided valuable insight into the context and interdependence of the topics or themes discussed in the texts. A frequent occurrence of certain words, for example, may indicate an emphasis on specific themes, such as environmentally sustainable management practices.

Based on the keywords, the main themes of the documents are renewable energy and environmental management. This is supported by the high frequency of words such as “biomass,” “energy,” “bioenergy,” “renewable,” “environmental,” “sustainable,” and “management.” Other related themes that may be present in the documents include research and analysis (e.g., “study,” “analysis,” “paper”) and the identification and analysis of challenges or obstacles (e.g., “barriers,” “drivers”). The presence of words such as “development,” “potential,” and “production” may lend credence to this interpretation. Surprisingly, neither “agroforestry” nor “residual biomass” were included in the keywords, implying that the majority of studies did not focus on the drivers and barriers of residual agroforestry biomass. Only 7 (4%) of the 194 documents screened by title and abstract were relevant to the topic [25–31]. These papers were published between 2009 and 2022, with the most cited paper [28] receiving 38 citations and none appearing in the top ten journals (Table 4).

Table 4. List of top 20 keywords

Words	Occurrences	Words	Occurrences
biomass	325	sustainable	90
energy	304	analysis	84
barriers	192	biogas	80
drivers	171	species	80
production	162	economic	79
development	142	management	79
bioenergy	122	results	76
environmental	117	technologies	75
potential	116	market	71
renewable	111	paper	70

3.3 Identification of Most Cited Documents

From Table 5 analysis, the most highly cited paper was [15], with 491 citations and an average citation rate of 30.69 times per year. Paper [15], was published in "Energy Policy", which is ranked as one of the top six journals in the dataset. Four other papers [19, 22–24], were published in the "Renewable Sustainable Energy Review", the highest-ranking journal in the dataset, with 130, 92, 87, and 82 citations, respectively between 2011–2016. Similarly, the Normalized total citation (NTC) field in Table 5 measures the impact of a researcher's work by dividing citations by years since publication. [14] has the highest NTC, with the value of 7.39 citations per year since it was published, indicating significant impact and influence in its field.

Table 5. Most Cited Papers

Paper	TC	TCY	NTC
[15] Verbong G.& Geels F, 2007, Energy Policy	491	30.69	2.9
[16] Dequiedt S. et al., 2011, Global Ecol. Biogeogr	170	14.17	3.22
[17] Darling E.S.et al., 2017, Coral Reefs	157	26.17	7.39
[18] Alam Hossain Mondal M.et al., 2010, Energy Policy	143	11	4.11

(*continued*)

Table 5. (*continued*)

Paper	TC	TCY	NTC
[19] Edwards J. et al., 2015, Renewable Sustainable Energy Rev	130	16.25	4.23
[20] Blanco H.et al., 2018, Appl. Energy	105	21	3.54
[21] Williams I.D.et al., 2015, Plos One	103	12.88	3.35
[22] Karakosta C.et al.,2013, Renewable Sustainable Energy Rev	92	9.2	2.24
[23] Karatayev M.& Clark M.L.,2016, Renewable Sustainable Energy Rev	87	12.43	2.59
[24] Adams P.W. et al., 2011, Renewable Sustainable Energy Rev	82	6.83	1.56

Note: TC-Total Citations, TCY-Total Citations per Year, NTC- Normalized Total Citation

4 Conclusion

This bibliometric analysis aimed to provide insights into the evolution of research on this topic and identify the most influential papers. The results of the analysis showed that literature on the drivers and barriers of residual agroforestry biomass valorization is scarce. From the 194 documents analyzed, only 7 were specifically related to the topic of residual agroforestry biomass [25–31]. Future studies must look into possible factors that are driving or hindering the valorization of residual agroforestry biomass, as well as potential strategies or solutions to overcome identified barriers. Studying the effects of residual agroforestry biomass on stakeholders such as farmers, policymakers, and the environment can provide insights into its potential as a renewable energy source. This research can aid in developing effective policies and practices for its sustainable use, and identify the benefits and challenges of using it for energy production, reducing dependence on fossil fuels.

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How Does Safety Affect Sustainability? an Empirical Study in the Chemical Industry

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Abstract. The chemical industry is considered indispensable for improving both the economy and the well-being of the population in many countries. However, despite making significant contributions to the global economy and society's welfare, the chemical industry also has adverse effects on the environment and human health and safety. To minimize its negative impacts and ensure a sustainable future, it is critical to prioritize sustainable production in the chemical industry. It is therefore imperative to comprehend the consequences of safety on sustainable production and the specific mechanisms through which safety can influence sustainable production performance. This paper reports an ongoing study to scrutinize the relationship between safety performance and sustainable production performance. The study comprises a systematic literature review to produce an initial theoretical framework and two phases of data collection to validate the initial theoretical framework. The first phase has been done, providing improvements for the framework, which will be further analyzed in the second phase.

Keywords: Chemical industry · safety performance · sustainable production performance · semi-structured interview structural equation modelling

1 Introduction

Due to its crucial and strategic importance, the chemical industry is considered indispensable for improving both the economy and the well-being of the population in many countries [1, 2]. Compared to other industries, the unique features of the chemical industry demand a workforce that is both trained and skilled. It has strong ties to virtually every other sector of the economy [3]. However, despite making significant contributions to the global economy and society's welfare, the chemical industry also has adverse effects on the environment and human health and safety [1, 4].

One of the significant concerns in the chemical industry is sustainability [5], which to date, has not been successfully achieved. The concept of sustainability encompasses the integrated development of economics, environment, and society to provide significant and enduring benefits to the world [6]. The Sustainable Development Goals, which

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encompass 17 objectives, were established by the United Nations General Assembly as a global agenda for achieving sustainable development (SDGs) [7]. Ever since, achieving sustainability has remained a crucial goal for numerous organizations, and there has been a growing emphasis on sustainable production within industrial sectors, including chemical industry [8].

Although there have been initiatives to encourage sustainable production, most of them have primarily focused on financial benefits while neglecting safety considerations. Consequently, there has been a decrease in safety standards in various instances [9], the exact opposite of what should have been taken. In order to establish a secure working environment, it is necessary for workers to receive sufficient support [10]. Merely being financially profitable does not make an industry entirely sustainable; it must also exhibit ecological compatibility and social responsibility [11]. Among the three pillars of sustainability, the social pillar is frequently the most overlooked [9]. The social pillar of sustainability encompasses several factors, including environmental protection and ensuring worker health and safety. The chemical industry has often faced challenges in integrating these critical aspects into its sustainable production process.

Therefore, it is imperative to comprehend the consequences of safety on sustainable production and the specific mechanisms through which safety can influence sustainable production performance, particularly in the chemical industry. Furthermore, the unique characteristics of the chemical industry seemingly exert an influence on the relationship between safety and sustainable production performance; however, this assertion warrants empirical scrutiny. This paper reports an ongoing empirical study that seeks to test the applicability of a theoretical framework involving companies within the chemical industry sector, with the objective of gaining deeper insights into the extent to which the propositions of the framework have been actualized in practice. The study started with a systematic literature review to produce an initial theoretical framework, followed by two phases of data collection to validate the initial framework. A systematic literature review had been conducted, producing a theoretical framework which was used as the basis of the study [12]. The first phase of data collection, qualitative study was then conducted, confirming most of the framework. The study is currently at the beginning of the second phase, quantitative study, to further validate the framework.

The remainder of the paper then proceeds in the following order. First, we explain the methods used in the study. We then continue with the presentation of results, and discussion that raised from it. We end the paper by presenting our conclusions.

2 Materials and Method

This study employs a mixed method approach to investigate the interplay between safety performance and sustainable production performance. The mixed method research is predicated on the notion that the incorporation of both quantitative and qualitative methods into a study serves to enhance each other's strengths [13].

The development of an initial theoretical framework was first undertaken following a meticulous review of the relevant scholarly literature [12], providing the groundwork for the subsequent qualitative investigation into the impact of safety performance on sustainable production performance in the chemical industry. The framework presents

a theoretical model (Fig. 1) that delineates the causal relationships between safety performance and sustainable production performance, with safety culture serving as the antecedent and industrial characteristics acting as a moderating factor. There are three propositions in the framework: 1) The better safety culture of an organization, the higher its safety performance; 2) The higher safety performance of an organization, the higher its sustainable production performance; 3) The industrial characteristics of an organization will influence the relationship between their safety culture and safety performance.

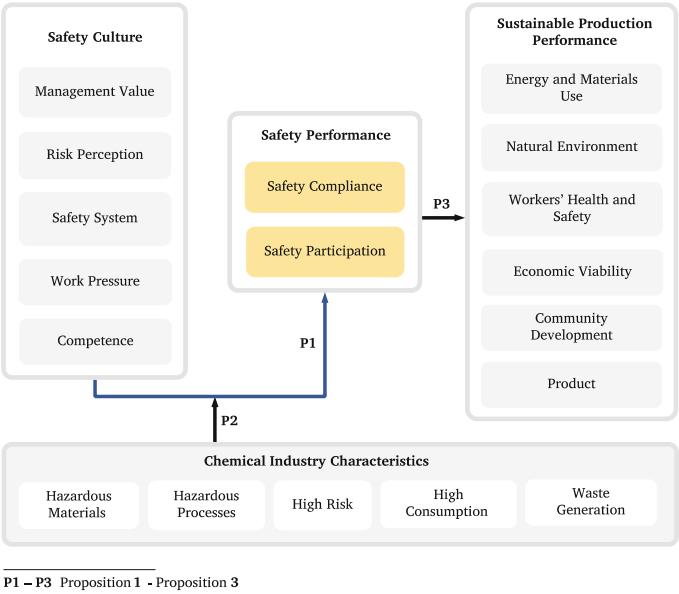

Fig. 1. Initial Theoretical Framework

The first phase of this study is a qualitative study, which generates both exploratory and in-depth data, a vital component in the investigation of various factors in research [14]. The theoretical framework previously developed serves as the foundation for the design of the case study, thereby setting the scope of the research, informing data analysis and interpretation, and guiding the elicitation of participants' perspectives, in accordance with the four primary building blocks. The research methodology involved the selection of a semi-structured interview approach, and a total of 19 online interviews were conducted with explicit consent from participants. The interviews were audio-recorded and later transcribed to facilitate qualitative analysis. The outcome of the qualitative approach will assist in formulating the subsequent phase of the study: the quantitative phase.

The second phase is a quantitative study, which will allow the formulation and testing of hypotheses based on the qualitative findings. During this phase, the initial theoretical framework will undergo revisions based on the findings of the first phase. The modified framework will serve as the foundation for forming hypotheses, which will then be used to make a structural equation model and will then be tested through an online survey.

To summarize, the relationship between safety performance and sustainable production performance will be thoroughly examined using a small group of participants in the initial phase, and the prevalence of its various aspects will be gauged in a larger sample during the second phase.

3 Results and Discussion

3.1 Data Collection and Analysis

Prior to the commencement of qualitative data analysis, the interview transcripts underwent coding using a basic yet effective qualitative data analysis template. From the initial framework, a group of pre-existing codes that also served as themes were identified, namely: 'safety culture', 'industrial characteristics', 'safety performance' and 'sustainable production performance'. If necessary, subthemes were added, which were designated as level 1 codes. To further delve into the responses provided by the interviewees, level 2 codes were generated for each subtheme, ultimately resulting in the final set of codes.

The coded interview excerpts were extracted and transferred onto a spreadsheet designed as a template to streamline data analysis [15]. This was done to facilitate data analysis. By limiting the selection to only relevant excerpts, the researchers were able to concentrate on significant data and disregard irrelevant ones. The results were subsequently compared to those of all other cases [15, 16].

The first part of the qualitative analysis is the within-case analysis, which provides a comprehensive examination of each case individually. Using the interview transcripts, each case was meticulously scrutinized based on the theoretical framework's themes. First, a comprehensive overview of the company, which delves into its industrial attributes was conducted. Followed by a discussion of the safety culture, which is widely embraced by most employees. The analysis then focuses on the safety performance of the company, which can bolster its resilience and minimize the likelihood of accidents. Lastly, the sustainable production performance of the company is examined.

The compiled interviews of 19 participants are categorized according to the industrial attributes, safety culture, safety performance, and sustainable production performance they describe. The theoretical framework previously established was utilized to analyze these cases. Through within-case analysis, the condition of each key construct in every case can be evaluated and assigned to one of four levels: very poor, poor, good, or very good, based on the construct's specific context.

After performing an analysis within each case, a cross-case analysis was carried out to contrast the cases to detect any patterns that may emerge from the analysis and to discover potential explanations for the research phenomenon [17]. The cross-case analysis was carried out by utilizing the factors out-lined in the initial framework and determining the shared attributes of corresponding factors across all cases. Despite its simplicity, this analytical approach proved to be a highly effective method in detecting patterns among the cases and uncovering potential explanations for the research phenomenon [18]. Upon completing the within-case analysis, the shared characteristic observed across all cases was subjected to further analysis.

3.2 Modification to the Theoretical Framework

The outcomes of the cross-case analysis demonstrate a degree of conformity between our original framework and the practices adopted by the industry. Specifically, the findings reveal a complete consensus across all cases concerning the interrelation between safety culture, safety performance, and sustainable production performance. Nevertheless, certain phenomena remain unaccounted for by our present framework.

First, while it was found that every case with a strong safety culture also exhibited good safety performance, indicating that safety culture is indeed an antecedent to safety performance, there were several instances where a strong safety culture coexisted with suboptimal safety performance. This finding implies that safety culture does not exclusively determine safety performance. Upon closer examination of cases characterized by both good safety culture and good safety performance, a common element was identified that was absent in other cases. The attributes that they possess exhibit a remarkable similarity to the organizational collective mindfulness.

As advanced by [19], the notion of collective mindfulness is grounded in five essential principles. These principles encompass a preoccupation with failure, a reluctance to oversimplify, a sensitivity to operations, a commitment to resilience, and a deference to expertise. Collective mindfulness is not simply the sum of individual mindfulness, but rather a product of concerted and mindful efforts undertaken by all members of an organization acting in unison [20]. Employing the five principles of collective mindfulness, organizations engage in a mindful processing of information regarding errors and failures, including possible avenues for recovery [21].

Second, despite some signs pointing in that direction according to our initial framework, our study cannot definitively verify whether industrial characteristics have an impact on the correlation between safety culture and safety performance. There are indications that their impact is more strongly observed in the relationship between safety performance and sustainable production performance, rather than in the correlation between safety culture and safety performance. Considering that more indications of influence from industrial characteristics were found in the relationship between safety performance and sustainable production performance, the framework was revised accordingly.

3.3 Hypotheses and Structural Equation Modelling

The qualitative research findings have yielded a new set of research propositions that will be employed to conduct a further analysis of the proposed relationships between safety performance and sustainable production performance. Following the results of the qualitative phase of this study, a series of testable hypotheses were formulated based on the empirical and theoretical evidence presented thus far to investigate the aforementioned relationships. Based on the previous result, the hypotheses were formulated as follows:

- H1: The higher the firm's safety culture, the higher the safety performance of that firm.
- H2: The higher the firm collective mindfulness, the higher the safety performance of that firm.

- H3: A Firm's safety performance positively impacts its sustainable production performance.
- H4: A Firm's industrial characteristics influence its relationship between safety performance and sustainable production performance.

A survey will be created and conducted online to verify these hypotheses. The survey is presently ongoing and planned to collect over 300 responses. Structural equation modelling (SEM) will be utilized to analyze the quantitative data, which is a second-generation statistical technique designed to address the limitations of first-generation methods such as multiple regression. With SEM, researchers can integrate unobservable variables that are indirectly measured by indicator variables into their analysis [22]. The model for SEM is given as follows (Fig. 2):

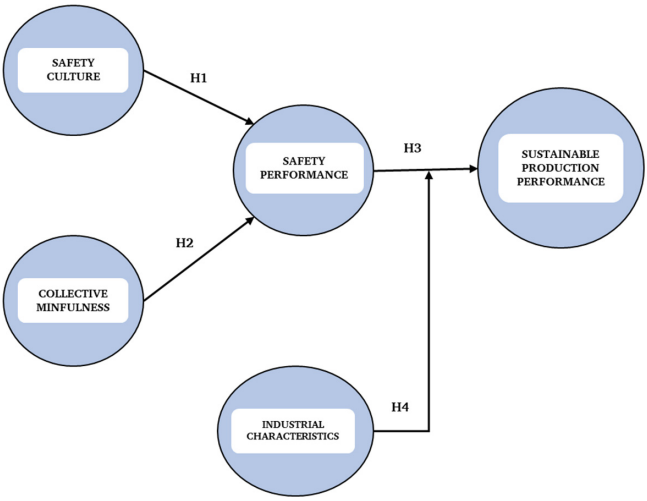

Fig. 2. The Model for Structural Equation Modelling

4 Conclusions

The purpose of this study was to investigate the implementation of the concepts outlined in the initial framework regarding the relationship between safety and sustainable production performance in the chemical industry. Strong correlation between the two can bring a new direction in achieving sustainability. Two phases of data collection and analysis will be carried out to validate the framework's applicability. The first phase, a qualitative study, has been done. The qualitative study validated some aspects of the original framework and provide two improvements for the second phase. First, another antecedent for safety performance was recognized. Collective mindfulness, which consists of five core principles, have been identified in several cases, influencing the safety performance of the firm. Second, the impact of industrial characteristics was more strongly observed in the relationship between safety performance and sustainable production performance.

Following the results of the qualitative phase, four testable hypotheses were formulated. The second phase involved a quantitative study to test these hypotheses. Structural equation modelling (SEM) will be utilized to analyze the quantitative data, and a model for SEM has been developed.

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Circular Economy in the Electronic Waste Reverse Chain in Brazil

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Abstract. The Brazilian territorial extension made it difficult to structure a reverse chain to deal with issues related to Waste Electrical and Electronic Equipment (WEEE). This is due to government requirements for the management of this waste by electronics manufacturers and importers. To compete with external competitors, companies need to use the circular economy, which further increases the complexity of the project. Thus, this research identified that the industries in this sector have difficulties in organizing themselves for the reverse logistics operation of electrical and electronic equipment. The objective of this study is to propose a structure for the reverse chain in the management of electronic waste in Brazil. The methodology used was a semi-structured interview with open questions with specialists in WEEE reverse logistics. As a result, the construction of a conceptual model for the reverse logistics of WEEE with the promotion of the Circular Economy. As a limitation, as it uses a semi-structured interview with specialists, it uses an exploratory approach and, therefore, cannot generalize the results.

Keywords: Circular Economy · Waste Electrical and Electronic Equipment · Reverse Chain · Reverse Logistics

1 Introduction

Due to the increase in production and obsolescence of electronic equipment, the volumes of waste generated present an impressive increase. It is estimated that the waste from electrical and electronic equipment (WEEE) increases by 3–5% each year [1]. Proper disposal of materials contained in WEEE helps maintaining the environment while conserving valuable resources. Furthermore, improper disposal can negatively impact the environment and decrease the value of an extra resource [2]. The reuse and commercialization of raw materials contained in the EEE such as aluminum, bronze, copper, iron, steel, silver, steel, and zinc can create economic opportunities. Thus, the disposal of WEEE can be economically beneficial because they can be reused and/or marketed for reuse [3].

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Federal Law No. 12,305/2010 [4] describes the specificities of the reverse logistics system in Brazil. Called the National Solid Waste Policy (PNRS), this law provides guidelines for the management of the WEEE reverse logistics system This law also establishes shared responsibility for the reverse chain of WEEE. Reverse logistics encompasses methods, procedures, and materials for collecting and processing materials for reuse in manufacturing or environmentally correct disposal. This operation helps to promote economic and social growth, reversing the process [4]. Reversing the cycle, providing a destination for materials and products before they are sent back through the cycle, is called reverse logistics. This involves planning, implementing, and controlling the reverse flow of materials, finished products or rejected or discarded materials. Minimizing environmental impact and following legal guidelines are necessary components of reverse logistics [5].

The PNRS observes that the sectoral agreements revolve around contractual laws of the public power involving participants in the reverse chain such as managers, distributors, importers, and manufacturers. These legal acts help ensure that reverse chain participants can adapt to the current solid waste management system [6]. In 2019, a sectoral agreement was signed that requires reverse logistics and the participation of EEE manufacturers, importers, distributors, and traders in waste collection. This was done specifically to increase the amount of WEEE collected [7]. Although this Brazilian sectoral agreement promotes reverse logistics, its failure is due to many factors that make the process ineffective, such as inconsistent WEEE collection channels and lack of feasibility assurance due to classification challenges [8]. Thus, studies that propose the organization of the reverse chain are recommended, since the PNRS, the sectoral agreement and the management of WEEE in Brazil have not yet reached operationalization despite having already been implemented.

The objective of this study is to propose a reverse chain for the management of electronic waste for Brazil based on interviews with specialists in the sector. The relevance of this study extends to more than just the field of business; it also affects organizational theories and practices. Due to Brazil's high production of 1.5 million tons of waste electrical and electronic equipment each year, this country is the second largest producer of WEEE in the American continent. In addition, the city of São Paulo approved a sectoral agreement for electronics in 2019. With that, it required the implementation of the reverse chain of WEEE. Thus, for the reverse logistics of WEEE in Brazil, industries find it difficult to organize themselves due to the extension of the territory.

The structure of this article presents in Sect. 2 the literature review on circular economy in the electronic waste reverse chain. In Sect. 3, the research methodology is described. In Sect. 4, the results of the most appropriate WEEE reverse chain to promote the circular economy in Brazil are presented. Section 5 discuss the results obtained. Finally, the last Section 6 presents the conclusion.

2 Literature Review

Shittu et al. [1] conducted a study on e-waste management and disposal in India, concluding that manufacturers play a crucial role in promoting the circular economy by being involved in the design, production and management of WEEE until the end of its

useful life. To illustrate the importance of WEEE management in the circular economy, five case studies were conducted in Ukraine, which highlighted the need for optimal collection points in reverse logistics, requiring new transport methods, consumer participation and new product designs [9]. Furthermore, Italy provided three case studies demonstrating the use of closed-loop WEEE recycling and reuse of materials in the secondary market [10], which contributed to achieving EU recycling and collection targets [11] and establishing a link with the industry [12]. The recovery of precious metals and the reduction of environmental impacts in the UK were also studied through a case study [13].

Thirteen studies focused on WEEE reverse logistics to promote the circular economy, with particular emphasis on the operation of recyclers. In Brazil, three case studies were conducted to explore the fate of recycling, reuse and reprocessing of WEEE in Rio de Janeiro, which became a source of income and job creation [14]. The impact of recycling routes, the generation of WEEE materials and the location of recycling facilities were also considered. New circular business models have been driven by the need to recycle, and Brazilian recyclers have examined management and remanufacturing practices associated with WEEE to gain insight into a circular economy, leading to increased revenue through increased recycling and remanufacturing [16].

Two case studies in Belgium investigated the economic and technological effectiveness of plastic recycling methods integrated into WEEE, leading to closed-loop reuse and the creation of the circular economy [17, 18]. Sengupta et al. [19] explored the extended responsibilities of WEEE producers in India, revealing that formal and informal WEEE recycling sectors can lead India towards a circular economy. A case study by Cordova-Pizzarro et al. [20] showed how Mexico manages the recycling of secondary WEEE material from cell phones and how the recycling and reuse of these materials stimulate the circular economy. In Sweden, a case study revealed the economic and environmental benefits of recycling, reusing and remanufacturing laptops at the end of their useful life, contributing to the circular economy [21]. Tong and others. [22] studied the effects of environmental regulations on Chinese recycling management, leading to better management and reuse of WEEE, which encouraged circularity. Levenen et al. [23] investigated the impact of business models on the management of the circular economy in two different countries, Finland and Chile, highlighting the importance of this interaction in the closed loop recycling and reuse process.

Parajuly and Wenzel [24], in their case study, emphasized the need for recycling centers to focus on the reuse of WEEE, making reuse and recycling necessary aspects to promote the circular economy. Hagelüken et al. [25] analyzed government regulations to refine the circularity process in German and Belgian WEEE recyclers, specifically in the recovery of precious metals. Finally, Sabtu et al. [26] presented a case study demonstrating how logistics companies in the Malaysian WEEE reverse chain led to financial savings, increased revenue and waste circularity.

3 Research Methodology

The methodology used was structured in five steps: (i) proposition of the questions by means of literature review, (ii) elaboration of semi-structured questionnaire, (iii) collection of electronic addresses, and (iv) analysis of the data. The first stage aimed

to understand the context of WEEE through a study based on publications in the area. Through an open exploration of the available information, it was possible to understand WEEE and build the necessary reasoning to formulate questions. According to Yin [27], establishing a strong theoretical foundation is essential for exploratory studies.

In the second stage, after carrying out the literature review, a semi-structured questionnaire consisting of open questions was prepared for data collection. The questionnaire contained the following guiding questions:

1) Does the EEE manufacturer manage WEEE internally?
2) Does the EEE manufacturer hire a WEEE manager?
3) Is the WEEE manager responsible for the collection points?
4) Is the WEEE manager responsible for hiring a logistics operator for transport, storage, separation and sending to treatment centers for segregation and pre-processing?
5) How do WEEE treatment centers perform segregation and pre-processing?
6) Does the logistics operator contracted by the WEEE manager remove waste for reuse at the manufacturer and/or secondary market?

In the third phase, the work included searching for the electronic addresses of specialists with in-depth knowledge in WEEE reverse chain management who knew and were actively involved with the actors, that is, producers, managers, and recyclers. The process involved nine highly specialized executives from EEE manufacturing and importing companies, all with in-depth knowledge of WEEE reverse chain management. These specialists interact regularly with the main players in the sector, such as manufacturers, managers and recyclers, and are actively involved in compliance with the Sector Agreement for the Implementation of WEEE Reverse Logistics. Then, the fourth step was to send a link with the address of the semi-structured questionnaire to the respondents and directly contact the person responsible for answering the semi-structured questionnaire in person. Based on the answers, a qualitative analysis of the questionnaires was carried out, which allowed the development of a structured model of the reverse chain of WEEE for the Brazil.

4 Results - Most Appropriate WEEE Reverse Chain to Promote Circular Economy in Brazil

According to the results of the "WEEE Management", which is considered the most favorable to manage the reverse chain of electronic waste through the promotion of circular economy, both in practical and feasible conditions [10, 28] and the Sectorial Agreement for the Implementation of the Reverse Logistics System for Electronic Products designate a collective management system used to organize reverse logistics. Manufacturers, importers and associations of these EEE manufacturers act as the backbone of this system through regulations involving technical management, as shown in Fig. 1.

The Brazilian "Sectorial Agreement" for electronics is the "Regulator" in the collective system for the implementation and management of the reverse cycle of WEEE. In addition to the management of the entire system, this agreement also promotes strategies that help to promote circular economy in terms of the circularity of materials and environmental compliance. The "PNRS" requires that this agreement also fulfill its requirements

with regard to environmental management, which is why it enacts laws applied with its Sectorial Agreement.

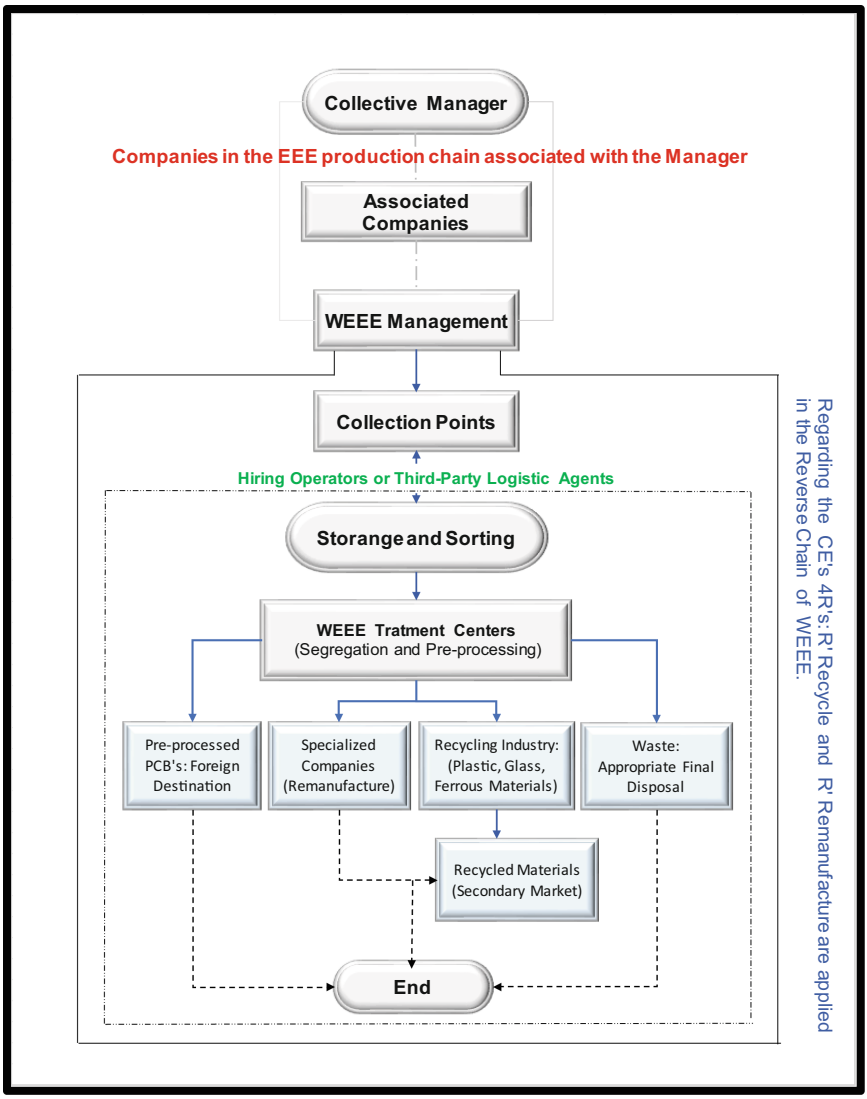

Fig. 1. Schematic Representation of the Player (Collective Management)

The "Collective Model" gives greater importance to the EEE Manager's related business ventures. Additional explanations of this system appear in the following paragraphs. The Collective Manager carries out the reverse processing of the WEEE chain, establishing collection points. This group also hires outsourced logistics coordinators or agents, who manage the logistical transport of WEEE throughout Brazil. Electronic

waste collected at collection points must be removed from storage and moved from one location to another before being treated. The results highlight the importance of a collective management system in the organization of electronic waste reverse logistics, collaborating with the study by Shit-tu et al. [1] Also emphasize the role of manufacturers, importers and associations [9] in the backbone of this system through regulations involving technical management.

Then, electronic waste needs to be separated, stored and forwarded to treatment centers that carry out pre-processing and segregation. Plastics, glass and metals considered to be ferrous are sent to specific recycling companies when they are still being treated at the WEEE treatment center. These materials are intended for use in the secondary market; remanufacturers use them again after treatment. The only places in Brazil to process pre-consumer items are recycling centers. These materials are then sent to companies specializing in the extraction of precious metals abroad. Effective treatment of WEEE requires proper disposal of unusable materials in accordance with current legislation. This can be done at WEEE treatment centers. Circular economy 4R's are currently in practical use in Brazil's reverse waste chain. As observed by the administrators of this chain, only the R Remanufacturing and R Recycling methods are applied in practice. It is essential to ensure that these materials are removed in an ecological way [13] and that the 4R's of the circular economy (Re-duce, Reuse, Recycle and Recover) are implemented according to Cordova-Pizzarro et al. [20] suggests in the reverse chain of residues.

5 Conclusion

Implementing a reverse logistics system in a country with a large territorial extension can be very costly. Therefore, it is essential to have an efficient reverse logistics system that minimizes costs and increases the use of collection points. This study provides a broader understanding of how Brazilian companies are dealing with electronic waste, presenting a WEEE management model. To manage the WEEE reverse chain, Brazil needs a "WEEE Management Company" that encourages manufacturers to avoid creating individual systems and implement WEEE management. As a limitation, because it uses a semi-structured interview with experts, it uses an exploratory approach, and therefore, it cannot generalize the results. For future research, it is suggested the creation and implementation of an application that assists in the collection of electronic waste for organizational practice.

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Greenhouse Gas Accounting for Manufacturers

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Abstract. Legislation and stakeholders increasingly urge European original equipment manufacturers (OEM) to disclose and reduce greenhouse gas (GHG) emissions of their operations and supply chains. However, a sector-specific reporting standard is not yet available for manufacturing industry. This study takes a stepwise approach to identify the GHG emission sources and intensities in further detail. The primary data of a case company, a Finnish gear manufacturer, was supplemented with secondary data from the literature. Using the proposed approach, an OEM share of the total emissions was estimated at 15%. Evaluating emissions of specific suppliers is more difficult as there is little access to the suppliers' data. The study gives insights for the manufacturers on how to get started with GHG emissions accounting in the factories and supply chains and to show their responsible actions in the climate change mitigation.

Keywords: Greenhouse gas · GHG · Accounting · Manufacturing · Gear · Factory · Supply chain

1 Introduction and Background

Greenhouse gas (GHG) accounting is a standardized quantification of the amount of GHG emissions produced by an organization [1, 2]. The European Union aims to be climate-neutral – i.e., an economy with net-zero GHG emissions – by 2050. To foster the disclosure and reduction of GHG emissions, the Corporate Sustainability Reporting Directive[1] will take effect in 2024. Manufacturing industry emissions account for 21% of EU's total [3]. Large manufacturers are expected to also report the GHG emissions of their supply chain, which are on average 6.5 times higher than the direct emissions of the manufacturer [3]. The EU commission will provide sector-specific reporting standards, which consider the Global Reporting Initiative[2], a program that aims on providing standards for 40 high-impact sectors. The standard will soon be available for the mining industry, while the steel and aluminum production is tenth and the machinery and equipment manufacturing sixteenth on the priority list.

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464.
[2] https://www.globalreporting.org/standards/sector-program/

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Basically, GHG emissions are identified in three scopes of a company's value chain [1]. Scope 1 direct emissions are a consequence of activities an organization owns or controls, which is mainly fuel combustion. Scope 2 indirect emissions result from the generation of purchased energy for the company's own use. Scope 3 (upstream) indirect emissions account for production of purchased materials and transportation. The standards for emissions reporting have not set definite system boundaries on the factory level [4], which is the focus of this study. Consider first the entire factory site as a single activity (unit process, UPR), i.e., the smallest element in a value chain for which inputs and outputs are quantified. The amount of GHG emissions is expressed as (kg of) carbon dioxide equivalents as follows:

$$CO_2e = \sum_i \text{Activity Data} \times \text{Emission Factor}_i \times \text{GWP} \tag{1}$$

In Eq. (1), activity data refers to activities that affect emissions (e.g., kWh electricity consumed), and the emission factor specifies the quantity of GHG emitted per unit of activity (e.g., CO_2e per kWh electricity consumed). By multiplying the two, an absolute emission per activity is obtained. For any GHG, the global warming potential (GWP) is the heat absorbed (typically over a period of 100 years) in the atmosphere as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (hence, GWP is 1 for CO_2). Carbon dioxide is by far the most significant gas emitted by EU's industry, accounting for 86 per cent of industry CO_2e.

The EU commission recently published the best environmental management practices (BEMP) for the fabricated metal products manufacturing sector [5], and previously for all relevant upstream sectors, including foundries, metals processing and surface treatment industries. The core manufacturing BEMP relate to, e.g., metal working fluids, reduction of standby energy of machine tools, post-processing of metal scrap, and hybrid machining.[3]

The authors' discussions with industry players support the view that not only legislation, but also increased environmental awareness of customers and other stakeholders urge companies for GHG accounting. Few sectoral working group initiatives[4] have already produced methodological guidelines and GHG inventories. In the manufacturing sector, studies propose emission mapping on the factory level functionalities and processes [4, 6] and the supplier production processes [7]. However, they have little practical value as they do not provide detailed guidelines along with industry cases. In addition, the most relevant literature sources, methods and concepts for mapping emissions should be compiled. This paper contributes to fill the mentioned gap by proposing a practical approach for GHG accounting along with a case study of an industrial gear manufacturer. Section 2 collects relevant activity and emission factors (Eq. 1), i.e., life-cycle inventory (LCI), data. The study concludes in Sect. 3 with managerial implications. The ultimate goal of the study is to understand the various activities and their impacts on GHG emissions in the supply chain.

[3] The BEMP also gives guidelines for environmental criteria when sourcing goods.

[4] E.g., steel products, freight transportation, and the electrical vehicle battery supply chain.

2 LCI Data Collection with Case Study

Figure 1 graphically illustrates an industrial gear manufacturing supply chain. For reference, it displays the average share in the GHG emissions accounted for by different stages of industrial equipment end products [3]. In this section, the LCI data is collected in the OEM gear factory (Sect. 2.1) and the intermediate production processes (Sect. 2.2), specifically subcontractor machine shop, as their manufacturing processes are closely related. The entire supply chain is also shortly assessed (Sect. 2.3).

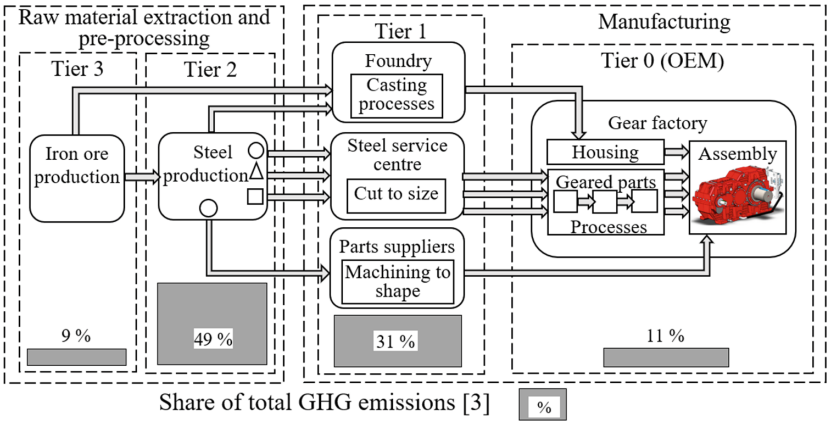

Fig. 1. The main stages of the supply chain

2.1 OEM Gear Factory

Factory Level. Figure 2 is an example of an input-output process in the OEM factory level. Among the various emissions, we consider only GHG (Eq. 1). The factory site-specific primary data are collected on an annual basis from the ERP system for factory outputs, material inputs, and energy inputs, in steps (1) - (11) below. The data collection template and the emission factors of Scope 1 and 2 activities were obtained from [8].

Factory Outputs. Calculate the weight in tons of (1) the end products and (2) components delivered. (3) Calculate the waste, the weight of metal scrap (by type), that can be recycled. This includes machining chips and defective components.

Purchased Material Inputs. Calculate the weight of (4) the foundry castings, (5) steel blanks, (6) machined parts, (7) other parts and sub-assemblies, and (8) process materials, each in tons by the material type and the supplier. The process materials (paints and thinners; cutting and other oils and fluids; water) are omitted from Fig. 3 as their emissions account for only 2% of the material inputs.

Purchased Energy Inputs. Calculate (9) the electrical and (10) the heating energy (by type), both in MWh. Calculate (11) the fuels, both gaseous (kg) and oil (liters).

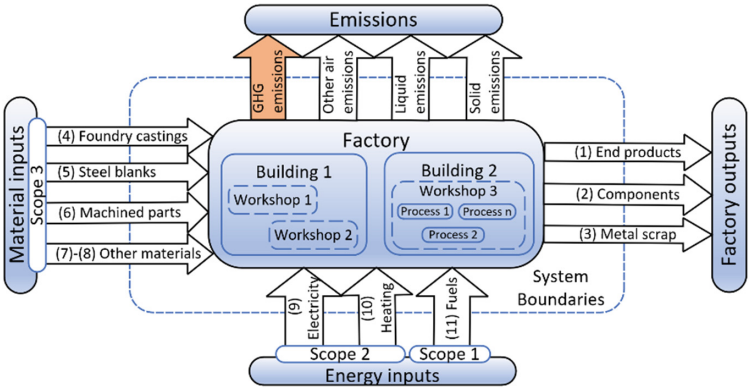

Fig. 2. Factory input-output diagram

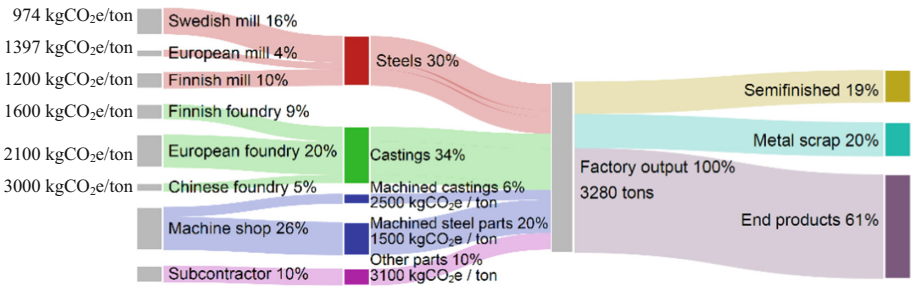

Fig. 3. Materials inputs and outputs in the case gear factory

Building and Workshop Level. The case company commissioned a waste heat mapping to obtain information on energy consumption in the building level. Figure 4 shows the electricity and district heat consumption in the gear factory building. It was estimated that 61% of the electricity is consumed for the property functions and 31% for the processes. 53% of the electricity is consumed in the three production areas (of which 56% and 32% in the geared parts and housing workshops, and 12% in the assembly).

The heat treatment building consumed 2400 MWh electricity and 148 MWh district heat. The fuels accounted for 4% and 7% of energy emissions in the two buildings. The following steps (12) - (20) are derived from the literature (secondary data) to assess energy consumption in (non-)process, machine tool (group), and unit process level.

Non-process and Process Energy [9]. (12) Collect the building information on utility (electricity and heat) bills, operating hours, and physical facilities (blueprints, layout, area, machine configuration). Calculate the (non-)process energy for each building by (13) estimating the non-process power intensity (W/m^2) for lighting, heating, cooling, and ventilation, (14) measuring the energy consumption and, further, the power intensity for each machine. According to [10], 40% of industrial process energy is employed on machine electric drives, 40% to heating and lighting, and 10% to compressed air.

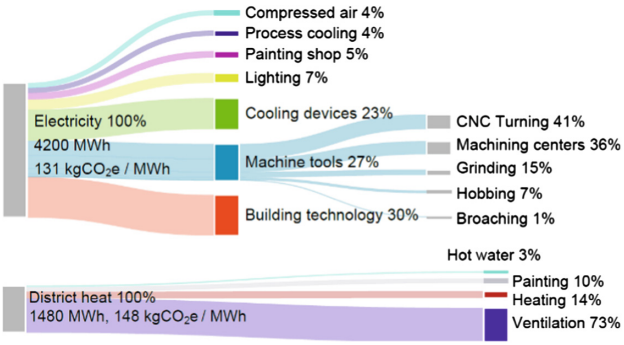

Fig. 4. Scope 2 purchased electricity and district heat consumption in the gear factory building

Machine Tool Group Level. The following approach was used to estimate the electricity demand of machine tool groups at a Volkswagen gearbox factory [11]. (15) Calculate the available quantities and the average power consumptions of machine tools (technologies) in each group (current and those in the investment plans). (16) Multiply two measures to get the total power demand. Three machine tool groups dominate: grinding machines are the most numerous, machining centers have the highest maximum power, and turning machines are in-between the two.

Machine Tool Level. Understanding the energy and materials loss intensities of machine tools is a prerequisite for reducing their emissions. The ISO 14955–3 standard [12] defines the methods to assess the power demands of machine tool operating phases, which are off, standby, setup/warmup, ready (idle), processing, and emergency stop. The case gear factory engineers measured the standby and ready phases electricity powers, which were about 25% and 50% of the rated power of each machine tool. Annual electricity consumption of each machine tool also required information on their operating hours. The analysis can also be performed in machine tool component and operating phase levels, like [13] with a hobbing machine.

Unit Process Life Cycle Inventory (UPLCI) In-Depth Approach. Machine tool operation is a manufacturing unit process, where material/chemical inputs are transformed into a material/chemical output. Kellens et al. [14] developed an UPLCI concept based on cooperative effort on process emissions in manufacturing (CO_2PE! initiative). An UPLCI has the following reference flow: "1 s of processing time for a specified load level of a unit manufacturing process for a specified material, based on a working scheme of 2000 h/year". This requires the following in-depth studies for which a template is available in [14]: (17) A time study identifies different operating phases and their respective shares in the studied time span; (18) A power study measures the consumed electrical power, (19) consumables study the material inputs and outputs (products and waste), and (20) emission study measures emissions for each operating phase. An UPLCI in-depth approach was used to collect LCI data during various sub-operations of a machining center [15] and gear hobbing machine [10].

2.2 Intermediate Production Processes

An OEM purchases materials (foundry castings, steel blanks, and machined parts) from specific intermediate product suppliers (Tier 1, in Fig. 1). They are less likely to provide their emission factors and process-specific data; hence, the OEM must often rely on company-unspecific secondary data. The emission factors (in $kgCO_2e$/ton, Fig. 3) for steel blanks are based on the supplier inquiries and [16]. The factors for castings are derived from [17] and the authors' experience.

Machined Parts. Many parts and components are machined by subcontractors, according to the OEM's specifications. Knowledge about subcontracted parts and related manufacturing processes helps the OEM to estimate their material and energy demands and emissions, in-house.

LCI Databases. The most widely used commercial database, Ecoinvent[5], comprises three material removal UPRs (turning, milling, drilling) for three workpiece materials relevant to our study (cast iron, steel, chromium steel). The data were originally collected and published in [18] using public environmental reports (years 2002 to 2005) of eight manufacturers representing a variety of company sizes and areas of mechanical engineering industry. The GaBi database[6] provides UPRs for steel turning as well as cast iron and steel machining (average from various material removal processes, industry data from the 2010s). The LCI databases also rely on extensive machining studies from the 1980s. Ecoinvent considers the following inputs per kg of metal removed (scrap) and per kg of metal product: metal working machine (construction), factory buildings (construction and disposal), machine operation (process energy, auxiliary materials), factory operation (non-process energy, waste disposal), and metal input. In high-volume production, the negligible impacts of the metal working machine [13] and the factory do not necessarily have to be considered.

From a machining point of view, the most important inputs are metal (kg) and process energy (electricity, kWh) per kg of product. The LCI databases assume that electricity consumption depends on the workpiece material, machining technology and the amount of material removed (the default scrap varies slightly). GaBi provides the power consumption gradient as a function of material removed (kWh/kg). This is often referred to as specific energy consumption (SEC). A range of SEC values for gear manufacturing UPRs can be found in [19]. By knowing the amount of material removed in each UPR (difference of the gross and net weight of a machined component), its energy demand can be estimated.

UPLCI Screening Approach. The rationale behind the CO2PE! UPLCI framework was to collect, document and provide LCI data for discrete manufacturing processes, more widely than LCI databases do [14]. Currently, at least 31 UPLCI documents exists [20]. Those relevant to gear manufacturing include sawing, turning, milling, drilling, grinding, carburizing, washing, and the auxiliary processes of compressed air and metal working fluids.

[5] https://v391.ecoquery.ecoinvent.org/Details/UPR.
[6] https://sphera.com/product-sustainability-gabi-data-search.

The UPLCI considers only the operating phase of the machine tool. The screening approach provides energy and mass loss calculations which use sets of equations and data from secondary sources to develop basic relationships between the most important parameters (in terms of environmental impact and process quality) and the energy/material use. Each UPLCI also includes a documented example of a representative input-output process, which makes them well reused. The major improvement over data in the LCI databases is the inclusion of significant idle and standby energy components. A set of UPLCIs for complex part manufacturing can also be studied [20].

2.3 Supply Chain

The total GHG emissions were calculated using Eq. (1) with the estimated share of the OEM (Tier 0) being 15% and upstream (Tiers 1 – 3) supply chain 85%. This is in line with [3] in Fig. 1. The World Steel association [16] provides cumulative emissions data of steel products (Tiers 3 and 2), while the addition due to intermediate processes (Tier 1) needs more research. Note that the results are highly dependent on the reference year, products, manufacturing settings and supply chains, which differ across OEMs.

3 Conclusions

This paper presented an approach for GHG accounting for manufacturers. LCI data was collected with a case study of an industrial gear manufacturer to identify and quantify most relevant activities that cause GHG emissions. The results suggest that one third of the factory electricity is consumed for processes, and the remaining for the property functions. Most supply chain emissions were produced in the primary and intermediate production processes. It can be difficult to access primary data from the parts suppliers but there are potential tools for estimating their activities and emissions. In addition to their own actions, manufacturers should guide their subcontracting network to a more sustainable direction that both benefit from. Established and transparent methods for emission calculation and reporting can be expected in the future when EU commission releases the sector-specific standard.

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Implementation of DL 101-D/2020 in a Service Building

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Abstract. Energy efficiency and environment decarbonization are domains of growing concern. There is an emphasis in the energy rehabilitation of buildings and in the study and research of improvement measures aimed to make the building an NZEB (Nearly Zero Energy Building). The regulatory framework issued by the member states of the European Union, establish different objectives and provide methodologies for the calculation of energy performance, establishing minimum requirements for new buildings.

This work addresses the implementation of the energy certification in a service building, applying the calculation methods to a case study. Improvement proposals are presented for the energy performance improvement that lead to a reduction in energy consumption.

The purpose is to demonstrate that the proposed measures for the rational use of energy, outlined in the energy certificate, contribute to increased energy efficiency. These measures foster the reduction of energy consumption and consequently the reduction of greenhouse gases emissions.

Keywords: Energy Efficiency · Sustainability · Energy Consumption · Energy Certification

1 Introduction

Currently, there is a great focus on the rational consumption of energy. The energy consumption in buildings represents a significant part of the general energy consumption.

The evolution of the regulatory framework and the resulting rising standards associated with the energy certification criteria contribute to limit energy consumption in residential buildings as well as in commercial and service buildings, mainly by encouraging the renovation of existing buildings, which present a remarkably lower energy efficiency than that of new constructions [1].

The main objective of this work is to follow the energy certification process, by analyzing in detail the use of energy in the building, by identifying, characterizing and

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analyzing the various parameters responsible for changing the energy behavior. After adequate dimensioning of the building, the energy requirements are estimated, and the building's energy classification is determined.

Measures that promote the rational use of energy are also proposed for implementation. These improvement measures contribute to enhanced energy efficiency, and thus to the reduction of energy consumption and to an improvement in the energy class of the building.

The rest of this article is organized as follows. Section 2 presents the main practical problems that are generally associated with energy efficiency in buildings. Section 3 briefly describes the methodology used. In Sect. 4, the real application of the proposed methodology is shown and measures to improve the energy class of the building. Finally, the conclusion about this case study is presented in Sect. 5.

2 Background

Currently, global warming is a major challenge facing society. This challenge to Humanity led most nations to aim at a significant reduction in greenhouse gases emissions, one of the most prominent of which being CO_2. This substance, accounting for the greatest percentual weight in greenhouse gases emissions, is followed by methane with 11% of the total, followed in turn by nitrous oxide and hydrocarbons with 6% and 2% of the global emission, respectively [2].

The capability to reduce greenhouse gases emissions is not even across the EU Member States. Such reality is reflected on the national targets, which are determined according to the gross domestic product (GDP) per capita [3, 4].

The study performed by [5] analyzes different standards of thermal comfort in buildings, by distinguishing the types of applications and estimating comfort levels with the use of natural ventilation, following the three international standards of thermal comfort, such as: "the American ASHRAE 55-2010 standard, the European EN15251 standard, and the Dutch ATG guideline".

Another similar application can be found at [6] where the authors carry out a statistical and restricted analysis of the use of HVAC systems applied in low-energy buildings in Norway, Sweden and Finland, seeking to develop a survey of current trends of systems used that enhance the NZEB concept.

When applying the implementation of energy certification in Portugal, there is a restriction of correlation with the conditions established by the legislation of the Country. It is proven that the member states belonging to the EU (European Union) need to adapt their legislation according to the adverse climatic conditions present in each country, among many other factors, thus implying the separate study of each member state by state. Member.

It is proven that, through the separate evaluation of the countries, it is necessary to have a variety of equipment that implies constant adaptation to the needs currently present in each region.

3 Methodology

According to the National System of Energy Certification of Buildings [7], all residential, service sector and public buildings, when constructed, remodeled, changed ownership, or rented, must be subject to an energy certification process.

The building's classification follows a pre-defined scale of 8 classes (A+, A, B, B-, C, D, E and F), in which class A+ corresponds to a building with better energy performance and class F corresponds to a building with the worst energy performance. Currently, the energy classes of residential, commercial and service buildings are the same.

In new service buildings, the energy classification varies between A+ and B. In buildings subject to major interventions, they must have a class equal to or greater than C. As shown in Fig. 1.

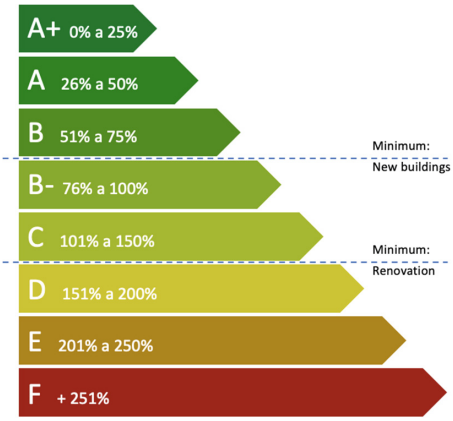

Fig. 1. Energy class model for service buildings [7].

Obtaining the energy class for commercial and service buildings is carried out using the calculation of a ratio, whose numerator corresponds to the value of the difference between the energy efficiency indicators of the predicted consumption of type S ($IEE_{pr,S}$) and renewable energy ($IEE_{pr,ren}$), and whose denominator translates the type S reference energy efficiency indicator ($IEE_{ref,S}$) [1].

$$R_{IEE} = \frac{IEEpr, S - IEEpr, ren}{IEEref, S} \tag{1}$$

The RIEE value is then framed based on the constant values presented in Table 1, directly obtaining the energy performance class of the building.

The calculation of the predicted IEE is done using the following formulas:

$$IEEpr = IEEpr, S + IEEpr, T - IEEpr, ren[KWh_{ep}/(m^2.year)] \tag{2}$$

$$IEEpr, S = \frac{1}{A_{tot}}.\sum(ES, i.Fpu, i)[KWh_{ep}/(m^2.year)] \tag{3}$$

Table 1. RIEE value range for commercial and service buildings [6].

Energy class	RIEE
A +	$R_{IEE} \leq 0.25$
A	$0.25 < R_{IEE} \leq 0.5$
B	$0.5 < R_{IEE} \leq 0.75$
B-	$0.75 < R_{IEE} \leq 1{,}0$
C	$1.0 < R_{IEE} \leq 1.5$
D	$1.5 < R_{IEE} \leq 2.0$
E	$2.0 < R_{IEE} \leq 2.5$
F	$R_{IEE} > 2.5$

$$IEEpr, T = \frac{1}{A_{tot}} . \sum (ET, i.Fpu, i)[KWh_{ep}/(m^2.year)] \tag{4}$$

$$IEEpr, ren = \frac{1}{A_{tot}} . \sum (Eren, i.Fpu, i)[KWh_{ep}/(m^2.year)] \tag{5}$$

On what:
IEEpr – Expected energy efficiency indicator [$KWh_{EP}/(m^2.year)$];
IEE pr,*S* – Type S predicted energy efficiency indicator [$KWh_{EP}/(m^2$. Year)];
IEEpr,*T* – Type T predicted energy efficiency indicator [$KWh_{EP}/(m^2$. Year)];
IEEpr, *ren* – Predicted renewable energy efficiency indicator [$KWh_{EP}/(m^2$ year)].
ES, *i* – Energy consumption of type S uses, by energy source *i* [KWh/ year];
ET, *i* – Energy consumption of T-type uses, by energy source *i* [KWh/ year];
Atot – Total floor area [m^2];
Fpu, *i* – Final energy to primary energy conversion factor for energy source *i*, including renewable [$KWh_{EP}/(m^2$. Year].

The reference energy efficiency indicators are determined for the specific conditions contained in [8], not considering renewable energy sources.

The calculation of the reference IEE is done using the following formula:

$$IEEref = IEEref, S + IEEref, T[KWh_{ep}/(m^2.year)] \tag{6}$$

On what:
IEEref – Reference energy efficiency indicator [$KWh_{ep}/(m^2.year)$];
IEEref,*S* – Type S reference energy efficiency indicator [$KWh_{ep}/(m^2.year)$];
IEEref,*T* – Type T reference energy efficiency indicator [$KWh_{ep}/(m^2.year)$].

4 Case Study

The presentation of the case study refers to a building that will be subject to future works and that can be classified as an existing building subject to renovation.

The existing building currently has industrial use (with office space) and the planned works intend to change its use to a service building, consisting of a restaurant and spaces inherent to the activity.

After characterizing the building and organizing the information by space, it is possible to estimate the consumption for a given usage profile.

This stage corresponds to the use of a detailed simulation program, in this case Carrier's software called Hourly analysis Program (HAP), which meets the requirements of the ASHRAE 140–2004 standard.

A representative model of the building's operation was created, and a simulation of the planned building and the reference building was carried out. The simulation results are used to determine the energy efficiency indicators (*IEE*) and the respective calculation of the energy classification.

The total value of primary energy consumption referring to regulated consumption assumes the value of 325 388 KWh_{ep}/year, as shown in Table 2.

Table 2. Primary energy consumption for regulated consumption.

IEE,prev$_S$	Energy type	Fpui	[KWh/year]	[KWhep/year]
			Energy consumption	Primary energy consumption
Heating [KWh/year]	Electric	2.5	38 749	96 873
Cooling [KWh/year]	Electric	2.5	12 342	30 855
Ventilation [KWh/year]	Electric	2.5	32 339	80 848
Lighting [KWh/year]	Electric	2.5	35 620	89 050
AQS(Solar)	Solar	1.0	14715	14 715
AQS(boiler Gn)	Natural gas	1.0	4755,43	4 755
Bobmas AQS	Electric	2.5	3 317	8 293
			Total	325 388

Given the total area of the building (2 527 m^2), the value obtained for the predicted energy performance indicator is 128.76 $KWh_{ep}/(m^2.year)$ calculated using Eq. (3).

It should be noted that the building has a system of solar panels for DHW, so the renewable energy efficiency indicator assumes the value of 5.82 $KWh_{ep}/(m^2.year)$, a value obtained by Eq. (5).

The following table shows the portions of the regulated consumption indicator as well as their value (Table 3).

According to the methodology for calculating the *IEEref,S* indicator, taking into account the regulated consumption, we obtain the total value of primary energy consumption in the amount of 300 655 KWh_{ep}/year, represented in the following table (Table 4).

Table 3. Expected energy efficiency indicator.

IEE,prevS [$KWh_{ep}/(m^2.year)$]	128.76
IEE,Ren [$KWh_{ep}/(m^2.year)$]	5.82
IEE,prevT [$KWh_{ep}/(m^2.year)$]	357.65
IEE,Total prev [$KWh_{ep}/(m^2.year)$]	480.59

Table 4. Primary energy consumption for regulated consumption for the reference building.

IEE,ref_S	Energy type	Fpui	[KWh/year]	[KWh_{ep}/year]
			Energy consumption	Primary energy consumption
Heating [KWh/year]	Electric	2.5	56 711	141 778
Cooling [KWh/year]	Electric	2.5	17 233	43 083
Ventilation [KWh/year]	Electric	2.5	0	0
Lighting [KWh/year]	Electric	2.5	40 181	100 453
AQS(Boiler Gn)	Natural gas	1.0	15342,17	15 342
			Total	300 655

Considering the total area of the building (2 527 m^2), the value obtained for the reference energy performance indicator S is 118.98 $KWh_{ep}/(m^2.year)$, value obtained by Eq. (3).

Considering the indicators obtained, through the calculation of the energy class ratio, the building presents energy performance C (Table 1) with a ratio of 1.033.

4.1 Improvement Measures

Improvement measures are indicated to improve the energy class of the building.

a. Installation of photovoltaic solar system.

This improvement measure aims to install a Production Unit for Self-Consumption. Thus, it is suggested the installation of photovoltaic panels for self-consumption, in the outer coverage area of the building. In this sense, the installation of 156 modules is suggested, with a unitary power of 0.455 KW and a unitary area of 2.18 m^2, making a nominal installation power of 71.0 kW. The system foresees an annual production of 91,273 kWh of electricity.

Considering the conversion factor of the different forms of energy to primary energy Fpu = 2.5 (KWh_{ep}/KWh).

With the installation of the UPAC, the renewable energy efficiency indicator assumes a value of 96.12 KWh_{ep}/(m2.year).

In this way, an A energy classification is obtained (Table 1), with a ratio of 0.274.

b. Replacement of existing light bulbs with more efficient light bulbs.

The measure is aimed at saving consumption in terms of lighting in the building, replacing higher-wattage lamps with more economical ones. It is expected that 205 light bulbs will be replaced, a power reduction of 4,417 KW and an annual energy reduction of 22,802.2 KWh.

With the implementation of the lighting, the value obtained for the Reference energy performance indicator S is 106.98 $KWh_{ep}/(m^2.year)$.

With this proposal, a B- energy classification is achieved, with a ratio of 0.84.

c. Joint implementation of the two previous measures.

With the implementation of improvement measures, the building is more efficient, which leads to a reduction in the level of consumption.

The joint implementation of the proposed measures foresees obtaining energy class A+ (Table 1) with a ratio of 0.08 and a payback period of 2.9 years.

We conclude that the global PRS is less than 3 years, therefore making the implementation of the measures feasible, considering that the interventions to be implemented result in significant improvements in terms of energy efficiency, guaranteeing a 37.41% reduction in energy consumption electricity and 20.42% in CO2 emissions compared to the forecast initial consumption situation.

5 Conclusions and Future Works

The present study aimed to implement energy certification measures in a rehabilitation project for a service building. By obtaining the energy consumption of the building, the value of the energy efficiency indicators is calculated, and the energy performance ratio is determined. When analyzing the result, the type C energy classification is determined.

Improvement proposals arise with the aim of increasing the energy rating and seeking to promote lower energy consumption.

The first proposal consists of the photovoltaic panels for self-consumption implementation. With its implementation, the building has an A energy rating, contributing greatly to the reduction of the building's energy consumption.

The second proposal for improvement consists of replacing existing light bulbs with more efficient light bulbs. With this proposal, the building obtains the energy performance class B-. The implementation of the measure makes it possible to reduce energy consumption in the lighting segment from 27% to 11%, with a PRI of 4.5 years, which makes it a viable measure.

The implementation of the two proposals, raises the building's energy performance class to A + and consequently leads to a reduction in the building's energy consumption.

As future studies in this field, the analysis of Internet of Things and (IoT) and Artificial Intelligence (AI) solutions in intelligent buildings, as it allows to originate a more detailed investigation on the increase of thermal comfort, quality of life, and at the same time promote the emergence of sustainable buildings with the constant quest to reduce the environmental footprint.

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Sustainability - B Corporation Geo Distribution

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Abstract. Nowadays, for companies to assert themselves in the markets, the focus on sustainability and social responsibility is preponderant and supported by academic research. For this, certification is considered an essential means to achieve high levels of social responsibility and sustainable development. In this study, we investigate the Geo distribution of the B Corp certification, a certification aligned with the main assumptions of the triple bottom line. Given its novelty, the B Corp certification phenomenon diffusion/evolution, namely its degree of implementation in different countries, has yet to be researched in depth. Hence, this study, supported by data gathered through the B Corporation certification system database, descriptive statistics, and geo-reference interactive maps, maps B Corp certified organizations' geographical distribution and worldwide growth. The sample refers to a total of 2262 companies certified between the period 2017 and March 2021. The result showed a strong presence in the United States and appreciable growth in Europe, allowing for a better understanding of the B Corp diffusion patterns and supporting companies and certification bodies worldwide to emphasize social responsibility and sustainable development.

Keywords: B Corporation · Sustainability · Triple Bottom line (TBL) · Social Responsibility · Certification · Geo-distribution

1 Introduction

Even though sustainability is a straightforward general concept and widely accepted as a good idea in theory, many still need to fully understand the impact and critical necessity of such sustainable development and growth practices. In the last two decades, economic growth has mainly come at the expense of the environment, impacting today's climate change and depletion of natural resources. The relevance of sustainable development (SD) is emphasized by United Nations 2030 Agenda for Sustainable Development [1]

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and the corresponding sustainable development goals (SDGs) that measure the progress towards SD. Companies are key actors in promoting SD, and emphasis on social responsibility has also increased lately, as socially responsible companies project more attractive images for consumers and shareholders, positively affecting their financial results. Nevertheless, the extent and speed of adopting sustainable practices are insufficient to achieve the Sustainable Development Goals as aspired [2]. Moreover, there is a need for sustainable business models that anchor sustainability at the core of the business and support business operations, preferably within a suitable framework and contribute to ensuring companies enduring success [3]. Due to the potential contribution of B Corp certification to the SDGs and sustainability among companies, the subject has received growing attention in the academic literature [4]. Moreover, there is increased evidence of the mutually beneficial and reinforced relationships between digital transformation and sustainability [5]. Since certification is an essential means for companies and organizations to achieve high levels of Sustainable Development and Social Responsibility [6–9], in this article, we contribute to the B Corporation certification model body of knowledge by studying its geo-distribution, in line with the main goals of the Sustainable Governance Indicators and Triple Bottom Line (TBL) framework. Hence, by highlighting the geographical distribution of B Corp certification worldwide, this study can provide valuable insights to companies that want to pursue sustainability and respond to present and future stakeholder needs.

2 State of the Art

The B Corporation certification model was created in 2006 in the United States and is not limited to the scope of products or services. Social responsibility (SR) emerged to deliver sustainable economic, environmental, and social value to the organization's extended stakeholders and society in general, and B Lab measures companies' entire social, economic, and environmental performance, which is the central pillar of the theory (TBL). The critical metrics measured during the BIA assessment process are the operations, the Supply and input of materials, charitable donations, business model, employees, community, environment, and customers. This certification proves that B Corporation companies are governed by the highest performance standards, giving them a seal of trust for interested parties [10]. Academic studies on the B Corporation reveal that it is a subject with great potential and emerging in the academic community [11], which supports the research question (What is B Corp Geo distribution?) for this investigation. This model is supported by transparency and accountability requirements where B Lab, a not-for-profit organization, administers B Corporation certification. Although little is known about the concept of B Enterprises, the commitment to the (TBL) philosophy catalyzes the sustainable development of the companies and organizations that adhere to it [12]. B Lab is already a well-known organization in the field of certification and is growing fast. Nevertheless, some companies are still reticent concerning the financial impact resulting from the implementation of this certification. However, as shown by a study carried out in the past on the subject, the positive effects on the growth of companies' turnover in the short term, resulting from the increase in transparency and the positive socio-environmental impact observed, outweigh the adverse

effects due to the rigorous procedure of audit [13]. The critical analysis of the potential of this certification, compared to the basic principles of the circular economy, allows an opportunity to portray multiple dynamic points of view concerning stakeholders [14]. Therefore, this research posits that adopting the B Corporation certification can activate circular economy paths due to the action of different stakeholders in an international context. The objective of B Lab is to improve the alignment of companies' missions and measure the impact of their business to meet the highest standards of society today [15]. The commitment to socio-environmental performance, sustainability, transparency, and legal responsibility is part of this pro-social movement and entrepreneurship strategy.

Some studies try to understand the reason and the most common reasons that lead companies and organizations to seek B Corporation certification. The main reasons for seeking this certification are that companies identify their mission with this model and attempt to enhance their values and identity in the markets [16]. Understanding the main reasons that lead interested parties to look for companies certified by the B Corporation is another perspective that deserves some attention. Regardless of whether this certification is a good tool for companies to identify more effective ways of integrating social values into markets, the adoption of green practices and the resulting environmentally friendly image, it can improve the quality of its services/products, which is a crucial success factor [17, 18]. In a survey carried out by academics, it was demonstrated that organizations and companies with strong brands in the markets often believe that they have already reached high ethical standards. However, they aspire for interested parties to know this [19]. According to the author, the B Corporation certification would give them that seal of legitimacy for foreign markets, investors, and customers.

The (TBL) alignment of B Corporation companies acts as driving and motivational forces on the overall assessment of the impact of benefits for the common good. In this context, the B Corporation movement competes alongside existing models as a new paradigm in sustainable development [20]. In the manufacturing scope, other tools, such as Lean, which contribute a lot to the sustainable development of companies [21], maybe an essential part of this sector's growth. The literature on the dissemination of certification (namely, ISO Management Systems certification) is extensive, and results found different geo-distribution patterns and approaches on a worldwide basis [22, 23]. However, given its novelty, the B Corp certification phenomenon diffusion/evolution, namely its degree of implementation in different countries, has yet to be researched in depth. Hence, by investigating the Geo distribution of the B Corp certification, this study provides valuable information for companies and certification bodies worldwide because it allows a better understanding of the B Corp diffusion patterns.

3 Method

The methodological basis of this paper followed a scheme for academic studies, where the social context, literature, database and discuss recent research articles are the principal focus [24]. Data was gathered through the B Corporation certification system database, and descriptive statistics and geo-reference interactive maps were applied to depict the B corporation Geo distribution. Therefore, ensuring these methods are reproducible by other researchers. The B Corp assessment method scores all impact areas

on a numerical scale in point terms, and a minimum of 80 points is required to obtain certification. Furthermore, this assessment is based on the company's performance over the last 12 months, which makes only companies with at least one year of operation eligible for B Corporation Certification. Directly from the B Corporation certification system database (https://bcorporation.eu/directory), data was collected on the evaluation process of 2262 companies, spread across 71 countries, that obtained the certificate. The collection period depicts data from certified B Corporation companies between the beginning of 2017 and March 2021. In addition to the scores data of these companies certified by B Corp, it was also collected the data related to the country, city, and the month and year of the certification. Therefore, this article's focus was supporting a concrete analysis concerning the system's georeferentiation and temporal evolution. Furthermore, the data obtained on the geo-reference of the certified companies during the sample period were inserted in an interactive map from the google maps platform, thus making it easier to perceive the distribution of B Corp among the regions of the globe.

4 Results

This section reports the results obtained through the B Corporation database. As expected, the country with the highest number of certifications, 30.1% of the total sample during the abovementioned period, is the United States, where the certifying body is original. The United Kingdom follows it with 13.4% of the total sample observed. As a result, these two countries comprise a percentage value of 43.5%, thus presenting a considerable weight and demand in the B Corp. Below is a small ranking of the ten countries with the highest representation (Table 1).

Table 1. B Corporation Rank Top 10.

Rank	Country	B Corps
1º	USA	681
2º	UK	303
3º	Australia	171
4º	Canada	171
5º	Brazil	107
6º	France	87
7º	Italy	87
8º	Argentina	73
9º	Netherlands	60
10º	Chile	59

It is essential to understand why the United Kingdom (despite being from another continental area than the USA) is the second country with the highest number of certifications. There may be a cultural approach, another indicator that may influence the demand for B Corp, or a clear negotiating strategy on the part of the United Kingdom to open up new markets. Portugal is in 25th place in the international panorama of B Corp certification, with ten certified companies by March 2021.

The following map (see Fig. 1) gives a better idea of the distribution of B Corporation certification worldwide.

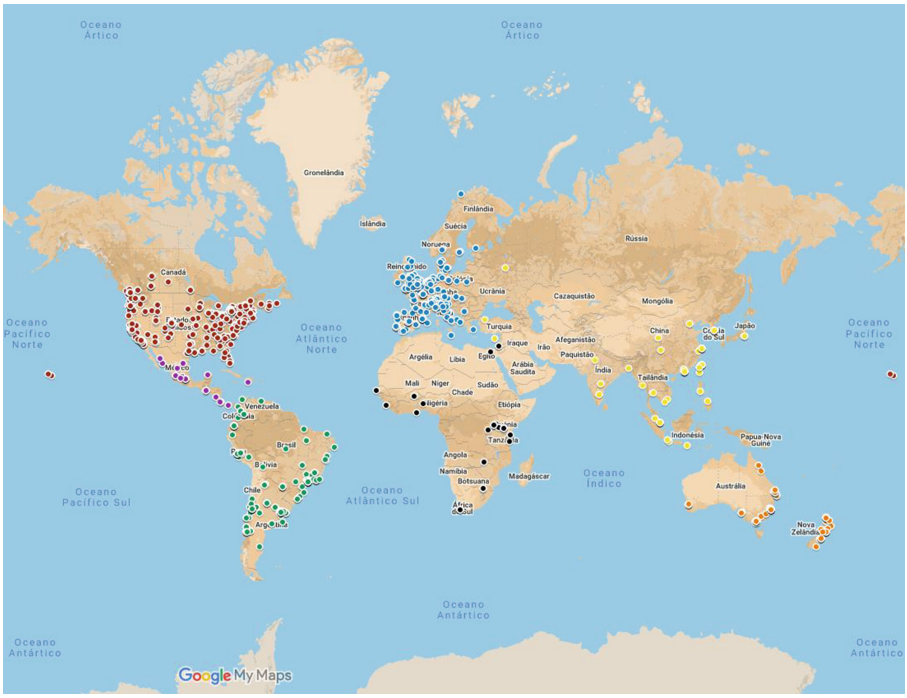

Fig. 1. Map of world distribution of B Corporation (2262 enterprises).

In Europe, the countries that stand out the most are the UK, with 303 certifications, followed by France and Italy, with the same number of B Corp companies, with 87 certifications in each country during the observable sample period. (see Fig. 2).

The most significant number of certified companies is concentrated in the main cities and capitals. However, the geographical distribution in Italy is more homogeneous and not only concentrated in the country's main areas. In addition, Italy was the first European country to introduce a legal framework for benefit companies [25]. This may have contributed significantly to the sedimentation of the B Corporation throughout the country.

The temporal analysis of certification makes it possible to understand in detail the direction of the certification system in recent years. Furthermore, through the data obtained, we could have a concrete perception of the growth of this certification model in all regions of the world.

As we will see below (Fig. 3), of the seven regions analyzed and illustrated in Fig. 1, Europe is the region with the highest growth when it comes to this certification B Corp. Contrary to expectations, the North American region showed, during the same observation period, a deceleration in the growth of the model (see Fig. 3).

The remaining regions with a less significant amount, such as South America, Oceania, and Africa, also showed a negative trend. On the other hand, Asia and Central America showed a slight growth trend with a negligible impact in terms of quantity.

Fig. 2. Map of Europe distribution of B Corporation (Jan.2017 – Mar.2021).

The data analysis also allows for a comparative evaluation relating the two geographical areas with greater representation of the B Corporation and the sector of activity of the companies that obtained the certification. Regarding sectors, the data collected reflects five distinct areas: wholesale and retail, services with minor and significant environmental footprint, manufacturing, and agriculture.

As can be seen from the graphs in Fig. 4, both in the North American region and Europe, the predominant sector of the B Corporation is undoubtedly the service sector with a low ecological footprint.

In proportional terms, we can conclude from this analysis that both regions follow similar sectoral patterns.

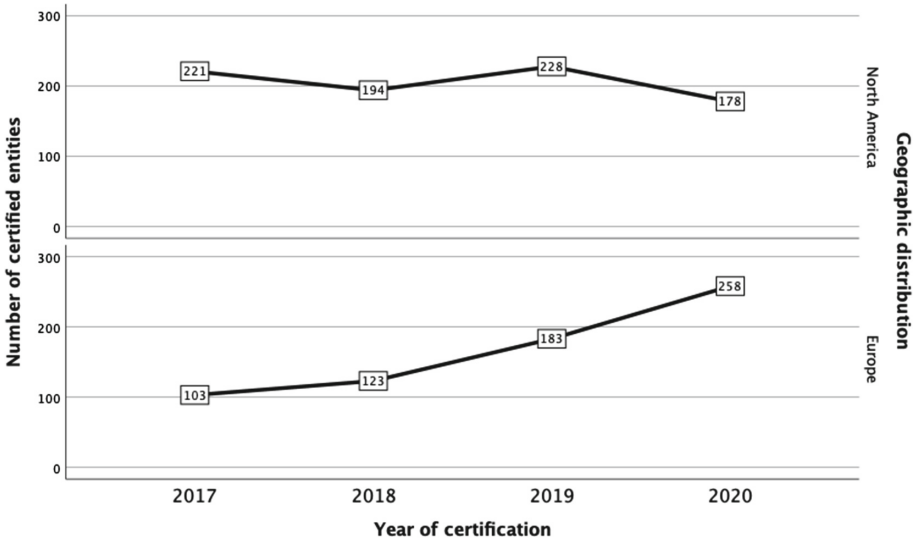

Fig. 3. Growth of the B Corporation in North America and Europe (Jan.2017 – Dec.2021),

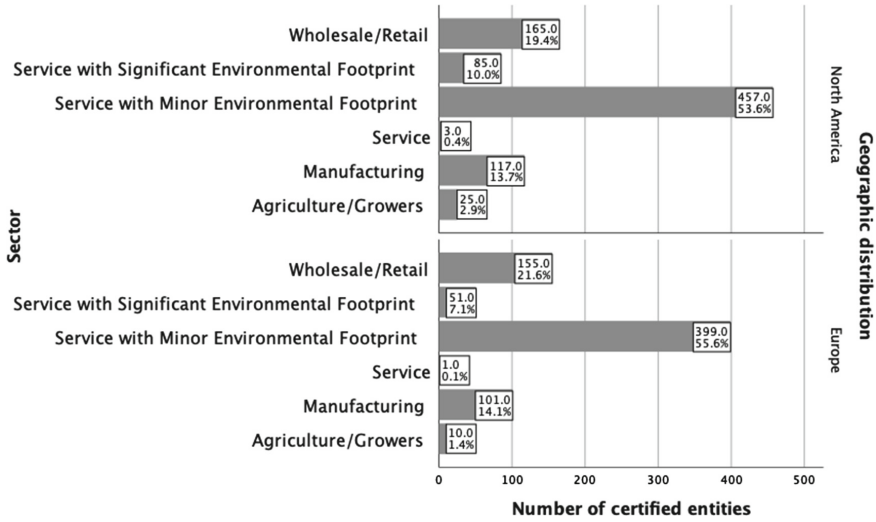

Fig. 4. B Corp certifications by activity sector in North America and Europe (Jan.2017 – Mar.2021).

5 Conclusion

The B Corporation certification model is a subject under development, and there are still many questions surrounding it. However, public articles on this topic have increased exponentially. Some authors, managers, and other stakeholders challenge academics to focus on understanding this certification system, exploring all the perspectives that

involve it to respond to fundamental questions about its evolution and importance in the prosocial context [15].

As we expected in our research, the results show a strong presence of this certification model in the United States, 30.1% of the total sample referring to 2262 companies that have obtained the B Corp seal. However, the countries most adhering to this certification model in the European region are the United Kingdom, ranking second with 13.4%, and France and Italy with 3.8% each. As it is possible to interpret through the graph in Fig. 3, Europe presents a growth trend, even higher than the region where this certification originated. Hence, although B Corp certification does not show the same worldwide spread as ISO Management System Certifications (such as ISO 9001 or ISO 14001), it is consistently growing in other geographic areas outside the United States and Canada, hinting that the B Corp worldwide dispersion is increasing.

Regarding the sectors of economic activity in North America and Europe, the sectoral distribution of the B Corporation is similar in proportional terms, clearly standing out in both the services sector with a low ecological footprint.

Authors [26–29] (e.g., Berrone et al., 2007; Fonseca et al., 2016; Margolis & Walsh, 2003; Mattingly, 2017), have argued that companies that implement social responsibility policies and satisfy the expectations of their stakeholders have higher economic benefits than competitors and achieve positive differentiation. Hence the firm investment policy in sustainability and social responsibility projects or the attempt to open new markets can be the main reasons that may drive European companies and organizations to join this certification. The potential contribution of B Corp certification to the SDGs and sustainability among companies can enhance its market competitiveness and business performance. Moreover, there is increased evidence of the mutually beneficial and reinforced relationships between digital transformation and sustainability [4].

This study gives a clear geographical idea of the demand for sustainable development methodologies. Furthermore, it highlights the differences between countries and world regions and that the manufacturing sector still needs to catch up compared to services. Therefore, additional research could focus on the reasons and conditions for implementing and certifying with B Corp in different world regions. Moreover, another proposed line of future research would be to investigate the role of B Corp within digital transformation and sustainability. Namely, how can B Corp support digital transformation and sustainability, and how does it evolve to ensure synergies with the new paradigms. The main limitation of this research is that the results obtained can be conditioned (i) by the accuracy of the data provided by B Corp and (ii) by the geo-reference interactive maps methodology.

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A Smart Vertical Farming System to Evaluate Productivity, Quality, and Sustainability of Agricultural Production

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Abstract. Traditional agricultural practices negatively impact the environment, and they usually don't allow flexible crop production. Vertical farming has been discovered to be an effective remedy for these problems. It has higher yields, and it can be more flexible and performant than open-field agriculture, because of its structural and technological characteristics. To get the best performance from vertical farming systems, it is necessary to consider several KPIs, which assess productivity, quality and sustainability aspects. The aim of this work is to identify both the input variables and the KPIs that must be considered in a vertical farming system. Furthermore, the experimental design of an aeroponic chamber is proposed, for conducting experiments varying the input variable values and collecting the related KPI. The analysis of such data will allow to find correlations between the input variables and the KPIs.

Keywords: Smart Agriculture · Vertical Farming · IoT · Sustainability · Flexible Agricultural Production

1 Introduction

Traditional agricultural practices, such as deforestation, intensive farming, and the use of chemical fertilizer, greatly contribute to the environmental crisis, resulting in CO_2 emissions, soil temperature increase, and water and air pollution. Continuous cropping techniques have also led to decreased soil pH and reduced enzyme activity, negatively impacting agricultural efficiency [1].

Moreover, traditional agriculture does not consent to flexible production, since it relies heavily on monoculture, which makes it difficult to adapt to changing conditions such as climate change, pests, and diseases [2]. Then, also the geographical and seasonal dependence of traditional agriculture makes crop production inflexible. These factors can lead to difficulties in adapting crop production to meet shifting demand or unexpected events, potentially resulting in reduced yields and economic losses.

Vertical farming (VF) systems are found to be a viable solution to address these issues. They allow plants to be raised indoors, without solar radiation, and with precise control of environmental parameters [3]. Specifically, VF uses vertical space by stacking

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plants on different shelves or in tall towers. It can be done with different techniques such as hydroponics or aeroponics. In hydroponics, plants are cultivated in a water-based nutrient solution while in aeroponics the solution is sprayed on the plant roots that are free of air [4]. Typically, the plants grown in these systems are leafy greens and herbs.

Vertical farms can be defined as a controlled environment agriculture system because different environmental and cultivation parameters can be controlled independently [3]. Plants are grown by controlling parameters that influence the physiological response of crops such as temperature, humidity, fertigation, CO_2 and even microbial community [5]. To achieve complete control over environmental variables, recently Internet of Things (IoT) architectures have been integrated with these systems [6]. IoT is an internet-connected network of multiple physical devices that allows data to be collected and shared without human intervention [7]. Through the sensors, the system acquires the input values given to the plant that affect its growth.

Several studies are present in the literature addressing the correlation between sensor measurements and crop yield or resources optimization [8]. However, the majority of such studies only analyzed the influence of one or few input variables on one KPI. Since many KPIs exist, which address different aspects of the crop (e.g., productivity, quality, sustainability), to conduct a proper evaluation of the VF system, the highest possible number of KPIs should be collected and analyzed to better define a complex biological system [9]. For this reason, this paper aims to first summarize the input variables and the KPIs that need to be considered in a VF system. Then, the experimental design of an aeroponic chamber is proposed, for conducting experiments varying the values of the input variables and collecting the related KPI. The analysis of such data will allow finding correlations between the input variables and the KPIs.

The rest of the work is structured as follows. Section 2 describes the input parameters in a vertical farming system. Section 3 reports the KPIs used to evaluate different aspects of the crop. Section 4 defines the initial experimental design of an aeroponic chamber based on the variables and KPIs identified. Section 5 concludes the paper and presents future developments.

2 Input Variables of Vertical Farming

The input variables of VF are the parameters that can be controlled or measured in real-time in an automatic way, and which influence plant growth and physiology. They can be divided into three categories: (i) environmental, (ii) climatic, and (iii) nutritional. Each category includes two to five input variables, as reported in Table 1.

The environmental category includes five input variables: CO_2 concentration, light intensity, light spectrum, photoperiod, and irrigation period. CO_2 is tightly related to the crop growth rate since it is improved by carbon fertilization [10]. Light intensity is an essential element for plant growth because it influences vital processes such as photosynthesis [11]. In terms of the light spectrum, the effects of red (600–700 nm) and blue light (400–500 nm) on plant development receive the greatest focus since photosynthetic pigments mainly absorb these wavelengths [12]. Moreover, the ratio between these two wavelengths has been studied [13, 14]. The photoperiod also affects plant growth since it helps differentiate photosynthesis's dark and light phases [11]. In

an aeroponic system, it is also essential to monitor the irrigation period, which can vary between day and night [15].

The climate category consists of two input variables, air temperature, and humidity. The temperature regulates the rate of plant growth. In fact, chemical reactions usually speed up as the temperature rises. High humidity also speeds up the plant growth rate since it maximizes the plant transpiration rate [16].

Finally, the nutrient category includes four input variables: pH, electroconductivity (EC), specific ions concentration, and solution temperature. The pH affects the wellness of the crops in two ways: on one hand, it guarantees the bioavailability of dissolved salts and, on the other, it preserves the root integrity [17]. EC is proportional to the salt dissolved in water and its value gives an idea of the number of nutrients present. However, such measures cannot discriminate between different nutrients. In fact, the ions not needed by the plant are also considered in the total nutrient concentration [18]. For this reason, the EC measurement should be supplemented with the ionic selective measure. Finally, the temperature of the solution must be monitored too because it also affects root growth [16].

Table 1. Input variables of vertical farming.

Category	Input variable	Unit of measure
Environmental	CO_2	ppm
Environmental	Light intensity	$\mu mol/m^2s$
Environmental	Red and Blue ratio (light spectrum)	NA
Environmental	Photoperiod	h
Environmental	Irrigation period	min/h
Climatic	Temperature	°C
Climatic	Humidity	%
Nutritional	pH	NA
Nutritional	EC	dS/m
Nutritional	Specific ions concentration	mol/L
Nutritional	Solution temperature	°C

3 Performance Indicators of Vertical Farming

In literature, several KPIs have been considered to evaluate different characteristics of VF. They can be grouped into three categories: (i) productivity, (ii) quality, and (ii) environmental sustainability, as shown in Table 2.

Productivity is the most studied category. The four KPIs belonging to this category are fresh total weight, dry total weight, leaf area, and stem diameter. They are evaluated at the end of the crop-growing period. Once harvested, the plants are weighed using a

centigram-sensitive scale to collect the fresh weight data, then they are weighed a second time, after a dehydration process, to collect the dry weight data. The stem diameter is measured above the roots with a caliber, while the leaf area can be measured either with a leaf area meter [19].

According to [20] vegetable quality may be divided into three sub-categories: safety functions and deliciousness. The latter is very important and includes KPIs such as shape, color, and taste. However, it is not currently included in our work because we are studying how to define and quantify these parameters. We hope to be able to include this kind of KPIs in future works. The safety category includes two indicators, bacterial load, and nitrate, while the functions category includes vitamin C, provitamin-A, and mineral content.

Bacterial load is strictly related to the shelf life of the crop, since the greater the starting amount of bacteria, the shorter the product's shelf life. Since the microbiological growth curve has an approximately exponential trend, knowing the initial value can well estimate the life span of the harvested crop [21]. As for conventional cultivations, the soilless approach also uses high levels of nitrogen in the growing medium, to optimize crop growth. Nitrate accumulation has been demonstrated to affect human health in several ways [22], and some authors already proposed solutions to avoid its over-presence in soilless cultivated crops [19]. Therefore, its measurements will provide insight into the safety-related quality of the crop.

Table 2. Performance indicators of vertical farming.

Category	KPI	Unit of measure
Productivity	Fresh weight	g
Productivity	Dry weight	g
Productivity	Stem diameter	mm
Productivity	Leaf area	cm^2
Quality-Safety	Bacterial load	UFC
Quality-Safety	Nitrate	mol/L
Quality-Functions	Vitamin C	mg/100g of product
Quality-Functions	Provitamin A	mg/100g of product
Quality-Functions	Mineral content	mg/g of product
Environmental	Water consumption	g FW/ L
Environmental	Land consumption	g FW/ m^2d
Environmental	Energy consumption	g FW/kWh

Vitamin C, also called ascorbic acid, is a well-known antioxidant molecule, produced by several plants to prevent damage due to photosynthesis-related stress [23]. Its concentration may be detected by spectrophotometry or with HPLC (High-Performance Liquid Chromatography) techniques [24]. Provitamin A, also called beta-carotene, is an orange-colored pigment compound, and it is part of the large group of phytochemicals

called carotenoids, that are commonly found in several plants. Once dietary intake turns into active vitamin A, a molecule can reduce the incidence of several chronic diseases [25]. Carotenoid bioproduction is connected to the growing conditions, especially to the light spectrum [26], allowing a tunable concentration of such molecules by the means of an adjustable spectrum and other input conditions. Many minerals are essential to plant growth, and they also have a high nutritive value in the diet. Among them are calcium, potassium, zinc, manganese, and iron. Their content in the plants depends strictly on their concentration in the growing media, but it is also related to the photosynthesis efficiency, which in turn depends on light intensity and CO_2 concentration [11].

Finally, based on the literature analysis, the three main environmental sustainability indicators are water consumption, land consumption, and energy consumption. It is known that VF systems can save considerable amounts of water and land compared to traditional methods [27], but they require more energy per unit of product [27].

4 Experimental Design for an Aeroponic Chamber

Previous studies analyzed the influence of some input variables on only one KPI, usually belonging to the productivity or sustainability category. However, in order to conduct a proper evaluation of the VF system, the highest possible number of KPIs should be collected. Once collected, data will be used to build a model that would help the automated management of the system both in terms of the resources used and the timing of growth, thus allowing flexible production.

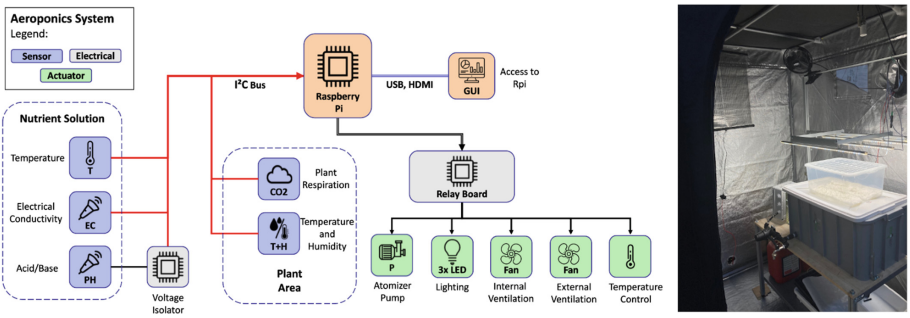

Fig. 1. Smart aeroponic system: IoT architecture (on the left) and chamber implementation (on the right)

We propose an IoT architecture to collect all the described input variables through sensors, for different crop cycles and the related KPIs values, to build a dataset to be further analyzed to derive knowledge about the relations among variables and KPIs. We start with the design of an aeroponic chamber for studying lettuce production. Figure 1 shows the IoT architecture and the implementation of the chamber. The system is equipped with sensors and actuators that can autonomously control crop development while sharing the collected data with the cloud.

Due to the high number of variables involved in the system and considering that on average lettuce crops need at least three weeks for growing, in order not to wait too much time to have results we decided to investigate the effects of three input variables, one for each category. We selected light intensity for the environmental category, temperature for the climatic category, and EC for the nutritional category. Thus, we fixed the values of all the input variables except these three, based on literature data. In turn, light intensity, temperature, and EC are designed to vary between two values. Table 3 summarizes the data of the experimental design. For each input variable, the following data are reported: (i) type, i.e., fixed or variable, (ii) minimum value found in literature, with reference, (iii) maximum value found in literature, with reference, (iv) selected value for our experiment.

Table 3. Ranges of allowed values and selected values for the input variables.

Input variable	Type	Min value	Max value	Selected value
CO_2	Fixed	400 ppm [13, 28]	1500 ppm [10]	Atmospheric conc
Light intensity	Variable	200 μmol/m^{2}s [12]	250 μmol/m^{2}s [14]	150 μmol/m^{2}s 250 μmol/m^{2}s
Red and Blue ratio	Fixed	2/1 [13]	3/1 [14]	2/1
Photoperiod	Fixed	16 h/8 h day/night [28]	16 h/8 h d/n [28]	16h/8h d/n
Irrigation period	Fixed	30 s/10 min [15]	30 s/24 min [8]	30 s/6 min
Temperature	Variable	19 °C [16]	28 °C [19]	21 °C 26 °C
Humidity	Fixed	50% [28]	70% [16]	55%
pH	Fixed	5.5 [18]	6.5 [18]	6
EC	Variable	0.9 dS/m [28]	2.5 dS/m [29]	1 dS/m 1.6 dS/m
Solution temperature	Fixed	24 °C [16]	25 °C [16]	Chamber temp

5 Conclusion

To achieve sustainable and flexible agriculture in vertical farming, it is necessary to identify the KPIs of the system and how they depend on the inputs provided to the plant. Therefore, we have summarized in this article the input variables and the KPIs that need to be studied for the vertical farming system. In addition, we briefly described the experimental setup of an aeroponic chamber that will be used to conduct experiments varying the input variable values and collect the related KPI. The data analysis will allow the finding of correlations between the input variables and the KPIs. Finally, a tradeoff

among the different KPIs should be studied, since it is not possible to optimize at the same time crop productivity, quality, and sustainability. Once the study is completed, it will be possible to obtain systems where plant growth and maturation times can be predicted well in advance, and thus complete management and control of the product's biological cycle will be achieved. Furthermore, we will develop the quality deliciousness KPIs and try to define a zero defect agricultural production starting from the zero defect manufacturing [30].

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Towards an Improvement of Airport Retail Waste Management Using the Double Diamond Design Process

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Abstract. This paper describes a research project to improve airport retail waste management, particularly in terms of waste segregation and effective processing according to current waste management practices. The Double Diamond design process was employed as the research methodology to identify and challenge these practices. On-site observations were conducted to begin the project by collecting data on the most recent airport waste management procedures and this was the demonstration of the Discover and problem identification phase of the Double Diamond methodology. Airports may apply this in the Develop and Delivery phases to boost recovery rates and handle waste more effectively and economically, lowering the waste transported to landfills or for incineration, and achieving their net-zero goals. This paper contributes to the body of knowledge on global waste management methods, especially in the aviation sector where little academic discourse exists on this issue. Practitioners can benefit from the Double Diamond's design structure to provide guidance for implementing and assessing airport waste management practices.

Keywords: Double Diamond design · waste management · airport waste · retail waste · net zero

1 Introduction

A significant issue which airports need to overcome is the six million tons of passenger waste produced annually worldwide [1]. Much of this waste is incinerated or dumped in landfills [2] which has negative impacts on the environment and human health. Efficient retail waste in airport terminals is prevented by several factors, such as passenger time constraints and restricted luggage capacity, a shortage of space for retailers to store and discard waste and manufacturers packaging goods the same way they would for traditional retail stores [3]. It is therefore crucial for the airport stakeholders to comprehend the underlying causes of retail waste and offer new initiatives for programs to prevent, reduce and effectively handle retail waste such as applying Circular Economy principles [4].

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The purpose of this study is to increase awareness for airport waste management practices and suggest possible areas for improvement by maximizing their current methods for reducing waste generation. In doing so, the study employs the Double Diamond design process [5] as the methodology allowing airports to challenge their approach to managing airport retail waste, including the separation of recyclables and nonrecyclables, various bin designs, color coding, improved instructions/signage, employee training, and the addition of more disposal and donation stations.

This paper is structured as follows. Section 2 describes the Double Diamond design process, which has been chosen as the research methodology. Section 3 discusses the findings from the study and identifies what needs to be developed in the subsequent diamond phases. The paper concludes with the implications of the papers and areas for improvement.

2 Materials and Methods

The Double Diamond design process was employed as the project's research methodology that at the same time served to elaborate the design and innovation process being adopted. Figure 1's representation of the Double Diamond approach shows two diamond shapes that stand in for the two primary stages of the design process, incorporating four distinct phases, named Discover, Define, Develop and Deliver.

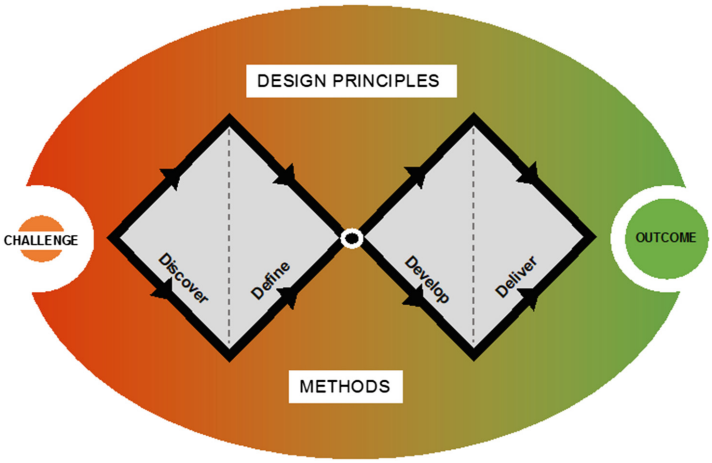

Fig. 1. The Double Diamond Design Process [5].

During the initial diamond phase, emphasis is placed on the strategic aspects of the design process and establishing a research foundation to guide the project's direction. The Discover phase of the Double Diamond design process involves a divergent approach that encourages extensive research and exploration of various possibilities without limiting the generation of ideas. After completing the foundational research and setting the scope, the Define phase of the Double Diamond design process was initiated.

During this phase, the problem identification process is initiated to scope which problems need to be addressed. In the second diamond, the focus shifts to generating and exploring various design concepts based on the refined scope developed in the first diamond. During the Develop phase of the Double Diamond design process, various design ideas are explored and experimented with to solve the problem and present the concept solutions which justify why the final concept was chosen. The chosen concept should be the most cohesive and clear among all options and can be presented as a deliverable ready for testing. The Deliver phase of the Double Diamond design process involves testing the different solutions, including the chosen solution from the Develop phase, on a small scale. Solutions that do not work are rejected, while modifications are made to those that do based on feedback. This involves ideation and creative exploration to arrive at the most suitable design solutions. According to Hawryszkiewycz and Alqahtani [6], the second diamond of the Double Diamond design process is primarily concerned with the creative development of the product, service, or system. In contrast, the first diamond is focused on conducting research and identifying problems that need to be addressed later in the design process.

The main advantage of the Double Diamond process is "repeatability" [7] through the iterative processes. The freedom for the designer to go back a stage to further clarify the problems or to make amends means that the concept solution is well developed and its features and characteristics to solve the problem are further justified. Leading companies, such as BlackEye - a company providing phone attachments universal to all smartphone devices to enhance photography and videography content - have applied the methodology to their research and development. This company applied the Double Diamond method to form a solid foundation for research and prototype development [7]. However, there are limitations of the Double Diamond design process as the users are involved in the process in much later stages during testing, modification and development rather than participating in the earlier strategic stages. Generally, this Double Diamond process may not involve heavy user feedback until a certain stage which may be too late to make major changes, hence wasting effort and resources [8].

3 Findings

3.1 Discover Phase

Various photographic and video media were taken to illustrate the observations made during the waste journey as part of the Discover phase, which was conducted at the airport's terminal. These observations cover the process from the terminals to the compactors located in the backrooms. Various tools can be applied in this phase, including user journey mapping [9] (for the passenger and airport staff) to identify the details of which waste management was more efficient and effective as well as concerns that could be raised. In addition, interviews were conducted with three waste management personnel: a representative from an onsite waste collector and a representative from a waste processor facility for treatment, recycling, recovery, and disposal of waste streams for general waste as well as the airport's waste manager.

The airport's terminal had a four-bin system for waste disposal. The bins are color coded with white for paper cups, blue for paper and cardboard, green for plastic bottles,

and black for general waste. A separate bin for coffee cups is necessary because the cups and lids are made of different materials, which require different waste processes. Similarly, sandwich packets need to be separated into their clear plastic case and cardboard. For security reasons, clear bags are used to collect waste, although waste personnel plan to add a green stripe on the paper and cardboard bin bags (blue) and plastic bottle bin bags (green) to identify paper and cardboard for segregation during the waste journey to the bin room and compactor. However, some observations showed leakage from tea or coffee cups, which results in contamination of wet and dry materials when passengers dispose of their half-empty beverage cups. The collection company collects the waste six-times a day and assists in separating waste at the source.

More observations included encountering stations which had been set up for liquid disposal at the airport where passengers can empty liquid from their bottles before security screening. This helps in separating wet and dry waste during the recycling process to prevent contamination. The station has a tank and wheels, making it easy to move and empty in the bin rooms. The personnel responsible for waste management stated that it cost around £1100 to import from Germany and install. Due to this high cost and limited budgets, they were not willing to install more stations in the airport. This demonstrates one of the financial and logistical barriers to sustainable waste management.

The bins present in the terminals are transported to the bin rooms where they are emptied into larger wheelie bins possessing the same color-coding system as the terminal bins and have visual aids and signage above them on the walls of the room. The bin rooms also have grates on the floor where the liquid waste from the tanks is emptied. Retail waste is also sent to these bin rooms; however, the retailers do not follow the same waste sorting system as the airport does because they have limited space and fewer incentives to segregate waste. Therefore, there is less control over the contents of their waste and what reaches the bin rooms. The terminal has a total of 29 bin rooms that handle both passenger and retail waste.

Display cages are exclusively used for transporting the wheelie bins from the bin rooms to the compactors. The cages have been painted with the same colors as the terminal bins and wheelie bins to ensure consistency in the color-coding system for different waste categories. The cages are meant for landside use only and cannot be mixed with airside waste bins due to security reasons. The cages are equipped with signage and clear messaging that provides information about what kind of waste is and is not permitted, which is placed at eye level to be easily visible. Despite these measures, the waste management personnel have reported that there are still instances of waste being placed in the wrong cage, indicating human error. For instance, in one incident, a wheelie bin was placed in the wrong cage despite the correct colors, messaging, and signage.

The final step in the waste journey within the airport terminal involves compacting the waste from the wheelie bins in the corresponding compactors. The colors of the compactors match the color-coding system used for the terminal and wheelie bins, except for brown for paper and cardboard instead of blue. The compactors are then collected by a recycling facilities company for processing at their own premises. There is an initiative within the airport consolidation center that consolidates all retail goods coming into the airport. This initiative involves sending all retail cardboard, paper, and packaging waste

from airport terminals back for recycling to be exchanged with the lorries transporting inbound stock. This helps to save on the distance and CO_2 emissions that would be required for two separate journeys. Moreover, the airport emphasizes the importance of segregation at the source due to the costs associated with segregating mixed materials at the contractor's processing plant. The presence of mixed materials and contamination in the waste stream can increase contractor costs, and extra effort is required to separate them. As a result, the airport prefers an onsite recycling facility where they can quality check the waste streams and thus reduce contractor costs overall. They also stress the importance of having a clean food waste stream and recovering oil to convert it into raw materials such as sustainable aviation fuel.

3.2 Define Phase

Single-use plastics contribute significantly to the amount of waste generated at airports, as these items are frequently not recycled and wind up in landfills or the environment, which considerably increase the quantity of waste produced at airports. This poses a problem for the airport as well as the wider community. Due to the continued production of waste, contamination because of inadequate segregation or separation of waste materials at the source is one of the major contributors and, as a result, a defined issue of waste management from the literature review and the airport visit. Little action is being taken by retailers to create an efficient segregation system since they have stated they do not have the time nor space for implementing measures such as a four-bin system at various retail locations.

The literature review and airport visit revealed the lack of segregation/separation of waste materials at the source as a major contributor to waste contamination, which remains a significant issue in waste management. Retailers have cited space and time constraints as reasons for not implementing a four-bin system, resulting in minimal efforts to improve segregation. Additionally, the liquid disposal station's effectiveness in segregating waste is compromised if passengers continue to dispose of their cups and bottles in regular bins.

The high levels of recycling contamination at the airport can be attributed to the current waste management system's heavy reliance on human behavior. Despite efforts to increase awareness through signage, messaging, and color coding, the effectiveness of waste processing ultimately depends on human behavior, which is prone to errors. This problem extends to passengers who may have varying levels of knowledge about waste sorting based on factors such as education, background, or language barriers. Therefore, there is a need for a more robust and automated waste management system to reduce recycling contamination and ensure effective waste processing.

There are several issues at airport terminals that hinder waste reduction and processing efforts. Firstly, facilities are not shared among stakeholders, leading to facilities not being optimized for use and more materials produced to build another facility for another airport. Additionally, airport staff are not required to use reusable coffee cups or beverage holders, leading to unnecessary waste generation of disposable cups. Another issue is the failure to donate unused aerosols and food to local shelters and charities, which can contribute to unnecessary waste generation. Cargo operations also generate significant amounts of recyclable materials, such as wooden pallets, plastic, cardboard,

and paper packaging, which are not repurposed for other uses. Lastly, disposing plastic bottles are a major contributor to landfill waste and harmful toxins generated from incineration. Furthermore, airports that do not utilize technologies to repurpose plastic bottles will continue to contribute to the negative effects of landfill waste and incineration. Addressing these issues can help to reduce waste generation and improve waste management practices at airport terminals.

The absence of stakeholder engagement and active involvement, along with a lack of understanding of their roles and responsibilities, has a negative impact on waste management targets. Airports involve numerous stakeholders who engage in multiple activities and operations, which can be complex and conflicting. For instance, while passengers have a significant impact on waste generation, they may not prioritize responsible waste disposal. On the other hand, the government may be interested in implementing policies such as banning single-use plastics in airports, reflecting their current political party values, and giving them a high level of power and influence for waste management change.

Overall, it is important to recognize and address the various barriers to sustainable waste practices at airports to promote a more environmentally friendly and sustainable aviation industry.

3.3 Develop Phase

During the Develop phase of the Double Diamond design process, various design ideas were explored and experimented with to solve the problem. It is crucial to record and demonstrate different concept solutions to justify why the final concept was chosen. The chosen concept should be the most cohesive and clear among all options and can be presented as a deliverable for the airport. Additionally, the Develop phase is not a linear process, as indicated by the back-and-forth arrows as new discoveries may require modifications and a return to the Discover and Define phases. The initial problems may also need to be reviewed to gain an overall understanding of how the concept solution can address these problems in a broader sense.

Three strategies were devised under the Develop phase: smarter product use, extension of product's lifespan and useful applications of materials.

Smarter Product Use and Manufacture. This strategy encourages airport retailers to increase the efficiency of their products/packaging by consuming fewer resources and materials used in the manufacture of products/packaging or redesigning them using innovative and more sustainable materials. Moreover, retailers should introduce sustainable products/packaging in daily operations and maximize their usage.

Extension of Product's Lifespan. The second strategy encourages airports to increase utilization of products/components which are still in satisfactory condition and can fulfil their original functions [10]. Furthermore, to continue utilizing products/components is by maintaining or restoring them to their original/accepted performance. Airports can also transform damaged/defective products/components into new products with different or enhanced functionalities, hence increase their value.

Useful Application of Materials. Airports can convert biological/non-biological waste into non-toxic/non-pollutant substances which can be safely released into the biosphere.

To obtain the same or lower grade material, airports can both upcycle or downcycle waste.

3.4 Deliver Phase

The chosen concept solution will be presented to waste management personnel, through an interview or a visit, as a physical deliverable for review of its viability as an industry framework or guide for the airport. The feedback received from this small-scale test can be used to make minor adjustments to the initial design(s) rather than creating a completely new concept solution.

4 Discussion and Conclusions

This work has identified human behavior as a significant cause of waste separation and segregation problems among both airport staff and passengers. For passengers, waste management is a low priority during their travel, which increases the risk of misplaced waste and contamination, leading to increased waste that could have otherwise been recycled. Among staff, there is a significant increase in the lack of waste separation and segregation during job rotations, annual leave, or staff changes, indicating that those who are not familiar with the process (possibly due to lack of training) fall into one of three categories: (1) they do not know the procedure, (2) they know the procedure but do not care (self-interest), or (3) they know the procedure but do not realize the wider implications of errors in the waste journey, resulting in more waste being sent to landfill/incineration, and do not consider the importance of segregating at the source. This finding is in line with what was aired by [11] exposing the need for continual support for airport shop floor personnel.

The findings also contribute to the global waste management discourse especially in the context of airport retail, where inefficient waste management practices can be addressed by considering many factors such as resources, time, budget and effort [12]. This improvement is expected to result in greater efficiency and cost-effectiveness of airport waste processing, because of an airport's large waste generation and the importance on diverting as much waste as possible from landfill and incineration. This will ultimately have a larger impact on global waste management and the achievements of net-zero targets.

There were time constraints that prevented the findings from being taken to the next phase of the Double Diamond design process which prevented suitable suggestions and new implementations to be considered and taken forward for testing. If the findings from the Definition phase could be categorized and clustered into specific areas for improvement within the airport terminal context with new implementations, then this may result in greater efficiency and cost-effectiveness of airport waste processing although costs associated were not analyzed with the solutions presented in Sect. 3.

Future work for this study would continue to refine the Develop phase by creating a concept solution as well as producing the deliverable to be tested on a small scale in an airport context. This concept solution would contain the relevant implementations for more efficient waste management changes which may be specific to that airport or waste

interventions which can be applied to airports in general. As part of the Develop and Deliver phases, appropriate modifications would be made to respond to the feedback from users such as the passengers, airport staff and waste management personnel. The iterative process may be exercised if needed. For instance, if the designer feels they do not respond to the problems identified in the first diamond, then it may be necessary to go back and reevaluate how the different concept solutions respond to the initial problem.

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A Game-Based Approach to Building a Sustainable Supply Chain

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Abstract. While firms in different industries face increasing pressure from society and regulatory bodies to address sustainability challenges, critical questions remain unanswered regarding how supply chains should prioritise processes, allocate resources, and integrate with other supply chains to develop bio-packaging products. We explore those questions by testing a Serious Game (SG) with stakeholders of the bioplastics supply chain in the UK. We find that SG facilitates the configuration of the BSC bio-packaging supply chain (BSC) for compostable products by prioritising the implementation of downstream processes integrated with the biofuel and agriculture supply chain and closed-loop business models (i.e., integration of production, commercialisation, and end-of-life) supported by normative regulations, communication and education with the consumers and investments at the end-of-life. In addition, under crisis scenarios (i.e., extended pandemic, climate change, and economic crisis), attention must be given to solutions that address local needs, downstream processes, and cost-effective bio-packaging.

Keywords: Serious Game · Supply Chain Management · Bioplastics

1 Introduction

Businesses in different industries face increasing pressure from society and regulatory bodies to minimize their environmental impact [1] and address sustainability challenges. Circular Economy (CE) is seen as a means of addressing sustainability challenges, but CE is subject to various definitions that capture its concepts differently and frequently only partially [2]. Systemic integration and collaboration between firms in the supply chain are hindered by corporate cultures driven by market barriers, government policies that fail to promote synergy, consumer's apathy and lack of awareness [3], and market and technological barriers [4].

Literature has revised the application of Serious Games (SG) [5, 6] in firms to develop labor competency, strategic and creative thinking abilities and simplify information [7]. For instance, based on a seminal game from Goodwin and Franklin [8], that simulates the beer flow processes from the raw materials to the consumption, Sarkar and Kumar [9] suggested that sharing disruption information is beneficial for improving the performance of the SC. Yet, so far, it has not been sufficiently clarified whether SG tools could help to simulate a sustainable supply chain adequately.

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Therefore, drawing on SG, we use a case study of the biobased biodegradable plastics packaging (from here onwards bio-packaging) supply chain due to its importance for the sustainability of the packaging industry; since it offers a potential alternative to fossil-based plastics. The bio-packaging supply chain (BSC) presents many challenges regarding cooperation among the stakeholders and integration with other supply chains [10]. Thus, our paper aims to enhance the potential configuration of a sustainable BSC from the view of the local stakeholders in the United Kingdom (UK), how the stakeholders should allocate resources, prioritise processes, and integrate with other supply chains and whether SG can contribute to facilitating the configuration of a sustainable BSC. We contend that SG can shed light on the future development of sustainable BSC by paying more attention to implementing downstream processes and closed-loop business models. In the short-term, strategies such as bridge technologies would facilitate this development. Besides, crisis scenarios (i.e. extended pandemic, climate change, and economic crisis) need to pay more attention to solutions that meet the local community's needs, downstream processes and cost-effective bio-packaging solutions.

The paper is divided into four sections. The next section presents the research methodology for developing the SG for managing a sustainable BSC – SIMBIO. Sections 3 and 4 present the findings, conclusion and discusses the implications for advancing SG, practical implications, and research limitations.

2 SIMBIO Game

The SIMBIO Game (See Fig. 1) was created as part of the Social Innovation Management for Bioplastics research project [11], which adapted and extended the Social Innovation Lab (SIL) methodology by Westley et al. [12] to study potential solutions for improving BSC in the UK (see Fig. 2). The SIMBIO Game was used during the prototyping phase of the research to facilitate the development of compostable products based on the findings that emerged from the previous stages of the research. The SIMBIO Game includes six components to configure the development of those products: specific compostable products (e.g., ready meal trays, coffee pods, and food caddy liners), policy objectives (relevant UK and EU policies), resources, processes, what-if scenarios, and timelines reflecting the solutions offered by the expert stakeholders for reconfiguring the BSC in the short, medium, and long term during previous research stages. The objectives of the SIMBIO game are as follows:

- Systematically and collaboratively design the development of a sustainable BSC, considering three timeframes (5, 10 and 20 years).
- Prioritise the main BSC processes in light of the distribution and limited availability of resources.
- Consider what-if scenarios and their impact on the development of a sustainable BSC.

2.1 Game Board Set up

At the beginning of the game, players are divided into groups (maximum 8 players) and are assigned one bio-packaging product and two scenarios (business-as-usual and a

Fig. 1. Supply chain processes and resources for the ready meal tray under a business-as-usual scenario. Source: [18]

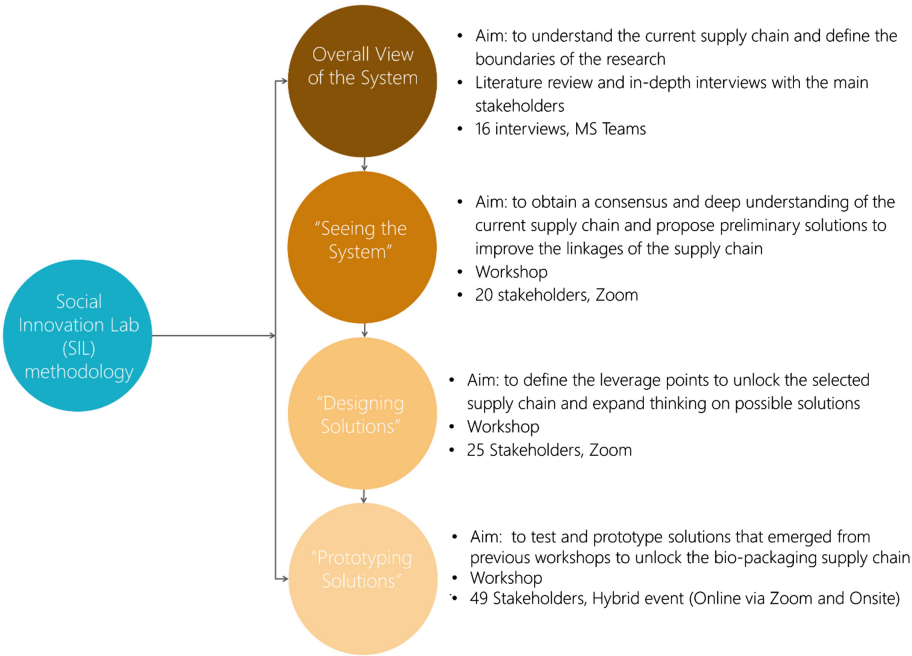

Fig. 2. Social Innovation Lab (SIL) methodology

crisis scenario). The setup also includes reading the rules to the players and laying out the board cards and tokens. Spaces on the board are designated for allocating product cards, objective cards, resource tokens, scenario cards, and process cards (see Fig. 3).

- Product cards: three product cards based on the Waste and Resources Action Programme guideline for bioplastics products (WRAP) [13] are available for the players; ready meal trays, coffee pods, and food caddy liners.
- Objective cards: four objective cards on which participants can match their scenarios with current policies or discussions are considered, such as the EU policy for single-use plastic banning [14], the Extended Producer Responsibility for packaging, the elimination of food waste to landfill by 2030 [15] and the separation of food waste collection all households in England from 2023 [16].
- Resource tokens: six streams of resources are displayed, such as communication, certification and labelling, end-of-life, policies, education, and research and development of specific products.
- Scenario cards: four scenarios are available; business-as-usual, climate change crisis, prolonged pandemic, and economic crisis.
- Process cards: sixteen process cards are available with current and proposed BSC processes created in previous social innovation labs [17–19].

2.2 Gameplay Rules

The game is played over two phases: business-as-usual and crisis scenarios. In each scenario, each player has to: (a) select two process cards that will influence the development of a sustainable BSC; (b) select a maximum of two resource tokens; and (c) explain how their decisions were made.

- The players take turns placing processes and resources on the board, considering the timeframe (5, 10, 15 years) and EU and UK regulations.
- Players are advised to collaborate in order to choose the most suitable configuration for a sustainable BSC.
- Participants can also invent new processes using a 'blank card'.
- The game continues until the group agrees on the right configuration for a sustainable BSC.

2.3 Methodology

The SIMBIO Game was held as part of the third UK SIMBIO SIL – prototyping solutions on the 25th of November 2021 at Coventry University Technology Centre [18]. Key stakeholders, including companies, public institutions, academic community, and consumers, were identified and invited to participate in the lab. A total of 20 participants attended face-to-face. See detailed information on the participants in [18]. Participants were divided into three groups, in which different scenarios and bio-packaging solutions were assigned (Table 1).

A researcher was assigned to each group to facilitate the game. The game was video recorded with the participants' permission, and a note taker also recorded each group's major decisions in a spreadsheet. At the end of the session, participants were asked to explain the configuration created. Using different methods to convey data reduced potential biases associated with relying only on players' narrations or notes. The data recorded were transcribed and analyzed with thematic analysis combining deductive

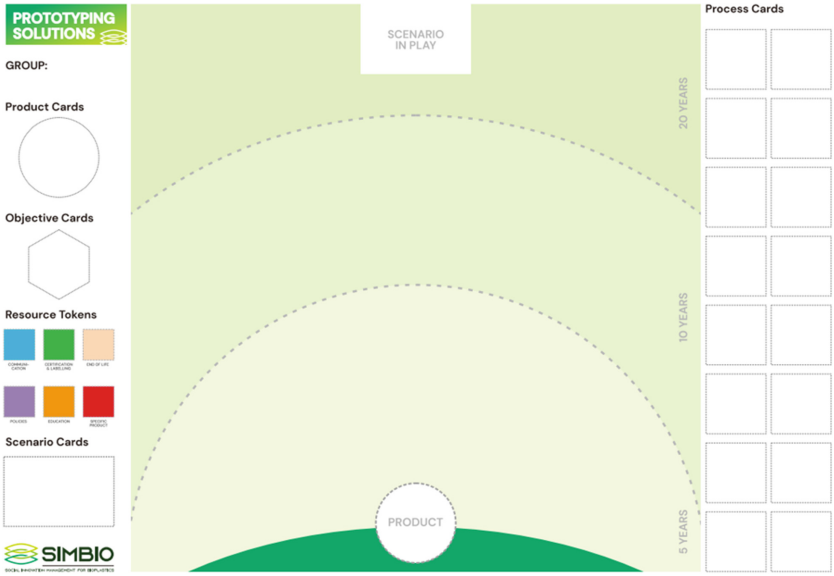

Fig. 3. Overview of the SIMBIO prototyping scenario board game. Source: [18]

Table 1. Board game scenarios and bio-packaging solutions per group.

Group/ scenarios	Group 1: Ready Meal Tray	Group 2: Food Caddy Liner	Group 3: Coffee Pod
Scenario 1	Business-as-usual	Business-as-usual	Business-as-usual
Scenario 2	Prolonged pandemic	Climate crisis	Economic crisis

and inductive methods into four steps. First, we compiled the main decisions based on the bio-packaging products, processes, resources, time frame and scenarios in 4 tables. We cross-referred the decision that the note takers recorded with the video recording to ensure the validity of decision rules (i.e., ensure that the researchers' observations and the video recording were consistent). Second, we summarised the decisions made in the business-as-usual scenario to provide a comparison. In total, 22 data points were retained for analysis of the processes. Third, based on the BSC area prioritised by the stakeholders for developing the BSC products in the business-as-usual scenario, an initial codebook driven by inductive thematic analysis was compiled. Following this, two authors independently coded the transcripts, in which new sub-codes emerged. Only codes with relevance to represent the main narrative of the decisions were kept. Fourth, the groups' scenarios were analysed separately to understand the main rationale behind the decisions. NVivo qualitative data analysis software was used for managing the coding process. The analysis process aimed at bringing together insights into the configurations of each BSC. This stage was carried out very detail through a series of

discussions between the researchers considering the narrative and the decisions made by the stakeholders.

3 Results

Comparing the different paths envisioned for the BSC reveals similarities and differences. In the business-as-usual scenario, the similarities lie in the emphasis on implementing downstream processes and closed-loop business models. High priority was placed on downstream processes such as collecting bio-packaging with food waste, sorting/separating bio-packaging from other waste (e.g., wet AD plants that cannot handle this type of packaging) and industrial processing (e.g., industrial comporting as part of anaerobic digestion post-processing) supported by normative regulations, communication and education with the consumers and investments at the end-of-life. However, the final bio-packaging product should be sustainable, specifically focusing on end-of-life. It is crucial to emphasize these points since the linear approach of the BSC cannot provide a sustainable alternative to fossil plastics in the long run.

Yet, there are differences in the short-term strategy (5 years) chosen for the different groups. A "bridge technology", which combines cellulose with other biodegradable biobased materials, was envisioned by the food caddy liners group for the short term to reduce plastic waste in the soil, allowing certification standards to include a broader range of bio-packaging and consumers to distinguish bio-caddy liners from fossil-based counterpart easily. In the short term, anaerobic digestion facilities could enable the processing of bio-caddy liners since current facilities mostly reject bioplastic packaging. To support this short-term strategy, certification and labelling, investments at the end-of-life, and policies driving dry anaerobic digestion are needed. During a prolonged pandemic, players prioritised solutions that meet the local community's needs, such as closed-loop commercialisation supported by a wide range of resources to encourage home and community composting. While as a result of exacerbated climate change, the downstream processes of anaerobic digestion, industrial composting, and the collection of bio-packaging products along with food waste, scrutiny of CO_2 emissions reduction processes and business carbon emission reporting were given greater importance.

Moreover, due to the economic crisis, the BSC processes would need to be adjusted to be more cost-effective. In this context, the coffee group argued that in a scenario of economic uncertainty, consumers would tend to be more reliant on themselves; therefore, they prioritised home composting as the first step, moving this process closer to a period of five years (rather than ten years for a business-as-usual scenario) and allocating communication as the main resource.

4 Discussion and Conclusion

In seeking to understand how businesses can address sustainability challenges, many have pointed out that a CE could be crucial to progress. However, it is unclear how firms could assign resources, prioritize processes, and integrate with other supply chains to achieve sustainability. Drawing on SG, this paper presented the development of a sustainable SC for specific bio-packaging products in the UK.

The analysis of the SIMBIO game revealed similarities and differences between the groups' approaches when a business-as-usual scenario was analyzed. The study found similar solutions for the current development of a BSC, such as a focus on improving downstream solutions and closed-loop business models. However, to achieve those solutions, other supply chains, such as agriculture and biofuel, must be integrated [10], greater collaboration between bioplastic packaging producers and the product manufacturers [20] and attention to addressing contamination issues in downstream processes [18] are needed. Moreover, in crisis scenarios (i.e., prolonged pandemic, climate change and economic crisis), more urgent attention should be paid to solutions that meet the community's local needs, downstream processes and cost-effective bio-packaging solutions. A practical application of this study is to explain how bio-packaging firms could configure sustainable supply chains: assign resources, prioritize processes, and integrate with other supply chains. The results can influence business practices, guiding enterprises to transform their business models (e.g., a closed loop) and supply chains following CE principles. Moreover, by studying the conducted analysis, SG can be developed to address firms' sustainability from other industries that could employ a similar approach to address future changes in their supply chains. However, it is important to note that due to the bio-packaging market is still in its early stages and having only a small number of BSC stakeholders; this qualitative study was limited to a limited number of participants. Quantitative methods are needed to generalize the results, and comparative perspectives with other countries could also be included in future research.

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How Lifecycle Assessment is Interrelated with Environmental or Sustainable Value Stream Mapping

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Abstract. The current globalization faces environmental and social challenges in lean manufacturing processes while simultaneously ensuring a sustainable evolution, even though there is a high margin in the lean approach. To deal with this challenge, this research aims to investigate some of the main extended versions of lean techniques such as sustainable (Sus-VSM) and environmental value stream mapping (E-VSM) simultaneously integrating them with lifecycle assessment (LCA) principles for better comparative analysis of environmental performance due to an indefinite number of approaches to evaluate sustainability. Moreover, the research tries to identify tradeoff methods of environmental, economic, and social indicators in the lean E/Sus-VSM tool for better decision-making, whereas there is no common suggested method. For this purpose, the method for the project initiates a search and a literature review of scientific sources to find which features of LCA are integrated with different E/Sus-VSMs and what tools are used in balanced decision-making by using the matrix table. The results are that many elements or similar steps of LCA are used in E/Sus-VSMs and the tradeoff tools to make decisions are various or new approaches are emerging. Finally, a conclusion is made for identifying and suggesting further research and limitations.

Keywords: Lifecycle assessment · Value stream mapping · Sustainability

1 Introduction

Several companies have incorporated lean methodologies and actions to improve environmental, economic, and social performance (so-called "triple bottom line" (TBL)) in the companies, but executives still need clear indicators that can assist by supplying data for decision-making through balance and the impacts and factors of environmental efficiency are not yet fully figured out in the production [1–3]. Therefore, aligning the green framework and its approaches and tools with lean thinking, which can be described as a system that finds and removes waste seems reasonable [4, 5].

Indeed lean and environmental actions are purposed with a similar approach to decreasing waste and lower pollution, but the environmental practices see only pollution (in the form of air emissions and dangerous waste) [6, 7]. One of the traditional lean

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tools, value stream mapping (VSM) does not consider environmental or societal impacts whereas it accounts for productivity or economic efficiency. Since its introduction as a lean tool, many studies have been carried out to integrate it with diverse metrics and its management for better eco-efficiency and productivity. An extended version of VSM which examines additionally only environmental performance is called E-VSM [8], and VSM which also evaluates TBL is considered generally Sustainable value stream mapping (Sus-VSM). As both broadened VSM types consider eco-efficiency, our focus in the research will be on specific eco-performance management systems.

The environmental techniques utilized with lean tools range from tools such as life cycle analysis or assessment (LCA) or designing products and services based on eco-friendliness to the utilization of Environmental Management (EM) frameworks by following different norms and regulations or eco-performance estimations [9]. Among them LCA is recognized as an accepted method for decision-making support in the legislative landscape for the assessment of environmental performance in general and its fundamental interpretation is described and identified in ISO 14040 and ISO 14044 which incorporates more technical details in the field of product and processes [10–13]. Since the inception of environmental and sustainable VSMs, many studies have been carried out by scholars to utilize additional LCA and other environmental techniques to evaluate additional eco-efficiency of production and logistic processes [14–17]. This research will be devoted to studying and observing how LCA can assist or at which level it is utilized in environmental assessment in different sustainable or environmental VSMs (RQ1) and identification of difficulties or integration ways of environmental performance evaluation methods with productivity (RQ2).

2 Literature Review

2.1 Environmental/Sustainable VSMs

Lai in 2015 suggests another framework for focused logistics processes of VSM by integrating Total cost analysis (TCA), life-cycle environmental impact analysis (LCIA), and an energy consumption analysis (ECA) [14]. The scholar uses the Eco-99 indicator for eco-performance evaluation and from the perspective of the operation's manager, he indicated that the operations manager wants to improve the current situation and evaluate a potential scenario. They care more about the difference between the two scenarios rather than the exact value of the potential scenario. It's important to clearly define the specification of system boundaries for the analysis to compare the two scenarios properly or when combining other economic indicators due to their complexity. Even with LCA, finding standard data to fill these models is still very difficult.

Sustainable manufacturing mapping (SMM), a novel methodology that combines traditional VSM with discrete event simulation (DES) and life-cycle assessment (LCA), was presented by [15]. This goal-oriented method is said to be extremely visual and user-friendly because it combines more widely used publicly accessible life-cycle inventory (LCI) data with DES and VSM. Despite having a large selection of sustainability metrics to choose from, there is not enough case study to prove how to correctly display the metrics on the VSM [16]. The suggested methodology considers ISO 14040 2006

standards and tries to adopt the full experts' view, the goal and scope definition, system boundaries, the environmental data, etc.

Further research performed the calculation of the Carbon footprint for each production process indicated in each VSM (current-state and future-state) and categorized the carbon footprint for each value-added and non-value-added process [18]. The emission factors of material and transportation were taken from Lifecycle Assessment open database [18]. Although, in his search of literature review, he finds out the view of [19] whereas the scholar states that LCA is out of the Green-Lean Paradigm's overlapping domain and is utilized in product design to make product optimized from an environmental point of view only. [18], in his carbon-value efficiency value stream mapping (CVE-VSM) concluded that it is challenging to integrate lean and green practices especially when there is a lack of resources, but the result of the case study gives quantitative benefits towards a need for further improvement.

Direct implementation of LCA together with VSM was recommended in [20]. However, regarding the evaluation of full sustainability performance (TBL metrics) the study considers almost the same visualization of the Sus-VSM framework suggested by [16] and, but emphasizes the exploitation of LCA for evaluation of environmental performance following standardized steps of ISO 14044 [12]. However, in his earliest trial of Eco-Function matrix-integrated VSM, the study exploited QFD (quality function deployment) and Eco-Function matrix for balancing between economic and environmental performance [21].

A new innovative approach proposed by [22] called overall greenness performance for value stream mapping (OGP-VSM) demonstrates the integration of productivity with environmental performance with its metrics and its implementation leads to a lack of practical integration of productivity with environmental performance, whereas some activities which are beneficial from a lean perspective, show a reverse effect on eco-efficiency [22].

3 Methodology

This literature review exploited a systematic searching and snowball approach to find the sources and a rigorous narrative approach to analyze and review studies relevant to the research question and it is considered non-reproducible. But the following frequent and common techniques were taken to find the answer to the questions.

1. Identification of relevant databases for finding relevant articles such as Emerald, ScienceDirect, Web of Science, Scopus, Google Scholar, IEEE Xplore, etc. But the databases changed over time, due to the low number of search results.
2. Common keywords for searching the title and abstract were ("Environment Value Stream Mapping" OR "Environmental Value Stream Mapping" OR "Eco Value Stream Mapping" OR "Green Value Stream Mapping" OR "Sustainable Value Stream Mapping" OR "Lean and Green" OR "Green Lean") AND ("Life Cycle Assessment" OR "LCA"). But, while reading articles, due to a lack of sources, a further search of articles went further through the references of found articles.

3. Inclusion and exclusion criteria: Studies were included if they met the following criteria: (a) published in the English language, (b) published between 1998 and 2023, (c) peer-reviewed, (d) addressed the research gap or question, (e) conducted in engineering, management, and production. Studies were excluded if they did not meet the inclusion criteria or were duplicates.
4. The selection of articles and documents of standards went further also based on the title of the article whereas, completely incompatible science domains and out-of-topic articles were removed.
5. Further steps in the study were content analysis and creating a matrix to identify whether there are direct statements of trial to integrate LCA steps, productivity, and eco performance tradeoff methods (at least leveling to prioritize and decide "P&E TM") or Problems encountered in aligning productivity and environmental performance in the case study of EVSMs (Table 1).
6. The next step is creating a similar matrix for identifying which LCA or similar elements are generally utilized in the case studies or suggested methods of E/Sus-VSMs. The choice is subjective and can vary in different sources based on the general similarity of elements. For example, if LCA indicates the system a boundary namely "cradle-to-grave" or "cradle-to-cradle" many E/Sus-VSMs do also own system boundary, but it is not named or indicated graphically as LCA does. If completely similar elements are found the cell is ticked and " ±" is inserted if there is partial usage of similar features of LCA elements (Table 2).
7. The result is analyzed and the conclusion is given by additionally providing suggestions and limitations for future improvements.

4 Results

4.1 Balancing the Tradeoff Between Different Metrics

Table 1 below demonstrates which studies directly (signed with ticks) or partially (signed with " ±") stated the integration of LCA steps in their E/Sus-VSMs. The column of LCA illustrates that there are only 4 studies carried out directly integrate LCA in their VSMs but tried to get some direct features and steps of LCA. In the case of identifying productivity & environmental performance integration, it is seen that several studies faced issues in balancing or they even did not mention issues regarding that.

Table 1. Identified methods to integrate environmental metrics with productivity and the usage of LCA in different research projects

Source	LCA	P&E TM
[4, 23–29]	–	–
[14]	√	The problem faced while balancing (P)
[8]	–	Partially, but with no specific method
[15]	√	eVSM software & "What-if" simulations

(*continued*)

Table 1. (*continued*)

Source	LCA	P&E TM
[21]	–	QFD (Quality Function deployment)
[16, 30, 31]	±	Partially mentioning faced issues
[18, 22]	–	The problem faced while balancing (P). Environmental indicators became worse and productivity increased
[17, 20]	√	–
[32]	–	VVLD (value-value load diagram)
[33, 34]	±	–
[35]	–	Manufacturing Sustainability Performance Assessment (MSPA) & Delphi method
[36]	–	Interview & Questionnaire for overall SI (Sustainability Index)
[37, 38]	–	AHP (Analytical hierarchy process)

However, the suggested methods started to emerge recently to balance between different indicators for a better tradeoff such as AHP, and value-value load diagrams. The analysis of the table gives comprehension that there is no common tool that assists integrated decision making and many studies did not mention issues balancing different indicators.

4.2 Identification of the Exploitation of LCA'S Steps in E/Sus-VSMs

During the path to identifying whether some elements of LCA are used in different E/Sus-VSMs, the study considered the general similarity of steps taken in the case studies or projects. The result demonstrates that most of the elements of LCA have similar features with steps indicated in different attempts in the creation of E/Sus-VSMs. For instance, both include the steps of identifying why eco-performance evaluation are involved and the data requirements (depending on industry type), data collection, and calculation processes in the assessment of the environmental part. As mentioned above, four studies that stated the direct integration of LCA in the eco-assessment of VSMs did not utilize all the steps of LCA.

Following are elements of Table 2: Goal & Scope definition (G1-G4); Lifecycle Inventory Analysis (LCI) (L1-L3); Lifecycle Impact Analysis (LCIA) (I1-I3) Lifecycle Interpretation (R1-R3); Without LCA integration (A1); Sources with direct LCA integration (A2); Sources with partial LCA mentioning (A3).

Unused elements or steps are the following: G4 Whether the outcomes are intended to be used in comparative statements meant to be revealed to the general public; S2 the functions of the product system or, in the case of comparative studies, the systems; S3 the functional unit, I3 calculation of category indicator results (characterization); R2 Evaluation that checks for completeness, sensitivity, and consistency.

Table 2. The utilization of LCA's similar elements in different E/Sus-VSMs

LCA elements [11, 12]	**A1:** [4, 8, 18, 21, 22, 24, 26–29, 32, 33, 35–37]	**A2:** [14, 15, 17, 20]	**A3:** [16, 25, 30, 31, 34]
G1 Intended application	√	√	√
G2 Reasons for carrying out the study	±	√	√
G3 Intended audience (to whom the results are communicated)	±	√	±
S1 the product or process system to be studied	√	√	√
S4 the system boundary	±	√	√
S5 allocation procedures & L3 Allocation	±	±	±
S6 LCIA methodology and types of impacts		±	±
S7 interpretation to be used		√	√
S8 data requirements and assumptions	√	√	√
S9 value choices and optional elements		√	±
S10 limitations	±	±	±
S11 data quality requirements		±	±
S12 type of critical review or format of the report required for the study	±	±	±
L1 Collecting data & L2 Calculating data	√	√	√
I1 selection of impact categories, category indicators, and, characterization models	±	√	±
I2 assignment of LCI results to the selected impact categories (classification)	±		
R1 Identifying important issues from LCI and LCIA results in LCA		√	
R3 conclusions, limitations, and suggestions	√	√	√

5 Conclusion

To conclude, the general similarity of the steps of LCA and E/Sus-VSMs should be more deeply discussed with experts in LCA due to limitations in the clear deduction. Even though scholars did not directly state that their study integrates LCA with their VSMs, it is clear that they unintentionally borrowed or utilized similar steps in LCA. Furthermore, the analysis of the result in the tables gives direction that more standardized usage of LCA features in E/Sus-VSM is beneficial since there is no clear and general technique to assess the environmental aspect of VSMs. In addition, the research shows that many new scholars have started recently to identify and implement some techniques to make a balance between different indicators of sustainability. However, it is not possible to define

and compare which tools better support decision-making processes and are suitable for E/Sus-VSMs.

The future investigation that can be carried out is carrying out more practical research and case studies on it for making the steps standardized in common E/Sus-VSMs. Moreover, in the direct integration of LCA in E-VSMs, there is should be a further investigation or finding reasoning into why some features of LCA are not utilized in their studies and the reasons behind that.

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The Influence of Ecolabel: Insights from the Indonesian Bioplastics Packaging Industry Stakeholders

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Abstract. Despite the potential environmental benefits of bioplastics, consumers remain confused regarding this innovative packaging material. One possible solution to mitigate these concerns is to introduce ecolabels to communicate this bioplastics material. This study aims to investigate the influence of ecolabel signals and other factors on the adoption and proper disposal of bioplastics packaging among consumers in Indonesia, as seen from the perspective of stakeholders in the bioplastics industry. Signaling theory is utilized as a theoretical lens to build a conceptual model to observe this phenomenon. A total of 17 case studies were collected from stakeholders in various sectors, including production, consumption, waste management, and academia. The findings reveal that while ecolabels can play a role in shaping consumer behavior towards bioplastic packaging, they cannot be the sole determining factor. Other factors such as packaging price, pro-environmental attitude, habitual practice, and access to appropriate waste management facilities also significantly influence consumer adoption and proper disposal of bioplastics. The study contributes as one of the earliest research efforts in this area. Furthermore, the study addresses gaps in bioplastics consumer communication research by highlighting the effect of ecolabels.

Keywords: Sustainable packaging · Visual communication · Consumer behavior · Solid waste management · Developing country

1 Introduction

To address the environmental concerns related to plastic waste, researchers have developed bioplastics as an alternative to conventional plastics [1]. Bioplastics are plastics that are either biobased, biodegradable or have both of those properties [2]. As a result, bioplastics have become an attractive alternative for businesses looking to reduce their environmental footprint [3].

Nevertheless, despite the potential benefits of bioplastics, consumers are still confused about this new packaging material [4]. Many consumers remain clueless about certain terms used in bioplastics packaging communication [5]. Moreover, there is a

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lack of awareness regarding the proper disposal of bioplastic packaging waste, which can potentially contaminate the waste management industry's input stream [6].

One approach to addressing these consumer concerns is through the use of ecolabel [6]. Ecolabel can provide consumers with clear and credible information about the environmental impact of a product or packaging [7]. However, a research gap exists on how ecolabels can influence consumers to adopt and properly dispose of these relatively new packaging materials, particularly in developing countries [6, 8].

This research aims to investigate the impact of ecolabel signals and other factors that influence the adoption and proper disposal of biobased biodegradable plastics packaging among Indonesian consumers, by looking from the perspective of stakeholders in the bioplastics industry in Indonesia. Through conducting case studies with industry stakeholders, we aim to gain insights into how ecolabels can be effectively used to promote the adoption and proper disposal of bioplastics among consumers.

2 Literature Review

With environmental awareness on the rise, bioplastics packaging has gained traction, but unclear communication with consumers regarding its purpose, use, and disposal has remained an issue [9]. On the other hand, marketing biodegradable plastics to consumers also has its own risks and challenges, including insufficient capital protection, changing consumer needs, competition, and the need for control of distribution channels [10].

To promote the uptake of bioplastics packaging, communication with consumers is crucial, nevertheless, it should be accompanied by a reconfiguration of daily practices and mechanisms for collecting the packaging waste [11]. Accordingly, it means that recycling systems will need to be reorganized [5]. Hence, continual communication to educate the consumers is also vital to ensure the correct disposal route and prevent unintended consequences such as increased plastic usage or littering in the environment [4, 5]. Highlighting the end-of-life benefits of biodegradable plastics packaging in the mid-term could be effective in communicating its benefits to consumers. However, in the long term, educating consumers on the true impact of various packaging options is necessary to align their perceptions with reality [7].

Another study has identified biodegradability and compostability standards used in Europe and corresponding ecolabels that are relevant for bioplastics packaging [3]. Developing a harmonized international certification scheme and ecolabel could alleviate confusion and promote bioplastics' uptake [5]. Ecolabels are commonly used in sustainability communication [3], but their effectiveness in bioplastics communication is not yet fully understood. Therefore, it is important to investigate their potential in influencing consumer behavior towards the adoption and proper disposal of bioplastics.

3 Theoretical Perspective

Through a systematic literature review process in Scopus, ProQuest and EBSCO with keywords related to "communication", "bioplastic packaging" and "consumer", 68 articles were obtained for inclusion. After reviewing these articles, it can be deduced that

this field has unique characteristics. Firstly, *unobservable quality* is a challenge as consumers struggle to differentiate bioplastics from conventional plastics due to the lack of visible cues of biobased and/or biodegradable features [6]. Secondly, there is *information asymmetry*, with producers having more knowledge about the biobased and/or biodegradability attributes of bioplastics packaging than consumers [5]. Lastly, there is the notion of *costly signaling*, as some companies invest significant resources to demonstrate their commitment to environmental sustainability through consumer education or by obtaining certified ecolabel [5].

The concepts of 'unobservable quality', 'information asymmetry', and 'costly signaling' support our choice of Signaling theory as a theoretical perspective to understand this phenomenon. Signaling theory explains how and why individuals and organizations communicate when there is a lack of information symmetry for a quality that is difficult to directly observe [12]. It helps understand information transmission and its impact on decision making [13]. Adapted from Connelly et al. [13], several elements build the signal. The *signaler* is the party with knowledge of the unobservable quality that the receiver does not have. The *signal* is the form of communication chosen by the signaler to inform on its unobservable quality. The *receiver* is the party that captures the signal to ascertain the unobservable quality of the signaler. In this research context, the signaler is the producer, the signal is ecolabel, and the receiver is the consumer.

Within the signal, several constructs influence consumers' adoption and disposal of bioplastics packaging through ecolabel design, including signal visibility, clarity, fit, cost and credibility. Signal *visibility* is the observability of a signal [13, 14], while signal *clarity* is its degree of clearness and ease of understanding for the receiver. Signal *fit* refers to the degree to which a signal correlates with an unobservable quality [13]. Implementing a signal incurs signal *cost*, which some signalers are better able to absorb than others [13, 14]. Signal *credibility* depends on the degree to which the signaller is truthful and conforms to signal quality [13, 14].

The receiver of the signal has attention and interpretation constructs. *Attention* refers to the degree to which receivers monitor the signaling environment to find the signal, while *interpretation* is the process of converting signals into perceived meaning [13]. By combining the information from the literature with this theoretical lens, several propositions was developed into a conceptual model to guide this research.

4 Research Method

This study uses a qualitative approach to understand the perspectives of stakeholders in the bioplastic packaging industry. A collective case study is employed to compare and contrast findings across different cases and identify patterns and themes. A collective case study is a type of qualitative research that comprises studying numerous cases simultaneously or sequentially in an effort to produce a still broader understanding of a certain phenomenon [15]. The main method for data collection is using semi-structured interviews, using a set of pre-determined questions, which makes it easier to compare and contrast informants' responses [16]. The interview questions covered the following topics: (1) consumer behavior towards ecolabels; (2) interpretation of ecolabels; (3) factors influencing ecolabels; (4) consumer attention, interpretation, and trust; and (5) effective ecolabels.

Table 1. Summary of cases and informants

Case	Sector	Organisation	Position
P1	Production	Packaging association	Executive director
P2		Packaging association	Chairman
P3		Bioplastic converter	Director
P3		Bioplastic converter	Vice director
P4		Bioplastic producer	Government and public relations manager
P4		Bioplastic producer	Marketing specialist
P5		Packaging association	Head coordinator at regency level
C1	Consumption	Student representative council	Chief
C2		Student association for profession	Chief
C3		Consumer protection NGO	Programme head
C4		Student union for faculty	Strategic research department
W1	Waste Management	Waste collector community	Head coordinator
W2		Upcycling & community composting	Director
W3		Material recovery company	Business development
A1	Academic	University	Agribusiness lecturer
A2		University	Information design lecturer
A3		Polytechnic	Packaging design lecturer
A4		University	Food packaging technology lecturer
A5		National research agency	Policy researcher

The main inclusion criteria for case selection are: (1) Organization position in the bioplastics packaging supply chain could represent one of four sectors, which is production, consumption, waste management or cross-sectoral that in this research depicted through the academic sector; (2) The organization location should be based in Indonesia. Purposive and snowball sampling methods are used for informant recruitment, with potential samples found mainly through social platforms such as LinkedIn.

Table 1 provides an overview of the case and informant profiles. Online interviews were used for convenience and to reduce barriers to participation [17]. Interviews were conducted using Microsoft Teams or Zoom, and transcribed as soon as possible then

analyzed using the template analysis approach based on the interview questions and relevant theories. Cross-case analysis was used to compare commonalities and differences across cases.

5 Findings and Discussion

The empirical study led to supported, newly emerge, and unsupported propositions, which were combined to create the refined conceptual model in Fig. 1.:

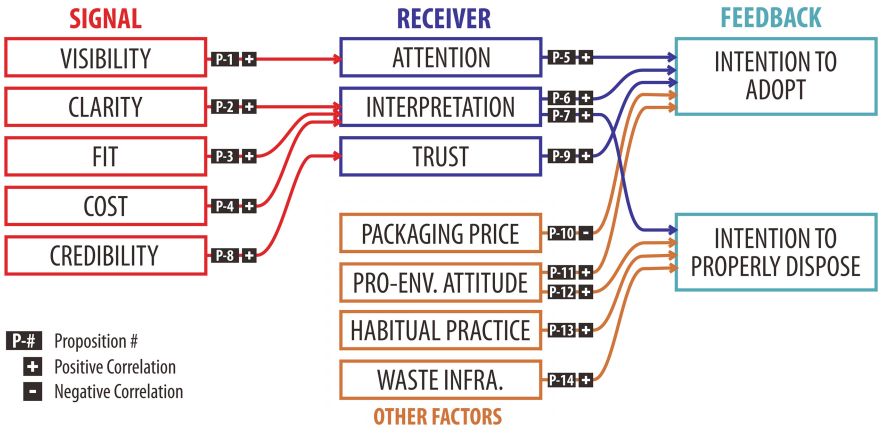

Fig. 1. Refined conceptual model

5.1 Supported Propositions

To be noticed by consumers, ecolabels must have good visibility, such as unique shapes, high contrast, considerable size and prominent position in the packaging. This leads to the first proposition (P-1): Higher ecolabel visibility will improve consumer attention. Next, empirical evidence suggests that consumers need information that is simple, have a clear meaning and not sophisticated. Therefore, the second proposition (P-2) is: Higher ecolabel clarity will improve consumer interpretation. The appropriate messaging devices, be it text or visual symbols, are necessary to represent the featured sustainability aspects, prioritizing forms that have become conventions in society. This leads to the third proposition (P-3): Higher ecolabel appropriateness will improve consumer interpretation.

Ecolabel owners need to invest in increasing their exposure and awareness in the community to make ecolabels understandable to consumers. This includes consumer education and community engagement. On the other hand, this approach will be difficult to imitate and risky if implemented by producers who use fake ecolabels. Therefore, the fourth proposition (P-4) is: The higher ecolabel cost will improve consumer interpretation.

Consumers' attention to the ecolabel on bioplastic packaging increases the likelihood of using such packaging. This leads to the fifth proposition (P-5): Better consumer attention to the ecolabel will increase the intention for bioplastics packaging adoption. Moreover, the correct consumer interpretation of the ecolabels on bioplastic packaging can encourage the choice of this packaging over conventional plastic packaging. Therefore, the sixth proposition (P-6) is: Correct consumer interpretation of ecolabel will increase the intention for bioplastics packaging adoption. In addition, the accurate understanding by consumers of the instructions in the ecolabel is perceived as a determining factor for the proper disposal of this type of packaging material. This leads to the seventh proposition (P-7): Correct consumer interpretation of ecolabel will increase the intention for bioplastics packaging proper disposal.

5.2 New Propositions

From the participants' information, ecolabel credibility has a direct impact on building consumer trust, which is the expectation held by consumers that the packaging manufacturer is reliable and can be relied upon to fulfil its promises [18]. Attempts such as involving government institutions, or displaying other convincing organizations' logo will influence consumers' confidence in the authenticity of the claims of the ecolabel. This leads to the eighth proposition (P-8): Higher ecolabel credibility will improve consumer trust. Building from that, the impact of consumer trust is the potential to adopt bioplastic packaging materials. The more consumers believe in the message conveyed by ecolabel, the more likely it is that consumers will prefer bioplastics packaging over conventional plastics. Therefore, the ninth proposition (P-9) is: Higher consumer trust will increase the intention for bioplastics packaging adoption.

However, price plays a significant role in consumer adoption decisions. The cost of bioplastics packaging or carrier bag is not as affordable as conventional plastics, which can even be obtained for free. Therefore, the tenth proposition (P-10) is: Higher packaging prices will decrease the intention for bioplastics packaging adoption.

Next, To encourage consumers to opt for bioplastics packaging materials, it is essential that they possess certain traits, such as knowledge, awareness, mindset, or an attitude of environmental consciousness first from the individual consumer, which we consider as a pro-environmental attitude. Pro-environmental attitude refers to a person's concern for the natural environment [19]. This leads to the eleventh proposition (P-11): Higher consumers' pro-environmental attitude will increase the intention for bioplastics packaging adoption. The pro-environmental attitude also influences consumers to adhere to disposing of bioplastic packaging waste according to the proper end-of-life route. Therefore, building a pro-environmental attitude is crucial for ecolabels to succeed as a nudge. Consequently, the twelfth proposition (P-12) is: Higher consumers' pro-environmental attitude will increase the intention for bioplastics packaging proper disposal.

For bioplastic packaging waste to be sorted and disposed of properly, consumers should have the right habits in sorting waste in the first place. These activities could be performed routinely in society and may also include social pressure or rewards to behave according to societal expectations as it is part of meaning-making. It could also include personal habits. We refer to this as habitual practice, the behavior of sorting and disposing of waste in its proper place. Therefore, the thirteenth proposition (P-13) is: Higher

habitual practice will increase the intention for bioplastics packaging proper disposal. Further, for bioplastics packaging waste could be disposed of properly, the proper trash bins and supporting infrastructure should also exist. The waste infrastructure in this regard is those designated for processing organic waste, including composting facilities, whether they are owned at the household level, community scale, or facilitated by the government. This leads to the fourteenth proposition (P-14): Greater accessibility of waste infrastructure will increase the intention for bioplastics packaging proper disposal.

5.3 Unsupported Propositions

When the protocol described above was applied consistently, then there are three propositions that were previously proposed from the literature, but not supported by empirical data, namely: (1) Higher ecolabel clarity will improve consumer attention; (2) Higher ecolabel visibility will improve consumer interpretation; (3) Higher ecolabel credibility will improve consumer interpretation.

It was discovered that consumer attention is more affected by visibility than clarity. Elements such as color, size and position of the ecolabel are considered to be more influential in attracting consumer attention than the legibility of text or images sharpness. Signal clarity, fit, and cost construcs stimulate better comprehension for consumer interpretation, while credibility impacts consumer trust rather than interpretation.

6 Conclusions

The results of the empirical research indicate that although ecolabels can impact the acceptance and correct disposal of bioplastic packaging through visibility, clarity, fit, cost, and credibility, they cannot achieve this alone. Other factors, such as the price of packaging material, pro-environmental attitudes, habitual practices, and access to suitable waste management facilities, need to be considered and in place as well.

To the author's knowledge, this is the earliest research that examines ecolabels' impact on the bioplastics packaging industry through the Signaling theory lens. The findings of this research will contribute to a better understanding of the role of ecolabels in sustainable consumption and how to effectively communicate the benefits of bioplastics to consumers. Conceivably, this research will help to promote sustainable practices in the packaging industry supply chain and contribute to a cleaner environment.

Given the specific focus of this study on bioplastics packaging industry within the Indonesian context, careful consideration is needed when extrapolating the findings of this study to other contexts. To validate the model, future research can benefit from a quantitative approach with a representative sample size. Additionally, exploring ecolabel design as an effective means of visual communication to consumers can be an interesting avenue for further study.

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Waste to 3D Printing: A Systematic Literature Review

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Abstract. Additive manufacturing is one of the most prominent technologies seen as an enabler for circular economy strategies, including the development of additive symbiotic networks. There is a gap in the literature regarding the understanding of how additive symbiotic networks can be developed, namely in identifying the wastes and by-products and additive manufacturing technologies that can be used to valorize these resources. This study aims to review the existing literature on the topics of industrial symbiosis and additive manufacturing. A sample of 83 documents was reached, with only 25 highlighting the potential for developing industrial symbiosis networks in the additive manufacturing context. Results show that the most used technologies to incorporate recycled materials included fused deposition modelling, fused filament fabrication and selective laser melting. Regarding waste or by-products exchanges, plastic polymers, biological wastes and metal powders are some of the most frequently exchanged materials. This makes evidence of the additive manufacturing industry's potential to develop additive symbiotic networks in which wastes and by-products from other industries may be used as material inputs for additive manufacturing processes and technologies.

Keywords: Additive symbiotic networks · Blockchain technology · Supply chain structure · case study

1 Introduction

The circular economy is a concept based on the natural cycle of life that centres on resources' usage while the used materials are kept in loops for as long as possible [1]. It can be defined as an economic system that replaces the concept of end-of-life based on a 4R framework ([2]): Reduce, Recycle, Reuse and Recovery of materials in distribution, production and consumption processes. In this context, industrial symbiosis has been identified as an approach to closing the loop of manufacturing systems through the transformation and conversion of waste from different industries and processes as feedstock to other industries [3]. Thus, creating the so-called Industrial Symbiosis Networks (ISNs) in which symbiotic relationships arise between different industries (stakeholders) that involve exchanging materials, energy, knowledge, and human or technical resources exchange, providing simultaneously competitive and environmental benefits.

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According to [4], sustainable development depends deeply on its relationships with technological development. In this sense, the concept of Industry 4.0 is the mixture of distinctive technological pillars that serve as the base for developing new interconnection technologies. Additive manufacturing (AM) is one of the most prominent technologies linked to the circular economy [5]. AM is an advanced computer technology that uses 3D printers to produce objects in successive layers and 3D digital design data [6]. A broad diversity of AM processes and technologies exists; thus, many opportunities arise to develop more sustainable means of production [7]. AM helps improve resources' efficiency, leading to the implementation of circular economy ecosystems [8] with benefits such as: lowering the overall emissions in the supply chain; generating small amounts of waste and allowing an extension of the product's life; and by holding a digital stock, it reduces the need for logistics and warehousing. Moreover, [7] highlighted that companies are starting to sell recycled filaments to their customers. Some organizations are beginning to recycle plastic waste to achieve a higher added value for their processes and products. This reveals increased potential for exploring the creation of ISNs within the AM industry [9].

Given its potential to promote sustainable concepts through repairing and remanufacturing activities and reduction in the production of waste [10], AM is seen as an enabler for circular economy strategies toward sustainability, which include the development of ISNs. In this study, we adopt the [9] definition of additive symbiotic networks: **"Additive symbiotic networks** can be understood as ISNs in which wastes or by-products from other industries are used in AM processes as material inputs. These networks can be understood as value networks constituted by several stakeholders exchanging resources between them".

There is an increased interest and publications exploring and developing additive circular ecosystems, such as [7, 11, 12]. The only published literature review that focuses specifically on the development of ISNs in the AM industry [13] considers a sample of 32 documents published until July 2020. Thus, there is a need to update that study to include new research developments on these topics. The main goals of this study are to update [13] the literature review related to industrial symbiosis and AM and to exploit the development of additive symbiotic networks. So, we replicated that study; we used the same research design (i.e. the exact keywords, databases, inclusion and exclusion criteria, as well as the same categories and subcategories for sample analysis), but the search timeline was extended until October 2022. This paper is organized as follows. Chapter 2 highlights the main results from the systematic literature review, including a bibliometric analysis and analysis of the documents in the sample. Chapter 3 presents the main conclusions and suggests future research venues.

2 Systematic Literature Review

2.1 Methodology and Sample Definition

A comprehensive search and analysis were performed for the documents reflecting the current research around industrial symbiosis and the AM industry. The search was done using the databases "Scopus" and "Web of Science", using the keywords "circular economy" and "additive manufacturing", considering a timeline until October 2022. It was

obtained 120 documents from the "Web of Science" database and 122 documents from the "SCOPUS" database. The documents from both databases were compared, and the duplicated documents were eliminated. A total of 161 documents were found. After applying the inclusion and exclusion criteria, the final sample containing 83 documents was reached (more 51 new documents were found than in [13]). Of these, around 81% are published in international journals, and the other 19% are concerned mainly with conference papers. Most of the documents in the sample (77%) employed empirical research methods using mixed methods and case studies.

Because of space limitations, the sample is available in the online appendix at https://doi.org/10.6084/m9.figshare.21433134.v4 (see table A). Table 1 summarises the sample size obtained in this review and the one obtained in [13].

Table 1. Comparison between samples

	Ferreira et al. (2021) [13]	Current review
Timeline	Until July 2020	Until October 2022
Total of documents found using the keywords "circular economy" and "additive manufacturing"	41	161
Total of documents after applying exclusion/inclusion criteria: - Only documents in English - Exclusion of publication type "Books" - Exclusion of documents that did not refer to reduce, recycle, recover and reuse from the 4R framework)	32	83
Final sample, i.e., total of documents relating to ISN in the AM industry	5	25

2.2 Bibliometric Analysis

Using the VOSViewer software, co-occurrence network maps, including key terms and keyword co-occurrence density diagrams, were generated to help identify the main trends and topics researched to date.

Analysis of Keywords in the Sample

The keyword analysis was conducted to assess the research results focusing on the circular economy and the AM industry. The analysis revealed that a total of 726 keywords were used in the sample keyword's fields and a total of 2370 terms in the title and abstract of the selected publications. Nevertheless, from the 726 keywords, only 26 emerged at least 5 times. The four keywords with the highest links strength are "Circular economy", "additive manufacturing", "3D printers", and "recycling". Figure 1 represents the keyword co-occurrence network map in which different colours' nodes represent

different clusters, and the size corresponds to the frequency [14]. The keywords can be grouped and classified into three main clusters:

- **Red cluster**: explores the circular economy concept within the AM industry towards sustainable development, mainly through product design, repair and remanufacturing activities and life cycle assessments.
- **Blue cluster**: explores Industry 4.0 technologies, such as the AM towards circular systems, focusing on the environmental impact of additive materials used in 3D printing.
- **Green cluster**: focus on recycling activities in the AM industry, mainly through polymers, with a particular emphasis on plastic recycling.

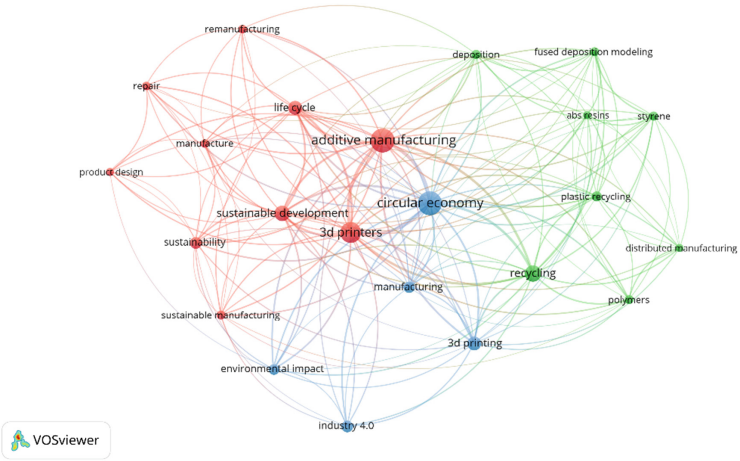

Fig. 1. Keywords co-occurrence network map

Figure 2 represents the density diagram. From the 2370 terms, only 28 relevant terms appeared at least 10 times. This diagram shows that most of the publications in the sample focused on circular applications through AM, which corroborates that the AM industry has been used to promote circular economy strategies, especially through the incorporation of waste, revealing the potential for developing additive symbiotic networks, through process and component repair and restoration.

2.3 Content Analysis

The sample was analyzed considering the categories proposed by [13]. Because of space limitation, the coding can be found at https://doi.org/10.6084/m9.figshare.21433134.v4 (see table B).

All of the documents under the sample focused on at least one R from the 4R's framework (Reduce, Reuse, Recycle, Recover) [2]. The "Recycle" is the most common to appear in the sample (36 documents mentioned recycling). In the sample, the most

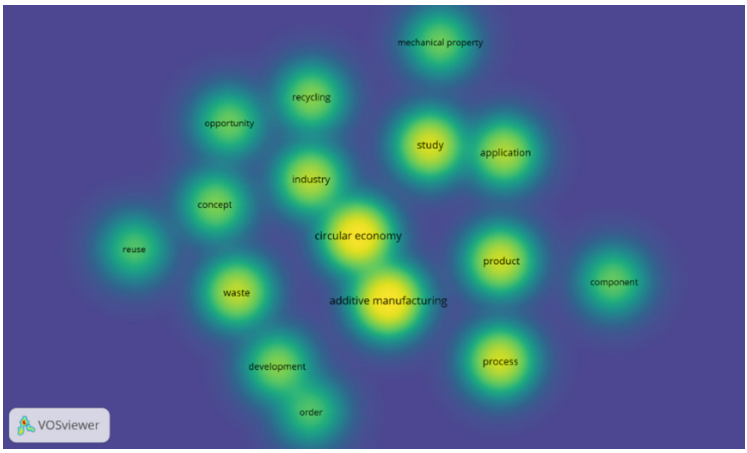

Fig. 2. Keywords co-occurrence density diagram

used technologies to incorporate recycled materials referred to fused deposition modelling (9 documents), fused filament fabrication (6 documents), selective laser melting (5 documents), fused particle/granular fabrication (4 documents), stereolithography (3 documents), and direct ink writing (3 documents). This research did not tackle issues related to the variability of the composition of wastes. In what concerns waste or by-products exchanges, we find the following evidence in the sample: plastic polymers (acrylonitrile butadiene styrene and polycarbonate are one of the most used) (12 documents), biological waste (including mussel shells and vegetable oils) (5 documents), metal powders (2 documents), scrap feedstock (2 documents) and post-consumer waste, wool, wood scraps, cork powder and even poultry feathers have been mentioned at least in 1 document in the sample.

For developing and implementing an ISN, there is a need to identify the resources that will be exchanged and the direct and indirect stakeholders that exchange resources in the symbiosis network. So, in the coding process, we looked for the following data: resources exchanged (i.e., wastes or by-products), direct/indirect stakeholders and type of AM technology used to valorize the materials. In the sample, a total of 25 documents refer to the specific exchange of wastes and/or other materials between industry sectors; we used this as a proxy for the possibility of developing ISNs within the AM industry.

To illustrate the coding process used in the sample analysis, the analysis of the paper by Byard et al. (2019) ([15]) is presented. In this paper, the direct stakeholders are Northwest Polymers McDunnough, Inc companies, a Green Fab Lab and a Sports company; the indirect partners were not identified. The physical resources (services and/or materials) exchanged are recycled acrylonitrile butadiene styrene, polypropylene, and sports goods (skateboard, snowshoes and a kayak paddle). Therefore, in Byard's [15], the potential ISN is described as two entities corresponding to the origin of the wastes, polypropylene and acrylonitrile butadiene styrene (McDunnough, Inc., and Northwest Polymers), in addition to an intermediary entity responsible for incorporating the wastes in a 3D printer to transform them into final products to be consumed. In this network,

the Green Fab Lab performs as a recycling centre and is the intermediary entity. The final 3D printed products consisted of sports mobility products.

Thus, this literature review highlights the potential of AM industry to create ISNs that valorize plastic waste streams, with plastic wastes and by-products being one of the most commonly exchanged resources. This is corroborated by the increase in the literature addressing the potential creation of ISNs in the AM industry – the additive symbiotic networks. A sunburst diagram (Fig. 3) was developed, highlighting how the several R's defining the circular economy (Reuse, Recycle, Reduce and Recycle) can be promoted through AM technologies using different wastes or by-products from other industries.

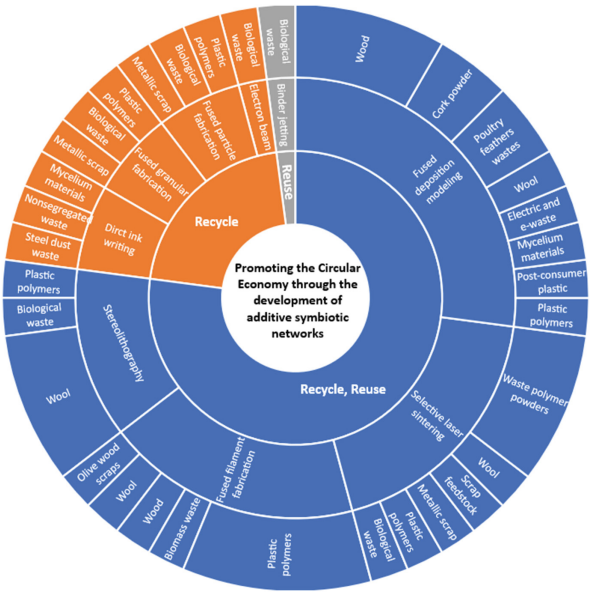

Fig. 3. Sunburst diagram showing how to promote additive circular ecosystems

3 Conclusions and Future Work

This literature review aimed to provide an updated analysis of the current research on the circular economy and AM topics. A sample of 83 documents was found to be relevant considering the topics of the circular economy and the AM. Compared to the previous systematic literature review (Table 1), this represents an increase of almost 159% in the number of publications from 2020 until 2022, with 51 new documents published on the topics of interest during this period. A bibliometric analysis was performed on the sample under study. Using the keywords co-occurrence network map, a cluster is highlighted comprising documents that focus on recycling within AM processes and technologies, with a particular focus on the use of plastics. Thus, corroborating the

potential of the AM industry towards achieving sustainability ([11, 16]. This is because the remanufacturing activity is still the main activity used by AM to promote the circular economy and industrial symbiosis, as reviewed in [13]. Furthermore, overall this research supports existing studies revealing how AM is one of the most promising Industry 4.0 technologies towards the implementation of circular ecosystems and sustainable business models [9, 17].

Only 25 documents from a total of 83 documents analyzed were found to be potentially linked to the development of ISNs within the AM industry – the additive symbiotic networks [9]. Even though the results revealed that the development of additive symbiotic networks is still in an early stage of research, there has been an increase in the interest in these research topics from 2020 until now, with a rise of almost 400% new documents published focusing on potential additive symbiotic networks. In these networks, plastic materials are the most common residue exchanged.

Although this study has identified and described the arising of additive symbiotic networks, several limitations need to be considered. Namely, it was not possible to quantify wastes and by-product exchange within this context in terms of quality and quantity produced. Moreover, this study did not consider any pre or post-processing operations.

When relating to the performed systematic literature review, the results considered only the sample under study; thus, other relevant works might not have been considered - specifically, publications in the form of industry reports, books and book chapters. Simultaneously, considering the knowledge on the topic under study is still limited, this opens space for the research community to address this research gap from many different perspectives. In this study, only the exchange of waste and by-products was considered. Other types of exchanges can occur in an industrial symbiosis setting, like energy exchanges or infrastructure sharing, and thus, future research should include more possibilities for exchanges within additive symbiotic networks. Furthermore, to enhance the development of additive symbiotic networks, there is a need for future studies that focus on quantity, quality and classification of the main outputs produced by the incorporation of wastes and by-products in AM technologies. In this context, a SWOT analysis is needed and should be carried out about the best practices and strategies to increase circular ecosystems within the AM context.

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SMD Components Recycling Procedure for Reuse in E-Textiles with Risk Analysis

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Abstract. This paper deals remanufacturing method for the reuse of adhesive bonded SMD components on stretchable textile ribbons for integration in e-textiles and its risk analysis. Nowadays, e-waste is an increasing problem in the world, and reducing this problem by using circular economy principles and reusing components is beneficial. In our research, the samples were submitted for accelerated ageing by dry heat and their quality was evaluated by the electrical resistance measurement. The recycling procedure was realized four times, and the mentioned risk analysis was realized before and after the experiment. The two main goals of our research were determined. The first goal was to demonstrate the applicability of our recycling procedure and the quality of samples with reused components after accelerated climatic ageing by dry heat. The second goal was to create and verify the risk analysis of our method and identify actions to mitigate the high and very high risks. The experiment showed that our recycling method is applicable several times without decreasing product quality. The results also present that reused samples are functional like new even after samples dry heat ageing. The risk analysis after the experiment showed seven high risks, which is necessary to solve primarily. These risk factors and actions to mitigate them are described in the paper.

Keywords: Recycling procedure · e-textiles · risk analysis · circular economy · SMD components reuse

1 Introduction

Nowadays, there has been an exponential increase in e-waste, as the European Commission or the World Health Organization have reported in their annual reports [1]. This is evidenced by a survey carried out by the Global E-waste Statistics Partnership (GESP) [2], according to which 53.6 million metric tonnes of e-waste were generated in 2019, and it is estimated that this figure will continue to rise and that up to 74 million metric tonnes of e-waste could be generated in 2030. In addition, it was found that for 2019, only about 17.4% of the total amount of e-waste was recycled, meaning that the valuable and usable materials found in these devices (gold, silver, copper, etc.) were mostly either

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thrown away or incinerated instead of reused. For example, prior to the Tokyo Olympics, the 2017–2019 collection of small electronic devices totaled 78 985 tonnes, from which 32 kg of gold, 3,500 kg of silver and 2,200 kg of bronze were subsequently recovered and used to make Olympic medals [3].

The reason for this rapid increase in e-waste in recent years is not only due to the growing population and therefore the increased demand for and consumption of these products, but also due to the short life cycle and the low number of repairs of these products [4]. Of course, the constant development of new technologies has also had an impact, but the Covid-19 pandemic has also contributed to this, causing a further increased interest in electronics not only among people who have had to work from home, but also among businesses which, as a result of the development of new technologies and the Covid-19 pandemic, have begun to modernize their production significantly in order to maintain their competitiveness in the market [5]. The amount and rate at which e-waste is produced is therefore a serious global problem, not only in terms of the environment but also in terms of human health. For this reason, more and more countries are addressing this problem and trying to regulate the growth of e-waste through their own, as well as supranational, legislation and directives, which not only specify collection rules and procedures for the management/disposal of e-waste, but also relate directly to the production of these products, such as eco-design [6]. Companies must therefore already include environmental considerations in the development and design of new products. However, at present, companies are faced with another obstacle, which is the lack of sufficient quantities of electronic components, chips and microcircuits that are necessary for the production of these devices. This shortage of components on the market has been the result of the fight against the spread of the Covid-19 pandemic, with the closure of many factories dedicated to the production of these components in 2020 [7]. Therefore, the reusability of components and equipment would also be beneficial and could serve as one of the solutions.

The structure of this paper is as follows. In the previous part, the importance of our topic was described. After the structure paragraph, the objectives of this article are set. The next Subsect. 1.1 and 1.2 describes the basic principles of circular economy and risk management. The Sect. 2 is focused on the materials and methods used in this research. The Sect. 3 contains the Ishikawa diagram and risk analysis of our recycling procedure. In Sect. 4, the results of the experiment consisted of 4 cycles of ageing and reusing samples in length of 2 weeks for each cycle are described. In the last chapter, the recalculation of risk analysis based on the knowledge from the experiment is contained.

The following main objectives were formulated for the research presented in this paper. The first objective is to demonstrate the applicability of our method of reusing SMD chip components on the e-textile and also the quality of samples with reused components after accelerated climatic ageing by dry heat. The second objective is to create and verify the risk analysis of our method and identify actions to mitigate the high and very high risks.

1.1 Circular Economy and Remanufacturing

The model of reusing materials with an idea for extension of product life-cycle, reduce amount of waste and amount of new raw materials used is called circular economy. It

is a model to ensure the sustainability of production according to the world population growing and limited amount of materials in the world. The one of the circular economy principle is special design of product according to the possibility of reusing. Then after the end of product life-cycle, the extension of life-cycle by recycling and reusing of some parts is done [8].

The main part of the circular economy is remanufacturing which is process of disassembling, cleaning, inspecting, repairing, replacing, and reassembling the components in product. The aim of these processes is extension of product life time [9]. The remanufacturing process consists of a few steps. Products have to be collected from the customer after the end of life-cycle. Then these products have to be disassembled to the individual parts. In the next step, these parts have to be inspected and tested to detect the current state and sorted into three groups (functional, repairable and destroyed). Then the functional and repairable components are cleaned and repaired if necessary. Then, the prepared components are reassembled to the new product and these products are thoroughly tested. Finally the products are sold to the new customers. This cycle can be repeated several times until the components are too worn and discarded [10].

1.2 Risk Management

Risk management is an important task in corporate governance. It is a continuous, recurring set of interrelated activities designed to manage risks and to reduce their occurrence and impact on the organization. Risk management refers to the application of a systematic approach to evaluation and mitigation on risks to ensure that the organization's objectives are achieved [11]. The risk management also includes the preventive activities to avoid crisis management. It is consisted of identification, analysis, evaluation, mitigation, management and monitoring of risks. If the level of risk value is unacceptably high, the actions to mitigate the risk to acceptable level have to be accepted. The implementation of risk management in company is currently standard not only according to the legislation [12]. The risk management can be also applied to the processes or to the product life-cycle management (PLM). In that case, the risk management of product during its life-cycle is standardly realized [13]. Also in the case of remanufacturing it is necessary to perform a risk analysis in order to cover the new risks resulting from the aforementioned remanufacturing. For this reason, in our research, the risk management is applied after the end of product first life-cycle, when the process of components reusing happened. The details of this risk management are described and applied in chapters below.

2 Materials and Methods

2.1 Textile Ribbons

In our research, the specially developed conductive textile stretchable ribbons protected by a national patent (308614) were used [14]. The ribbons are consisted of polyester threads in warp and weft [A] (strength and durability), rubber threads in warp [B] (stretchability) and hybrid threads [C] (electrical conductivity), see Fig. 1 left. The hybrid threads

are consisted of polyester monofilaments and eight silver coated copper microwires for each thread. The yarn inside the threads are arranged in a horseshoe pattern (see Fig. 1 right) to enable repeated ribbon stretching without damage. The ribbon has four conductive lines with sufficient electrical resistance for e-textile applications.

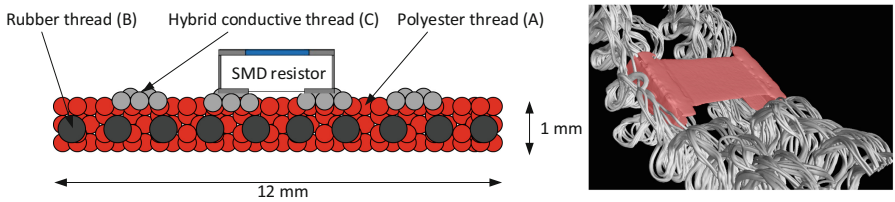

Fig. 1. Schematic cross-section of the conductive textile ribbon (left) and CT scan of SMD chip component connected by a non-conductive adhesive onto a conductive ribbon (right).

2.2 Conductive Connection Technique by Non-conductive Adhesive

The electrical connection of SMD components (with 0 Ω resistance with case size 1206) to the conductive lines in ribbons was realized by special contacting technique with using the non-conductive UV curable acrylic adhesive (NCA) [15]. The procedure of this technique is as follows (see Fig. 2). The adhesive is dispensed onto the space between conductive lines on ribbon and the component is placed into the adhesive. Then the components is pressed by mandrel into the adhesive with a force of 30 N, the adhesive is squeezed out the ribbon and direct electrical contact is created. At this state the adhesive is cured by UV light and component is fixed in this contacted position. Finally the mandrel is removed and the hole from it and the whole resistor is encapsulated by the same adhesive.

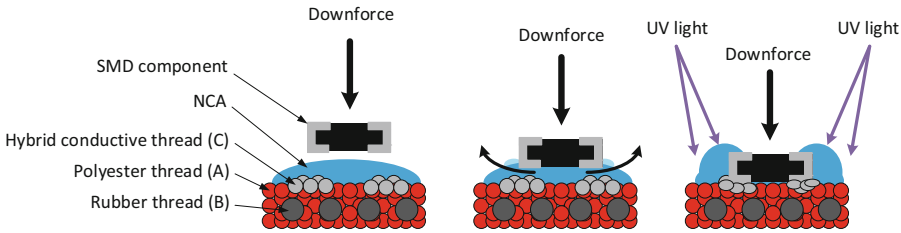

Fig. 2. Principle of special contacting technique

2.3 Accelerated Ageing by Dry Heat (85 °C) and Measurement of Samples

The accelerated ageing by dry heat of the samples was chosen to test the functionality of the recycling procedure after the accelerated simulation of standard usage of samples.

The ageing was realized in drying oven with temperature 85 °C for 336 h according to the standard IEC 60068–2-2 Environmental testing - Part 2–2: Tests - Test B: Dry heat [16].

The contact electrical resistance of each sample was measured by the device DMM Keithley 7510 by four wire sensing method of resistance measurement.

2.4 Recycling Procedure for Reuse the Components in E-Textile

The ribbons with components are sewn onto the standard textile, connected with the power supply battery and e-textile is created. The product is used by the customers until the significant deterioration in the product properties when the end of the product life-cycle occurs. In our previous research (e.g. [17]), the reliability of joints of components connected on the ribbons by our method (from Sect. 2.2) was tested and the results showed that hybrid threads in ribbons or joint between SMD chips and conductive lines are the most common cause of e-textile damage. It follows that components can be reused again. The e-textile is collected back when its stops working, in accordance with the principles of circular economy and the remanufacturing procedure is started. In this procedure, the ribbons are removed from collected e-textiles and placed into the acetone bath for 20 min with the component above the bath. Then the components are removed from the ribbon and old ribbons with acetone are environmentally friendly disposed. In the next step the functional and visual check of components is realized and the components are sorted into the three quality groups (perfect, minor damage without affecting function, broken components). The broken components are disposed and the rest of components are cleaned from residues by isopropyl alcohol. Then these components are reused and contacted onto the new ribbons with the same contacting technique and new e-textiles are created.

2.5 Brainstorming and Ishikawa Diagram

The Ishikawa diagram, also called fishbone diagram, is method for root cause analysis of a specific event. Related causes for a specific event are grouped into predefined categories. The typical categories in these diagrams are Materials, Methods, Machines, People, Environment, Measurement, etc. All information are graphically represented in a diagram, which is shaped like a fish skeleton [18]. For creation of this diagram, the brainstorming technique can be used. In this technique, the group of experts (ideally diverse people) discuss established topic to find new ideas (in our case causes and effect, resp. Risk identification). If these ideas are not immediately evaluated, people are able to think spontaneously without limits and find new ideas. The brainstorming meeting leader writes down all the ideas. These ideas are evaluated only after the meeting.

2.6 Semi-quantitative Risk Assessment Method

In this methodology, the risks are identified on the basis of information from fishbone diagram and expanded by new brainstorming session. After the setting of risks, the impact

(I) and probability of occurrence (PoO) has to be determined. The level of these parameters can be different in semi-quantitative approach. The risk value (RV) is calculated by multiplying the two previous parameters (I and PoO) [19, 20].

In our case, the probability of occurrence (PoO) is describe like possibility of occurrence of the risk and has five levels. 1 = rare, 2 = unlikely, 3 = possible, 4 = probable, 5 = highly probable. The impact (I) of the risk describe the impact when the risk occurs and has five levels. 1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high. The risk value (RV) is from 1 to 25 and has four levels. 1–3 = low risk (green), 4–9 = medium risk (yellow), 10–19 = high risk (orange), 19–25 = very high risk (red).

3 Ishikawa Diagram and Risk Analysis

The first step of our analysis was creation of the fishbone diagram with our team of experts by using of brainstorming technique, see Fig. 3.

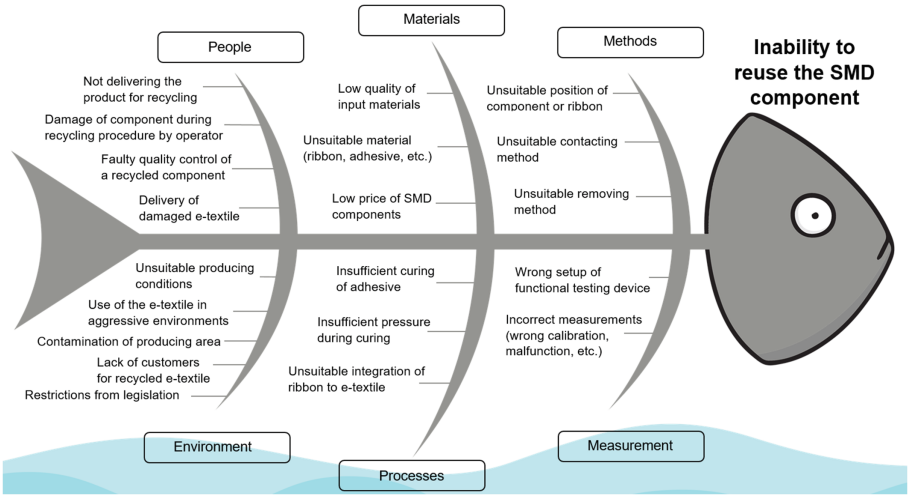

Fig. 3. Fishbone (Ishikawa) diagram of causes and effect.

In the next step, the causes from the fishbone diagram were used for the identification of risks of our recycling procedure. The list of risks has been extended by information from another brainstorming session. Finally, the impact (I) and probability of occurrence (PoO) for each risk were determined in cooperation with experts and risk values (RV) were calculated, see Table 1.

The table shows that our recycling procedure has one very high risk and six high risks. These risks should be solved primarily. The very high risk (B) is **delivery of damaged e-textile** from customers as an input material to the recycling procedure. This risk can be partially mitigate by thorough visual inspection of e-textile on receipt from the customer and discarding all damaged pieces from process. The first high risk (A) is **not delivering the product (e-textile) for recycling** and the resulting shortage of input

material. This risk can be solved by setting a fair purchase price from customers or a discount on the new product when the old one is delivered. The second high risk (C) is **damage of component during recycling procedure by operator**. This risk can be mitigate by operator training and strict adherence to the work procedure. The third high risk (D) is **faulty quality control of a recycled component** that causes the reuse of a defective component or disposing a perfect component. This risk can be mitigate by determining the appropriate test parameters for each component and measuring them consistently. The fourth high risk (G) is **low price of SMD components**. If reused SMD components are cheap, the financial balance of reuse is not positive. For this risk mitigation, the selection of components suitable for the recycling procedure has to be applied (only more expensive or scarce components are suitable). The fifth high risk (H) is **unsuitable position of component or ribbon**, which means that the component on ribbon or ribbon on e-textile is placed on the place where significant mechanical damage occurs or removing component from old ribbon is not possible. This risk can be mitigate by following an appropriate design and placing. The sixth high risk (N) is **lack of customers for recycled e-textile**. This risk has to be solved partially by marketing department and partially by demonstration of sufficient reliability of recycled products.

Table 1. The list of identified and evaluated risks.

No.	Identified risk	I	PoO	RV
A	Not delivering the product (e-textile) for recycling	5	3	15
B	**Delivery of damaged e-textile**	**5**	**4**	**20**
C	Damage of component during recycling procedure by operator	5	3	15
D	Faulty quality control of a recycled component	5	2	10
E	Low quality of input materials	4	1	4
F	Unsuitable material (ribbon, adhesive, etc.)	5	1	5
G	Low price of SMD components	5	3	15
H	Unsuitable position of component or ribbon	5	2	10
I	Unsuitable contacting method	5	1	5
J	Unsuitable removing method	5	1	5
K	Unsuitable producing conditions	3	1	3
L	Use of the e-textile in aggressive environments	4	2	8
M	Contamination of producing area	4	1	4
N	Lack of customers for recycled e-textile	5	2	10
O	Restrictions from legislation	5	1	5
P	Insufficient curing of adhesive	3	1	3
Q	Insufficient pressure during curing	5	1	5
R	Unsuitable integration of ribbon to e-textile	5	1	5
S	Wrong setup of functional testing device	5	1	5
T	Incorrect measurements (wrong calibration, malfunction, etc.)	5	1	5
U	Lack of money	4	1	4

4 Experimental Testing

For the experiment, fifteen SMD chip resistors with case size 1206 and zero ohm resistance were used. These resistors were connected to the ribbons by NCA bonding technique. Then the electrical resistance of new samples was measured and samples were submitted to the accelerated ageing test for 85 °C/336 h. After the ageing process, the

electrical resistance was measured again. Then the components from aged ribbons were removed by our removing process and reused onto the new ribbons. Overall, four cycles of testing (i.e. resistance measurement, ageing for 336 h, removing components and reuse components) were realized. The details of materials and procedures are described in Sect. 2.

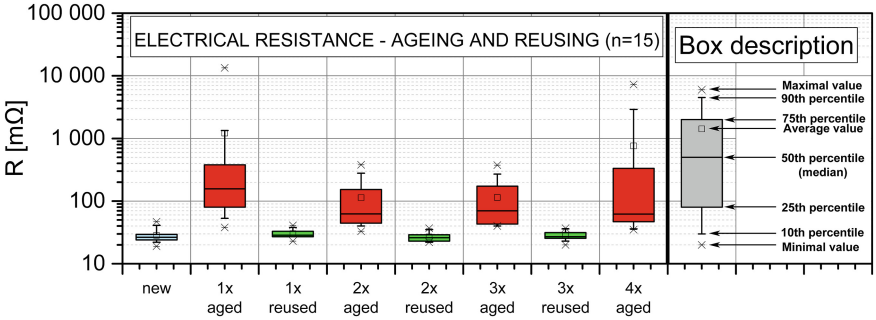

Fig. 4. Boxplot diagram of NCA bonded joint electrical resistance after ageing and reusing.

The results show (see Fig. 4), that electrical resistance grows during the accelerated ageing by dry heat from around 25 mΩ to values between 60 to 300 mΩ. These values are still acceptable for many applications. The results also show that electrical resistance of samples with reused components is essentially same like samples with new components. It follows that reusing of components has not significant effect on quality of new joints on textile. The results also show that electrical resistance of samples with reused components after the accelerated ageing is comparable with resistance of samples with new components after the same ageing. In the experiment 4 life-cycles of components were tested. In our opinion the condition of component after the fourth live-cycle was not perfect for another cycle but was still usable. It follows we can recommend maximally the four life-cycles, but it depend on the operator caution and the current state of the components. During the experiment, we also tried some mechanical tests of another samples and we have verified that the mechanical damage of encapsulated resistors is very hard. The experiment also gave us information and practical experience with our reusing method and this knowledge were used for recalculation and adding of risk factors.

5 Recalculation of Risk Analysis

The recalculation of risk analysis was realized after the performed experiment based on the new knowledge from it. The experiment also showed some new risks added to the recalculated analysis (see Table 2). Unchanged risks from initial analysis (Table 1) were removed from Table 2. The recalculated analysis shows that our recycling procedure has seven high risks. These risks were a little changed compared to the first risk analysis. These risks should be solved primarily. Actions to mitigate these risk factors are described below, except of factors where RV has not been changed (these actions are same and were described in Sect. 3).

The first high risk (A) is **not delivering the product (e-textile) for recycling** (actions in Sect. 3). The second high risk (B) is **delivery of damaged e-textile**. The impact of this risk was decreased because the experiment showed that it is relatively hard to damage the component for reuse during the product life-cycle. The RV of this risk was decreased but we can still recommend visual inspection of e-textile on receipt from the customer and discarding all damaged pieces from process. The third high risk (C) is **damage of component during recycling procedure by operator**. The PoO of this risk was increased because experiment showed that damage of the component is relatively easy. But also impact of this risk was decreased, because the experiment showed that small mechanical damage of components is not a problem for their function and reusing. For this risk mitigation is necessary to have skilled or experienced operator and also the operator must be careful when removing the component. The fourth high risk (D) is **faulty quality control of a recycled component** (actions in Sect. 3). The fifth high risk (G) is **low price of SMD components** (actions in Sect. 3). The sixth high risk (N) is **lack of customers for recycled e-textile** (actions in Sect. 3). The seventh high risk (W) is **shortage of skilled labours**. The experiment showed that skilled or experienced operator is necessary, it follows that regular practice and education of operators is necessary. Also employee remuneration system is suitable to maintain the quality staff. The RV of risk (H) unsuitable position of component or ribbon was decreased to medium risk level because impact of this risk was reduced. Experiment showed that encapsulated component is well protected against mechanical damage. It follows that worse position of component or ribbon, where the mechanical stress is higher, is not a big problem for component.

Table 2. The list of recalculated risks based on the realized experiment. Unchanged risks are in the Table 1.

No	Identified risk	I	PoO	RV
B	Delivery of damaged e-textile	3	4	12
C	Damage of component during recycling procedure by operator	4	4	16
H	Unsuitable position of component or ribbon	3	2	6
V	Incomplete and inaccurate cost estimates	4	2	8
W	Shortage of skilled labours	5	3	15

6 Conclusion

The first objective of this paper (**demonstration of the applicability of our method** for reusing SMD chip components on the e-textile and the quality of samples with reused components after accelerated climatic ageing by dry heat) **has been achieved** in the experiment described in Sect. 4. The experiment provided proof that:

- our recycling **method is applicable**
- the electrical **resistance** of **reused** components is **comparable** with **new** components

- the samples with reused components endure the dry heat ageing in similar condition like new samples

The experiment also showed that **our method can be used for a few times** (ideally not more than four life-cycles).

The second objective of this paper (creation and verification the risk analysis of our method and identification of actions to mitigate the high and very high risks) was realized in two steps. In the first step, the Ishikawa diagram and initial risk analysis were realized. In this step, the **actions to high and very high risk mitigation were determined**. In the next step, the experiment described in Sect. 4 was realized and the new knowledge and information were acquired. Based on these knowledge, the recalculation of risk analysis was realized and also the actions to high and very high risk mitigation were modified or newly determined.

Our recycling procedure can be used for e-textiles, where SMD chip components on electrically conductive textile stretchable ribbons are used. These **procedure** can **save** the raw **materials**, **reduce** the **waste** and also production **costs**. This method is especially **suitable for components with high value or shortage components**. In our future work we plan to develop this topic, especially the testing of the samples with reused components endurance in other ageing tests with more challenging conditions.

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Embedding Perceptual Quality in Omnichannel's Touchpoints in Product Development Lifecycle Management Using Data Analytics

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Abstract. Nowadays, the importance of social media and its influence on customers for customer behavior transformation has been highlighted. This has introduced the importance of analyzing the impact of social media on Product Lifecycle Management (PLM) phases and how to use it for more efficient product development cycles. The paper has shown through the literature review, the lack of contributions for benefiting from the potentials of social media platforms for PLM refinement. Especially, the capabilities of social media analytics for extracting customers' emotions and perceptions are neglected. Moreover, the paper has highlighted the importance of perceptive quality and has and investigated it with a focus on the Omnichannel concept. Customer satisfaction and perceptual quality as two crucial factors which directly can be influenced by social media platforms have been considered. Using the system dynamics approach, a cause-and-effect model for demonstrating the relations and effects of these factors in product lifecycle management frameworks has been developed. Also, a social media data analytics model has been developed to formulate customer satisfaction and perceptual quality. The approach applies sentiment natural language processing and analysis to provide a basis for relating the mentioned factors. The findings have provided insights for embedding social media analytics in PLM analytical frameworks.

Keywords: Perceptual quality analytics · Product Lifecycle Management (PLM) · Social media data analytics · Sentiment analysis · Omnichannel

1 Introduction

Nowadays, Product Lifecycle Management (PLM) systems have faced serious challenges due to more customer-oriented markets, and challenging product development lead times [1]. PLM systems are highly dependent on their Product Data Management (PDM) systems [2, 3]. PDM can be considered the backbone of the PLM framework

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for providing different stakeholders with integrated and synchronous data [4]. Engineers noted the need in the 1980s to maintain the growing volumes of design data generated by and contained in a variety of automated and semi-automated systems, such as Computer-Aided Design (CAD) files, identifications, and essential documents, Computer- Aided Manufacture (CAM) programs, and Computer Aided Engineering (CAE) analysis [5–7]. PDM empowered them to store and control all product data, manage document issue levels, maintain Bill of Materials (BOM), and visualize the relationship between parts and assemblies in real-time [8, 9]. However, simply being able to manage data was insufficient. There was an obvious necessity to manage the entire product lifecycle, and product development is only one component which should be integrated with various information technology supported disciplines [10, 11].

A product lifecycle can be divided into five stages: development, introduction, growth, maturity, and decline. Product development includes the first three stages, but engineers needed a more detailed system to support both product development and the entire product lifecycle [2, 12]. PLM is an essential factor because it can be interpreted as a basic plan of the product lifecycle in a specific business or product area. It is a collection of business rules, methods, processes, and guidelines, as well as instructions for implementing the rules [8]. PLM aims to expand the scope of PDM over and above design and manufacturing into other areas such as marketing, sales, and after-sales service, while also addressing all product-relevant parties during its lifecycle [3].

There are challenges in the PLM field related to marketing; however, gaps are detected in the field of using data from customers using data analytics tools (using Marketing segments) and integrating it with PLM phases for more efficient product development. From the customer's perspective, perceptual quality is a critical factor that has a direct impact on customer satisfaction and sales growth. Touchpoints are Omnichannel channels that connect customers and manufacturers [13]. Omnichannel has the ability to interact with customers through Omnichannel channels, so frameworks for understanding conceptual quality from the customer side and embedding it in PLM are required.

Advancements in technology have altered the way consumers behave and redefined the connection between individuals and companies. The digitalization trend has had a profound impact on various industries, forcing many to either adapt or change their operating models [14]. As the business environment continuously evolves, many conventional retailers and service providers have shifted to an omnichannel approach to stay competitive and better meet the needs of their customers [15]. In essence, being an omnichannel organization places the customer at the center of the company's operations by seamlessly integrating channels, maintaining consistency, and providing a smooth customer experience [16].

This paper has focused on social media data analytics merits for enriching the PLM frameworks. This investigation is targeted toward the possibility of evaluating the preceptive quality from the point of view of customers by applying natural language processing and sentiment analysis. Using the outcomes of social media analytics, the PLM frameworks can be enhanced for more effective product development. The paper investigates the gaps in the literature for the application of social media analytics in PLM. It aims to apply a system dynamics approach to allocate social media analytics in PLM

frameworks. Also, the paper intended to highlight the insights gained by applying social media analytics for customer quality perception evaluations using customer interactions through Omnichannel touchpoints.

2 Literature Review

PLM is a strategic business method for the efficiency and utilization of a company's intellectual capital. Globalization, outsourcing, mass customization, rapid innovation, and tracking are some of the hurdles that product development teams face today. These hurdles highlight the importance of collaborative environments and knowledge management throughout the product lifecycle phases [17]. PLM systems are becoming more popular for controlling all data about a company's products across all of their entire lifecycles, from conception to operations and disposal. PLM theory and systems are intended to assist a wider variety of engineering and business operations [18]. In the present economy, most medium and large enterprises prioritize addressing international business impediments. Whether they want to grow their customer base in emerging businesses or utilize more cost-effective assets, doing business on a global scale is indispensable [19]. With increased cost and time assets, anything and everything related to better quality can be accomplished. The real difficult activity is to achieve optimal perceptual quality standards within offered technological, development time, production system abilities, and budget restrictions. As a result, perceptual quality must be monitored throughout all phases of a product's development [20]. From the marketing point of view, customer satisfaction is defined as a critical determinant that is heavily reliant on the behaviors of customer-facing service providers. Consumers should be handled as investments, and their necessities, desires, and purchasing behavior change depending [21]. For the last several years, business intelligence has been a prominent area that employs data analysis to generate critical insights for decisions. Social media analytics is the technique of analyzing the information gathered from social media platforms (Omnichannel's touchpoints) and blogs in order to make business decisions (SMA). This technique, which goes further than simple tracking or retweet analysis, provides an in-depth understanding of the social end-user [22].

For almost a decade, social media has been the most efficient and powerful platform for customers to express themselves thanks to its simplicity of use and flexibility [23]. Similarly, a percentage of clients freely share their thoughts about a product or service [24] by submitting or posting comments on varied word-of-mouth channels like Facebook, Twitter, and Amazon. Particularly, many users simply post on social media about their satisfaction or emotions about something like a product or service, whilst some influencers can provide comprehensive reviews of the main features of a product or service and/or honest complaints of their limitations. Such affective customer viewpoints could indeed influence whether or not other potential customers buy a product, since a majority of customers' purchase decisions are likely to be influenced by the experiences of people who have utilized the product or service [25].

Several researchers have accumulated a massive proportion of customer-generated data from social media and obtained statistical results, measurable satisfaction ratings, or text key points that can assist advertising companies in making tactical choices in their business world.

Especially, [26] gathered customer reviews of the Samsung Galaxy Note 5 from Reddit, one of the social networks, and recorded customers' concerns about battery life, touch identification, camera, and so on by implementing topic modeling to the data collected. Furthermore, they used sentimental analysis and an opportunity algorithm to determine the satisfaction and significance rankings, as well as the chance rating for each topic. Such information, which they obtained, could indeed aid the related company's decision-making in the design of a product or service by improving product characteristics with high significance scores but low satisfaction.

As [27] aimed to investigate the use of social media in BI studies as well as the current developments in the field of research. This was accomplished by analyzing open social media platforms as input data and performing a comprehensive analysis of publications that performed social media-based BI investigations.

PLM phases are in charge of ensuring product/service quality. This quality term is technical quality; another term is perceptual quality, which is measured by customers. There should be a link between customers and businesses to understand the customer's understanding of quality. This link connects PLM to the Omnichannel touchpoint, which is the point of customer interaction. This is a gap (see Table 1) in the literature; there is no bidirectional connection between PLM and Omnichannel touchpoint.

In this study, a framework is considered for connecting PLM to Omnichannel touchpoints in order to collect data from social media channels, analyze it by using data analytics tools, and use this information in PLM phases. In other words, it incorporates customer-side data into PLM phases. The information gathered from the customer side is classified as Perceptual quality and Customer satisfaction.

Table 1. Literature review highlighting the lack of customer satisfaction model relying on customer perceptive quality

Research	Technical quality perspective	Perceptual quality perspective	Customer Satisfaction evaluation model
Sudari et al. 2019 [28]			The impact of marketing on customer satisfaction by using questionnaires and the Sobel test
Saraph, et al. 1989 [29]	Define 8 important parameters to evaluate the quality		

(*continued*)

Table 1. (*continued*)

Research	Technical quality perspective	Perceptual quality perspective	Customer Satisfaction evaluation model
Ravichandran and Rai 2000 [30]	By using Partial Least Squares analysis, a model is proposed for measuring quality improvements		
Mândru, Hârlab, and Camarda 2009 [31]	using indicators to measure quality (qualitative level of the products)		
Stylidis, Wickman, and Söderberg 2020 [20]		Using PQAIR Method and pilot experiment to measure perceived quality and rank the importance of it	
Steenkamp 2017 [32]		An empirical study for measuring perception quality in food industry	
Lee et al. 2016 [33]			Propose two satisfaction level of CSI models for resource decision making

3 Embedding Social Media Analytics for Customer Perceptive Quality Evaluation

3.1 System Dynamics Approach for Perspective Quality in PLM Domain

The effect of social media on PLM is modeled using system dynamics as illustrated in Fig. 1. As illustrated, in the Causal loop model, with the help of social media platforms, online feedback is divided into positive and negative comments after the product is sold. In traditional PLM, after receiving negative feedback and analyzing it, some of them opt for a modification. The issue here is that it takes time to make changes, and it is unclear whether the customer will be satisfied with the modified/new product. During this time, the company will experience sales losses. Two key factors are considered in this paper to save time and money while ensuring that the modifications are based on customer requirements. First, negative comments are analyzed, and customer needs will be clear and perceptive quality, which is defined as the customer's understanding of the actual product and is unrelated to physical product quality. Customer satisfaction is a

key component of Omnichannel Strategy, and it is considered in this model. And this paper attempted to establish a link between customer satisfaction and perceptual quality. Customer satisfaction is represented by stars that can be given when providing feedback, and perceptive quality is represented by comments written by customers.

Fig. 1. The causal loop of system dynamics model positioning customer perceived quality and customer satisfaction

3.2 Using Data Analytics to Establish the Relationship Between Customer Satisfaction and Perceptual Quality

This paper has focused on sustainable cloth products. This is mostly due to this fact that it has garnered significant attention in recent times due to the concept of fashion sustainability. This concept refers to the creation of clothing that not only minimizes its impact on the environment but also takes into consideration the well-being of those who are involved in its production. In simpler terms, sustainable fashion is both ethical and eco-friendly. For finding the relation between these two variables, the analysis was carried out using a script written in the Python programming language (version 3.10.8) from mid-July to mid-August. The hardware used is Windows 11 powered machine, Intel

11th gen i5 x64 bit processor. The libraries listed below were used: matplotlib. Pyplot, nltk, and transformers. The time interval for this project was two days per week, so the entire process of retrieving, cleaning, and analyzing the data took three months. The data collection and cleaning took one month, with the data retrieved in the first three weeks and the cleaning taking another week. The analysis, which included graphs, emotions, and scores, took up two of the remaining months.

First, the title, rating, and body were converted into a data frame with rows and columns, with each row containing one complete feedback and columns containing the "title, rating, and body". The Sentiment Analyzer function was then applied to each entry in each row using the nltk library. A web scraper was implemented to gather customer feedback data from the Amazon website. The web scraper made use of the request from html library. The scraper parsed the data and developed .json files, which were later converted to text files. Sustainable clothing products mostly with the tag "Climate Pledge Friendly" were chosen, and customer reviews with the tag". The function analyzed the words in the entries and assigned each one a "positive," "negative," "neutral," or "compound" score. Based on the rating and the words used in the title and body, a specific score indicated the intensity of that specific emotion in the data row. A higher positive score, for example, indicated that the emotion behind the data row was more positive. In addition, the compound score is the sum of the three scores. A higher compound score indicates a more positive emotion behind the data row. The feedback data frame now contains all the score columns. Then, using the seaborn and matplotlib libraries, Fig. 2(a) has been created, which shows the rating group (on the x-axis) and their average compound scores (on the y-axis) see Fig. 2(a). Higher star ratings result in higher average compound scores. The same libraries were used to create Fig. 3(a), 3(b), 4(a) and 4(b), which depict the rating group (on the x-axis) as well as their positive, neutral, and negative ratings (on the y-axis).

The transformers library was then applied to the customer data to perform emotion sentiment analysis. The emotion function was applied to the body column, which generated a unique emotion for each feedback row based on the words in the customer feedback's body. The emotion intensity rating provided by the function indicated how strong the provided emotion was. Scores closer to one indicated more intense feelings of that emotion. The feedback data frame was updated with the emotion and scores.

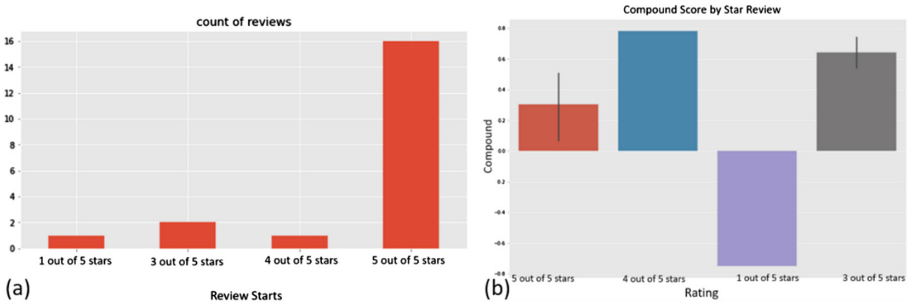

Fig. 2. Categorizing rating group of comments: (a) count of reviews from 1 to 5 starts, (b) The compound score for star reviews.

Eventually, a count plot was created to show how much feedback from various emotions there was, See Fig. 5. This graph can be used to predict the average customer's reaction to a product. The customer feedback data was cleaned and refined after it was obtained. The cleaning process began with translating the feedback from German to English, correcting spelling errors, and removing feedback that made no sense, such as numbers/characters in place of words. The data was also filtered to only include the most recent entries.

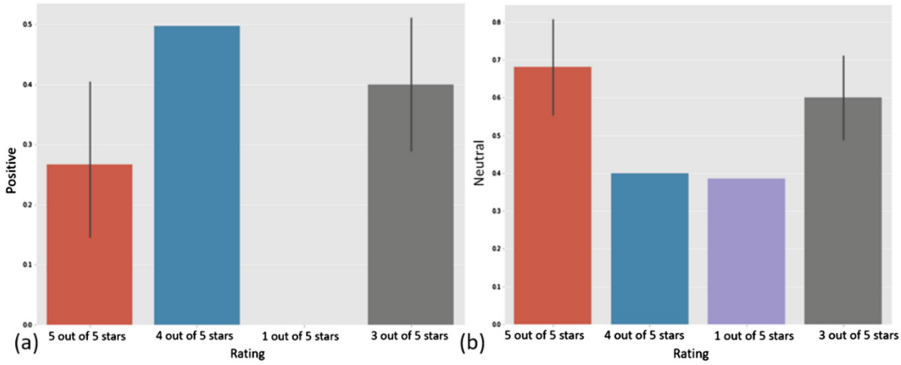

Fig. 3. Reviews analysis for spectrum of assigned starts (a) Positive, (b) Neutral

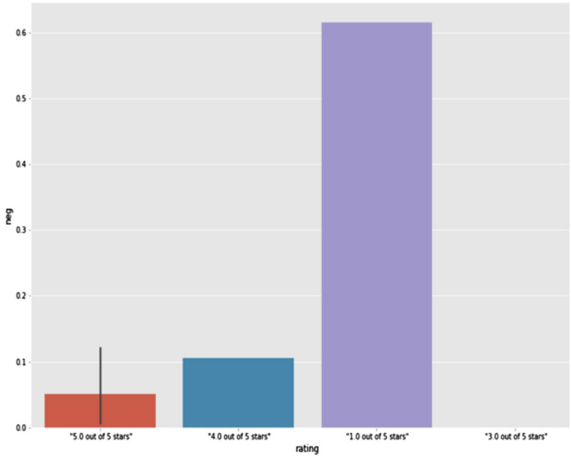

Fig. 4. Negative reviews analysis for spectrum of assigned stars

The results obtained from data analytics module provide as association model which can provide the perceptive quality by the customer expression in their comments. The paper has proposed a simple algorithm illustrated in Table 2., to predict the perceptive quality. The yielded perceptive quality can be used in system dynamic model for analyzing the PLM strategies and their effects on customer.

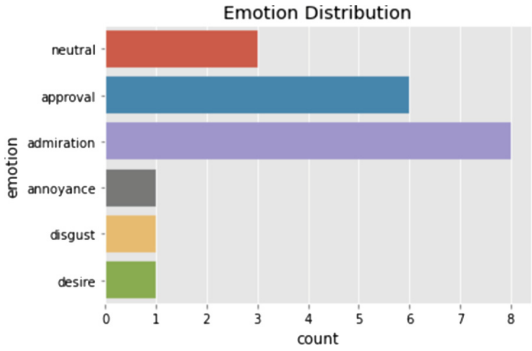

Fig. 5. The emotional analysis of comments based on sentiment analysis

Table 2. The Pseudocode for assigning stars based on customer satisfaction.

```
Select the negative comments by Argument 1 and Argument 2 by positive comments and
Argument 3 by neutral comments in the customer satisfaction state
{if Argument 2 is less than 0.28 then set perceptive quality to 5 stars}
{if Argument 2 is greater than 0.4 then set perceptive quality to 4 stars}
{if Argument 2 is greater than 0.28 and smaller than 0.4 then
set perceptive quality to (random x = rand.uni(0,1) > 0.5: 4 else 3)}
{if Argument 1 is smaller than 0.05 then set perceptive quality to 5 stars} then
{if Argument 1 is greater than 0.05 and smaller than 0.1
set perceptive quality to 4 stars}
else
set perceptive quality to 1}
{if Argument 3 is greater than 0.6 then set perceptive quality to 5}
{if Argument 3 is greater than 0.4 and less than 0.6 then
set perceptive quality to 3
end
```

4 Discussion

Considering the results, the challenges of companies for improving their PLM frameworks in dealing with customer data and expectations obtained from omnichannel touchpoints can be highlighted. The gap in realizing the capabilities of data analytics and integrating it into product development can be recognized as an important challenge. The paper emphasizes on the integration of social media data analytics for enriching PLM models. Moreover, the application of system dynamics approach for developing models which embed the omnichannel touchpoints, such as social media, in PLM can be highlighted. The value of social media interaction and analytics is highlighted, and the causal model provides the opportunity of using customer perceptive quality in PLM. This can be extracted from omnichannel touchpoints using natural language processing and sentiment analysis. Considering the conducted case study, application of social media platforms to analyze customer comments and evaluations for satisfaction in the

emerging omnichannel strategy concept can be recognized. The paper created an estimator for evaluating perceptual quality with the help of social media analytics and used it to develop traditional PLM and create new PLM structures.

5 Conclusion

Considering the potentials of social media market for enriching the PLM frameworks can be mentioned as one of the necessities of modern product development. This paper has investigated the literature for integration models for social media analytics and PLM improvements. The proposed framework in this paper provides a basis for embedding social media analytics tools in the PLM framework and increasing the agility and accuracy of PLM strategies. The paper suggests further studies to apply sentiment analysis for categorizing and prioritizing marketing strategies for product launches. The proposed framework can be used for simulating pre- and post-launch phases and increasing the success factors of new products.

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Intelligent Management for Second-Life Lithium-Ion Batteries with Backup Cells

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Abstract. Governments and the market have stimulated replacing fossil fuel vehicles with electric mobility. As a direct effect, the demand for Lithium-ion batteries (LIB) has risen significantly. This technology has several advantages compared with other storage systems, especially the high energy density, capacity, long lifetime, and cycles. On the other hand, LIB is still expensive and is suitable for vehicles when its remaining LIB lifetime is above 80%. After that, the batteries do not satisfy the demands. Since recycling is complex and takes a long time, LIB is used as second-life batteries (SLB) for stationary systems and low-speed vehicles. Although the SLB has low performance, they need smart mechanisms to fit the application, operate under safe conditions, and perform the maximum possible cycle time. Therefore, this work presents an intelligent Battery Management System (BMS) to prolong the discharge time (DT) of a mini-packing of four cells, one of which is used as a reserve. Two configurations were present to guarantee the longest discharge cycle time and avoid cell failures. The first version could improve the DT by 22%, while the second increased to 72%. Therefore, the proposed mechanism is suitable for prolonging the DT of LIB for SLB applications such as stationary solutions or low-speed vehicles.

Keywords: lithium-ion batteries · intelligent BMS · reserve cell mechanism · second-life battery · data-driven

1 Introduction

The demand for LIB has grown significantly in the last few years, mainly due to the government and market incentives to replace fossil fuel vehicles for EV [1].

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LIB is state-of-art technology for storage systems because it can store energy in a density and for a longer time than similar technologies [2]. However, LIB can supply enough energy for vehicles until their state of health (SOH) is above 70–80% [3]. Conversely, Saxena et al. [4] described that a LIB cannot work satisfactorily daily, with SOH below 80%. Thus, these batteries should be retired and recycled to avoid waste production because it contains heavy metal that can contaminate the water and soil [5].

Despite that, the recycling metal process is complex and expensive to apply at the first moment. Therefore, due to the environmental pressure and the shortage of natural resources, these batteries should be involved in a second-life application as stationary systems, such as, energy storage systems (ESS) for homes with solar panels or even on low-speed vehicles such as golf carts [5]. Nevertheless, to guarantee higher return for the EV buyer, it is necessary to understand the best moment for the End-Of-Life (EOF) and the beginning of the second life, because these cells do not have high performance anymore, as cells with SOH equal to 100%. In this way, it is necessary to have anti-aging mechanisms and intelligent BMS to control and get the most performance and, in the same way, avoid aging speed-up of second life LIB [5,6].

Besides, an EV contains a packing of LIB composed of modules and cells with different ages, capacities, or even in some cases, different components. Thus, passive equalizers in the majority EV will not satisfy the control. Therefore, hybrid equalizers with active processes and intelligent BMS concepts should control the batteries, avoid failures and abuses, and guarantee a more extended packing operation until the EOF of SLB [6]. In addition, Font et al. [7] present a review and perspectives for the SBL. According to the authors, the SBL application will demand artificial intelligence approaches to select and classify the cells according to their SOH to build new packs with similar cells. Besides, dedicated BMS will be required to control the packing respecting the performance and safety requirements. And finally, the work presents a need for connectivity systems to monitor the main parameters of the cells in real-time.

With this motivation, this work presents a concept of a BMS with intelligence discharging control using a reserve cell and a connected system to monitor every cell parameter (temperature, current and voltage). The following manuscript comprises the state-of-the-art in section two, which describes present works in the intelligent BMS scenarios in the literature. The third section will describe the proposed idea. Then, in the fourth section, it is possible to find the setup experiments. In the fifth, there are discussions about the results, and finally, we can find our conclusions.

2 State-of-the-Art

BMS is a fundamental electronic component of an EV. This device has several functions to maintain the EV operation in safety conditions [8]. Despite that, the equalization process can be indicated as the primary function of the BMS. In the literature, it is possible to find passive and active equalizers. Passive BMS

is commonly found in applications due to its simple construction and operation with passive elements. In this case, while the cells with low energy are charging, the circuit eliminates the cells' energy with higher voltage by passive components such as resistors. This method will maintain the cells at the same voltage level but drain the batteries' energy [9].

On the other hand, active BMS can reuse and transfer the remaining energy from high-voltage cells to cells. This method uses active elements, such as, capacitors and inductors to manage the current direction of the batteries. Thus, active equalization is more efficient than passive equalizer, although the process is more complex [9–11]. It is possible to find several studies with both types of BMS in the literature. Despite that, according to Hu et al. [5] and Mubenga et al. [6], applications of SLB must be operated by a sophisticated mechanism to get the maximum performance of the old cells. Therefore, managing these cells with active equalization is essential to avoid failures and abuse issues. This way, the intelligent BMS concept maximizes the SLB cells' operation. Hossain et al. [12] review articles published between 2010 and 2022 about smart management for storage systems. In the same direction, Choi et al. [13] present an algorithm to detect fault by balancing count. This approach needs little software and hardware resources.

Wang et al. [10] present an active equalization method with buck-boost at the charging process. The mechanism transfer energy back and forth in a string of cells, equalizing the batteries through the different SOCs. Another approach is found in Galvao et al. [11]. The authors present a simulation of a hybrid BMS composed of active equalization at the stack level and passive control at the module. The authors demonstrated promising results compared with other similar works. Teodorescu et al. [14] present an intelligent approach to prolong the lifetime of LIB batteries. The authors describe using artificial intelligence to relax the cells during the operation with minimal loss of performance in the load to reduce the degradation rate of the battery. The bypass system enables/disables the function of the cell and could improve the lifetime of the cells by about 80 %. In a similar direction to the cited articles, this works shows an intelligent BMS concept to be applied in SLB LIB to prolong the DT of the batteries.

3 Methodology Description

Traditional passive and active BMS have low performance in operating SLBs because they do not respect the individual characteristics of the cells. This operation can not only damage the cells, but also reduce the performance of the cells and accelerate the aging process of the batteries [5,6]. Therefore, although the cost of the mechanism should be considered due to the individual control of each cell, this mechanism can intelligently equalize the energy of SLB cells to keep all cells at the same voltage level and prolong the cycle of the cell.

The proposed intelligent BMS controls a mini-packing of three cells with a fourth battery as backup. The application is directed to SLB 18650 LIB cells and the packing of multiple distinct batteries with different capacities. The proposed mechanism is composed of an Arduino Mega and sensors (NTC10K for

temperature and ACS712 5 A for current) used to monitor the variables of the cells during the discharging process.

Figure 1 details the circuit that monitors the cells and controls the discharging. Four digital outputs (D2 to D5) control the operation of each cell individually by enabling or disabling the operation of each cell. If the relay is closed, the cell is under operation; else, the cell is waiting. An internal routine in the Arduino controls the relays according to the experiment target.

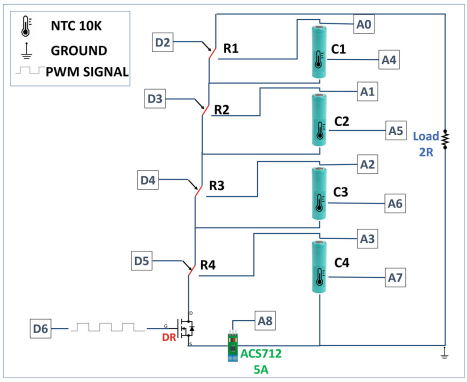

Fig. 1. Circuit of the intelligent BMS connected to an Arduino Mega.

On the other hand, a Pulse Width Modulation (PWM) D6 manages the MOSFET IRF44ZN, controlling the current rate equal to 1100 mA (0.5 C) of the discharging process. This control is a routine with a close loop created in the Arduino Mega fed by the analog channel A8. This channel measures the current from the Hall effect current ACS712 5 A sensor. This value entry in the function increasing or decreasing the PWM signal to open and close the MOSFET in order to guarantee the maintenance of the current target value.

Moreover, the temperature of each cell is monitored by the thermistor NTC10K. Four NTC10K (one for each cell) are connected to the Arduino Mega in the A4, A5, A6, and A7 analog channels. In the same direction, the voltage of four cells is measured by the analog channels A0, A1, A2, and A3. A routine in the Arduino Mega was created to monitor and correctly identify the voltage of each cell. A load of 2R is used to discharge the cells.

The proposed idea comprises Smart BMS v1 (SBMS1) and Smart BMS v2 (SBMS2). For the SBMS1, the discharging process begins with one cell as a reserve. When the voltage of the first cell comes below 2.5 V, the mechanism replaces the cell with the lowest voltage for the replacement, and the process goes ahead. Otherwise, when the voltage of the second cell comes below 2.5 V, the cycle is over.

For SBMS2, one cell also begins the discharging process as a reserve. However, every minute, the mechanism check the voltage of the four cells and replaces cell

with the lowest voltage by the reserve if it has more than 2.5 V. The replacement is done with the relays. The process repeats every minute until there are only two cells with a voltage higher than 2.5 V.

To validate the idea, three types of experiments have been proposed: (I) 5 cycles without BMS named WBMS, (II) 5 cycles with SBMS1, and (III) 5 cycles SBMS2. For the fifteen experiments, cells with different ranges of capacities are used: 2200 (Cell 11), 1500 (Cell 12), 1200 (Cell 13), and 800 mAh (Cell 14). The discharge current was equal to 1100 mA (0.5 C) for all experiments.

The initial experiment was set up to be operated without a BMS (I). Each test of the five ran until the first cells voltage came below 2.5 V. No replacement was done after this condition. Then, five experiments have been carried out to validate the SBMS1. And, finally, five experiments have been performed with the SBMS2. During the experiments, the main parameters of the cells have been monitored and saved in CSV files. The proposed idea is limited to discharge process and were prepared to operate with 18650 SLB cells. The results of this mechanism will be described in the next section.

4 Results

After the experiments, the data were uploaded to the Anaconda Environment to be analyzed. Firstly, five experiments without BMS were carried out. Figure 2 shows a cycle of the WBMS before the SBMS1 was in action.

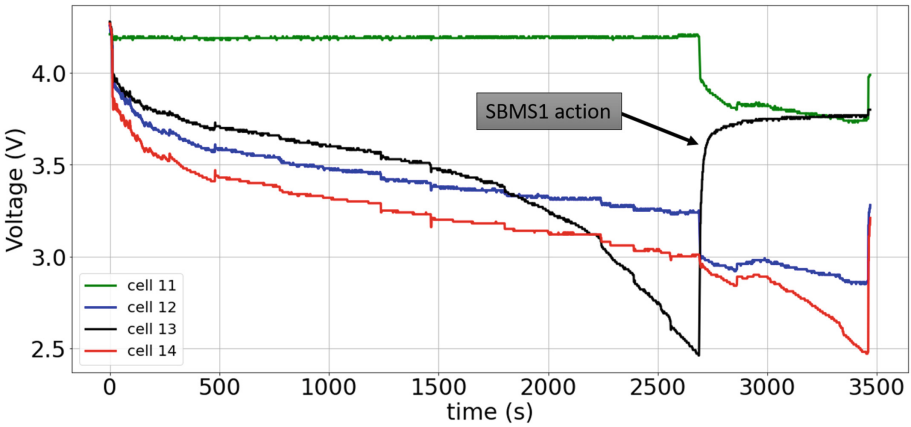

Fig. 2. Voltage of one cycle from cells 11, 12, 13 and 14 under the experiment with proposed mechanism version 1.

According to Fig. 2, the voltage of cell 13 (lowest capacity) is higher than cell 12 (middle capacity) for almost 1800 s. But after 1800 s, the voltage of cell 13 began to decay until its voltage was below 2.5 V, where the experiment was finished. No

cell replacement has been performed in this experiment. According to Table 1, the best DT had 2910 s, while the worst had 2810, and on average, the DT was 2846 s.

For the SBMS1 experiment, five tests have also been performed. According to Fig. 2, when cell 13 came below 2.5 V, cell 13 was replaced by cell 11. This action could give more time for the DT. Then, as expected, cell 14 came below 2.5 V as the next cell, and the experiment was over. According to Table 1, the best cycle of SBMS1 had 3600 s, while the worst had 3400 s and, on average, was 3490 s.

Besides that, an attractive characteristic in cell 13 was observed. After the replacement, cell 13 (see Fig. 2) was in relaxing time, and its voltage came to close to 3.5 V, which indicates that this cell could deliver more energy if needed. This behavior motivate the exploration of the SBMS2. On average, this technique could improve the DT by 22% compared with the cycle of WBMS. Finally, Fig. 3 shows the experiment's results with SBMS2.

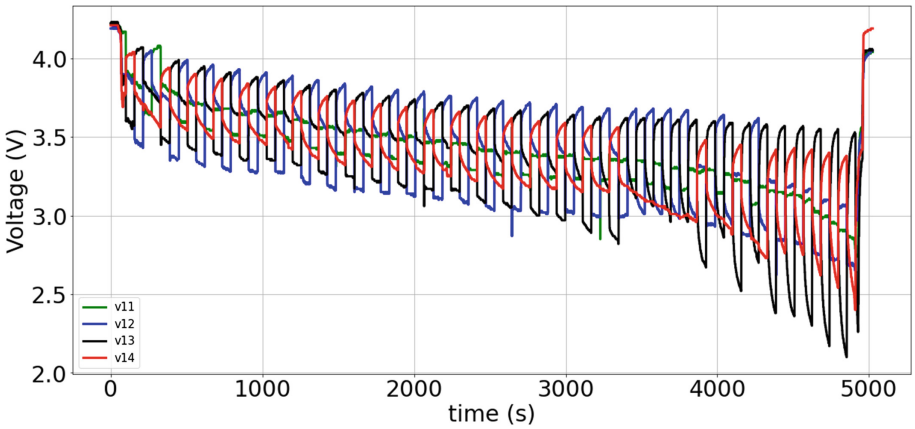

Fig. 3. Voltage of one cycle from cells 11, 12, 13 and 14 under the experiment with the intelligent BMS version 2.

As described in the last section, BMS checks each cell's voltage every minute and replaces the lowest voltage for the reserve cell. This action guarantees more time for DT. Table 1 reveals that the best cycle had 5000 s, while the worst had 4800 s and, on average, was 4900 s. That indicates that the cycle could be improved at 40% compared with the SBMS1 technique and 72% compared with the WBMS process.

Although the SBMS2 can cause more stress in the cell due the frequently replacements, however, Teodorescu et al. [14] demonstrated in their work that a relax time in the cell efficiently reduces the degradation process of the cell. Therefore, the proposed work can not only extend the DT but also reduce the speed of the ageing process of the batteries.

Table 1. Cycle time (in seconds) discharging process at 0.5 C. A comparison between WBMS, SBMS1 and SBMS2.

Method	#1	#2	#3	#4	#5	Mean
WBMS	2910	2810	2850	2860	2800	2846
SBMS1	3500	3450	3600	3500	3400	3490
SBMS2	5000	4970	4910	4820	4800	4900

5 Conclusions

LIB is the state-of-the-art technology for ESS nowadays. This high demand occurs due to the growing EV market. Despite that, LIB can supply energy for an EV until its SOH is above 80%. After that, LIB should be recycled or reused in the SLB. Second-life for LIB is an exciting alternative for LIB regarding ambient and cost reduction. Despite that, this reuse needs several changes to adequate the batteries for the destination application. Besides, some new packing can be built with different capacities, and some cells can be discarded unless they fit in the packing.

Therefore, this work presented an intelligent mechanism composed of an Arduino Mega, sensors and relays to equalize the packing of batteries with reserve cells. A mini-packing with four cells (one as a reserve) is presented to test the proposed idea. Fifteen experiments in three different configurations (WBMS, SBMS1 and SBMS2) and capacities have been completed. The main parameters (voltage, current, and temperature) were collected during the experiments.

The proposed mechanism increased the cycle-time by 22% (compared with an experiment WBMS) in the first version, with only one replacement at the SBMS1. On the other hand, in the second version, the intelligent BMS replaces the cell with the lowest voltage every minute. The gains of the second version were 40% higher compared with the first version and 72% compared with the WBMS.

While the passive BMS does not work efficiently with SLB, this mechanism can equalize the cells during the discharging process according to its characteristics. Therefore, this application can extend the DT of the pack and prolong the cells' lifetime by applying the relaxation time in the cells due to the existing backup. This work's evolution consists of monitoring and controlling the cell itself without a master BMS in a battery pack.

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Circular Economy and Sustainability: What Are They Saying About It? – A Literature Review

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Abstract. Circular economy (CE) and sustainability are two interrelated concepts that are increasingly gaining attention in the fields of business, economics, and environmental studies. Although both concepts share similarities as they both aim to reduce the negative impact of human activities on the environment and promote sustainable development, they have predominantly been addressed separately as two independent areas of knowledge, and continue to be ambiguous. Their relationship in literature has not been clarified, which may be obfuscating their overall usage. The aim of this article is to clarify the concepts of circular economy and sustainability, to examine how these two constructs have evolved in the last decades, and to identify their similarities and differences. In this regard a specific literature review was performed. For this purpose, 48 publications were identified, and a content analysis was conducted. Based on the aforementioned literature review, key findings relatively to circular economy and sustainability are presented.

Keywords: Circular economy · Sustainability · Concepts · Differences · Similarities

1 Introduction

Circular economy (CE) and sustainability are two concepts that have gained increasing importance in recent years due to the pressing environmental and social challenges that the world faces currently. These concepts are closely interlinked and share common goals, although they differ in their approach and scope [1]. Sustainability is a broad concept that seeks to ensure that present generations can meet their needs without compromising the ability of future generations to do the same. Sustainability involves the sustainable use of resources, reducing waste and pollution, and promoting social and economic equity. Sustainability can be viewed through three interconnected dimensions: environmental, economic, and social [2–4]. On the other hand, CE is an economic system that aims to keep resources in use for as long as possible by reducing waste, and

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by resorting to the R-Principles. It seeks to minimize the extraction and use of virgin materials and reduce waste generation, thereby reducing environmental impacts, and also to promote economic benefits and enhance social equity [5–15].

Although CE and sustainability differ in their approach and scope, they are complementary concepts that share similarities. Both concepts aim to reduce negative environmental impacts, promote sustainable development, and achieve social equity. Additionally, both concepts require a systems thinking approach that considers the interconnectedness of environmental, social, and economic systems. The integration of CE and sustainability can lead to numerous benefits. By promoting a circular economy, the sustainable use of resources can be enhanced, waste can be minimized, and pollution reduced. This, in turn, can promote sustainable economic growth and enhance social equity. Furthermore, CE can be seen as a pathway towards a more sustainable future by enabling a decoupling of economic growth from resource consumption and waste generation. In conclusion, the concepts of circular economy and sustainability are closely related and can complement each other in achieving environmental, social, and economic goals. Their integration can promote sustainable development and a more prosperous future for all. This article stands out as a contribution to the conceptual development of circular economy and sustainability, their origins and evolution, their similarities and differences, and also to clarify their correlation. This research article is organised as follows. Section 2 presents the origins of the concept of circular economy and further considerations on its development. Section 3 introduces the methodology adopted. Section 4 provides the discussion on the concept of sustainability and its background. Section 5 introduces the similarities found between these two constructs, and Sect. 6 introduces their main differences. Section 7 contains the most relevant conclusions to this study.

2 Circular Economy and Sustainability

2.1 Circular Economy Origins and Concept

The concept of CE has its origins in the early 1970s, when the environmental movement gained momentum, and concerns about resource depletion and pollution began to emerge. The concept was initially proposed by an economist, Kenneth Boulding, in the 1966 essay "The Economics of the Coming Spaceship Earth." Boulding argued that in a closed system such as the earth, the linear model of production and consumption, which takes resources from the environment and generates waste, is unsustainable. Therefore, a circular model in which resources are continuously reused, and waste is minimized, was proposed [16]. In the 1980s, the idea of a circular economy gained further momentum with the publication of the book "The Entropy Law and the Economic Process" by Nicholas Georgescu-Roegen, who argued that the laws of thermodynamics limit the amount of resources that can be used by humans, and that a circular economy, based on the principles of conservation and recycling, is necessary to achieve sustainability [17]. This concept was firstly introduced to academia by Pearce and Turner (1990), as observed by Su et al. [18], Ghisellini et al. [19] and Geissdoerfer et al. [20]. It is also recognised by these authors that natural resources play a central role on economic systems and also that the contemporary linear economic system which follows a

'take-make-dispose' paradigm [7] is no longer sustainable. In the 1990s, the concept of industrial ecology emerged, which further developed the idea of a circular economy. It seeks to model industrial systems on natural ecosystems, where waste from one organism is a resource for another. In the late 1990s, the term "cradle-to-cradle" was coined by William McDonough and Michael Braungart, which emphasized the importance of designing products that can be continuously recycled and reused [1]. The concept of circular economy gained further prominence in the 21st century, with the publication of the report "Towards the Circular Economy" by the Ellen MacArthur Foundation in 2012. The report outlined a vision for a circular economy, where waste is minimized, resources are kept in use, and the environment is protected [9]. The report argued that the linear "take-make-dispose" model of the traditional economy was unsustainable and called for a transition to a circular model that would not only reduce environmental impacts but also provide economic benefits. The circular economy model would help to reduce waste and create new opportunities for businesses, as well as enhance resource security and reduce dependence on scarce resources. This report led to increased awareness and interest in the circular economy, and many governments, businesses, and organizations began to embrace the circular economy principles. In 2015, the European Commission launched its Circular Economy Package, which included a range of measures to support the transition to a circular economy in Europe, such as increasing recycling rates, reducing landfilling, and promoting sustainable consumption and production [21]. Today, CE has become a global movement, with governments, businesses, and communities embracing the principles of circularity. The European Union has adopted a circular economy strategy, by proposing The European Union's Circular Economy Action Plan, launched in 2020, which aims to aims to accelerate the transition to a circular economy in Europe and includes measures such as promoting circular design, increasing recycling rates, and reducing waste. The plan also emphasizes the importance of ensuring that it benefits all stakeholders, including workers, consumers, and disadvantaged communities. Furthermore, numerous countries have launched circular economy initiatives [22]. In the private sector, many companies are adopting circular business models, such as product-as-a-service, where customers pay for the use of a product rather than owning it. This model allows companies to retain ownership of their products and encourages them to design products that are durable, repairable, and recyclable [9, 23–27]. In the last decades, many countries have launched circular economy initiatives and strategies. For example, China's Circular Economy Development Strategy (2016–2020) [28] set targets to increase the proportion of renewable resources in the economy, promote circular production and consumption, and enhance the circular use of resources. In the private sector, many companies have also embraced the circular economy principles, recognizing the business opportunities that can be created by adopting circular business models [9, 29].The circular economy also offers opportunities for innovation and job creation. For example, it creates new markets for recycled materials and encourages the development of new technologies and processes that promote resource efficiency and reduce waste. According to a report by the Ellen MacArthur Foundation, the circular economy could create 700,000 new jobs in Europe alone by 2030 [30]. It has also has important implications for global sustainability. By reducing waste and promoting resource efficiency, CE can help to reduce greenhouse gas emissions, conserve natural resources, and protect

biodiversity, it can also help to address social challenges, such as poverty and inequality, by promoting inclusive and sustainable economic growth [27]. In conclusion, the concept of CE is more relevant than ever in the present day, as we face growing environmental and social challenges. It offers a solution to these challenges by promoting resource efficiency, waste reduction, and sustainability. As governments, businesses, and communities continue to embrace the principles of circularity, circular economy is believed to become a key driver of global sustainability and economic growth. It offers a solution to the contemporary challenges by promoting resource efficiency, waste reduction, and sustainability.

2.2 Sustainability Origins and Concept

According to Geissdoerfer et al. [20], the concept of sustainability has its roots on the French verb 'soutenir', that means 'to hold or to support' [31]. Nevertheless, its contemporary definition is based on the field of forestry [32–34] particularly in the silviculture assumption which establishes that the quantity of wood harvested should not surpass the amount that is cultivated [20]. In the course of time, this assumption was adopted by ecology, and was associated with the capacity that nature holds to restore itself [35]. However, the modern concept of sustainability emerged in the 20th century as a response to the environmental and social challenges that emerged from industrialization and rapid economic growth. In the 1960s and 1970s, concerns about pollution, deforestation, and other environmental issues began to grow, and the concept of environmentalism emerged. Environmentalism focused on protecting the natural environment and preserving natural resources. It was during this period that the first Earth Day was celebrated in 1970, and the United Nations held its first Conference on Environment in 1972, in Stockholm, with the disclosure of the report Limits to Growth [25]. This report acknowledged that decreasing the ecological footprint per unit of consumption, in order to avoid transcending the world's natural boundaries, was an imperative. In the 1980s, the concept of sustainable development emerged, which sought to balance economic development with environmental protection and social equity. The United Nations' Brundtland Commission, established in 1987, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Since then, the concept of sustainability has continued to evolve, incorporating a broader range of social and economic concerns, such as poverty reduction, human rights, and corporate responsibility. The United Nations' Sustainable Development Goals, adopted in 2015, provide a comprehensive framework for sustainable development, with goals such as ending poverty, promoting gender equality, and reducing inequality. Today, the concept of sustainability is an integral part of global discourse, and governments, businesses, and organizations around the world are working towards achieving sustainability. It is viewed as a critical component of long-term economic growth and social stability, and it is increasingly recognized that sustainable practices are essential for the well-being of people and the planet [20]. It stands out as a multifaceted concept that encompasses economic, social, and environmental dimensions. The economic dimension of sustainability refers to the need to create long-term economic growth and prosperity while ensuring that resources are used in a way that

is sustainable and does not deplete them for future generations [36]. The social dimension is concerned with promoting social equity and justice, ensuring that all people have access to basic needs such as clean water, food, and shelter, and that the benefits of economic growth are shared fairly. This includes addressing issues such as poverty, inequality, and social exclusion [37]. The environmental dimension is concerned with protecting the natural environment, preserving natural resources, and preventing environmental degradation. This includes reducing greenhouse gas emissions, promoting renewable energy, conserving biodiversity, and reducing pollution [37]. Sustainability is often seen as a balance between these three dimensions, and achieving it requires an integrated approach that takes into account the interconnections between these three factors. For example, a sustainable economy would be one that creates jobs and economic growth while also protecting the environment and promoting social equity [38]. Achieving sustainability requires a transformation in the way we live and work, with a focus on creating more sustainable and resilient systems. This includes transitioning to renewable energy, promoting circular economy principles, reducing waste and pollution, and adopting more sustainable modes of transportation and food production [39]. Sustainability is also closely linked to the concept of resilience, which refers to the ability of social, economic, and environmental systems to withstand and recover from shocks and disruptions. Building resilience is essential for achieving sustainability, as it enables societies to adapt to and mitigate the impacts of climate change, natural disasters, and other challenges [40]. In conclusion, the concept of sustainability encompasses economic, social, and environmental dimensions, and achieving it requires an integrated approach that takes into account the interconnections between these dimensions.

3 Methodology

In order to examine circular economy and sustainability potentials it is essential to understand these constructs' origins and state of the art. And so, the most obvious and logical method to accomplish this goal is to conduct a literature review, carried out in such a way that it covers contemporary literature published within the fields of CE and sustainability, so that an up to date picture is displayed. In this regard, the aforementioned concepts, their similarities and differences referred to in literature were identified and are perceived to be of significant importance, as their relationship is often blurred. In this regard, a set of 27 studies of referenced scholars' publications relatively to the constructs origins and evolution, carefully selected from the Web of Science, Scopus, and Google Scholar databases, were considered and their content analysed. Of the remaining studies, 5 pertained the similarities and differences between the two concepts, and 15 studies were considered to reinforce the aforementioned similarities and differences as research in this area is not abundant. Table 1 shows the studies considered.

Table 1. Distribution of studies considered in the literature review.

	Origins and evolution	Similarities	Differences	Additional references
Circular Economy	[1, 9, 16–30]	[20, 41, 42]	[20, 43–45]	[2–8; 10–15;, 46, 47]
Sustainability	[20, 25, 31–40]			

4 Circular Economy and Sustainability – Similarities

Circular economy and sustainability share many similarities, as both concepts are concerned with promoting a more sustainable and resilient future for people and the planet [20]. One of the key similarities between circular economy and sustainability is their focus on reducing waste and promoting resource efficiency. Circular economy seeks to minimize waste by keeping materials and products in use for as long as possible, while sustainability seeks to ensure that resources are used in a way that does not deplete them for future generations. Both concepts recognize the finite nature of resources and the need to use them more efficiently and sustainably [20]. Another similarity between circular economy and sustainability is their emphasis on systems thinking and the interconnections between economic, social, and environmental factors. Both concepts recognize that complex systems such as the global economy and the natural environment are interconnected, and that changes in one area can have impacts on other areas. This requires an integrated approach that takes into account the interdependencies between different systems and works towards creating more resilient and sustainable systems [41]. Circular economy and sustainability also share a focus on innovation and new technologies. Both concepts recognize the need for innovation and new technologies to drive sustainability and create more efficient and effective systems. This includes developing new materials and products that are more sustainable, as well as new technologies that can help reduce waste and promote resource efficiency [42]. Finally, circular economy and sustainability share a common goal of promoting a more sustainable and resilient future. Both concepts seek to create a world that is better equipped to address the challenges of climate change, natural disasters, and other global challenges. They recognize that achieving sustainability requires a long-term perspective and a commitment to building more sustainable and resilient systems. In conclusion, circular economy and sustainability share many similarities, as both concepts are concerned with promoting a more sustainable and resilient future for people and the planet. They both emphasize the importance of reducing waste, promoting resource efficiency, and taking an integrated approach that considers the interconnections between economic, social, and environmental factors. They also share a focus on innovation and new technologies, and a common goal of creating a world that is better equipped to address the challenges of the 21st century.

5 The Differences Between the Circular Economy and Sustainability

Although circular economy and sustainability share many similarities, there are also some key differences between the two concepts. One of the main differences between circular economy and sustainability is their scope. Circular economy is primarily concerned with reducing waste and maximizing the use of resources by designing systems that keep materials and products in use for as long as possible, by creating loops. In contrast, sustainability is a broader concept that encompasses economic, social, and environmental dimensions, and seeks to ensure that resources are used in a way that does not deplete them for future generations [20, 43, 44]. Circular economy and sustainability also differ in their approach to innovation. Circular economy focuses on developing new technologies and business models that can help reduce waste and promote resource efficiency. In contrast, sustainability takes a more holistic approach that considers the broader social and environmental impacts of technological innovations and seeks to ensure that they are sustainable and equitable. Finally, circular economy and sustainability differ in their governance and policy implications. Circular economy is primarily a business and industry-led concept that seeks to promote voluntary action and market-based solutions to waste reduction and resource efficiency. In contrast, sustainability requires a more proactive role for government and policymakers, as it seeks to address complex global challenges such as climate change and social inequality [45]. In conclusion, although circular economy and sustainability share many similarities, there are also some key differences between the two concepts. Circular economy is primarily concerned with reducing waste and maximizing the use of resources within specific industries and supply chains, while sustainability is a broader concept that encompasses economic, social, and environmental factors. Circular economy focuses on developing new technologies and business models to promote waste reduction and resource efficiency, while sustainability takes a more holistic approach that considers the broader social and environmental impacts of technological innovations. Finally, circular economy primarily relies on voluntary action and market-based solutions, while sustainability requires a more proactive role for government and policymakers. Table 2 summarizes the differences found between the aforementioned constructs.

Table 2. The Differences between the circular economy and sustainability.

	Circular Economy	Sustainability
Scope	Allows the reduction of waste; Maximizes the use of resources by designing systems that keep materials and products in use for longer periods of time by creating loops	Encompasses economic, social, and environmental dimensions, in order to keep resources for future generations

(*continued*)

Table 2. (*continued*)

	Circular Economy	Sustainability
Approach to innovation	Focus on the development of new technologies and business models which enable the reduction of waste and promote resource efficiency	It follows a more holistic approach which considers the broader social and environmental impact of technology ensuring that these are equitable and sustainable
Governance and policy implications	Business and industry-led concept that promotes voluntary action and market-based solutions to waste reduction and resource efficiency	Governmental and policy-makers proactive role in addressing complex global challenges

6 Conclusion

In conclusion, both circular economy and sustainability are important concepts that share many similarities, while also having some key differences. Both concepts aim to promote a more sustainable and resilient future for people and the planet by reducing waste, promoting resource efficiency, taking an integrated approach that considers economic, social, and environmental factors, and embracing innovation and new technologies. However, circular economy focuses more specifically on reducing waste and maximizing resource efficiency within specific industries and supply chains, while sustainability takes a broader view that considers all aspects of human society and seeks to ensure that resources are used in a way that does not deplete them for future generations [46]. Additionally, circular economy primarily relies on voluntary action and market-based solutions, while sustainability requires a more proactive role for government and policymakers. Ultimately, both circular economy and sustainability are crucial concepts that must be embraced if we are to create a more sustainable and resilient future for all. In spite of the similarities and differences found between these two constructs, their affinity is not clearly explicit in literature as a number of authors focus their research on the environmental performance of CE, instead of considering the three dimensions proposed by sustainability [20, 29, 47]. In this regard, these concepts still require to be further investigated and defined in order to fully clarify their correlation. Therefore, future research in this domain is mandatory and initiatives are desirable.

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Supply Chain

Reinforcement Learning for Layout Planning – Automated Pathway Generation for Arbitrary Factory Layouts

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Abstract. As an intermediary step to enable solving the facility layout problem with reinforcement learning (RL), this paper presents an algorithm to automatically derive a path network from a given factory layout. It is represented as a graph with additional measures like pathwidth, segment length and segment orientation annotated as edge properties. The information can be utilized in subsequent processing steps to allow programmatic evaluation of the quality of generated layouts to aid in reward calculation for reinforcement learning. This is necessary since the material flow as a widely used evaluation criterion for algorithms solving the layout problem is not expressing the factory design goals clearly enough for a RL agent to learn. Material flow is typically computed based on transport costs and transport distance, which is abstracted as Euclidean distance between centre points of workstations. Using the path network derived by the presented algorithm enables a calculation of transport distances closer to the true distances travelled in the factory, thus enabling a more accurate reward signal.

Keywords: Layout Problem · Reinforcement Learning · Factory Planning · Material Flow

1 Introduction

One of the many challenges in factory planning is the facility layout problem. There have been over six decades of research accumulated on this problem, including far over 100 published solution approaches (Anjos and Vieira 2017, Sharma and Singhal 2016) ranging from swapping workstations, branch and bound algorithms, simulated annealing, genetic algorithms and neuronal networks. Since the problem is NP-hard and practical planning tasks have a multitude of constraints, considerable simplifications are necessary to be able to compute solutions in a reasonable timeframe. Most of the published algorithms focus on special cases like the single row layout problem or simplify all workstations to a rectangular base area. The output of these algorithms is an ideal layout, that needs to be adapted by an expert to incorporate additional constraints that could not be modelled in the planning algorithm. The adaption process is an iterative task, that is repeated until a solution, which adheres to all external constraints, is found. This process is time consuming and overwhelming since there is so much information to

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process. The final layout may drift away from the ideal solution, ending in a sub optimal result.

A solution approach which has not been extensively applied to the facility layout problem is reinforcement learning (RL) (Burggraf et al. 2021). It has shown immense potential in many applications, for example in training dexterous hand robots or playing complex games such as chess, shogi, go and StarCraft (Andrychowicz et al. 2020). Using RL to solve the factory layout problem could provide a software tool to assist human factory planners in the complex and iterative task of factory design. Since response times of a trained RL agent are fast, compared to the runtime of the most optimization algorithms, it would facilitate faster iterations of factory layouts, thus leading to better and more productive factories. (Unger and Börner 2021) presented a concept of how to model the layout problem in a way that can be solved by RL, while leaving enough degrees of freedom to incorporate as many of the multitude of constraints that a factory planning project may contain as possible. To consider all these constraints, the RL environment needs to be able to compute a reward signal that evaluates the current state of the planned factory with respect to the project requirements.

The widely employed optimality measure for factory layouts is the material flow, as efficient material flows are strongly correlated with an efficient factory leading to lower operating costs (Bracht et al. 2018). Most algorithms dealing with the factory layout problem model material flow using transport intensity, transport cost and transport distance (Kusiak and Heragu 1987). Transport distance is usually computed as the Euclidean distance between centre points of workstations, since this measure is easily derivable even in rough planning stages. However, since our goal is to have a RL agent learn the entire factory planning process, we cannot rely solely on material flow and a transport distance estimation. The routing of transports on fixed paths and roads in factories may lead to much longer distances than what is calculated as a point-to-point distance. The true design goal of the factory is not captured in this evaluation.

To compute a reward signal for an RL agent, there is a need for true distances in the material flow calculation according to a path network in the factory. Furthermore, a path network could be used to compute additional measures of quality of a factory layout, thus providing the opportunity to include more design goals in the reward function. As a partial step towards applying RL to the facility layout problem, our goal for this paper is to present an algorithm to generate a path network from an existing layout consisting of workstations and a factory building.

2 Related Work

While to the best of our knowledge there are no published algorithms for automatic generating of roads or paths in the context of factory planning, there are some related research domains with published solutions. One related area is the generation of navigation meshes or navigation graphs for non-player characters in video games, which has a considerable overlap with the routing of autonomous robots. Another related area is the derivation of indoor navigation models in buildings, either from 3D scans, point clouds or from Building Information Modelling (BIM) data. In general, there are two approaches to provide navigation information for virtual worlds – navigation meshes

(Snook 2000) and navigation graphs (Stout 2000). For the routing of materials in a factory, as well as for obtaining true distances between sinks and sources of material flow, the navigation graph approach seems better suited, as navigation meshes result in jagged and unnatural looking paths.

There are several approaches in computational geometry that can be used as a basis for a navigation graph. One of the oldest solutions is to utilize medial axis of corridors (Lee 2004), which has weaknesses when it comes to non-convex shapes and large open spaces (Lewandowicz et al. 2019). Nevertheless, it is adopted as a starting algorithm by countless papers such as (Flikweert et al. 2019; Mortari et al. 2014) and is extended according to the needs of each use case. The other typical method is based on the visibility graph of vertices of shapes, which allows to compute the shortest path between two points but has the disadvantage of generating parts of the graph very close to walls.

There are also hybrid solutions, such as the Visibility Voronoi Diagram (Wein et al. 2007), which uses Voronoi diagrams to modify the visibility graph algorithm to produce more natural looking paths.

As a more recent alternative, straight skeletons of polygons developed by (Aichholzer et al. 1996) for a different application domain, have been employed as the basis of navigation graphs (Fu et al. 2020). There have also been approaches that make use of deep neural networks to facilitate the generation of navigation graphs. One example is (Niu and Song 2019), which relies on Region Based Convolutional Neural Networks (R-CNN) to build a topological map but operates on pixel data.

The described algorithms from other research domains are not entirely suitable for the application in RL, since they are designed to be run just once on their input data. Usage in RL has some implications which are detailed in the next section and need to be addressed for a solution that is feasible.

3 Description of the Algorithm

3.1 Design Goals

For the use case of RL, we need to consider some constraints, that do not usually apply to classical navigation problems. RL works because an agent tries to solve a problem in an environment by randomly exploring and learning which actions had the best results. This implies that the algorithm may be executed several million times during the training of an agent. A short runtime is therefore crucial. Ideally, the algorithm should have a scaling parameter to choose between fast execution time and accuracy of representation. This would allow for fast initial training until the RL agent has grasped the general concept of the task, as well as the ability to compute detailed and accurate results for final presentation.

Furthermore, the factory planning domain differs from indoor navigation planning in the aspect that the objects within the outer boundary (factory building) do not need to be completely avoided by the generated path. Each inner object (workstation) may have one or more sources and sinks that need to be connected to the factory paths to facilitate material transport. As the routing of transports in the factory is performed on the calculated paths, it is necessary to derive the pathwidth of all edges. This allows us to determine whether roads need to be one-way or two-way. To be able to decide which

transport device (e.g. forklift or hand pallet jack) can reach certain areas, it is necessary to know the minimum clearance of a subsection located between intersections of the constructed road network. This implies the need to split the generated navigation graph into subsections and calculate measures as minimum clearance at the subsection level.

The proposed algorithm adhering to these design goals consists of serval steps, which are described in individual paragraphs. The outline of the algorithm and a small overview picture of the data processed in each step is displayed in Fig. 1.

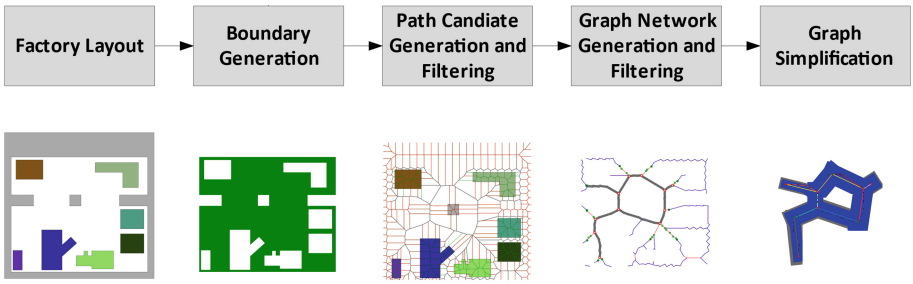

Fig. 1. Overview of the algorithm steps

The inputs for the algorithm are a list of polygons *W,* representing the shape of the outer and inner walls of a factory layout and a list of polygons *M,* describing shape of the individual workstations including buffer areas in the factory. Additionally, a bounding box *bb* of the area to be considered in the algorithm may be passed in. Workstations are assumed to be located inside the area described by the walls.

3.2 Boundary Generation

The first stage of the algorithm constructs the general area in which paths are permitted to exist in the factory. If no bounding box is given as input, it is constructed as the minimum rectangular area containing all walls. The valid path area is generated as the Boolean difference between *bb* and the union of all polygons contained in the lists *W* and *M*, ignoring all polygons which are located outside of the bounding box. The resulting polygon *A* represents the currently unused space in the factory. It contains the corner points and their connections (edges) of all workstations and walls. To facilitate the requirement of a parameter to choose between performance and accuracy, we calculate a list of equidistant points distributed along all wall and workstation edges and append it to *A* generating *A'*. The distribution distance of these points determines the number of points used for further processing, which directly affects the required computations and the accuracy of the path representation.

As described in Sect. 2, the two most used approaches to path generation are the straight skeleton and the median axis/Voronoi diagram. Since the time complexity for the straight skeleton is $O(n\ (\log n)\ \log r)$ (Cheng et al. 2014) and linear time complexity for the medial axis/Voronoi diagram (Chin et al. 1995), our algorithm uses the Voronoi diagram of *A'* as the basis for path generation. The result of the first step of the algorithm

can be seen in Fig. 2 (a). It shows contours of different workstations, as well as the factory walls (grey). The result of calculating the Voronoi diagram of *A'* is a list of lines (Voronoi edges) overlayed in Fig. 2 (a) in in black, red and green.

3.3 Path Candidate Generation and Filtering

The Voronoi edges represent potential paths in the factory layout. Since paths inside workstations and walls are not usable, the next processing step is filtering the list of lines. For general processing, an intersection test between walls or workstations and the list of lines is sufficient and saves computation time. For visualisation purposes in Fig. 1, additional tests have been performed to extract different line classifications (inside walls or touching workstations – red, and inside workstations – green), which adds significant runtime to the algorithm. Lines which fail this intersection test are removed from the list. All remaining lines are merged into line strings by connecting all line segments which share a common point, resulting in a list of route lines strings *R*. This allows performance optimisations in the subsequent processing steps since duplicate start and end points are removed.

3.4 Graph Network Generation and Filtering

Higher level reasoning about routing requires the derivation of a proper network graph containing nodes and edges. This is achieved by iterating over all the line segments in *R,* each consisting of a start point and an end point. Each of these points is translated into a node of the graph, while duplicate points are merged. The resulting graph represents possible paths inside the factory layout. This graph may contain paths, which are too narrow to be traversed by typical factory logistics equipment. To be able to filter out these narrow passages, the next step is to compute the maximum possible pathwidth at each node of the graph. For each node, the minimum distance to a point in *A'* is calculated. Due to the mathematical properties of the Voronoi diagram, all the closest points are equidistant and located around the circumference of a circle centred at the node, as shown in Fig. 2 (b). Since *A'* contains all corner points of walls and workstations, the diameter of each circle can be interpreted as the maximum possible pathwidth at the node.

Depending on the chosen density of points distributed around the circumference of walls and workstations, the pathwidth estimation becomes more continuous and accurate along a route. The pathwidth calculation on node level needs to be aggregated to be more useful. We calculate the minimum pathwidth of an edge, spanning between two nodes in the graph, by determining the minimum pathwidth of the start and end node. The Euclidean distance between the two nodes serves as the edge weight for later routing, representing the length of this subsection of the path.

The resulting graph may contain very narrow path sections that are not suitable for transport and need to be filtered out. A minimum pathwidth threshold parameter is used to remove all narrow passages. Removing elements in the graph can result in loose parts. As these parts cannot be reached due to narrow passages, they are filtered out as well by performing a connected components analysis on the graph. Only the largest component is retained.

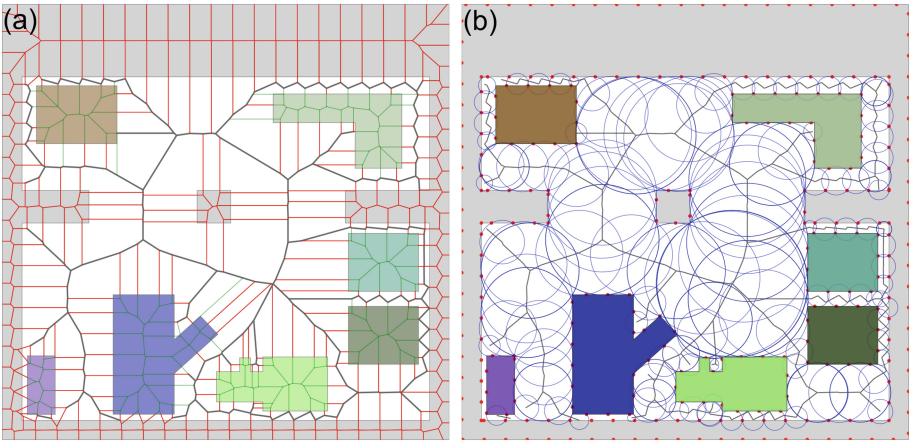

Fig. 2. (a): filtered Voronoi diagram (green – inside workstation, red - inside wall or touching workstations), (b): pathwidth calculation (blue circle) and boundary input points *A'* (red dots)

Since space in a factory layout should not be wasted, paths wider than a maximum width parameter are set to the width of this parameter, while the true width is stored as an additional edge property. Paths wider than a minimum two-way threshold are also marked in an edge property.

Due to the nature of the Voronoi diagram, the graph may contain short dead ends, especial in concave corners. If these dead ends are not the closest point on to an input or output port of a workstation on the graph, they serve no purpose in the context of a road network and can be eliminated. The endpoints of dead ends can be selected by finding all nodes with only one connected edge. On a graph the degree of a node is defined by the number of edges connected to the node. Dead ends have a degree of one. We check the distance to the next crossroads node (degree three or more) against a threshold parameter. This allows us to remove all "short dead ends" by removing the respective endpoint and all nodes in the graph until the next crossroads node is reached. Figure 3 (a) shows a visualisation of the filtering operations and the resulting remaining graph in dark grey.

3.5 Graph Simplification

For better performance in routing applications, intermediate nodes between crossroad nodes and dead-end nodes are not necessary. For this reason, we compute a simplified meta network graph containing only the relevant nodes, while preserving the true distances in the edge weights. The original nodes that were present on a subsection are annotated on the new meta-edges of the simplified graph, to enable their use for rendering or evaluation purposes. The algorithm used to identify the subsections of the graph for simplification is a modified depth-first search approach.

The search starts at dead-end nodes or, if there are none, at crossroad nodes. Since all other remaining nodes in the graph have a degree of two, we can choose one of the neighbours of the starting node and follow the path of node neighbours until we

reach a node with a degree different from two. At this point we found a new edge for the simplified graph. The edge weights of the path traversed are summed up and the minimum pathwidth of all nodes on this path is calculated, since the narrowest spot determines the traversability of this path section. These results become properties of the new edge in the simplified graph. To avoid jagged paths, such as in the lower centre of Fig. 3 (a), the nodes on the path taken are smoothed by applying the Douglas-Peucker algorithm. This process is repeated for all crossroad and dead-end nodes, until no unvisited neighbour nodes remain in the original graph.

Testing has shown that the use of support nodes Fig. 3 (b), marked in green) is necessary, to maintain approximately the same path shape after simplification. Support nodes are defined as nodes with a degree of two, where the angle between the connected edges is greater than a cut-off threshold parameter. Support nodes are used as additional stop nodes during the simplification process, thus generation more subsections.

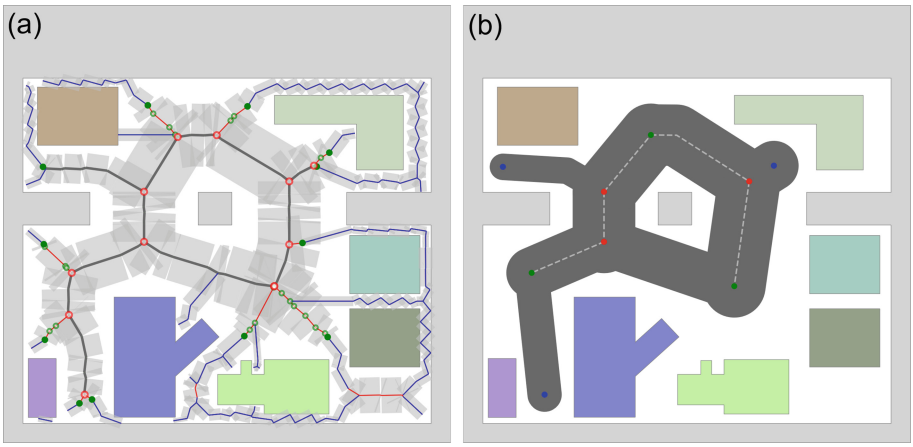

Fig. 3. (a): graph filtering (blue – narrow passage, red – loose parts, red with green endpoint – short dead-end, red dot - crossroads), (b): finished and smoothed graph with two direction sections marked (red dots – crossroads, blue dots – dead-ends, green – support point)

4 Results

The results of the algorithm are two graphs, one containing all details of the calculated paths for the input factory layout and one meta graph containing just the relevant nodes like dead-ends and crossroads for navigation purposes. The detailed graph has edge attributes indicating the length and width of all path segments, as well as information if this part of the path is wide enough for one-way transport or two-way transport.

Figure 3 (b) shows a rendered example of the final output of the algorithm. The properties annotated on the edges of the graph have been used to style the rendering.

The graphs can be used to determine exact lengths of material flows between workstations, by applying classic graph routing algorithms like Dijkstra's or the A* algorithm

to find the shortest path on a graph starting from the nodes closest to each workstation. The length of each edge is saved in the graph, so the true transport distance can be computed as the sum of the edge lengths on the shortest path. Compared to the classic Euclidian distance between workstation centres, this result is much closer to the real distance of the material flow. Since the width of the path is computed as well, the suitable methods of transport (e.g. forklift or hand pallet jack) can automatically be determined. Since these methods have different transport costs, the total costs of transport can be calculated much closer to reality compared to using average transport costs. This conveys the factory design goals better to an RL agent when used as a part of the reward calculation.

The graph acts as a foundation to compute many additional rating measures for a factory layout. Examples are reachability of workstations, length of the main transport axis, number of dead ends, straightness of transport routes, utilization of usable area regarding path area or continuity of pathwidth. In the context of RL these measures can be used to evaluate the quality of a layout generated by the RL agent and calculate a suitable reward to encourage further learning.

5 Conclusions

In this paper we have presented an algorithm for generating suitable paths for factory layouts constrained by wall polygons and workstation polygons. The algorithm has performance scaling parameters that allows its use in a real-time rendering application for reasonable layouts with up to 40 workstations on a current AMD Ryzen 9 5900X processor, as well as an intermediate step for the evaluating of layouts in the context of reinforcement learning. The constructed layout graph contains several edge annotations to facilitate the automated evaluation and rating of layouts.

Our further work will focus on generating meaningful measures for the factory layout based on the results of the presented algorithm. This will be the main content of a subsequent publication. For further evaluation and improvement of all components of the RL framework, we plan to create an interactive debugging tool that displays the current state of the layout, allows interaction, and provides feedback on the quality of the current layout.

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Towards a Blockchain-Enabled Social-Life Cycle Assessment Service for Increased Value Chain Sustainability

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Abstract. As sustainability requirements are growing, more and more companies are falsely claiming to supply sustainable products, thus creating an unfair playing field for companies that do comply. The Textile and Clothing (TC) industry is one of the least sustainable and transparent industries, often manufacturing products in low-cost countries with inadequate working conditions and environmental standards. The purpose of this study is to investigate how social sustainability assessments can be conducted, to increase the reliability of sustainability claims. The paper proposes a concept of a Social-Life Cycle Assessment (S-LCA) service that is based on site-specific primary data and is grounded in the international Social Accountability (SA) 8000 certification system, to increase the reliability of sustainability claims. United Nations recommends the SA8000 in their S-LCA guidelines. The S-LCA service is also enabled by Blockchain to secure that critical data remains unaltered. The concept and service are being developed through the Design Science methodology, combining: i) case studies in an EU project, to understand the practical problem, ii) a S-LCA literature study, and iii) action research, to iteratively apply the service to the cases and refine it with project contributors representing the entire TC value chain. The concept consists of a workflow diagram, preliminary user interface, data collection template, and an overview of critical data to be secured by Blockchain. To the best of our knowledge, this is the first research paper about a concept of a site-specific S-LCA service that is integrated with an international certification system and a Blockchain-enabled platform.

Keywords: Social-Life Cycle Assessment · Value Chain Transparency · Sustainability · Textile and Clothing Industry · Social Impact

1 Introduction

As sustainability requirements are growing, more and more companies are inaccurately claiming to supply sustainable products, thus creating an unfair playing-field for companies that do comply. However, the anti-counterfeiting methods are ineffective [1]. In

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the TC industry, a common practice is to use sustainable materials to manufacture the product lots that might be controlled or audited, and non-sustainable, cheaper materials for the other product lots [2]. Moreover, it is reported that nearly 10% of the chemicals used in the TC sector are of potential concern to human health and that almost 6% of the TC workers get injured every year [3]. The TC sector is the 4th highest 'pressure category' in EU, in terms of use of primary raw materials and water, while Food is the highest [4]. Unlike the food sector, most of the pressure and impact linked to TC occurs outside the EU, making the value chain transparency and sustainability goals even more challenging. The TC production typically takes place in developing countries with lower production costs, but also poorer working conditions and environmental standards [4]. Other social impacts include long working hours, child labor, poor salary rates, and limitations to freedom of association [4–7]. Increasing the value chain transparency would imply disclosing data such as the origin of the products, suppliers, health and safety reports, testing results, and sustainability reports [8]. While assessments such as the Life-cycle assessment (LCA), S-LCA and Life-cycle Costing are seen as a good starting point when evaluating environmental, social, and economic sustainability [5], verifying the results through internationally accredited audits and securing critical data by help of technology like Blockchain would facilitate transparent processes, unaltered data, and reliable results [9].

In recent years, the S-LCA research and development has been increasing, particularly after the UN Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) had published the 'Guidelines for Social Life Cycle Assessment of Products' in 2009 [10]. S-LCA databases and services that have been developed include the Social Hotspots Database (SHDB) and Product Social Impact Life Cycle Assessment (PSILCA). These are also recommended by UNEP [11], and SimaPro, a software commonly used for LCA is providing the possibility to import the SHDB database [12]. Nonetheless, existing solutions are primarily based on secondary data, like country-specific indicators [e.g., 13–14]. Site-specific assessments are more accurate and can lead to significantly different results [14]. However, a site-specific S-LCA would further increase the criticality of ensuring the reliability of primary data. Even though several S-LCA relevant policies were developed in the last decades (e.g., Fairtrade and SA8000 certification) [11], the effectiveness of Blockchain for securing critical data was mainly investigated for LCA [e.g. 15]. Finally, only a few peer-reviewed case studies have been published on S-LCA's for the entire life cycle of TC products [e.g., 13,14]. The purpose of this study has been to investigate and better understand how social sustainability assessments can be conducted in order to increase the reliability of sustainability claims. The paper proposes a concept of a Blockchain-enabled and site-specific S-LCA service, for increased reliability of product sustainability claims.

2 Methodology

The research methodology that we applied was the Design Science, as described by Holmström et al. [16]. This methodology is recommended both for the development of artifacts with enhanced practical relevance – such as a digital service – and for the development of new knowledge (e.g., [9, 10]). As Design Science is a multi-method

strategy, this study combined TC case studies within a Horizon 2020 EU project, a systematic literature review and action research. First, to understand the practical problem of the case companies, we studied their needs, as well as the inhibitors and enablers of these user needs. Second, a literature review was conducted, on the topic of S-LCA. Third, a preliminary concept was developed based on the literature. Thereafter, over a 5-month period, the concept was iteratively refined together with the project partners-through the action research method. To this end, workshops and semi-structured interviews were organized with the project partners representing the TC value chain. The research contributors comprised traditional and technical TC manufacturers, yarn and fiber producers, an online retailer of second-hand clothing, a platform provider for the sourcing of TC production capacity, a recycling company, a customs agency, service and platform developers, and research partners. When the service prototype will be completed, the project partners will use it to conduct specific S-LCA studies and the service will be further refined.

3 Literature Review

This section outlines the literature background for the proposed S-LCA concept.

The S-LCA was developed by the United Nations and SETAC [5] and it is a method that is applied for the assessment of the actual and potential social impacts (positive or negative) of a product through its life cycle. The goal is to safeguard and enhance workers' well-being while improving business performance [6]. It addresses the extraction and processing of raw materials, manufacturing, distribution, use, reuse, maintenance, recycling, and final disposal. It can use generic and site-specific data and can be quantitative, semi-quantitative or qualitative [11].

The S-LCA users may have roles, such as the producer of a final product, component or raw material, the supplier or subcontractor that provides goods or services to the producer, the sub-supplier, the S-LCA expert within or outside the organization initiating the study, and the independent reviewer [11]. The S-LCA main activities comprise the definition of the S-LCA goal and scope (e.g. system boundaries), the data collection ('life cycle inventory'), the calculation of the results for the (sub)category-indicators that were selected ('life cycle impact'), and the interpretation of results and reporting. To increase the transparency, apart from a summary of the main activities, the report should include details about the data quality and about the findings prior to any data aggregation [11].

Currently, there are more than 450 environmental and sustainability labels [17]. Relevant policies for the S-LCA that the UN recommends include: UN's Guiding Principles on Business and Human Rights from 2011, Good Weave label, Fairtrade, Rainforest Alliance label, SA8000 standard, ISO 45001, Global Reporting Initiative, and the Accountability 1000 Assurance standard [11].

The social performance of an organization depends on the relation that it has with its various stakeholders. For each stakeholder categories there are defined impact subcategories. The main stakeholder categories in the S-LCA are the workers (e.g. with 'fair salary' as an impact subcategory), local communities (e.g. 'local employment'),

value chain actors (e.g. 'fair competition'), consumers (e.g. 'health and safety'), children (e.g. 'community education'), and the society at large (e.g. 'contribution to economic development') [11]. PSILCA, one of the databases recommended by UN aims to provide transparent and up-to-date information for almost 15,000 industry sectors and commodities, and for 69 qualitative and quantitative S-LCA indicators [18].

4 The S-LCA Service Concept

This section presents the concept of the site-specific, Blockchain-enabled S-LCA service, which was developed based on results from the literature study, case studies and action research (see Sect. 2). It consists of the workflow and preliminary user inter-face (Fig. 1), and the data collection needs (Table 1).

The upper part of the Fig. 1 depicts the main user activities (pink) and their connection to the Blockchain enabled platform (blue). The lower part of Fig. 1 illustrates the preliminary service interface, which consists of the main S-LCA study page and is based on the data categories in Table 1. The figure also indicates the certification status of the relevant value chain actors. The data categories in Table 1 are based on the SA8000 standard, while the data indicators are based on the PSILCA database. Section 5 includes further details about the concept.

5 Discussion and Conclusion

This section discusses the proposed S-LCA concept - the workflow diagram and user interface in Fig. 1 and data needs in Table 1 - in light of earlier literature.

The service workflow consists of the user roles and activities that the research participants selected among the literature findings. Compared to UNEP and SETAC's recommendations [11], these roles were synthesized into the producer, its internal or external S-LCA expert, the supplier/subcontractor of goods or services and the reviewer, which is the accredited certification auditor. The *producer* starts by selecting the product that fits the *goal and scope* [11] of the assessment and by appointing an expert, for ex. Its Health and Safety coordinator. The *expert* is registered on the data management platform, and (s)he initiates the life cycle inventory [11] process by retrieving the list of materials, suppliers, and subcontractors, which had been previously uploaded on the platform. The participants regarded the cost-benefit of uploading this document on the Blockchain layer of the platform as high, as this would mitigate the risk that a producer would later replace the product materials with less sustainable ones. Thereafter, the producer or the expert uploads its own primary data on the user interface of the S-LCA service (lower part of Fig. 1), and the data is stored on the platform.

Next, the expert evaluates the compliance of each of the S-LCA categories and sup-ports her/his assertions with appropriate documentation. The participants strongly rec-ommended the integration of an internationally acknowledged certification process in the concept, to maximize the reliability of the suppliers/ subcontractors' self-assessments. They selected the SA8000 standard [19], as this certification is aligned with the S-LCA guidelines [11] and enables a site-specific S-LCA. Table 1 summarizes all the

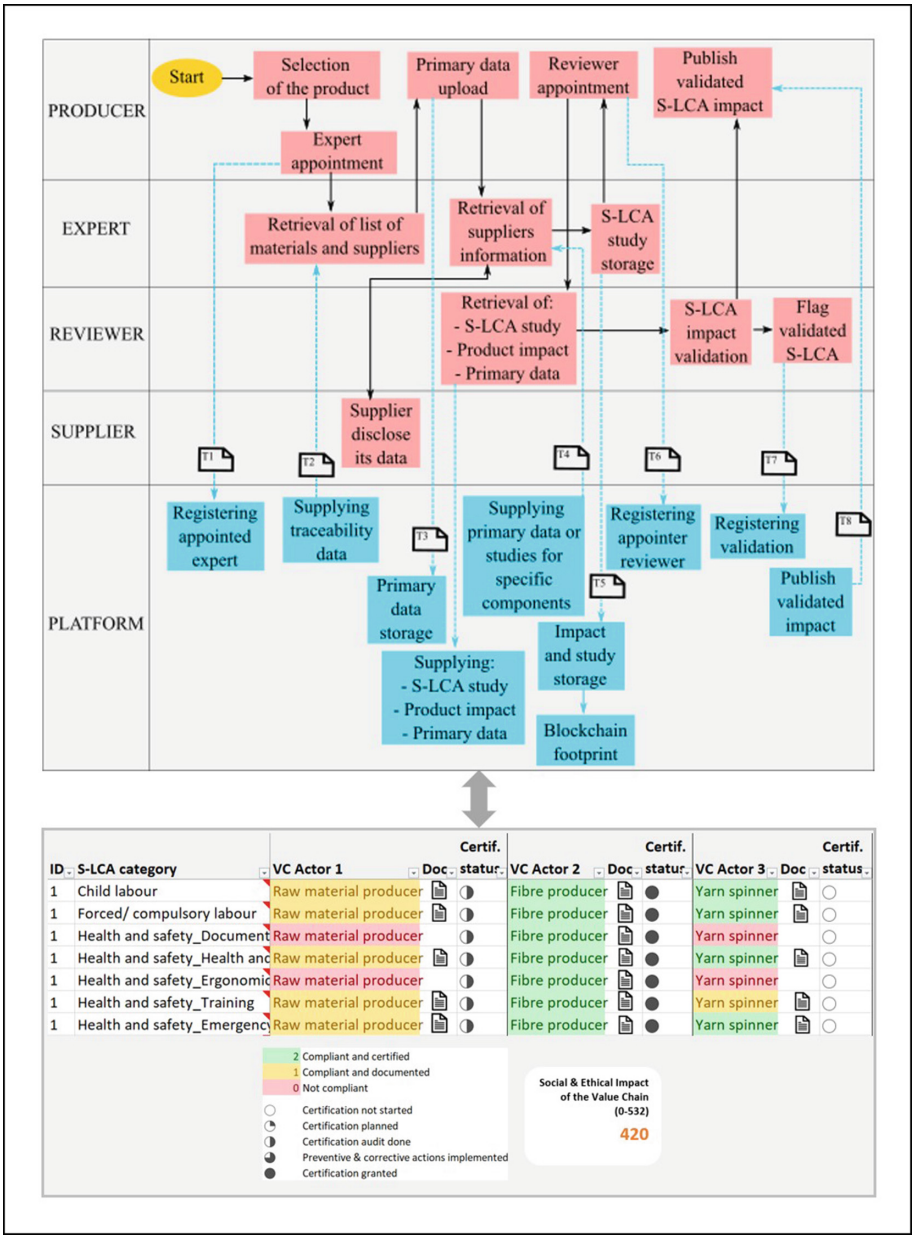

Fig. 1. The workflow (up) and preliminary S-LCA service interface (down); VC-value chain

categories in this standard. In line with [14], the user interface enables the evaluation and visualization of the compliance of all value chain actors. Inspired by the popular.

Likelihood-Impact Risk Matrix [21]*, the Selected Scale in This Concept is from 'not Compliant'/ 0/ Red Color, to 'Compliant and Documented'/ 1/ Yellow, and 'Compliant*

Table 1. Categories of necessary data for a site-specific S-LCA and potential indicators for a general S-LCA (based on [19] and [20])

DATA CATEGORY	POTENTIAL INDICATOR
Child Labor: Verifiable proof of age documentation for every worker. No children under 15 years in work areas (or the minimum age by local law, if this is over 15y)	-Female personnel ages 7–14 [%] -Male personnel ages 7–14 [%] -All personnel ages 7–14 [%]
Forced or Compulsory labor: No involuntary work under threat of punishment/ retaliation or demanded as debt repayment. No human trafficking. Security measures do not unduly restrict worker's movement	-No. of goods produced by forced/ compulsory labor -Cases of forced labor/ 1,000 inhabitants in the country -Tier placement (referring to trafficking in persons)
Health and Safety: Addresses the topics, 'Documents/ licenses/ permits/ certificates', 'Health and Safety (HS) committee', 'Ergonomics', 'Training', 'Emergency preparedness', 'Fire extinguishers', 'Alarm system', 'Personal Protective Equipment (PPE)', 'General working environment', 'Water, air, noise and temperature', 'Electrical safety', 'Machine guards and safety', 'Chemical and hazardous waste handling and storage', 'Medical care', 'Restroom facilities', 'Kitchen, cafeteria and canteens', 'Dormitories', and 'Childcare facilities'	-Fatal accident cases/ 100,000 employees and year -Accident cases/ 100,000 employees and year -Disability-adjusted life years (DALY)/ 1,000 inhabitants in the country -Workers affected by natural disasters [%]
Freedom of association and right to collective bargaining: Workers, trade union and other worker representatives indicate that workers can freely form, join and organize trade unions of their choice, and collectively bargain with the organization	-Employees organized in trade unions [%] -Right of association [0–3 scale] -Right of collective bargaining [0–3 scale] -Right to strike [0–3 scale]
Discrimination: The organization shall not engage/ support discrimination in hiring, remuneration, etc., based on race, political orientation, etc. Incidents and their remediation are documented	-Females in the economically active population [%] -Ratio of women in the sectoral labor force -Gender wage gap [%]
Disciplinary practices: The org. Shall not engage in the use of corporal punishment, or mental/ physical coercion. All disciplinary actions are documented and signed by affected workers	-

(*continued*)

Table 1. (*continued*)

DATA CATEGORY	POTENTIAL INDICATOR
Working hours: The work week shall not exceed 48h. Overtime shall not exceed 12h. Timecards/ electronic bar card system/ attendance sheets (signed by workers) are used to measure actual working hours and break times	-Hours of work/ employee, per week
Remuneration: Addresses the topics, 'Living wage estimate', 'Living wage step-approach', 'Wage payment', and 'Payroll documentation'	-Living wage/ month -Minimum wage/ month -Sector average wage/ month
Management system: Addresses the topics, 'Policies, procedures, and records', 'Social Performance Team (SPT)', 'Risk identification and assessment', 'Monitoring', 'Internal involvement and communication', 'Complain management and resolution', 'External verification and stakeholder engagement', 'Corrective and preventive actions', 'Training and capacity building plan', and 'Management of suppliers and contractors'	-

and Certified'/2/green. Based on this method, one can also get a broad overview of the *'product life-cycle impact'* [11]. For ex., a value chain with 7 actors, which are all eval-uated as 'compliant and certified' on all the 38 categories in Table 1, would get the maximum score of 532 (i.e. 7*x*2*x*38). Thereafter, the expert asks the *suppliers/ subcontractors* to disclose their primary data, unless this is already on the platform, and repeats the same procedure as for the producer. When completed, the report consisting of the S-LCA study, 'social impact' and the expert's recommendations is stored on the plat-form and secured through a Blockchain footprint. Then, the expert appoints accredited SA8000 *auditors* to review the report and primary data, and to visit and audit the value chain actors. When the S-LCA is validated and a value chain actor is certified, the au-ditor flags the certification, and the platform publishes the results. As the SA8000 cer-tification can be a lengthy process, the user interface has a status function. Based on Deming's popular Plan-Do-Study-Act circle [22], the options are 'certification not started', 'certification planned', 'audit done', 'preventive/corrective actions imple-mented' and 'certification granted'. Finally, apart from the qualitative SA8000 categories, Table 1 includes relevant quantitative indicators based on the PSILCA database. Since these are generic indicators, for an entire country, region, or sector they are not sufficient for a SA8000 certification. However, they can be used to quickly assess potential suppliers from different countries/ regions before selecting them.

To conclude, the purpose of this study was to investigate how sustainability assessments can be conducted to increase the reliability of sustainability claims. The paper

proposes a concept of a S-LCA service that is integrated with the international certification system, SA8000 and a Blockchain-enabled platform, in order to increase the reliability of sustainability claims. The service also addresses the entire value chain, assessing organization-specific data. The concept is based on a literature review and is developed in close collaboration with the project participants in a Horizon 2020 EU project, representing the whole TC value chain. It consists of a workflow diagram, a preliminary user interface, data collection template and an overview of critical data to be secured by Blockchain. The concept is arguably comprehensible and easy to replicate in future studies. As it has a low maturity level, the concept should be further validated with case companies within various industries, and from both high- and low-cost countries. As part of the EU project, the service is to be finalized, implemented at the case companies, and refined by August 2023.

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Enhancing Inventory Management Decisions in a Bakery: A Case Study

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Abstract. This work aims to establish assertive inventory policies for the raw materials in a Portuguese bakery. The demand behaviour of some items was analysed, using the ABC classification, and 14 main items were prioritised. Using Holt-Winters' additive method, the demand for these items was forecast until the end of 2023. With these forecast data, the paper presents a simulation and comparison between two different inventory policies, the continuous review model and the periodic review model, and also presents an estimate of current inventory costs. As expected, the periodic review model presented higher inventory costs than the continuous review model, due to the higher safety stocks needed. The results of this paper are a starting point for the company to decide what inventory management method fits better.

Keywords: inventory management · demand forecasting · bakery · case study

1 Introduction

In practical terms, management inventory systems aim to optimise inventory levels and product flows in order to meet the forecast demand [1]. According to Vandeput [2], inventory policies aim to define when and how much a product has to be ordered or produced.

In a bakery environment, the irregular consumption of the raw materials and expiry date restrictions are a complex daily reality. Consequently, the use of inventory policies to guarantee good service levels and reduce costs are needed.

Also the nature of the demand over time plays a significant role in control of the inventory levels. In this context, and using historical data for raw material items of a Portuguese bakery, the Holt-Winters additive method was used to forecast the demand of some items until the end of 2023. This analysis made it possible to simulate and quantitatively compare two different inventory management policies and compare their results to the current inventory costs.

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This paper is organised as follows: Sect. 2 briefly presents the forecasting method and inventory policies used. Section 3 describes the adopted methodology and present the gathered results, and finally main conclusions are presented in Sect. 4.

2 Forecasting and Inventory Models

The following subsections contain information regarding the forecasting and inventory models used to carry out this work.

2.1 Holt-Winters Additive Forecasting Method

Among the most diverse demand forecasting methods, according to Ackermann and Sellitto [3], "qualitative and causal methods are better associated with medium and long-term forecasts. In addition, the analysis of time series and the methods of the diverse types of averages and exponential smoothing are mentioned as the most suitable for short-term forecasts". Besides that, in accordance with Billah et al. [4], "exponential smoothing methods are relatively simple but robust approaches to forecasting", since they require minimal data retained and have the ability to adapt to changes of forecasting data [5].

The calculation of exponential smoothing methods is primarily based on weighted averages which decay exponentially as the observations are updated [6]. In the category of exponential smoothing methods, the Holt-Winters' additive method was chosen to be used in this work, because it is a most completed model, based on three equations to characterise the behaviour of demand according to level (see Eq. 2), trend (see Eq. 3), and seasonality (see Eq. 4). Besides that, the seasonal variations of the historical data are roughly constant through the series, a characteristic that is indicated for additive methods [6]. In addition, one objective of this work is to forecast short-term demand, for the year 2023 (see Eq. 1).

The characteristic equations of the method are formulated below, where l_t, b_t and s_t are the level, trend and seasonality forms, respectively [6]. In addition, α, β and γ are the smoothing constants that minimise the forecast errors, Y is the observed demand, $\hat{Y}$ is the forecast demand, m is the period of seasonality, t is the observed period and h is the forecast period.

$$\hat{Y}_{t+h|t} = l_t + hb_t + s_{t+h-m(k+1)} \tag{1}$$

$$l_t = \alpha(Y_t - s_{t-m}) + (1-\alpha)(l_{t-1} + b_{t-1}) \tag{2}$$

$$b_t = \beta(l_t - l_{t-1}) + (1-\beta)b_{t-1} \tag{3}$$

$$s_t = \gamma(Y_t - l_t) + (1-\gamma)s_{t-m} \tag{4}$$

for $0 \leq \alpha \leq 1$, $0 \leq \beta \leq 1$, $0 \leq \gamma \leq 1$, $h, t, m, k = 1, 2, 3...$

2.2 Inventories

The main role of inventories is to ensure a good "service level" for the customers by increasing the product's availability, whether finished goods, products in process or raw materials [5]. On the other hand, holding inventories entails significant costs for companies. In general, there are three important cost categories to define and apply inventory management methods [5]. The holding costs are related to the storage of materials. This cost can be calculated through Eq. 5, where Q is the order quantity, C is the product unit cost and I is the holding cost per year per unit [5].

$$Holding\,Cost\,(yearly) = \frac{ICQ}{2} \tag{5}$$

Ordering costs are associated with ordering a new batch of products from external or internal suppliers. It can be calculated through Eq. 6, where D is the annual demand and S is the cost per order [5].

$$Ordering\,Cost\,(yearly) = S\frac{D}{Q} \tag{6}$$

A stock-out rate can be defined as the percentage of traded items that should be available for sale but are not [7]. In addition, stock-out may be related to the uncertainty of demand and supplier lead time and they are avoided by safety stocks. The stock-out costs can be classified as lost sales costs or back-orders costs [5]. In this work, only back-order costs were considered.

The Basic Economical Order Quantity (EOQ) model aims to optimise the order quantity in order to minimise the inventory total costs. It is a basic model because it assumes continuous demands and only the balance between holding costs and ordering costs are considered. The EOQ is calculated through Eq. 7 [5].

$$EOQ = Q^* = \sqrt{\frac{2SD}{IC}} \tag{7}$$

2.3 Inventory Management Policies

According to Hoffer [8], the most applicable inventory management policies in real situations are the continuous review model and the periodic review model.

The Continuous Review Model is a management system in which the stock level is continuously monitored, and a new order is made when the stock level reaches a certain limit, known as reorder point (ROP) [2]. In this policy, the two main fixed parameters are the order quantity Q^* and the reorder point ROP. In order to calculate the continuous review model parameters, some equations are defined. According to Ballou [5], the demand during replenishment lead time ($DDLT$) is "known as a normal distribution probability" with mean X' (see Eq. 8), standard deviation s'_d (see Eq. 9), and probability P of being in stock during the lead time. LT is the average lead time, d is the demand (forecast or

previous), s_d is the demand standard deviation and s_{LT} is the lead time standard deviation.

$$X'(DDLT) = d \times LT \tag{8}$$

$$s'_d = \sqrt{LTs_d^2 + d^2 s_{LT}^2} \tag{9}$$

In order to calculate safety stocks and ROP (see Eqs. 10, 11), it is important to define the term z as the number of standard deviations from the mean of the demand during lead time distribution. In other words, the term z is used to calculate the probability P of being in stock during the lead time [5].

$$Safety\,Stock\,ss = z(s'_d) \tag{10}$$

$$ROP = d \times LT + z(s'_d) \tag{11}$$

In the continuous and periodic review model, the holding costs regarding safety stocks (see Eq. 12), as well as the stock-out costs (see Eq. 13) have to be considered. Therefore, the EOQ must be recalculated (see Eq. 14), where k is the stock-out cost per unit and $E_{(z)}$ is the integral loss function [5].

$$Holding\,Cost\,Safety\,Stock = ICzs'_d \tag{12}$$

$$Stock - out\,Cost\,(yearly) = \frac{D}{Q} kE_{(z)} s'_d \tag{13}$$

$$Q^* = \sqrt{\frac{2D(S + ks'_d E_{(z)})}{IC}} \tag{14}$$

Finally, the probability P of being in stock during the lead time can be defined [5]. The main goal of the continuous review model is to optimise Q and P aiming for cost reduction.

$$P = 1 - \frac{QIC}{Dk} \tag{15}$$

The Periodic Review Model, is a management system in which inventories are controlled through fixed review periods T^* and through a maximum stock level M^*. In other words, the order quantity Q is variable, according to the quantity available in stock at the time the order is placed, and the review periods are pre-established [2]. Using this policy, total inventory costs are expected to be higher because the safety stock must be sized for uncertainties during the lead time and during the review period [5]. In order to calculate the periodic review model parameters, some equations are defined below [5]. Equation 16 defines the time review interval where Q^* can be approximated by Eq. 7 and D is the annual demand. The standard deviation of the demand during $(LT + T^*)$ is given by Eq. 17, and the maximum stock level (M^*) is obtained through Eq. 18.

$$T^* = \frac{Q^*}{D} \tag{16}$$

$$s'_d = \sqrt{(LT + T^*)s_d^2 + d^2 s_{LT}^2} \tag{17}$$

$$M^* = d \times (T^* + LT) + z s'_d \tag{18}$$

3 Methodology and Results

This study was carried out in a traditional bakery, located in the northern region of Portugal, which supplies fresh and frozen bread throughout all the country. Since the company works with high turnover food raw materials and restrictions on shelf life and storage capacity, the need to carry out a study on the management of raw material inventories was identified. This study is important for the company to reduce downtime due to a lack of raw materials, as well as to reduce inventory costs and loss of raw materials.

Until now, the company does not have a very assertive control over the real raw materials consumption. To overcome that gap, monthly data regarding the orders of some products were collected: such as item code, order date, quantity, unit price and total price. All these data were collected from the company's integrated management system, with a time horizon from January 2019 to April 2022 and they have been treated in MS Excel 2016 spreadsheets. Additionally, the database was compared with the company's accounting information, in order to guarantee data reliability.

3.1 ABC Classification

A total, 76 stock items were identified. Then it was necessary to establish prioritisation criteria in order to choose the most representative ones. Therefore, an ABC Classification was used to evaluate the relationship between consumption, investment and quantity of items [9]. Using this methodology, 14 items were selected as Class A items, representing an accumulated impact of 82.7% in total expenditures on purchases of raw materials during 2021. These items were the focus of this case study.

3.2 Demand Forecast

Data was divided into four-month periods since product sales are very characteristic at Easter time (January-April), during the high tourist season (May-August) and at Christmas season (September-December). After that, the historical demand data were graphically analysed and level, trend and seasonality components were identified, justifying the choice of the Holt-Winters method.

Holt-Winters' method was initialised using Eqs. 19, 20 and 21 where N is the number of observations and m is the seasonality period. Then Eqs. 1, 2, 3 and 4 were used to forecast the demand until December 2023.

$$l_m = \frac{1}{m} \times (Y_1 + Y_2 + ... + Y_m) \tag{19}$$

$$b_m = \frac{\sum Y_t(t) - N\bar{Y}\bar{t}}{\sum t^2 - N\bar{t}^2} \tag{20}$$

$$s_1 = Y_1 - l_m,\ s_2 = Y_2 - l_m\ , ...,\ s_m = Y_m - l_m \tag{21}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Y_t - \hat{Y}_t)^2 \tag{22}$$

Constants α, β and γ were optimised using the Solver add-in in MS Excel 2016 in order to minimise the Mean Square Error (MSE) (see Eq. 22) [6]. Table 1 shows the obtained forecasts (until 2023) for the 14 prioritised items.

Table 1. Demand Forecast Results

Raw Material (Kg or Lt)	Demand 2020/1 Obser.	2020/1 Forec.	2020/2 Obser.	2020/2 Forec.	2020/3 Obser.	2020/3 Forec.	2021/1 Obser.	2021/1 Forec.	2021/2 Obser.	2021/2 Forec.	2021/3 Obser.	2021/3 Forec.	2022/1 Obser.	2022/1 Forec.	2022/2 Forec.	2022/3 Forec.	2023/1 Forec.	2023/2 Forec.	2023/3 Forec.	MSE ($x10^4$)
RM 1	40360	54284	58840	52227	41190	41961	63085	56604	30140	54548	48850	44282	68780	58925	56869	46602	61246	59190	48923	141989
RM 2	26075	15344	13685	15538	13880	16311	14470	14275	11850	14469	22625	15243	11130	13207	13400	14174	12138	12332	13105	27173
RM 3	14675	16844	17325	20438	13200	13408	11550	15560	12724	18963	15375	12523	18700	13902	16851	12261	14036	16008	11418	14372
RM 4	1472	2946	652	498	920	827	1734	1954	660	477	810	769	2147	1710	473	680	1857	360	567	354
RM 5	438	978	0	161	0	0	935	933	0	148	0	0	977	932	136	0	937	136	1	49
RM 6	240	49	250	438	300	150	430	380	450	390	500	440	425	570	590	640	565	730	780	18
RM 7	279	516	104	137	204	191	874	639	0	260	51	314	1056	761	382	436	884	505	559	48
RM 8	250	554	730	555	612	821	592	354	708	791	538	708	891	647	792	630	946	869	707	45
RM 9	0	506	0	71	369	147	140	342	0	37	378	200	200	269	13	240	235	0	227	55
RM 10	696	1836	346	217	476	391	760	905	300	154	360	298	1030	655	103	190	761	0	39	216
RM 11	900	998	580	609	700	679	710	785	470	443	540	557	660	596	352	433	524	225	306	3
RM 12	750	884	1350	1393	1500	1476	750	1060	1400	1569	1700	1653	1500	1237	1745	1829	1413	1922	2005	31
RM 13	570	994	280	109	240	173	760	828	180	195	230	215	900	812	202	235	863	215	248	32
RM 14	975	1038	2075	1450	425	1713	2075	1001	0	1414	2200	1676	1050	964	1377	1640	927	1340	1603	784

3.3 Inventories Management Policies

In order to apply both the continuous and periodic review models, the first step was to collect the inventory information described in Table 2. The standard deviation of the demand, s_d, was calculated using the demand historical data, and the 2023 forecast demand was obtained through Holt-Winters' method. All other information was estimated in accordance with the company. The stock-out cost per unit k was obtained through Eq. 13 considering the total stock-out cost in 2021 (see Table 2). The variables z and $E_{(z)}$ were calculated through the probability P of being in stock during lead time (see Eq. 15).

Table 2. Inventory Information

Raw Material (Kg or Lt)	2023 D.	s_d	C	I	S	Shelf life (days)	Storage Capacity	Stockout Cost 2021	LT (days)	s_{LT} (days)	P 2021
RM 1	169359	1197	€ 0,34	20%	€ 25	180	20000	€ 0	7	0	100%
RM 2	37575	392	€ 0,39	20%	€ 25	180	12000	€ 240	7	0	98%
RM 3	41463	586	€ 0,30	15%	€ 25	180	3750	€ 0	2	0	100%
RM 4	2785	72	€ 1,49	20%	€ 25	20	400	€ 600	5	0	90%
RM 5	1073	53	€ 3,70	20%	€ 25	180	1000	€ 400	10	1	90%
RM 6	2076	36	€ 3,22	15%	€ 25	180	200	€ 80	5	0	98%
RM 7	1948	60	€ 3,55	20%	€ 25	180	1000	€ 400	10	1	90%
RM 8	2523	19	€ 1,61	15%	€ 25	365	140	€ 480	5	0	92%
RM 9	462	16	€ 4,89	15%	€ 25	180	120	€ 400	10	1	90%
RM 10	799	52	€ 1,30	20%	€ 25	180	200	€ 300	5	0	95%
RM 11	1054	34	€ 1,19	20%	€ 25	30	150	€ 1.200	5	0	90%
RM 12	5340	30	€ 0,64	15%	€ 25	2000	975	€ 0	10	2	100%
RM 13	1326	27	€ 1,46	20%	€ 25	180	200	€ 300	5	0	95%
RM 14	3870	32	€ 0,18	15%	€ 25	2000	975	€ 0	5	0	100%

Due to the shelf life and storage capacity restrictions, it was necessary to adapt the optimal inventories parameters. For that, two restrictions were established: (i) the maximum inventory level (ROP + Q* for the Continuous Review Model and M* in the Periodic Review Model) divided by the average daily demand must be lower than the shelf life, and (ii) the maximum inventory level must be lower than the storage capacity. In order to satisfy these two restrictions, the optimum Q^* and T^* were reduced.

Table 3. Inventory Policies Results

Raw Material (Kg or Lt)	Continuous Review Model					Periodic Review Model					Cost Δ
	Q*	ROP	ss	P	T. Costs (year)	T* (month)	M*	ss	P	T. Costs (year)	
RM 1	11349	4755	1461	99,4%	€ 871	0,8	17523	3069	99,4%	€ 994	14,1%
RM 2	4935	1297	567	99,9%	€ 434	1,6	7182	1572	99,9%	€ 522	20,1%
RM 3	3146	604	373	99,3%	€ 422	0,7	3750	1235	99,3%	€ 582	38,1%
RM 4	52	103	64	98,6%	€ 1.410	0,1	155	86	98,6%	€ 2.429	72,3%
RM 5	279	110	81	99,6%	€ 266	2,9	537	250	99,6%	€ 407	53,1%
RM 6	132	68	39	99,6%	€ 452	0,5	200	80	99,6%	€ 652	44,4%
RM 7	382	138	84	99,2%	€ 331	2,3	659	235	99,2%	€ 453	36,6%
RM 8	80	60	25	99,9%	€ 811	0,3	140	42	99,9%	€ 1.032	27,2%
RM 9	81	39	26	99,8%	€ 196	1,3	120	57	99,8%	€ 308	57,1%
RM 10	137	63	53	99,4%	€ 174	0,7	200	122	99,4%	€ 495	184,0%
RM 11	37	51	36	99,5%	€ 738	0,2	88	55	99,5%	€ 1.471	99,3%
RM 12	729	246	97	99,8%	€ 230	1,5	975	143	99,8%	€ 246	6,9%
RM 13	149	51	32	99,8%	€ 256	0,9	200	82	99,8%	€ 381	48,9%
RM 14	875	100	46	100,0%	€ 124	2,3	975	179	100,0%	€ 147	18,2%

Table 4. Current Inventory Costs

Raw Material	RM 1	RM 2	RM 3	RM 4	RM 5	RM 6	RM 7	RM 8	RM 9	RM 10	RM 11	RM 12	RM 13	RM 14	Cost Δ
Current Inventory Costs (Year)	€ 1.055	€ 927	€ 880	€ 2.685	€ 657	€ 779	€ 822	€ 962	€ 629	€ 1.117	€ 3.315	€ 233	€ 840	€ 132	
Continuous Review Model	€ 871	€ 434	€ 422	€ 1.410	€ 266	€ 452	€ 331	€ 811	€ 196	€ 174	€ 738	€ 230	€ 256	€ 124	55,3%
Periodic Review Model Costs	€ 994	€ 522	€ 582	€ 2.429	€ 407	€ 652	€ 453	€ 1.032	€ 308	€ 495	€ 1.471	€ 246	€ 381	€ 147	32,7%

Finally, Table 4 shows the results and a percentage cost difference between the continuous review model and the periodic review model. Aiming a comparison, the current inventory costs were estimated and a cost comparison between the analysed policies and the current inventory costs is highlighted in Table 3.

4 Conclusion

In this work two inventory management policies were analysed in a bakery context. Comparing current inventory costs with those based on the ROP model or on the periodic review model, the average cost reduction is significant (55,3% with the ROP model and 32,7% with the periodic review model). Therefore, the advantages related to the application of these management policies are evident.

Regarding the two inventory policies, as expected, the total cost of the periodic review method is higher in all cases due to the higher safety stock, representing an average percentage increase of 50,7%. Despite this, as both methods

presented satisfactory results in relation to service level P, the decision of which model is more suitable must also take into account the operating costs for the company of both methods.

As suggestions for future work, it is important to evaluate and compare the operating costs of the two inventory policies, as well as to apply the models in the others raw materials. It is also possible to test others demand forecasting methods, such as Holt-Winters' multiplicative method, in order to compare and evaluate which one is more suitable to the available data.

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Transshipment Location Problem: A Bibliometric Review

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Abstract. The transshipment and location problem (TLP) has been recently gaining increased attention in the literature, much due to organizations need to improve their logistical processes and distribution network. This Bibliometric analysis aims to understand which authors, countries, journals, research areas, and keywords are most relevant to the TLP. In addition, it will also be looked at the perspective of the theme's growth over time. Through the Bibliometric analysis, it was possible to identify that the interest in this problem has been growing over the years and that optimization tools and approaches are mostly used. It was also observed which countries and authors most helped in the development of the theme, and what are their quantitative participations related to citation. This research brings an overview of the development of TLP and its importance in the logistics environment. In addition to showing the main authors who address the topic and their respective countries.

Keywords: Transshipment · Location · Transshipment-Location Problem · Location-Transshipment Problem · Bibliometric Analysis

1 Introduction

The transshipment and location problem (TLP) is a variant of the classic transshipment problem, which has been approached since the 20th Century and has been developing over time. The transshipment and location problem occurs when the goods you want to locate are between the point of origin and the point of destination [1]. For Nagy and Salhi [1], the problem of transshipment and location often occurs in the transport of hazardous materials. However, there are studies that consider the TLP for non-hazardous goods, such as Perboli et al. [2], and Çömez et al. [3] who use the TLP to the transportation of goods, not considered dangerous, in urban areas. For Zhou and Wang [4], there are two types of transshipment addressed in the literature: proactive and reactive transshipment. Proactive transshipment is planned to occur in specific situations, in which there is a specific care and schedule for the balance of stock in storage places. The other type of transshipment is reactive, which takes place in an emergency, when there is a shortage of stock.

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With the populational increase and the technological evolution, the logistics networks problems have increased, in which the use mathematical tools, such as modeling and simulation in routing problems, has been shown [5], location [6] and transshipment [7] became evident. Location problems are usually strategic, whereas routing and transshipment may be considered tactical or operational, depending on the perspective of the work. The work is a bibliometric analysis, which quantitatively measures the analysis of contents and citations of the literature of a specific theme, which tends to value the trends that are in development regarding the bibliographic basis, such as keyword, journal, author, institution, funding agency, country and reference [8].

This methodology is used in all areas of knowledge, aiming to guide researchers through the path where they should work. Therefore, this article aims to answer two questions:

(1) What are the main authors, countries, institutions, journals and research areas that address TLP?
(2) What is the panorama of scientific production on TLP?

The main contributions of this work are to show through the quantitative statistical results referring to authors, keywords, countries, journals and institutions through tables and scientific maps the status of TLP research. The Scopus database and the Vosviewer software were used to assist in the analysis of bibliometric characteristics.

The rest of the article is organized as follows: Sect. 2 presents the methodology and how the data collection was carried out. In Sect. 3, we have the statistical results from the Scopus database. In Sect. 4, we use Vosviewer to help create scientific knowledge maps and generate bibliometric results. Finally, in Sect. 5 we have the conclusions.

2 Methodology and Data Collection

The database selected in this article is Scopus. The reasons for choosing Scopus for bibliometric analysis are: (1) Scopus contains approximately 19,500 titles from over 5,000 international publishers, covering 16,500 journals, and is the leading database in engineering and exact science research. (2) Our research focuses on visual analysis of authors, countries, keywords, journals, and institutions, and Scopus not only contains a range of data from which this information can be obtained, but is also generated in a format directly readable by the VOSviewer software. (3) Due to the duplicate documents, the usage of other databases, such as ScienceDirect and Web of Science, would produce very similar results. VOSviewer is an important tool to map and visualize the behavior of network structures with data obtained from the main databases, such as Scopus, Web of Science, and ScienceDirect [8].

The search in the Scopus was carried out on November 1, 2022, with the following advanced search formula:

TS = (“Transshipment” AND “Location”)

which basically means that research that addresses one of the above expressions of transshipment and location issues in their work has been chosen for analysis. It is intended to verify the entire trend of evolution involving TLP, considering any type of document like articles, reviews, book chapters, books and conference papers, in addition to all

categories of areas. From the search strategy, 403 articles in English were selected, analyzing the title, abstract and the keywords of each of them, and the oldest article being published in 2000 by Bruns et al. [9].

For the credibility of the research, the articles were directed to the StArt and VOSviewer software to avoid the possibility of duplication. A descriptive analysis was performed to describe the number of publications, trends, productivity and citations. The influence of authors, countries, keyword analysis, journals and trends related to the theme were also analyzed. It was considered the affiliation of the first author and the institution that he/she is to assign research papers to the countries. Network analysis was performed through data visualization and through scientific mapping, including (1) cluster analysis and authors; (2) keyword co-occurrence analysis; (3) topic evolution analysis.

3 Basic Statistical Analysis from Scopus

The interval of the selected articles was from 2000 to 2022 when we had a significant number of papers, in which TLP is a problem that has been relevantly explored: in 403 selected works we have 269 articles, 117 articles in conferences, 16 book chapters and 1 book. In Fig. 1, the details of each type of work can be observed.

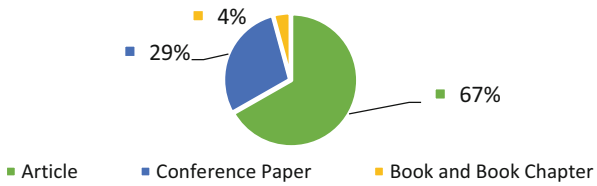

Fig. 1. Document types in TLP research.

Through the statistical results of 403 documents exported from Scopus, the production of annual publication results from 2000 to 2022 is shown in Fig. 2. As can be seen, the number of publications along the interval shows an upward trend, which demonstrates that the TLP research topic has received a lot of attention from researchers and has made significant progress in the last 22 years. The number of documents published per year did not exceed 20 articles from 2000 to 2008, with an annual publication average of 9.62 and few studies were published during this interval, with some fluctuations. Between 2008 and 2014, the number of publications fluctuated, decreasing between 2013 and 2014, in which the average of articles in this range reached 20. Between 2015 and 2022, there were two sharp fluctuations in the number of publications, more precisely in 2017 and 2020, the number of publications dropped from 24 to 19 in 2017 and of little relevance in 2020, when the average annual publication was 26.57. So far, the number of publications on TLP has not peaked, which may indicate a lasting interest in this area. Transshipment problems have brought more relevance to the academy with the evolution of e-commerce. In the last six years (2015–2022), the number of publications is 186, which represents approximately 46.15% of the sample size, reaching the highest

number of documents published annually in 2021 with 32 publications. Figure 3 shows the main categories of areas where the TLP was addressed. It is possible to observe that in the vast majority of categories the exact sciences prevail, and engineering, decision sciences, computer sciences and mathematics stand out in an expressive way.

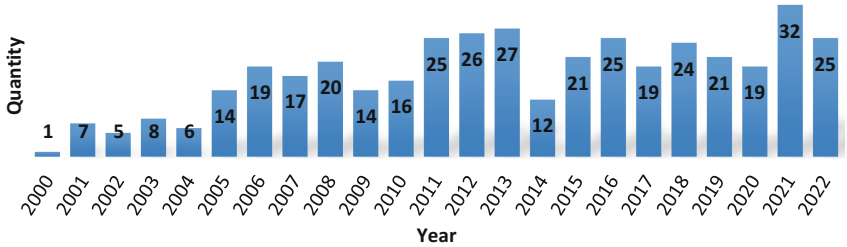

Fig. 2. Annual production of publications from 2000 to 2022.

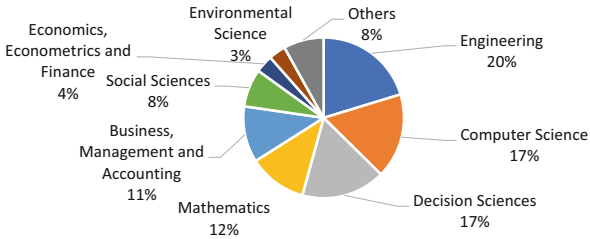

Fig. 3. Documents by subject area

The percentage of works in the four main areas corresponds to about 66% of the works selected in this review, but the work may belong to other categories. In Fig. 4, the top 10 journals that the TLP approached are shown, with most publications in the "Europen Journal of Operation Research", which is a very traditional journal with an impact factor of 6.363 for 2021.

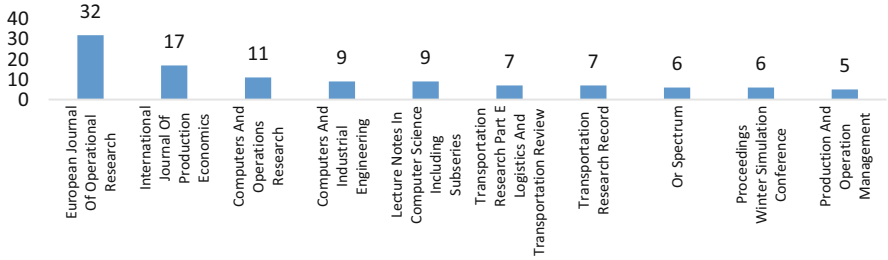

Fig. 4. Top 10 journals in which papers were published.

In Fig. 5, it is possible to observe the main countries that contributed to the TLP theme. USA, China, Germany, Canada and Singapore lead the ranking of countries

that most participated with publications, representing about 73.91% of the publications selected for this Bibliometric Analysis. However, from 2015 to 2022, China ranked first in the number of publications, showing its growing evolution in the last 7 years.

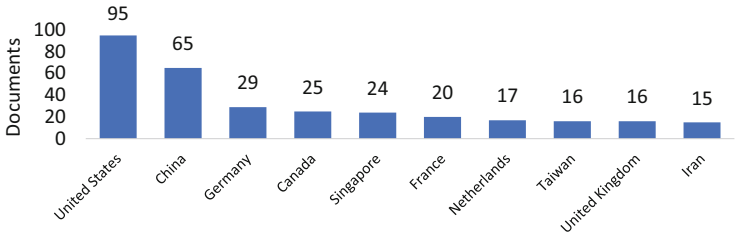

Fig. 5. Top 10 countries publishing on the TLP.

4 Bibliometric Analysis Based on VOSviewer

In this section, the Bibliometric analysis and visualization of the author and keywords were performed. Basically, the purpose of author analysis is to find out which researcher is most relevant to the topic. As can be seen in the map of the authors' collaboration netwok in Fig. 6, in which VOSviewer organized it into 5 clusters, in the cluster with the largest number of authors, with exactly 13, we have Herer, Y. T as the author who has published the most. In Fig. 7 we have the most cited authors with their respective articles, and as can be seen Alumur and Kara [10], Rudi [11] and Paterson [12] are highlighted in a network map with 18 clusters. In Table 1, it is possible to observe the number of citations and publications of the authors around TLP.

Fig. 6. Map of the TLP authors' collaboration network.

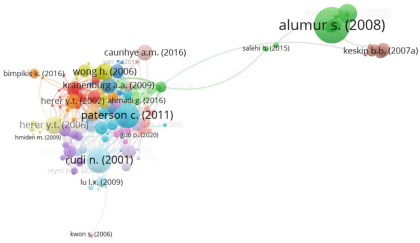

Fig. 7. Map of the network of articles most cited by TLP authors.

It is important to notice that the author Herer, Y. T. is the first considering number of papers, as he has a great contribution as a co-author, showing his participation even in works by Özdemir, D. In Table 2, we can see that Herer, Y. T., is not the most cited. The most cited are Alumur and Kara [10], with the article "Network hub location problems: the state of the art", with 676 citations. However, by analyzing the network map, Herer,

Table 1. The 10 authors who published the most about TLP.

Authors	Publication author First/Second		Number of Citation Author/Co-author		Institution	Country
Herer, Y.T.	5	6	299	102	Israel Institute of Technology	Israel
Yücesan, E.	0	9	0	324	INSEAD	Singapore
Chew, E.P.	0	7	0	467	National University of Singapore	Singapore
Lee, L.H.	2	4	143	324	National University of Singapore	Singapore
Chou, C.C.	5	1	241	12	National K. University of Science and Technology	Taiwan
Ben Said, L.	1	4	6	3	Université de Tunis	Tunisia
Ghedira, K.	0	5	0	9	University Ibn Khaldoun-Tunis	Tunisia
Hmiden, M.	3	2	2	6	Institut Supérieur de Gestion de Tunis	Tunisia
Tan, K.C.	0	5	0	291	NUS Business School	Singapore
Özdemir, D.	5	0	92	0	Yasar University	Turkey

Y. T., has relevance in citations, once other relevant authors, such as Paterson et al. [12], mention him in their papers.

When analyzing Table 2, it is possible to observe that the most cited work comes from the journal that most published about TLP, in this case the "European Journal of Operational Research". The magazine appears in first, third and seventh places, accumulating more than 1127 citations. In the third most cited article, by Paterson et al. [12], a literature review was carried out to discuss the stock models using lateral transshipment, of the same echelon. The keywords used in the works listed in Table 2 are linked in certain situations. In Fig. 8, the main keywords can be seen, with their appropriate frequency represented in the occurrence network map itself, and in Table 3, which also shows the frequency of each keyword quantitatively. As can be seen in Fig. 8, the three main keywords that stand out are "Location", "Inventory Control" and "Optimization", which makes sense, since the methods most used to address TLP are in the area of optimization [13], with some exceptions from works that use another method such as simulation [7].

In addition, also brings us some conclusions regarding the frequency of its keywords: (1) the researchers emphasized the use of optimization, that is, the vast majority using linear integer programming modeling and mixed integer linear programming. (2) Most articles show the importance of mathematical tools to solve transshipment and location problems, such as algorithms and computational methodologies. (3) Shows how the

Table 2. The 10 most cited papers in the literature on TLP.

Title	Author	Number of Citation	Year	Source
Network hub location problems: the state of the art	Alumur and Kara [10]	676	2008	European Journal of Operational Research
A two-location inventory model with transshipment and local decision making	Rudi et al. [11]	284	2001	Management Science
Inventory models with lateral transshipments: A review	Paterson et al. [12]	283	2011	European Journal of Operational Research
The relative cost of biomass energy transport	Searcy et al. [14]	209	2007	Applied Biochemistry and Biotechnology
Berth management in container terminal: The template design problem	Moorthy and Teo [15]	173	2006	Or Spectrum
Port selection factors by shipping lines: Different perspectives between trunk linears and feeder service providerns	Chang et al. [16]	172	2008	Marine Policy
A multiple-crane-constrained scheduling problem in a container terminal	Bish [17]	168	2003	European Journal of Operational Research
An integrated model for berth template and yard template planning in transshipment hub	Zhen et al. [18]	161	2011	Transportation Science
Location models for airline hubs behaving as M/D/c queues	Marianov and Serra [19]	156	2003	Computers and Operations Research
A fuzzy MCDM method for solving marine transshipment container port selection problems	Chou [20]	139	2007	Applied Mathematics and Computation

supply chain is directly linked with TLP, in addition to compelling studies on stocks. The TLPs may be considered old and still being developed within the literature, and this Bibliometric analysis shows its growth trend, displaying a significant increase in the number of publications in the past 7 years.

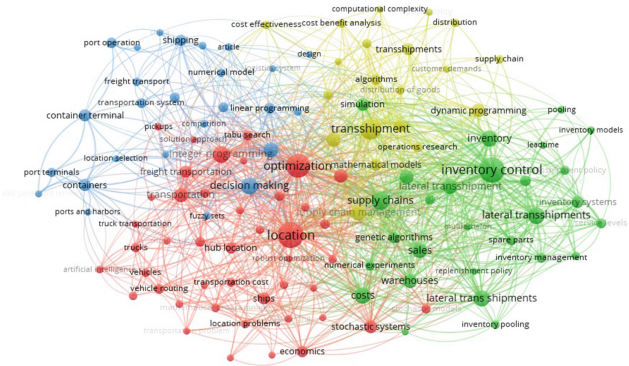

Fig. 8. Network map of occurrence of keywords in TLP.

5 Conclusion and Future Trend

Based on 403 relevant documents included in the Scopus core collection, this study first identifies the basic status of TLP research in terms of publication trends and category distribution. Moreover, the results of the scientific knowledge maps and the bibliometric analysis are presented based on five dimensions: author/cited author, cited journal, country, institution, and keyword.

The main conclusions are: (1) The annual number of publications related to TLP research shows a general upward trend, and this trend may continue in the coming years. The statistical results of the distribution of subjects by areas show that the TLP research is comprehensive, with “Engineering”, “Operational Research and Management Science” and “Computer Science” being the most relevant categories. (2) The analysis of the authors shows that Herer, Y. T., is the most prolific author, mainly as a second author and Alumur and Kara (2008) are the most cited authors. (3) The results of the country analysis show that the main contributions of the TLP research are mainly in North America (USA and Canada), Asia (China and Singapore) and Europe (Germany and France). Europe and North America have a relevant number of publications in the world when addressing the keyword TLP. However, China is the country where there was the highest growth in the number of publications in the last seven years. Nonetheless, there are still limitations to this article because not all related documents on TLP were selected between 2000 and 2022, as many authors may have used other keywords or may have published after our analysis. The future study intends to find insights into TLP and its mathematical models applied in urban logistics, being an area of great development, mainly because of e-commerce.

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Logistics Flow Improvement in a Leather Goods Industry

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Abstract. This paper presents an optimization case study developed for a leather company, which aims to improve operational performance at the technical team level in routing and apply improvements that impact it. This project aims to create a route optimization model for what were initially intuitive routes. Since the assignment of work hours by the central team varies, there is a fluctuation in the material shipped to each customer. Considering that this fluctuation is relatively small and only happens every quarter, the fixed route system can be considered as functional, needing updating when there is a new time allocation. Thus, the objective is to minimize the total transportation cost, which in this case is provided by the cost per kilometer. To this end, five scenarios, obtained by a decision support tool, were studied. The VRPTW model, together with decisions concerning the routes, namely cross-docking in Orléans, allowed the reduction of costs by more than 30%, maintaining the customer's and company's requirements regarding the service level. These gains refer to one of the scenarios studied, in which it was possible to guarantee all last-mile distribution with three vans, within expected time windows and demands. Although the scenario with the greatest margin for gains is the one that presents a distribution center according to the gravity method, it also requires renting a warehouse in the Perrusson area (area indicated by the gravity method).

Keywords: Vehicle Routing Problem (VRP) · Supply Chain · Logistics · Leather Industry

1 Introduction

With the search for efficiency and sustainability, the optimization of the supply chain by companies becomes crucial. For this reason, in recent years, the Vehicle Routing Problem (VRP) has gained greater notoriety in distribution systems, to add value to the transportation system. The objective of the classic VRP is then, through the knowledge

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of the customers' geographic locations and their needs (demand and possible demands), to trace an optimal sequencing to pick or deliver orders with the minimum cost, through a limited fleet [1]. Many companies and organizations, due to a lack of resources, choose to create their routes through intuitive methods, however, there is a significant improvement in reliability and cost when routing is performed with the aid of mathematical methods. The objective of this study is to optimize the distribution system of a leather company, by improving the operational performance in routing that was done empirically. This project aims to create a route optimization model. Since the assignment of work hours by the central team varies, there is a fluctuation in the material shipped to each customer. The methodology chosen to structure the report in the implemented case study was action research (AR). AR is a research process that balances the research process in an industrial environment with data analysis in problem-solving. It enables understanding underlying causes and making future predictions about changes needed in the organization. Since this method has a practical component that assists in everyday industrial problems and has the goal of bringing about changes in the functioning of the organization, it proves to be the most suitable for this project [2]. In the first phase, diagnosis of the problem, the problem must be justified, and all theoretical concepts associated with it must be investigated. In the case analysis, one collects all the information that one considers pertinent to analyze to proceed with the study. At this stage, it is interesting to make a comparison between case studies to see if the information collected is sufficient. After this analysis, it is possible to make a forecast of possible scenarios. In the third phase (feedback and action plan), it is verified, through the previous steps, which methodology is best to adopt, and an implementation plan is drawn up. After a thorough investigation, to avoid errors, it becomes feasible to apply the proposed measures. Finally, if possible, one should evaluate the impact that the measures had on the organization and which improvements could have a positive increment in the organization. The remaining paper is structured as follows: Sect. 2 presents a literature review; Sect. 3 the problem description and formulation; Sect. 4 presents the results of applying the model with five real scenarios; the conclusions are presented in Sect. 5.

2 Literature Review

For most organizations, monitoring the flow of information and matter, from the beginning to the end of their journey, has proven to be fundamental. Since the entire market has become increasingly competitive, increasing the efficiency of processes has been paramount for companies to make positive progress in their business.

In logistics, there are five key points: Transportation; Warehousing; Inventory management; Packaging; Information processing. In transport, it is necessary to take into consideration the mode of transport (air, sea, land, multimodal or intermodal), the infrastructure, the geographical conditions, the type of delivery (express, normal, long distance, night), routing and scheduling. Regarding warehousing, the most important considerations are its location, the number of warehouses (associated with the storage policy as the central and decentralized concept), and the size and type of storage (in the case of cargo requiring special packaging conditions or other factors). Inventory management is mainly about making decisions ("What to store?", "How much to store" and "Where

to store?"). It is often confused with warehouse management, however, as inventory management is concerned with the amount of product or raw material stock, the warehouse deals with the allocation of that stock. All products (raw materials, semi-finished and finished products) need packaging. Hence, this associated with its standardization becomes an important aspect of logistics [3]. Clearly, an effective and efficient logistics system needs an integrated system that unites these pillars.

All companies that belong to a network of entities are interconnected by the flow, from the raw material to the final consumer. This network is called the distribution chain. According to Lambert and Cooper [4] Vehicle Routing Problem (VRP) is a generic name that refers to all classes of problems involving the design of optimal routes for a fleet of vehicles to serve a set of customers, given certain constraints. Depending on some factors such as the nature of the goods transported, the quality provided and the characteristics of the customers and vehicles, one can opt for one of several variants of VRP [6]. The transportation routing problem, although recurring nowadays, was introduced in 1959 by Dantzig and Ramser [7]. Currently, the previously referenced VRP model is outdated since industrial development has increased the need to incorporate new constraints so that the theoretical model resembles real situations as much as possible, and several variants of VRP arise [5]. VRP with time windows (VRPTW) adds to the original model time windows associated with each customer, that is, each customer provides a previously defined time within which a certain task or service must be completed [8, 9]. According to Qi et al. [10], it is also necessary to think about spatial constraints, due to the position of customers scattered in a particular region. Different vehicles can be combined, such as trucks and drones. To achieve coordination of these different means of transportation, a VRPTW was applied, and an integer programming model was used to minimize the total travel costs [11].

3 Problem Description and Formulation

In the group's various ateliers, the flow of materials follows two different paths. On the one hand, there is the *acheté* flow, and on the other, the *fabriqué* flow. In the first, the raw material is bought in its totality by the company's suppliers, and the cutting process is done internally, while, in the second, the leather and the metallic pieces are bought by the client who does the cutting process, sending afterwards the material to the company. The company's intended goal within the network optimization and transport flow is to find improvement opportunities to obtain a significant overall cost reduction (between 15% and 25%). For this, it is imperative that the level of service is maintained or obtain gain and the guarantee that the lead time (LT) defined by the group is met. Company's current transport network offers a maximum delivery time of four weeks to its customers, from the moment the order is placed. For the United States of America (USA) air transport is used, while for France and Spain (the subject of this study) vans are used, totaling an annual cost of approximately 2 M€ (between routes, cabs, and express). With the current scenario, in Europe, the company has 21 destinations, satisfied by 25 routes.

3.1 Current Route Analysis

To identify the largest problems and understand where the level of improvement is highest, a detailed analysis of each route was made. It showed that several routes intersected, i.e., that different drivers delivered goods at nearby locations on the same day. Another aspect that proved relevant was the existence of more than one daily delivery for some customers, namely on Friday (morning and afternoon). Analyzing the data and associated costs of each route (company's CMR file), there is great variability of occupancy indicators (between 36% and 93%) and cost (between 0.77 €/km and 1.10 €/km; between 381 €/pallet and 914 €/pallet). At first sight, the routes from Spain, are the most worrying, as they are served daily and have an average load factor of less than 45% (Table 1).

Table 1. Summary table of the main problems of the initial situation.

Lack of data	Route duplication and non-optimization	Distinct delivery frequencies	Low vehicle occupancy
Import data is not consolidated The typology of the dispatched boxes did not always correspond to reality Variation in the standard for creating pallets between ateliers	Several customers are shipped twice on Friday There are routes on the same day that cross each other, serving close customers	There are no geographic hubs with similar delivery frequencies that would allow routes to be formulated according to this criterion	A discrepancy in vehicle occupancy rate (between 36% and 93%) About 45% of the routes have an occupancy of less than 70% of the vehicle capacity Spanish routes have an average occupancy of less than 45%

3.2 Desired Distribution Model

Given the company's constant state of evolution, there is a need to adapt the current routes or formulate a completely new system to meet the customers' needs. After a thorough analysis, it was concluded that the most beneficial scenario would be to incorporate a cross-docking center in France and from there run a milk run. To reduce the costs of this operation, using a central warehouse of the company located in Orléans was considered. As the gravity method proved, the best location for a warehouse is in Perrusson, which is relatively close. This way, long-haul trucking from all customers can be used, passing by the Spanish customers, and from there, a capillary distribution to the remaining customers can be done by van. Note that all vehicles must be exclusive when servicing the company, in the same way, that they must respect the customer's required time windows. When analyzing the long haul to Spain and then to France, it was found that the route traced to Orléans passed fairly close to two customers: L and K (Fig. 1).

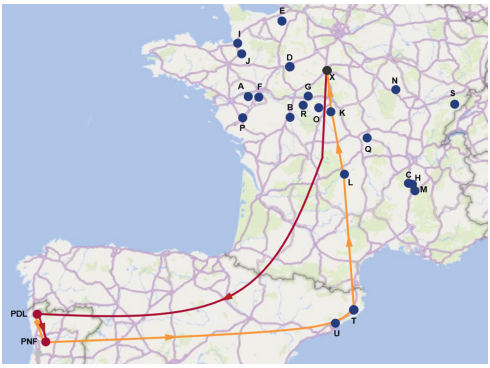

Fig. 1. Long-haul routes (roundtrip).

It would thus make sense not only to incorporate the Spanish customers into the long haul but also to do the same with these French customers. This way, there would be two long-distance routes: a one-way starting in PDL, then passing through PNF, U, T, L, and K and ending in X (Orléans) with a total of 1730.6 km, and a direct return route from X to PDL that would then go on to PNF to finish its route (1140.78 km). Considering some values obtained through contact with some carriers and in order to cover some values that may oscillate over time, it was considered that the cost of the long distance will present a cost of 1 €/km. Thus, considering the above, with these stops at customers, these routes will be worth about 2871.38 €. Now comes the most complex step and the reason for using the IBM CPLEX 12.8.0.0 optimization software: the milk-run. All the scenarios envisaged for this purpose were the result of applying the model described above to the software. From the solutions provided by the model, it was possible to draw some conclusions. Just as for the long-haul, the price applied by the market in terms of mileage was extensively studied. The one most used by transporters is obtained by weighing the driver's salary (in France, in this case), the consumption of the van, the fuel cost, the vehicle depreciation, and of course some profit margin. Thus, the value arrived at was around 0.70 €/km. Due to the relatively low service level of the company, it was decided to make the long courses and daily milk-runs to try to overcome this issue.

3.3 Mathematical Model

Decision variables

$$x_{ij}^{k} = \begin{cases} 1, \ if \ \ vehicle \ k \ travels \ from \ client \ i \ to \ client \ j \\ 0, \ otherwise \end{cases}$$

$$b_i^k = time \ when \ the \ service \ starts \ at \ client \ i \ by \ vehicle \ k, \ with$$
$$i = 1, 2, \ldots, n; \ k = 1, 2, \ldots, m$$

$$y_i^k = fraction \ of \ \ customer \ demand \ i \ delivered \ by \ vehicle \ k$$

Parameters:

n Number of customer.
m Number of vehicles.
e_i Upper time window of customer i.
l_i Lower time window of customer i.
a_k Maximum capacity of vehicle k.
s_i Customer's service time i.
M Big number.

Objective function:

$$minimize\ the\ cost\ of\ the\ routes = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{m} d_{ij}^{k} c_{ij}^{k} \tag{1}$$

Subject to the following constraints:

$$\sum_{j=1}^{n} x_{0j}^{k} = 1, k = 1, 2, ..., m \tag{2}$$

$$\sum_{i=1}^{n} x_{ip}^{k} - \sum_{j=1}^{n} x_{pj}^{k} = 0, p = 1, 2, ..., n; k = 1, 2, ..., m \tag{3}$$

$$\sum_{k=1}^{m} y_{i}^{k} = 1, i = 1, 2, ..., n \tag{4}$$

$$\sum_{k=1}^{m}\sum_{i=1}^{n} x_{ij}^{k} \geq 1, j = 1, 2, ..., n \tag{5}$$

$$\sum_{i=1}^{n} q_i y_{i}^{k} \leq a_k, k = 1, 2, ..., m \tag{6}$$

$$y_{i}^{k} \leq \sum_{j=1}^{n} x_{ij}^{k}, i = 1, 2, ..., n; k = 1, 2, ..., m \tag{7}$$

$$b_{i}^{k} + s_i + t_{ij} - M_{ij}\left(1 - x_{ij}^{k}\right) \leq b_{j}^{k}, i = 1, \ldots, n; j = 1, \ldots, n; k = 1, ..., m \tag{8}$$

$$e_i \leq b_{i}^{k} \leq l_i, i = 1, \ldots n; k = 1, ..., m \tag{9}$$

$$y_{i}^{k} \geq 0, i = 1, 2, \ldots, n; k = 1, 2, \ldots, m \tag{10}$$

$$b_{i}^{k} \geq 0, i = 1, 2, \ldots, n; k = 1, 2, ..., m \tag{11}$$

$$x_{ij}^{k} \in \{0, 1\}, i = 1, 2, \ldots, n; j = 1, 2, \ldots, n; k = 1, 2, ..., m \tag{12}$$

This mathematical model VRPTW ensures, through the objective function (1), that the cost associated with each route in the milk run will be minimized. The first constraint

(2) guarantees that each vehicle will leave the central warehouse and arrive at a given customer. The second (3) ensures the flow; the vehicle that ar-rives at a client should leave that client after the service. The third (4) and fourth (5) constraints ensure that the customer's demand will be met and that it is visited at least once by at least one vehicle, respectively. Constraint (6) indicates that the vehicle cannot carry more cargo than its maximum capacity. Equation (7) ensures that the demand of each customer is satisfied. The Eq. (8) is used to define a minimum time to start serving the customer on a given route and to eliminate possible subroutes. The Eq. (9) guarantees that all the time windows required by the customers will be respected. The constraints (10) to (12) are the technical ones that characterized the decision variables.

4 Results

Five scenarios with different variations were studied to see how the model would respond to them, see Table 2.

Table 2. Summary table comparing different scenarios.

Scenario	1	2	3	4	5
Distribution center location	Orléans	Orléans	Orléans	Orléans	Perrusson
Distance traveled (km)	2530,07	2926,71	2175,92	2536,36	2154,09
Cost (long-haul plus milk-run, €)	4642,88	4920,08	4394,48	4646,88	4379,28
Number of vehicles used	4	5	**3**	5	4
Change in customer demand	–	**x2**	–	–	–
Change in time windows	–	–	–	**−40%**	–
Change in spend of Scenario 1	–	+ 9,65%	-5,35%	+ 0,09%	−5,68%

The first would have normal conditions, with the distribution center in Orléans; the second would only have double the demand; the third would have fewer vehicles; the fourth would have reduced time windows; and the fifth would have its cross-docking center in Perrusson (a city obtained by applying the gravity method). It was found that more gains would be obtained in the fifth option; however, the company would have to rent a warehouse for this purpose, unlike in Orléans, where the business group already has a central warehouse. It turned out that five vehicles were more than enough to satisfy the milk-run since, under exaggerated conditions (doubled demand and reduced time windows by 40%), no more vehicles were needed. Under normal conditions, with no need to rent any external distribution center, the best scenario would be the third one, which would guarantee more than 30% monetary gains while ensuring daily delivery to all customers. It became apparent that improving this flow was possible and would yield a wide margin of gains. Although the result is quite satisfactory, due to some restrictions from customers and even from the company itself, the routes are not as optimized as possible.

5 Conclusion

This paper presents the VRPTW of a leather company that has to distribute its production to distribution centers and shops. Considering the routing process per-formed so far (22 weekly routes), the need to update this method became apparent. To this end, a decision support tool was used, whose primary function is to reduce transportation costs.

The study of the customers' constraints underpinned the decision to establish a crossdocking point in a distribution center in France, with long-haul trucking from Portugal to said warehouse, passing through Spanish clients, and finally by van for capillary distribution to all French clients for the last mile. Whenever possible, customers who were intersected by the long-haul route were included. It became apparent that improving this flow is possible and yields margins of more than 30% in monetary gains.

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Outbound Movements in a Temperature-Controlled Warehouse

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Abstract. The temperature-controlled supply chain in Portugal is on a par with the most developed cold logistics markets. With a growing and increasingly demanding market dynamics, it is essential that companies in the sector adopt strategies aimed at increasing the efficiency of their operations, promoting an increase in the level of service and a decrease in their operating costs. The need to decrease operational costs should not have any impact on quality, and it is expected that the focus will be on the continuous improvement of internal logistics operations. A study of the outgoing movements of products from a temperature-controlled warehouse of a logistics and transport services company was developed. An integer linear programming model was built and applied, in order to minimize the costs of the logistics operator with the operation of picking and storage. It was possible to obtain savings of about 30.9% compared to the initial scenario.

Keywords: Cold Chain Logistics · Warehouse Operations · Mixed Integer Linear Programming Model

1 Introduction

This article focuses on the study of warehouse outbound movements, in a Portuguese company that provides logistics, transport and storage services for goods under controlled temperature. The Warehouse Management System (WMS) used by the logistics operator adds a wide range of movements with different specificities and objectives. The subject of this study is the main movements of boxes and pallets stored in the warehouse that occur when customer orders are being prepared.

Picking and storage operations result in the highest concentration of annual costs of warehouse operations, corresponding to 55% and 20% respectively [1–3], which reveals the relevance of companies to focus on the continuous improvement of these operations and consequently the reduction of associated costs.

Warehouse design has been addressed previously. Different ways of assigning products to storage locations have different impact on the travel time required to retrieve products from storage areas in response to customer requests [4]. Bindi et al. proposed the correlated assignment strategy for the food service industry, which suggests that products that are frequently ordered together in multi-item orders should be stored near each

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other. Yener & Yasgan [5] analysed the storage assignment of different types of items in pallet racks of a refrigerated warehouse, from a Turkish company with a customer portfolio including grocery stores and supermarkets in the retail sector. Warehouses often have a reserve area dedicated for storage and a forward area more efficient for order picking [6]. The forward-reserve allocation problem, addressed by Gu et al. in [7], intended to determine the set of Stock-Keeping Units (SKU) and their space allocations in the forward area to maximize the forward area's benefit, by trading off the relevant costs of order picking and internal replenishment. Key productivity performance indicators for each function of the warehouse are discussed in [8]. Performance improvement can also be achieved when both travel distance and ergonomic criteria are targeted for determining the picking area layout and storage design [9].

Mixed Integer Programming (MIP) is a popular method to address warehouse design problems. Storage-location assignment in warehouses impacts productivity of other warehouse processes. Using a non-linear integer programming model, a class-based allocation of storage space is proposed in [10], that resulted in shorter pick-travel distances. In [11], Öztürkoğlu presented a MIP bi-objective mathematical model, to decide the put-away quantity and locations of the received SKUs, considering two simultaneous objectives: minimizing total travel time, and maximizing average storage usage. The model is compared with a heuristic algorithm, using actual data from an international company that distributes home appliances in Turkey and neighboring countries. Another MIP model has been developed by Geraldes et al. [12] to study the trade-offs among the different warehouse costs, to achieve global optimal design. This model considered the costs of picking and other warehouse operations, for products stored in a reserve area and in a forward area.

The purpose of this study is the minimization of costs for the logistics operator with the picking and storage operation and respective optimization of the products' allocation in the warehouse. Section 1 introduces the topic, while providing some reference works, and the next section presents the methodology, the characteristics of the warehouse movements and the assumptions of the study. In Sect. 3 the mathematical model is explained in detail; its results are presented in Sect. 4, and conclusions are drawn in Sect. 5.

2 Study of Warehouse Outbound Movements

2.1 Methodology

The adopted methodology consisted of three phases: collection of data, respective analysis and data processing, and planning.

As literature advocates [5], storage assignment should take into consideration customer's consumption patterns. Therefore, the first stage consisted of collecting data and the necessary information from the company operation, capable of supporting the understanding, development and achievement of the defined objectives. Specifically, a large client that stores a variety of frozen products in this Portuguese logistics company was selected for case study. Data related to the outgoing movements of 228 products of this client in the year 2021 was extracted from the WMS of the logistics operator.

The analysis of the movements out of the temperature-controlled warehouse allowed to identify potential changes in the company's operation, and lead to the construction of a mathematical model using Mixed Integer Linear Programming (MILP). The model intends to minimize costs of the picking and storage operation through a better planning and organization of the places occupied by the products in the warehouse. This mathematical model was implemented in AMPL - A Mathematical Programming Language, and solved with the Gurobi solver.

2.2 Types of Movement

The customer under analysis has products in the warehouse's frozen chambers that have a place on the floor of the warehouse for picking, with the remaining quantity of product stored at height in a reserve area. It also has products in which pallets are stored entirely at height on a rack. Table 1 describes, by way of summary, each of the outbound movements targeted by the study.

Table 1. Description of PRES, PHOM, PPIC movements.

Type of Movement	Description
PRES (Product in Reserve area)	It corresponds to the movement of lowering a pallet to the ground and removing the number of boxes necessary to satisfy a certain request/order (List-Pick). After removing the required amount, the pallet is lifted back to its original storage location. For products that have PRES-type movements, that is, where the storage place is defined as a reserve area, there is no allocation of a picking place (place on the floor)
PHOM (Whole Pallet Order Movement)	In consists of a direct pallet being removed from the storage location, that is, with the entire amount of product it currently has, to serve a merchandise order (Pallet-Pick). This quantity can be the same which the pallet initially entered the warehouse, or the quantity that remained after removing some items to serve another order (through PRES type movements)
PPIC (Product Picking)	It consists of collecting stored products, in order to gather the right product, in the correct quantity, according to the order in preparation (List-Pick) Products that have PPIC-type movements have a designated picking place on the warehouse floor

In view of the presented storage method scenarios, PHOM and PRES type movements are associated with the storage of pallets in height on a rack, in a reserve area. In turn, PPIC-type movements represent the place on the warehouse floor, under the shelves – picking hole, in the picking area. In this way, PRES and PPIC type movements are incompatible movements, and therefore do not occur simultaneously for a product in storage. PRES type movements occur when there is no picking hole for the product in question. If these two types of movement both appear in the records for a product during the period considered, it means that there has been a change in the way this product is stored and prepared.

2.3 Data for Outbound Movements of Products

The client selected for this study has daily order preparations, in the warehouse of the logistics operator, that include List-Pick, Pallet-Pick and the combination of the two preparations, List & Pallet-Pick. Data was extracted from the WMS of the logistics operator, for the year 2021, referring to 228 different product references. Table 2 summarizes the number of movements by type, as well as the total number of boxes moved and the respective average per movement in the period considered.

Table 2. Number of movements and boxes handled in 2021 of the customer under study.

Type of Movement	Number of Movements	Number of Boxes	Average number of boxes	Number of related products
PRES	916	21989	242	91
PHOM	6311	589597	2993	197
PPIC	1298	31300	1159	27
Total	8525	642886		228

Considering 253 business days in the year 2021, it is possible to state that, on average, around 34 outgoing movements of goods were carried out for this customer daily and around 2541 boxes were handled. Most of the goods leave the warehouse through orders that include the output of direct pallets – Pallet-Pick. The PHOM-type movement occurred in the greatest amount (6311), in relation to the other types of movements. This type of movement is more productive and economical and corresponded to around 74% of the total number of movements carried out in 2021 for this client.

2.4 Costs with the Picking and Storage Operation

According to information obtained from the company under study, the space on the warehouse floor in the picking area costs 12 times more than a storage space in height on the rack, in the reserve area. Further, the productivity associated with picking in a reserve zone (PRES movements) and picking carried out in a picking zone (PPIC movements) is, respectively, 150 boxes/h and 200 boxes/h.

The following hypotheses will be considered for the optimization of these operations and respective reduction of associated costs:

- The place on the warehouse floor, in the picking area, represents a higher cost for the logistics operator, so this must be optimised;
- A picking place on the warehouse floor is optimized if associated with the product there is a high number of movements (PPIC) and also a considerable number of boxes to go out in orders;
- If picking is requested from a large number of boxes and/or there is a large number of PRES movements associated with a product that is stored in a reserve area, it may prove to be more efficient and productive for that product to have a place on the warehouse floor in the picking area.

PRES-Type Movements
Of the 91 products with PRES-type movements, 11 products were selected, on which an analysis was carried out of the evolution of the number of movements that occurred, and the number of boxes handled over the months of the year 2021. The selection was based on the previously mentioned hypothesis, and therefore, the products selected for the analysis are those with a high number of PRES movements and handled boxes compared to the calculated average, representing potential for optimization.

PHOM-Type Movements
As this is the type of storage movement and warehouse exit that is already more economical and productive for the logistics operator, it excludes from the analysis products that have this method of exit from the warehouse exclusively, that is, about 54% of this customer's products, 122 products.

The selection of products for analysis with PHOM-type movements consisted of the combination of already established criteria, that is, products that have a picking hole, with reduced PPIC movements and products with high PRES movements.

PPIC-Type Movements
Only 6 products of the client under analysis, about 3%, have exclusively PPIC type movements. There are also 12 products that have the three types of movements and 8 products with PPIC and PHOM type movements.

According to the analysis of movements by type carried out, only 19 products can be considered to have only one type of movement and have potential for optimization through possible changes in the way they are stored and moved when preparing orders.

3 Mathematical Model

A mathematical model was developed, based on the Mixed Integer Linear.

Programming method, for a possible minimization of costs with the picking and storage operation. This model considers only the predominant type of outgoing movement for each product.

The set of products $N = \{1,\ldots,n\}$ is considered. Parameters include the total number of movements during 2021 for each product (nt_i), which is broken down into three parts: n_i^R, n_i^H, n_i^P namely, the number of movements of the PRES, PHOM or PPIC type, respectively, for product i in 2021.

Regarding each type of movement out of the warehouse (PRES, PHOM, PPIC), the fixed costs, C_F^R, C_F^H, C_F^P, and variable costs, C_V^R, C_V^H, C_V^P, are defined based on the information provided by the logistics operator. Fixed costs are related to the cost of space in euros (€), considering an average annual cost of €120 for storing a pallet on a rack in a reserve area and for a pallet in a picking area, a cost 12 times higher. The fixed cost associated with a PRES-type movement is 4 times higher than that for a PHOM type movement. In turn, variable costs correspond to the cost per movement performed (€/hour), which includes the cost per operator (€/hour) in the amount of €9.65/hour and the time in hours for each type of movement. The time needed to carry out each movement was calculated taking into account productivity values for the number of boxes/hour.

The aim is to obtain the storage configuration and picking method for the products that represents a minimum total cost for the logistics operator. For that, potential changes in the type of movement of each product will be inspected by the model. An alpha parameter (α) will be considered to set a maximum number of possible changes of the type of movements for the products under study. There is also a limit *NP* for the number of places available in the picking zone.

The decision variables x_i^R, x_i^H, x_i^P represent the new number of movements of each type for product *i*. In turn, y_i^R, y_i^H, y_i^P are binary variables that identify the type of movement for product *i*, while the binary variables z_i identify when there is a change in the type of movement of product *i*.

MILP MODEL

$$\text{Minimize} \quad \sum\nolimits_{i \in N} C_F^R y_i^R + C_V^R x_i^R + C_F^H y_i^H + C_V^H x_i^H + C_F^P y_i^P + C_V^P x_i^P \tag{1}$$

$$\text{s.t.} \quad x_i^R + x_i^H + x_i^P = n_i^R + n_i^H + n_i^P \quad \forall i \in N \tag{2}$$

$$y_i^R + y_i^H + y_i^P = 1 \quad \forall i \in N \tag{3}$$

$$x_i^j \leq y_i^j \times nt_i \quad \forall i \in N \quad \forall j \in \{R, H, P\} \tag{4}$$

$$\sum\nolimits_{j \in \{R,H,P\}} \frac{n_i^j \times x_i^j}{nt_i^2} + z_i = 1 \quad \forall i \in N \tag{5}$$

$$\sum\nolimits_{i \in N} z_i \leq \alpha \times n \quad \forall i \in N \tag{6}$$

$$x_i^H \leq n_i^H \quad \forall i \in N \tag{7}$$

$$x_i^j \geq 0 \quad \forall i \in N \quad \forall j \in \{R, H, P\} \tag{8}$$

$$y_i^j \in \{0, 1\} \quad \forall i \in N \quad \forall j \in \{R, H, P\} \tag{9}$$

$$z_i \in \{0, 1\} \quad \forall i \in N \tag{10}$$

The objective function (1) to be minimized represents the value of the total operating costs of picking and storage. Constraints (2) control that the total number of movements of each product is maintained. Constraints (3) and (4) allow for only one type of movement for each product. When a product changes its type of movement ($z_i = 1$), constraint (5) forces variables x_i^j to be zero when the previous number of movements of that type n_i^j was not zero. The maximum number of products that can change its type of movement is defined by (6) and the limit of changes for the PHOM-type is defined by (7) to respect the available space in the warehouse.

4 Results

The mathematical model was implemented in AMPL, and the results were obtained almost instantly using the Gurobi solver.

Running the model for $\alpha = 0$, that is, considering the current configuration of the products in the warehouse and without any exchange taking place, the total cost that the logistics operator obtained with the storage and preparation of orders for the nineteen products under analysis, in the year 2021 was €15,510.43. Several values of α were tested (Table 3). For $\alpha = 0.3$, the model allows the exchange of only five products, and the value of savings is €4,799 compared to the initial scenario of 2021. Smaller steps of α do not allow different changes. Larger values of α either lead to the same optimal solutions or to non feasible secenarios in practice.

Table 3. Minimum savings compared to the initial scenario of 2021.

Value of alpha α	Total Cost (€)	Value of savings compared to the 2021 scenario (€)	Savings compared to the 2021 scenario (%)
0	15510.43	–	–
0.1	14550.50	960	6.2
0.2	12630.70	2880	18.6
0.3	10711.00	4799	30.9

The results obtained and the individual analysis of the movements carried out previously allowed the definition of a new warehouse configuration for the 19 products under analysis. The new configuration includes the alteration of 5 of the 19 products, that is, five products that in the initial scenario had a place on the warehouse floor in the picking area, now have all their merchandise on a rack in the reserve area. With these exchanges, is possible to conclude that the savings value that this logistics operator would obtain for these 19 products would be 30.9%.

5 Conclusions

This work addressed the outbound movements of goods in a temperature-controlled warehouse. PPIC-type movements represent products with a place on the warehouse floor, under the shelves, in the picking area, while PHOM and PRES type movements are associated with the storage of pallets in height on a rack, in a reserve area. The PHOM-type movement, which is more productive and economical, occurred in the greatest amount, in relation to the other types of movements.

The main strength of this work is the formulation of a mathematical model that made possible a minimization of costs for the logistics operator with the picking and storage operation and respective optimization of the places occupied by the products. The results obtained allowed the creation of a new configuration for the nineteen products under analysis. Compared to the initial scenario, the new warehouse product allocation and

corresponding outbound movements may obtain savings for the logistics operator of around 30.9%. Assuming only one type of movement per product is a limitation of this model that can be overcome in future studies.

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The Impact of the Fit Between Supply and Demand Uncertainty and Supply Chain Responsiveness on the Performance of Portuguese Companies

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Abstract. This paper analyses how the harmonization between supply and demand uncertainty and supply chain responsiveness (SC fit) impacts business performance. The study analyses data obtained from a sample of 179 manufacturing companies from Portugal. The business performance of companies with different types of SC fit (high-high fit and low-low fit) and misfit (positive and negative) were analyzed and discussed. The results indicate that SC fit is positively related to business performance, economic and productivity, and commercial performance separately. This study advances the literature as the results indicate that SC fit positively affects both commercial and economic, and productivity performance. In contrast, previous empirical studies have mainly addressed the impact only on financial and operational performance.

Keywords: Supply chain fit · Supply and demand uncertainty · Supply chain responsiveness · Performance

1 Introduction

Recent crises, such as the COVID-19 pandemic and the war in Ukraine, have demonstrated that the lack of harmonization between the characteristics of the environment where companies operate and the design of supply chains (SC) can have a significant impact on the resilience of companies [1]. The growing complexity and uncertainty of the business environment has demonstrated the importance of flexibility and adaptability of SCs to be ready, to respond and to recover from unexpected events [2]. As part of being prepared, one of the first steps towards resilience can be considered the SC fit, which refers to the compatibility of the design of the SCs with the characteristics of the demand, a concept that has gained ground in the literature in the last years [3–5].

Previous studies have suggested that SC fit – where fit is related to the consistency and harmony between two or more variables [6] – has a positive impact on financial

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and performance of companies [3, 4, 7]. This paper investigates how the compatibility between supply and demand uncertainty (SDU) and SC responsiveness (SCR) impacts business performance, considering commercial and economic and productivity aspects.

This paper contributes to the theory, by analyzing characteristics of SC fit that have not been tested before and extending previous studies on the topic. This paper also contributes to practice, as its results may support managers in improving SC fit.

The rest of the paper is organized as follows: Sect. 2 provides the theoretical background of the paper, presents a literature review about the topics under analysis and provides the research hypotheses. Section 3 presents the methodology used in the study, including data collection and measurement scales. In Sect. 4, the analysis results are presented, followed by the discussion. Finally, the conclusions and implications of the study are presented in Sect. 5.

2 Literature Review

The relevance of supply chain management (SCM) has been largely highlighted in recent years, and its effects on performance have been broadly discussed and recognized by practitioners and researchers. The demanding task of having a proper design of the SC in accordance with the internal and external characteristics is a very relevant and current topic [8, 9].

The concept of SC fit was coined from the research of Fisher [8], who suggested that the match between (1) innovative products with responsive supply chain strategy and (2) between functional products and cost-efficient strategies could generate better results for companies and SCs. From this assumption, several studies indicated that companies should align their SC strategy and design with the characteristics of their products and the environment where they compete [10–12].

SC fit can be understood as a balance between supply and demand uncertainty (SDU) and SC responsiveness (SCR) [3, 7]; where SDU is measured by the level of uncertainty of the supply and demand; and SC responsiveness reflects the strategic choices of a company related to its capacity to respond to changes in supply and demand. Wagner et al. [3, p. 441] define SC fit as "the perfect strategic consistency between a product's supply and demand characteristics (such as demand predictability, life-cycle length, product variety, service, lead-times, and specific market requirements) and supply chain design characteristics (such as inventory strategy, product design strategy, and supplier selection aspects)". This concept is based on the notion of "fit as matching"; that fit is a theoretically defined match between two variables [6].

Besides the idea of the perfect fit, where a company has SC strategies perfectly aligned with the environment characteristics, previous studies suggest that a company has a high-high fit when presenting high levels of SDU and high levels of SCR; and a low-low fit when presents low levels of both SDU and SCR [13–15]. Companies that demonstrate high levels of SDU and low levels of SCR are said to have a positive misfit, while companies with low levels of SDU and high levels of SCR have a negative misfit [3, 14].

3 Methodology

Data were collected from manufacturing companies operating in Portugal. The sample, composed of 1,000 companies in Portugal, was randomly selected from a database provided by Bureau Van Dijk. Data were collected from September 2017 to January 2018, totalling179 complete and usable responses. The response rate was 17.9%, which is not unusual when the unit of analysis is a company and the research involves an extensive organizational-level survey. Table 1 presents the composition of the sample.

Table 1. Sample composition.

Variable	Number	%
Employees		
<50	10	5.6%
50–100	19	10.6%
101–500	69	38.5%
501–1000	43	24.0%
>1000	38	21.2%
Total	179	100.0%
Industrial Sector*		
Food and beverages	42	23.5%
Automotive and parts	40	22.3%
Construction and materials	17	9.5%
Textiles and apparel	10	5.6%
Industrial metals	9	5.0%
Household goods and personal care	9	5.0%
Chemical	9	5.0%
Other	43	24.0%
Total	179	100.0%

* The manufacturing sectors were defined according to the statistical classification of economic activities in the European Community (NACE Rev. 2).

The questionnaire was developed using previous literature and made available in an online survey platform. Following Zhao, Flynn, & Roth [16], a set of methods was used to ensure the reliability and validity of the instrument, such as translation and back translation (Portuguese and English) and pilot tests with companies and academic experts. The questionnaire was answered by two respondents in each company according to the characteristics of the information to be provided, following the suggestions of

Craighead et al. [17] and the principles discussed by Krause, Luzzini and Lawson [18] and Flynn, Pagell and Fugate [19].

SDU and SCR were measured based on the items proposed by Wagner et al. [3] and Gligor [7] using ten questions regarding the main product line on a five-point scale (1 = low, 5 = high): five related to SDU and five connected to SCR. SC fit was calculated following the concept of fit as matching [3, 6, 20] where:

$$SCFit = |SDU - SCR| \tag{1}$$

A seven-point Likert scale presented by Gonzalez-Benito [21] was used to measure business performance (five items to commercial and three to economic and productivity).

In this study, the effect of SC fit on business performance will be tested as stated in the research hypothesis:

RH. *Supply chain fit is positively related to business performance.*

4 Analysis and Results

A set of methods were applied to assess the reliability and validity of the constructs. Table 2 presents the analysis of the convergent and discriminant validity. All composite reliability (CR) measures are above 0.7, exceeding the minimum values of 0.6 [22], and all constructs exceed the estimates of 0.50 to the Average Variance Extracted (AVE) [23].

Table 2. Convergent and discriminant validity.

	CR	AVE	MSV	MaxR	1	2	3	4
1.SCR	0.781	0.512	0.180	0.803	**0.690**			
2.Commercial	0.872	0.689	0.463	0.921	−0.220	**0.709**		
3.Eco Prod	0.805	0.593	0.443	0.885	−0.322	0.606	**0.782**	
4.SDU	0.841	0.522	0.187	0.860	0.282	0.348	0.306	**0.717**

Note: n = 150; Reliability coefficients are presented along the diagonal

The fit indices of the structural model were also tested, and the results obtained are adequate ($p < 0.001$, IFI = 0.918, TLI = 0.901, CFI = 0.915 and RMSEA = 0.053), supporting the nomological validity of the measurement model hypothesized.

A descriptive analysis of the companies' SC fit was made to understand their position in the following groups: SC fit (high-high or low-low fit), positive misfit or negative misfit. Table 3 shows the means and standard deviation for SC fit and business performance constructs.

The analysis of the frequency of the differences between SDU and SCR, presented in Table 4, shows that 168 (94%) companies present misfit (SDU $\neq$ SCR), while 11 companies (6%) have a theoretically perfect balance between the characteristics of their SCs and the features of the environment where they compete, which is called a "perfect"

Table 3. Means and standard deviation for the constructs of SC fit and business performance.

Item	Mean	Std Deviation
SDU	2.84	0.706
SDU1	2.56	0.989
SDU2	2.79	0.977
SDU3	2.85	0.989
SDU4	3.00	0.881
SDU5	2.99	0.821
SCR	3.43	0.607
SCR1	3.25	0.928
SCR2	3.51	0.824
SCR3	3.22	0.802
SCR4	3.62	0.842
SCR5	3.54	0.816
CP1	4,92	1,159
CP2	5,44	1,209
CP3	5,36	1,110
DC4	5,02	1,384
DC5	4,83	1,154
DF1	4,77	1,236
DF2	4,77	1,155
DF3	4,68	1,163

SC fit (SDU-SCR = 0). The majority of the companies (136 or 76%) present negative misfit (SDU < SCR). These results align with previous studies – although higher [3, 5], showing that many companies act in environments with lower uncertainty than they are prepared to face. On the other hand, 32 companies (18%) have a positive misfit (SDU > SCR), meaning that they compete in environments with higher uncertainty than their level of responsiveness.

A zone of strategic fit was defined [3, 24], including companies with less than one standard deviation from the perfect SC fit (positioned between the two non-dashed lines in Fig. 1). Besides the 11 companies with perfect SC fit (in the dashed line), 89 companies were added to the strategic fit zone. Figure 1 shows the companies' position in the SC fit's representative graph.

Finally, linear regression analysis was used to test the impact of SC fit on performance. The results supported the research hypotheses that SC fit impacts business performance ($\beta = 0.425$; $p < 0.001$). These results are in line with previous studies on the topic. The effects on economic and productive ($\beta = 0.440$; $p < 0.001$) and commercial performance ($\beta = 0.357$; $p < 0.001$) were also tested and confirmed separately.

Table 4. Distribution of the companies according to the degree of SC fit and misfit.

SC fit	Companies	%
Perfect fit	11	6%
Misfit	168	94%
Total	**179**	**100%**
Positive misfit	32	18%
Negative misfit	136	76%
Strategic fit zone	100	56%

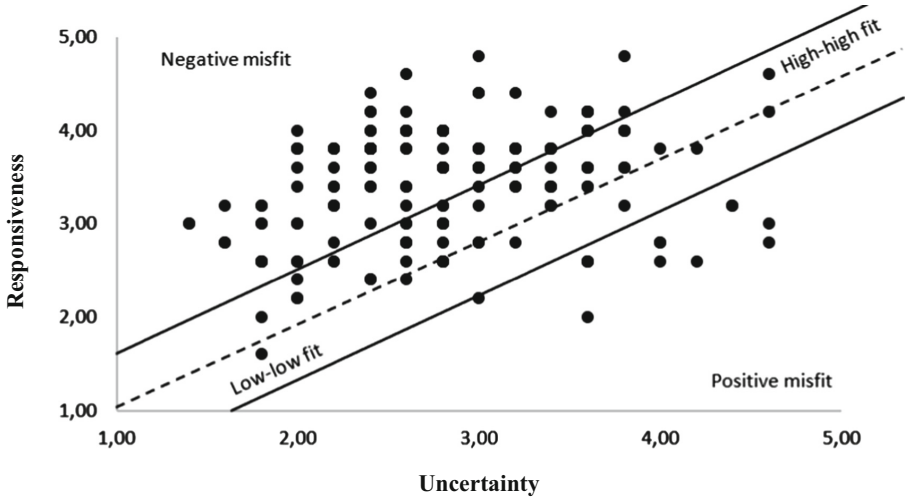

Fig. 1. Distribution of companies according to SC Fit.

5 Conclusions

This paper aimed to analyze and discuss the effects of SC fit on business performance using data from Portuguese manufacturing companies. The results supported the hypothesis that SC fit is positively related to business performance, and economic and productivity and commercial performance separately, confirming and extending the assumption that SC fit positively impacts performance.

The results are in line with previous studies that support that SC fit has a positive impact on performance [3–5, 7], and contribute to deepening the knowledge through the test of this impact on different types of performance. The results indicate that managers need to comprehend the context where companies act, the features of the demand and supply of the products and the characteristics of their SCs to make better decisions related to the design and the strategies to be adopted in the context of SCs. These results are even more relevant when analyzed in the context of the high complexity and uncertainty that characterize the contemporary business environment, where companies need to find

ways to increase the resilience of SCs. Thus, besides theoretical contributions, this paper presents a variety of managerial implications, as managers need to deeply understand their context and adopt the right SC practices and strategies to be more competitive.

Finally, limitations and opportunities for future studies can be highlighted. The limited sample size means that any generalization of the conclusions has to be made carefully. Moreover, the geographical coverage of the sample is also limited. As so, future research using data from different countries can be relevant and contribute to the discussion. Future research can also analyze the mediation and/or moderation effects of other constructs on the relationship between SC fit and performance.

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Decision Aided Tool for a SME Supply Chain Sustainable Digital Transformation

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Abstract. The economic inflation that the whole world is currently experiencing and particularly Europe, in addition to globalization and the versatility of customer demand, encourage the companies to find innovative solutions to be more competitive. Indeed, for this competitiveness, industry 4.0 concepts have been successfully implemented in large companies supply chains as a tool to increase the company global performance. These concepts of digital transformation require to be adapted to SMEs expectations. The integration of sustainability aspects contributes to accelerate the concepts integration in SMEs by providing evolutive solutions appropriated to the SME singularity. This paper focuses on the design and development of an intelligent decision aided tool for well managing the sustainable digital transformation of SMEs. In this paper, the concepts and tools of the literature review, based on the supply chain 4.0 context and sustainability, industry 4.0, artificial intelligence and decision aided tools, have been briefly presented. Then, the paper next sections focus on the general approach and the decision intelligent system that are elaborated. An example is shown to validate these concepts and tools.

Keywords: Supply chain performance · Industry 4.0 · Artificial intelligence · Sustainability · Decision aided tool

1 Introduction

Industry 4.0 concepts contribute to the company digital transformation through the integration of new technologies in the manufacturing processes. Indeed, the company supply chain optimization by exploiting these concepts is a success and needs to be improved in SMEs [1]. This paper focuses on the introduction of sustainability as main criterion in addition to cost, quality and lead time in the SME supply chain digital transformation. Tools such as cyber-physical systems [2], internet of things [3], robotics [4], cloud computing [5], artificial intelligence [6] and digital twins [7], are used for this transformation. Thus, intelligent systems related to these new technologies can be exploited to manage and increase the company processes performance. This paper aims to design and develop an intelligent decision aided tool being able to manage the SME digital transformation. An intelligent decision aid tool is a software application that is designed

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to assist individuals or groups in making decisions by providing information, guidance, and other resources. Decision aid tools can be used in a variety of settings, including healthcare, finance, education, and government. They can be designed to help with a wide range of decisions, from simple, everyday choices to complex, strategic decisions. To be effective, a decision aid tool should be tailored to the specific needs and goals of the organization and regularly updated to reflect changes in the supply chain [8]. Different kind of decision aided tools are used in the supply chain optimization. Simulation tools allow users to model different scenarios and checking the potential impacts on the supply chain. Optimization algorithms [9] use mathematical models to identify the optimal solution to a given problem, such as minimizing costs or maximizing efficiency. Decision trees help users weigh the pros and cons of different options by organizing them in a hierarchical structure. And multi-criteria analysis is exploited to evaluate options related to multiple criteria, such as cost, quality, and sustainability. This next section of the paper focuses on the concepts based on supply chain 4.0 and sustainability, industry 4.0, decision aided tools and artificial intelligence, that could be used for the software system development. Then, the concepts and methodology elaborated for the SME sustainable digital transformation are presented. The global architecture of the intelligent system containing the decision aided tool is exposed. Finally, the illustration section explains the beta version of the tool that has been developed.

2 Literature Review

This section presents concepts of the literature review on sustainable supply chain, industry 4.0, decision aided tools and artificial intelligence that can contribute to the sustainable methodology elaboration and the development of the intelligent system supporting this methodology.

2.1 The Supply Chain 4.0 Context and Sustainability

Supply chain sustainability (SCS) is an approach that takes into consideration environmental (waste, gas emissions…), economic (market competitiveness, transport and financial aspects of the network) and social (health and well-being of workers) of supply chain processes, components, technologies and logistics. When Corporate social responsibility (CSR) and environmental issues are at the heart of business concerns, the sustainable supply chain has become an imperative and commercial issue but also a daily challenge. The implementation of this sustainable supply chain requires a high degree of commitment from the entire company to a CSR approach, which involves reviewing each step with a dual objective: reducing the environmental impact as much as possible and ensuring performance. Only a global approach will make it possible to obtain a lasting result [10] through deploying a responsible purchasing policy, investing in “high environmental quality” logistics buildings and implementing good practices to limit waste and packaging.

The supply chain plays a role predominant not only in the performance economic of the company, through its capacity for agility and resilience, but also and above all in the transformation of the company and the societies that surround it towards more durable

[11]. Good social practices have to be integrated in the supply chain management The establishment of supply chain good practices allows to take social issues into account. The concrete decisions that can be taken are, for instance, related to stock management [12] such as automatization to reduce tedious tasks, arranging the safety of workstations and promoting social reintegration. The sustainable optimization of the supply chain involves the definition of criteria by exploiting ISO 26000, ISO 14000, ISO 50000 and ISO 9000 that could be exploited to increase the company performance. Then industry 4.0 concepts can contribute to achieve goals of the SMEs. The following sub-section presents these concepts.

2.2 Industry 4.0

This section focuses on the integration of new technologies in the company manufacturing processes for their digital transformation.

Industry 4.0 is a term used to describe the fourth industrial revolution that is happening in the manufacturing industry, and it is changing everything. This term was created by the German government in 2011 to describe the trend towards automation and data exchange in the manufacturing sector. Industry 4.0 is based on 10 pillars such as cyber-physical systems (CPS), the Internet of Things, big data, 3 D printing, artificial intelligence, information systems, cloud computing, digital twins and advanced robotics. These technologies come together to create a connected factory where machines can communicate each other and make decisions autonomously. This allows for greater efficiency and flexibility in the manufacturing process, as well as better quality control and reduced waste [13].

The goal is to be adapted to new consumption patterns by being able to produce personalized services and products in limited series or in reduced quantities, without incurring additional costs. Industry 4.0 is agile and responsive, able to quickly change efficiently production quantities, qualities and methods.

Driven by the emergence of new technologies, the industry 4.0 designates a new generation of connected, robotic and intelligent factories. With the digital revolution, the boundaries between the physical and digital world are shrinking to give life to a factory 4.0 network in which people, machines and products interact. The industry 4.0 is a challenge and a real opportunity for French industry [14]. Indeed, the use of these new technologies in large companies is a success but the concepts need to be adapted for SMEs. The integration of sustainable aspects presented above will ensure to elaborated a better methodology for the SME digital transformation. The implementation of this methodology in SMEs requires the management of data, information decisions, and technologies. The next section focuses on concepts that could be used to develop the aided tool that will support the SME transformation.

2.3 Decision Aided Tools

This section examines concepts to be used for developing a decision aided tool supporting the methodology. A decision aid tool is a software application or other tool that is designed to assist individuals or groups in making decisions by providing information,

guidance, and other resources. There are several steps that are typically involved in the development of a decision aid tool:

- **Define the problem** or decision that the tool will be used to address. This may involve conducting research to understand the context in which the tool will be used and the needs of the users.
- **Identify the factors** that will influence the decision. These factors may include information about the options available, the potential outcomes of each option, and any risks or uncertainties associated with each option.
- **Gather and** analyze information. Collect and analyze relevant data, including the potential options, risks, and benefits associated to each option.
- **Identify the stakeholders**. Consider who will be using the tool and how it will impact them.
- **Determine the format and structure of the tool**. This may include deciding on the type of interface that will be used (e.g., a web-based application, a mobile app, or a paper-based tool) and the types of information and resources that will be included [15].
- **Develop the content of the tool**. This may involve gathering and organizing information about the options and their potential outcomes, as well as developing any guidance or resources that will be included.
- **Test and evaluate the tool.** This may involve pilot testing the tool with a small group of users to gather feedback and make any necessary refinements.
- **Launch and disseminate the tool**. This may involve marketing the tool to potential users and making it available through various channels [16].

It is important to note that the development of a decision aid tool is an iterative process that may involve refining and updating the tool based on feedback and additional research. They also help small and medium-sized enterprises (SMEs) optimize their supply chain by providing a structured and systematic way to evaluate and compare different options. Some of the benefits of using a decision aided tool in supply chain optimization are the efficiency improvement through the identification of bottlenecks and inefficiencies in the supply chain, and the suggestion of ways to streamline processes and reduce waste, the cost reduction by comparing different options and considering factors such as price, lead time, and transportation costs, a decision aid tool can help identify cost-saving opportunities, the sustainability increasing by considering environmental impacts and helping SMEs to make more sustainable choices in their supply chain, and the better decision-making by providing a structured framework for evaluating different options, which can help decision-makers make more informed and confident choices [17]. The development of a decision aided tool for supporting the sustainable methodology will increase the efficiency in the SME sustainable digital transformation. The next section presents artificial intelligent tools that can be exploited in the decision tool for increasing the company performance.

2.4 Artificial Intelligence

This section shows the artificial intelligence concepts that could contribute to the intelligent system development. Artificial Intelligence (AI) is the simulation of human intelligence processes by machines, more specifically, computer systems. These processes

include three phases: learning, that is to say the acquisition of information and its rules of use; reasoning, or the use of rules to draw approximate or definitive conclusions; and self-correction, particular AI applications including narrow AI, the facial recognition and the computer vision. Artificial intelligence is composed of many tools such as multi-agent systems, expert systems, neural network but also machine learning and deep learning represented in Fig. 1. It is what makes a system or process working automatically. For instance, RPA (Robotic Process Automation) can be programmed to perform repetitive tasks faster than humans.

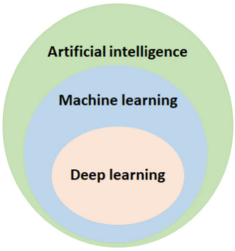


Fig. 1. Description of artificial intelligence, machine learning and deep learning

Machine learning is the science of making a computer doing things without programming it. Deep learning is a subset of this, which can be thought of as the automation of predictive analytics. There are three different types. All first of all, supervised learning, where datasets are labeled so that patterns are detected and then reused. Then, unsupervised learning, where the datasets are not labeled, but are sorted based on similarities or differences. And finally, reinforced learning, where the datasets are not labeled, but the AI receives feedback after taking action. It is a technology that captures and analyzes visual information using a camera. It is used in signature identification or the analysis of medical images. Natural language processing is the processing of human language by a program. Spam detection is an old example. However, current approaches are based on machine learning. They therefore include the translation of text, the sentiment analysis and voice recognition. It is about the design and manufacture of robots. They are then used in assembly lines for automobile production, or by NASA to move large objects in space. Researchers are incorporating machine learning to build robots that can interact in social contexts. These vehicles combine computer vision, image recognition and deep learning. Thus, artificial intelligence develops an automated ability to drive a vehicle. And this, while staying in a given lane and avoiding unexpected obstacles, such as pedestrians [18].

Deep Learning allows computational models composed of multiple layers of processing to learn representations of data with multiple levels of abstraction. These methods have significantly improved the state of the art in speech recognition, visual object recognition, object detection, and many other fields such as drug discovery and genomics. Deep learning helps discover complex structures in large datasets using the backpropagation algorithm. This allows to indicate how a machine should modify its internal parameters which are used to calculate the representation in each layer compared to the representation of the previous layer. Representation learning is a set of methods for feeding a

machine with raw data and automatically discovering the representations needed for detection or classification. Deep Learning methods are representation learning methods with several levels of representation. These are achieved by composing simple but non-linear modules that each transform the one-level representation (starting with the raw input) into a slightly more abstract, higher-level representation. The composition of a sufficient number of these transformations makes it possible to learn very complex functions. For classification tasks, the upper layers of representation amplify aspects of the input that are important for discrimination and remove irrelevant variations [19]. The essential aspect of Deep Learning is that these feature layers are not designed by human engineers: they are learned from data using a general learning procedure [20]. Deep Learning is making major advances in solving problems that have resisted the best attempts of the AI community for many years. It has proven to be very effective in discovering complex structures in high-dimensional data and is therefore applicable to many fields of science, business and government. In addition to breaking records in image recognition and voice recognition, it has beaten other machine learning techniques in predicting the activity of potential drug molecules, analyzing particle accelerator data, reconstructing brain circuits and predicting the effects of non-coding DNA mutations on gene expression and disease.

The concepts presented in this literature review will be exploited to elaborate the decision aided tool. The following section explains the concepts and methodologies that have been combined for developing the intelligent system.

3 General Approach

3.1 The Sustainable Methodology

Most of the existing supply chain 4.0 companies focus exclusively on the technological tools but none on the social, societal and environmental dimensions. A combination of both aspects is required to develop the sustainable and efficient Industry 4.0 for SMEs. The decisional transformation of the company is realized by using GRAI ("Graphe de Réseaux D'Activités Intereliées") methodology. GRAI methodology is one of the main methodologies of enterprise modelling structured around five models (functional, physical, decisional, processes, and informational) for totally describe, analyze the company and improve its performance. And the informational transformation involves the introduction of new technologies for improving the company performance. This framework is used on SMEs (Small and Medium Enterprise) which are not available for implementing existing industry 4.0 concepts. The idea is to continuously optimize the supply chain performance of this company in a sustainable way. Sustainability is considered as the core of the company transformation. Sustainability parameters are social, societal and environmental dimensions and combined with new technologies such as CPS [21], flexibility and aspects related to change to increase business performance [22]. A hybrid methodology containing lean manufacturing tools such as VSM (Value stream mapping) has been developed to achieve the transformation and ensure the company performance improvement. The supply chain 4.0 is constantly measured by using the criteria described above (cost, quality, deadline, social, societal and environmental). The process is detailed and optimized by leveraging the hybrid methodology with a particular

focus on lean manufacturing. The VSM tool is used to find non-added values at each stage of the production processes and to eliminate them. Tools adapted to 6 new technologies are used for the digital transformation [23]. The operational management of the supply process requires the implementation of an automated storage. Transporting raw materials from storage to production lines requires the use of automatic trains, or AMR (Autonomous Mobile Robot). Indeed, the company transformation will be managed by decisions and investments in the short, medium and long term. Due to the amount of data circulating in the company and the consequences of the transformation, it is important to design and develop a data analysis tool and to set up an information system to facilitate the management of the business. Around the philosophy of sustainability, the company's processes will be transformed by exploiting new technologies such as AMR, the stacker crane, monitoring tools, IoT and organizational methods [24]. By focusing on sustainability as the kernel of the SME digital transformation, this methodology provides an efficient response to treat brakes of SMEs in the industry 4.0 concepts implementation. This methodology is based on the entire participation of employees at each step of transformation and the integration of their expectation for defining the most adapted new technologies and tools that have to be implemented in the company. Then, this methodology requires the development of an intelligent tool for supporting data and steps of the transformation [25].

3.2 The Decision Aided Tool Development Concepts

The programming language used for the development of this tool is Python. Python is a programming language that distinguishes itself from other programming languages by its flexibility, simplicity, and reliable tools required to create modern software. Python is consistent and is anchored on simplicity, which makes it most appropriate for machine learning. The Python programming language best fits machine learning due to its independent platform and its popularity in the programming community. People like using Anaconda Python because it simplifies package deployment and management. It also comes with a large number of libraries/packages that can be used in projects. Since Anaconda Python is free and open-source, anyone can contribute to its development. MongoDB is a document-oriented database management system that can be distributed over any number of computers and does not require a predefined data schema [24]. It is written in C++. PyMongo is the official MongoDB driver for synchronous Python applications. In this PyMongo tutorial, a simple CRUD (Create, Read, Update, Delete) application using FastAPI and MongoDB Atlas will be built. MongoDB stores data objects in collections and documents rather than tables and rows like traditional relational databases (see Fig. 2). Collections contain multiple documents and act as the equivalent of relational database tables. Documents comprise several key-value pairs and form the basic unit of data in MongoDB. The structure of a document can be changed by simply adding or removing existing fields. Documents can define a primary key as a unique identifier, and values can be of various data types, including other documents, tables, and document tables.

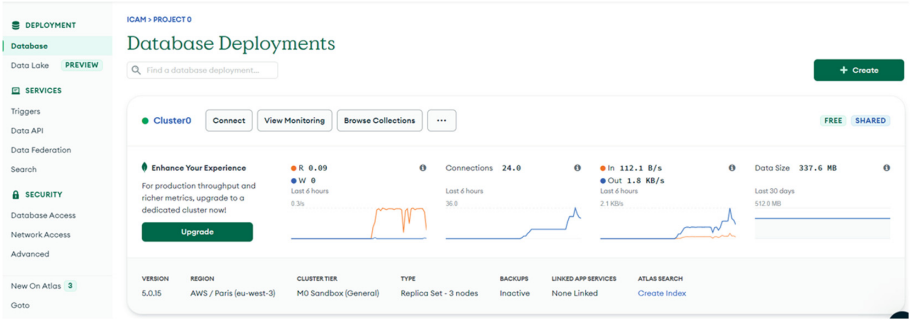


Fig. 2. MongoDB database

4 The Decision Aided Tool of the Intelligent System

In this part, the architecture of the intelligent system that supports the sustainable digital transformation of the SME supply chain is shown and presents the architecture of this intelligent system. The coordination module contains a database for managing all the information of the system [25]. The human/machine interface (HMI) creates interactions between the machines, cobots, robots, the information system and people during the supply chain transformation. The decision aided tool (see Fig. 3.) based on the decision aided theory [26] is intended to measure and optimize the SME performance through the sustainable and digital transformation. The modeling module is used for realizing the modeling of the SME.

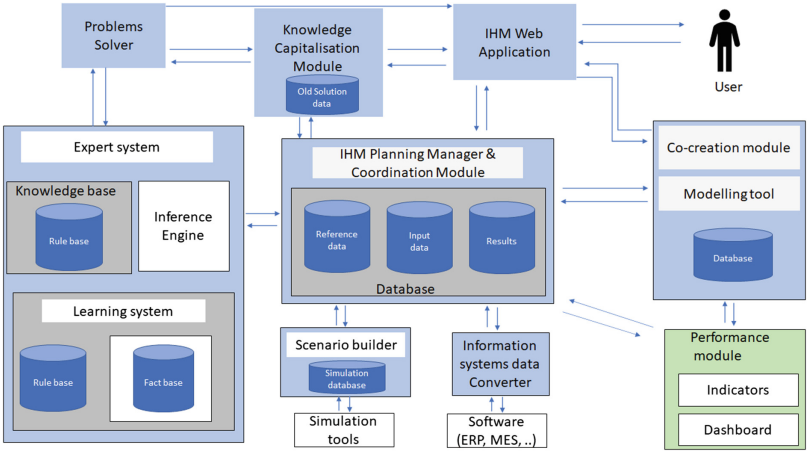


Fig. 3. The decision aided tool architecture

The expert system exploits expert rules for the company digital transformation for analyzing the existing system. The problem-solving module is used for finding solutions based on human expertise. The knowledge capitalization module contains the old situations that could be reused for transforming the company. The simulation module serves

to elaborate the company digital twin by exploiting existing simulation tools such as Flexsim, Anylogic and PTV VISSIM. The scenario builder, on the base of the digital twin contributes to the test of different situations for finding optimized solutions.

5 Illustration

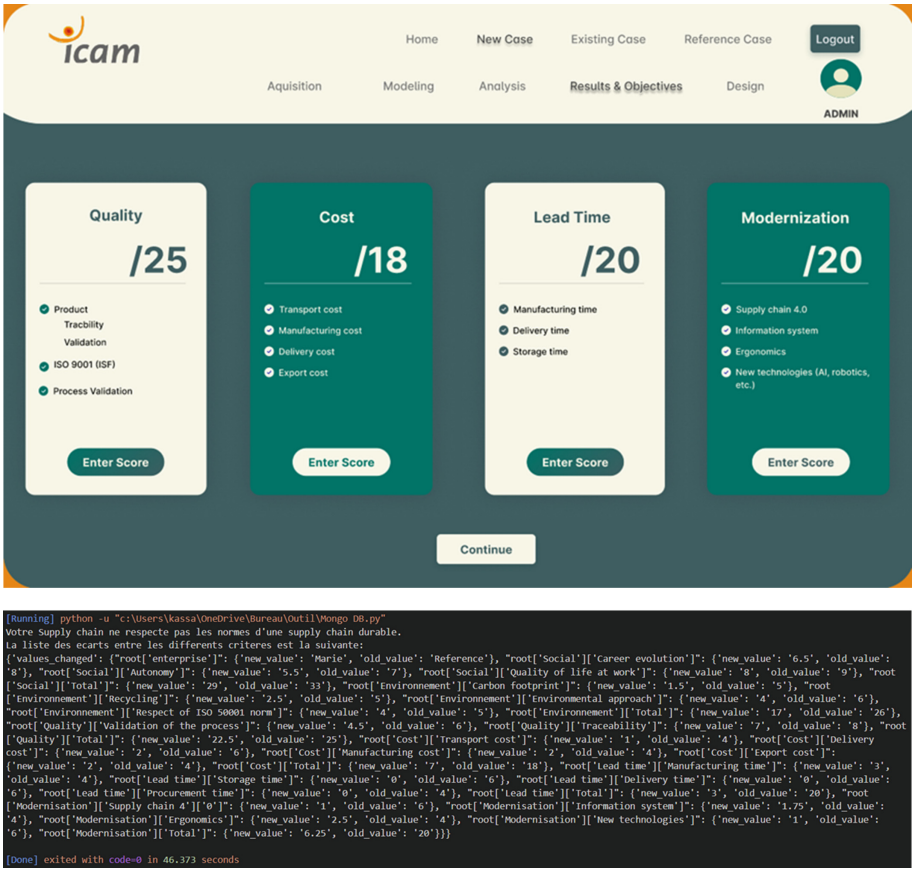
The decision aided tool has been developed and has been tested on two companies. The first company is specialized in industrial food cooking business and the second Mobile home elaboration. These companies are being Both transformations are being realized. The first step of the study consists in modeling the existing system of both companies. Then, the decision aided tool has been used for supporting the qualitative survey. This tool has been done for measuring the actual (and future) state of each company. For instance, the actual modernization performance of the food company has been elaborated. The user interface has been developed and tested (Fig. 4).

Fig. 4. User interface

The modernization maturity concerns sub-criteria such as new technologies, supply chain, information system and ergonomics. Each sub-criterion is also divided into parameters that are measured for obtaining the result presented above. For instance, 9 parameters (IoT, Robotics, etc.) are proposed for the modernization criterion. This structuring has also been realized for the other criteria (cost, quality, lead time, social, societal and environmental aspects) involved the company transformation. These measures have shown that the company needs to be transformed digitally. The performance measurement process is subdivided into several blocks, that allowed to collect information on the company state. Structured and non-structured Data acquired on each company have been exploited for analyzing the company situation.

An ideal situation defined in the decision aided module have been exploited for suggesting decisions for the company transformation (see Fig. 5). For instance, the

decision to increase the use of new technologies in collaboration with operators has been taken and use cases on working stations including cobots and operators have been tested. The results allow to validate 10 this human-cobot collaboration. The next step will be the use of the intelligent system for transforming each company according to the recommendations of the expert system (analysis tool). Indeed, the company digital transformation is ongoing. Then, only partial results allow to deduce the company performance improvement.

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[Running] python -u "c:\Users\kassa\OneDrive\Bureau\Outil\Mongo DB.py"
Votre Supply chain ne respecte pas les normes d'une supply chain durable.
La liste des ecarts entre les differents criteres est la suivante:
{'values_changed': {"root['enterprise']": {'new_value': 'Marie', 'old_value': 'Reference'}, "root['Social']['Career evolution']": {'new_value': '6.5', 'old_value':
'8'}, "root['Social']['Autonomy']": {'new_value': '5.5', 'old_value': '7'}, "root['Social']['Quality of life at work']": {'new_value': '8', 'old_value': '9'}, "root
['social']['Total']": {'new_value': '29', 'old_value': '33'}, "root['Environnement']['Carbon footprint']": {'new_value': '1.5', 'old_value': '5'}, "root
['Environnement']['Recycling']": {'new_value': '2.5', 'old_value': '5'}, "root['Environnement']['Environmental approach']": {'new_value': '4', 'old_value': '6'},
"root['Environnement']['Respect of ISO 50001 norm']": {'new_value': '4', 'old_value': '5'}, "root['Environnement']['Total']": {'new_value': '17', 'old_value': '26'},
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cost']": {'new_value': '2', 'old_value': '6'}, "root['Cost']['Manufacturing cost']": {'new_value': '2', 'old_value': '4'}, "root['Cost']['Export cost']":
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Fig. 5. The performance measurement tool development

The presentation of the final results in the future will allow to validate the decision aided tool and the sustainable methodology.

6 Conclusion

This article presents a sustainable methodology based on industry 4.0 and exploiting sustainability as one the main criterion, for transforming digitally SMEs and improving their performance. This methodology corresponds to a response to the SMEs chilliness on the industry 4.0 concepts implementation. The sustainability, as the kernel of the company digital transformation involves the use of Triple Bottom Lines method for defining specific criteria in addition to quality, cost and lead time.

The data management, and the processes continuous transformation imply the development of an intelligent system for supporting this sustainable method and increase the transformation efficiency. Indeed, the decision aided module presented in this paper validates the existing and future systems measures and the use of a reference model as an aid in the decision taking process.

The research-action method including the use of real cases of companies allows to validate the sustainable methodology efficiency and shows that the new technologies acceptability by SMEs will increase. The intelligent system is being developed and a global study using qualitative and quantitative methods will be used to definitively validate the sustainable methodology and its tool.

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Internal Logistics Restructuring to a Production Growth: A Case Study

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Abstract. For companies to remain competitive in the current market, they need to find ways to reduce as much as possible their operational costs. To achieve this, one area that is often the focus of improvement is internal logistics. This paper is focused on the restructuring of the internal logistics process in a case study company that has plans for doubling its production levels within a year. To do so, a new production supermarket and a milk run routing plan will be designed with lean concepts in mind. What makes this research different from most existing literature is the use of carts as a way of storing parts in the supermarket, instead of the common shelves. The strategy developed is able to reduce the number of workers required and is estimated to bring up to 145 000 euros in profit, depending on the future kitting time, considering a production growth of 100%.

Keywords: Internal Logistics · Milk run · Supermarket · Transport carts

1 Introduction

JORDAO is one of the leading European suppliers of tailored refrigeration equipment solutions for small, medium, and large stores, which has been growing at an impressive rate in the last few years. This growth, however, has been limited by the current production capacity of the company, which cannot keep up with the increasing demand. To solve this, a plan was devised to double the production rate, and with it came complications regarding logistics which would need to be improved for the company to stay as competitive as it is in the market.

Currently, the parts produced in the several sections of the company are transported by carts to a location near the assembly lines by logistic operators who push the carts and from there they are transported to the assembly lines, when required, by kitters. The plan to be implemented in the future revolves around the usage of a Milk run to transport the carts into a newly designed supermarket and from there, the kitters transport the parts to the assembly lines using picking carts. It is important to note the distinction between carts and picking carts explained above as these terms will be used various

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times during the article. What makes this process such a complex one, is the fact that the company works by engineer-to-order, meaning that the number of different parts produced is immense (over 200 000 in total) and so is the variability found within each production section.

This article focuses on the development of a routing plan for the Milk run and a supermarket for future production levels, in which the company predicts a 100% growth in current production. Milk run systems are a common concept for transportation that enable frequent deliveries of various materials, usually from a central storage area to various production locations or vice-versa [1] and so it is expected that the routing plan proposed reduces waste associated with transporting, considering this is one of the 7 + 1 wastes of lean. As for supermarket optimization, with this research it is expected the improvement of the kitting task, reducing both motion and transportation waste while also reducing the risk of accidents.

The paper is structured as follows: in Sect. 2 related works are briefly presented; in Sect. 3 the research strategy and design are presented; then, in Sect. 4 the case study is described and in Sect. 5, the results are shown; finally, Sect. 6 is dedicated to the conclusions.

2 Brief Literature Review

Warehouse design and optimization are very broad topics that have been studied a lot in the existing literature. Several articles focus on presenting literature reviews on these topics, like [2] which defines a warehouse as operating optimally when it can satisfy all its customers and completing all its processes in the cheapest way and shortest time possible. The literature review developed in [3] revolves around order picking while [4] focuses on the design and performance evaluation of a warehouse and [5] provides a general framework of steps to design a warehouse. Lots of very detailed information regarding this topic can be found in [6], which addresses topics ranging from the context of warehousing to the equipment used. Order picking is a key task in supplying the assembly lines and greatly impacts internal logistics performance. With this in mind, [7] analyses the concept of order picking in industry 4.0 and, with the objective of reducing order picking times, storage location assignment is studied in [8].

The existing literature regarding Milk run systems, also designated as mizusumashi, is vast and largely based on lean principles. Some methods based on those principles, studied in [9], such as the implementation of a standard route with an associated cycle time and visual systems, were the base for some of the methods used throughout our study. Article [10] also provides possibilities for improving logistics and warehousing using a lean-based approach. Milk run systems need constant improvement and in [11] a 15% reduction in Milk run lap time was achieved by adopting strategies such as the development of an information-sharing tool. In [1] three strategies for handling demand peaks are presented but containers are used, which differs from the method used in this paper. Some studies also focus on the development of mathematical models, such as the one in [12] which is designed to improve surface productivity.

Despite the great number of studies conducted regarding internal logistics, such as the ones mentioned above, no article was found exploring the concept of using carts as

transport units and as storage units at the same time. Due to the rarity of such topic, it is believed that this paper will be an interesting addition to the existing literature.

3 Research Strategy and Design

The case study strategy was taken during this research since it allows the exploration of complex issues in their real-life settings [13, 14]. Besides, a deep understanding of the phenomenon was needed. The unit of analysis was the plant level and the main instruments used, to achieve multiple sources of evidence, were interviews, direct observation, data collection and documentary analysis. A summary of the research steps and instruments used in this research is presented in Fig. 1. However, this paper is focused on the supermarket creation and the milk run routes definition.

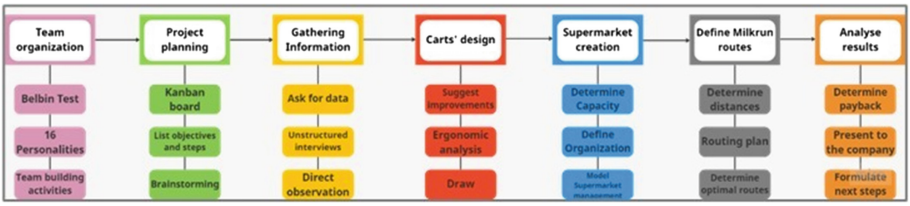

Fig. 1. Summary of project steps and instruments used

4 Case Study

4.1 Gathering Information

An Excel document containing the demand (in parts) for each section for the last five months was provided. More information (such as the number of parts produced in each section, its size range, special transporting care and how many would fit, on average, on a cart) was collected by direct observation and conducting unstructured interviews with the workers from all the production sections. This task proved to be very challenging, but mean values were determined.

4.2 Supermarket Organization

Being one of the main objectives, the development of the supermarket was heavily invested in. The first step was determining the warehouse layout, followed by the calculation of its occupation, and lastly analyzing and modeling supermarket organization.

There are a few factors to be considered in the layout design of a warehouse, such as: the area available, width and the number of the aisles, the number and shape of cross aisles (if existent) and the position of the input and output gates [2] which are important to our study. When designing the supermarket, the team was given a few premises, such

as an aisle width of 1.6 m, the fact that carts in which the parts come in are to be used as storage units, excluding the possibility of stacking upwards, the position of the output destiny (production lines) and the input gate and an area of 589 m^2.

The cost of order picking has been estimated to be as much as 55% of the total expenses in a warehouse [3]. Taking this into consideration, alongside the fact that businesses get more competitive by the day, it was decided that the supermarket layout would revolve around reducing the order-picking effort. The first step to determine the supermarket's layout was to ask the current kitters for any recommendations on which sections of the supermarket should optimally be closer to each other or the production lines. With no significant recommendations from the kitters, a method involving the combination of two factors, difficulty in transport and demand, was created. The objective of this method is to reduce both the risk of accidents (by getting the hardest items to transport closer to the production lines) and the distance traveled during kitting (by allocating the sections with more demand closer to the production lines). To combine the two factors, it was first given a classification "*d*" from 0 to 20 (20 being most difficult) to each section regarding the difficulty in transport, considering several characteristics such as size, special handling requirements and weight. The classifications were later validated by an engineer. For the next step, a second classification "*r*" was given, regarding the demand of each section. The latter classification was obtained by converting the demands into a scale of 0–20. With the two values obtained, the following equation was formulated.

$$x = f\,d + (1 - f)\,r \tag{1}$$

The coefficient f ranges from 0 to 1 and represents the weight that the difficulty in transport has in the arrangement of the supermarket. Once the value x was obtained, the sections were allocated to a space in the supermarket. The ones with a higher value of x were put closer to the lines. After a sensitivity analysis to the value of f and not finding important changes in the outcome, it was set as 0.5 since there was not enough data to analyze the correlation between difficulty in transport and the number of accidents yet.

As previously mentioned, during the information gathering phase, the team obtained the demand for each section for the last 5 months. Through simple conversion, considering that this period contains 4 weeks of 5 working days (100 days), a daily average of components produced by each section destined for production lines was obtained. Information regarding the number of components per cart was also obtained in the information gathering phase, which allowed us to calculate the average number of carts that would leave each section and go to the supermarket daily. Another premise of the company was that the supermarket should hold enough materials to feed 3 days of production, so the space needed for each section was calculated by multiplying the production in number of carts per day by 3 and then multiplying by the area occupied by a cart from that section. Once that was determined, a layout design was created in CAD (Fig. 2). The layout for the expected future scenario meets most of the requirements imposed by the company, apart from a small area in which the aisle width is scarcely inferior to 1.6m. It was expected that not only the parking lot for empty carts would be ensured by the layout, but also a zone for future warehouse components. This layout has an occupation rate of 72% excluding the parking lot for empty cars and the warehouse component section, and a total of 212 carts.

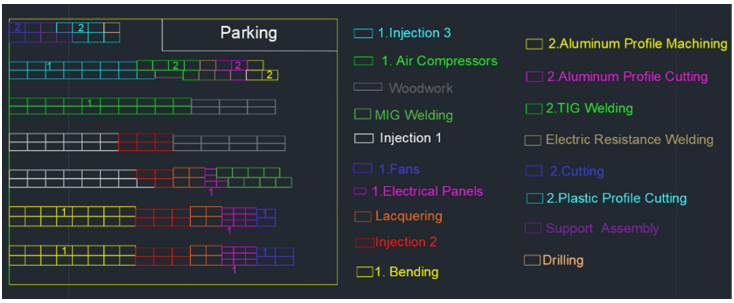

Fig. 2. Supermarket design considering current production levels

4.3 Milk Run Routes

With the average number of carts that leave each section daily and the duration of the work shifts of each section, the time it took for a cart to be ready was estimated. Another important piece of information for optimizing routes was the distances between sections and the supermarket, which were represented in a distance matrix.

The next step was to list the estimated time at which each section would have a cart ready over 2 days. One of the limitations of the Milk run was its capacity, which could carry 5 carts at a time so, to reduce waste between each route, using the maximum capacity of the Milk run whenever possible was prioritized while choosing the sections and the starting time of each route. Obtaining the sections where the Milk run would pass through each route, as well as the start time of each route, it would be necessary to validate whether there were no overlaps of hours, that is, whether one route would not start before the previous one had ended, as well as calculate the distances and times of each route and optimize their route. To do this, a script was created in python where, through the previously calculated distances between sections and the supermarket, it would indicate the best sequence of the route, as well as the distance traveled.

The plan developed for the Milk run has a 2-day cycle, with 11 routes on day 1 and 12 on day 2, with a utilization rate of 74%, which should allow the usage of the Milk run in reverse logistics if necessary. The itinerary for each route was determined and routes 1 and 2 can be seen in Table 1, as an example. The start and arrival times of the first two routes and the last one, for both days, can be seen in Table 2.

4.4 Planning Internal Logistics

Having the supermarket's design complete, the next phase was to decide how it would be managed, as well as its coordination with the Milk run arrivals, in other words, plan the internal logistics of the company regarding the supermarket's supply.

The basic flow of materials was already predetermined. The parts would be transported in carts from the several production sections to the supermarket using the Milk run and from there, they would be transferred to picking carts that would be transported to the production lines by the kitters. The reverse logistics process needed also to be planned. After brainstorming, a visual system was developed to organize this process.

Table 1. Milk run itinerary for routes 1 and 2

Route Number	Sections sequence (from left to right)				
1	1	7	11	6	14
2	8	8	11	11	17

Table 2. Milk run schedule

Day	1			2		
	Route	Start Time	End Time	Route	Start Time	End Time
	8	08:00	08:35	1	08:00	08:35
	9	08:35	08:45	1	09:10	09:45
		…			…	
	4	16:25	16:55	7	16:25	17:00

5 Results

The final step of this project was to calculate its expected benefit. For the project to be profitable, the number of workers reduced when compared to a logistics solution without the Milk run should reflect a saving in early salary greater than the expected early cost of the Milk run. As such, the benefit in the first year can be calculated by subtracting the total savings in salary from the cost of the Milk run (including operational costs).

The first step taken was to assess how much a single logistics worker costs the company per year as well as the Milk run costs. Those values were established as 15000 € for the salary and 20000 € for the Milk run. The high uncertainty related to the increase in production meant that to calculate the benefit, a few levels of production needed to be taken into consideration. For that reason, increments of 0, 25, 50, 75 and 100 were used. With a current production rate of 27 final products per day, the number of kits needed was calculated. After that, the cycle time was determined (considering 470 min of worktime) which was needed to assess the amount of logistics workers needed to satisfy such demand, without the usage of a Milk run (knowing that for the current production level 8 workers are needed). The last value needed to calculate the reduction in workers was the kitting time. Without the opportunity to make a few trials that could provide such information, the team took into consideration a range of possible values given by the company. All the values mentioned before are showcased in Table 3. Upon getting all the values needed, the reduction in the number of logistics workers was calculated and with it, the monetary gain. For a company, the financial benefit is one of the most important aspects of a project, hence the need to calculate how much it amounted to. The values for benefit in monetary value can be seen in Table 4.

It is important to note that these results correspond to the profit obtained in the first year, and that they were calculated by comparing the transporting method suggested and the one currently used, not considering further options.

Table 3. Values used to calculate the benefit

Increment in production (%)	Production rate (kits)	Cycle Time (min/kit)	Workers needed without the Milk run	Kitting time with Milk run (min/ kit)
0	27	17	8	30
25	34	14	10	60
50	41	11	12	90
75	48	10	14	

Table 4. Benefit in euros

	Workers needed without Milk run				
Kitting Time (min)	8	10	12	14	16
30	55 000	70 000	100 000	115 000	145 000
60	25 000	40 000	55 000	70 000	100 000
90	−5 000	10 000	25 000	25 000	40 000

6 Conclusion

In conclusion, this project demonstrated that the implementation of a Milk run system for the supply of an internal supermarket is an effective strategy to improve logistics efficiency and reduce operational costs, allowing, as shown by the benefit calculated, to reduce the need for logistics operators that can be reallocated to more critical sections of the company. Despite that, the project proved to be extremely challenging due to the specificity of the initial problem, since the transport unit and consequent storage would be the section carts themselves, something that the team did not find an example in any literature. Therefore, it is considered that this can be a first step in the study of the topic in question and in the implications that this concept can have in the industry.

Regarding the results obtained, it was verified that all of them met the objectives proposed. The layouts not only revealed an identical distribution of sections, but also levels of usage rate similar to those expected by the company. The adoption of an internal supermarket for components also allowed to combat other problems already identified in the company, such as lack of organization and consequent loss of quality of the components or even their disappearance. Nevertheless, this layout will need to be monitored and studied after its implementation, due to the uncertainty of the demand data and the consequent uncertainty of the number of carts per section, which may require adjustments. Another factor that causes uncertainty is the data used to calculate the time interval that each section takes to fill a cart of components, namely the use of average demand and the use of average pieces per cart which can vary significantly and also the fact that the team considered this same time interval constant. Even with these drawbacks, the routing plans are useful not only for meeting specific requirements

and transporting the carts from the sections to the supermarket as well as meeting the requirements of reverse logistics.

Despite the good indications obtained with such results, some limitations are found, such as the fact that it was applied to only one case study, and therefore the results achieved cannot be generalized. Finally, as suggestions for future research, it could be studied the application of a modernized version of the current Milk run that integrates real-time tracking and monitoring to optimize the delivery and replenishment process [10] and the development of a simulation model to enhance the analysis of the results.

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Mathematics Applied to Industry and Services

A Meta-analysis Regression on Efficient and Productivity Energy Research

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Abstract. This paper presents a meta-analysis regression of efficiency and productivity papers on energy. The objective is to know if there are differences in the value of technical efficiency (TE) by applying different estimation methods. In the energy sector, over the recent decades, many studies have been published that analyse firms' performance, using as a measure of technical efficiency the estimated values from parametric and non-parametric methods. In the literature there is no study that addresses whether different estimation methods can influence the value obtained for TE. The analysis of these factors is an important instrument for performance evaluation, by enabling firms to adopt more precise lines and benchmarking techniques. The data consist of 162 models, reporting on 63 scientific articles which empirically analyze the level of efficiency and productivity in the energy sector, from 1979 to 2013. The meta-regression model enables an understanding of the effects that different specifications of the models may have on the estimated values for efficiency. The results identify positive and negative effects on efficiency, but the most important is that neither method is preferable to the other.

Keywords: Meta-Analysis · Stochastic Frontiers · Data Envelopment Analysis

1 Introduction

Since 1957, after the extension made by Farrell [1] to Koopmans's work [2], the methodology for measuring the technical efficiency (TE) and the ability to evaluate the performance of firms has become a more clear and precise method. The possibility of comparing the actual performance of a unit (whether it be productive or not) with a frontier of good practice has attracted growing research in many sectors of activity [3]. However, no studies exist that use meta-analysis to quantify the degree to which methodological differences influence the diversity of the results in the literature.

This paper innovates in this context, by studying the factors that directly affect the technical efficiency scores for the energy industry. Efficiency in energy is a theme that has attracted much research over recent [4]. In the energy sector, the main methods used in the estimation of technical efficiency are the DEA [5, 6] and SFA [7, 8] approaches. In

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this paper, through meta-analysis, we study the impact of these methods in the calculation of the values obtained for TE, as well as for other variables. The objective is to find out if the method for estimating TE has an influence on the value obtained for TE.

2 Data and Methodology

The list that represents the set of observations for the meta-analysis consists of 162 observations, taken from 63 articles published between 1979 and 2013. The search was carried out in the main databases on economics - Econlit and Web of Science, in which were used keywords such as "energy", "efficiency", "technical efficiency", "productivity", "DEA", "SFA", "production frontier" and "cost frontier". The articles in the sample are originate from different international with a high impact factor and are indexed to SCOPUS and the greater representation are Energy Policy, Energy Economics and the Journal of Productivity Analysis. An individual critical assessment was carried out for each study, with the aim of ascertaining whether the efficiency models used are valid and applicable. The nonparametric method is the most used, with 74% of these using the DEA approach, whilst the remaining 26% apply the SFA approach. Table 1 presents the variables used in this study and the definition of each of them.

Table 1. Variables

Variable	Name	Definition
MTESCORE	Efficiency Value	Average efficiency value reported in each study
TREND	Time	A time trend variable
TREND2	Time squared	A time trend variable in quadratic form
EPOLICYJOURNAL	*Energy Policy Journal*	A dummy variable which assumes value 1, when the journal in which the study is published is about Energy Policy, and zero otherwise
EECONOMICSJOURNAL	*Energy Economic Journal*	A dummy variable which assumes value 1, when the journal in which the study was published is about Energy Policy, and zero otherwise
NONPAR	Nonparametric method	A dummy variable which assumes value 1, when the estimation method used was DEA, and 0 when it was SFA

(*continued*)

Table 1. (*continued*)

Variable	Name	Definition
SFARANDOM	Random effects model	A dummy variable, equal to 1, if the SF model was the random effects model, and 0 if it was the fixed effects one
DEACCR	DEA constant returns to scale	A dummy variable, equal to 1, if the DEA model used was the BCC model (variable returns to scale), and 0 if it was the CCR model (constant returns to scale)
INPUTORT	Model orientation	A dummy variable, equal to 1, if the model has input orientation, and 0 if the orientation is output
COSTFUNCTION	Function	A dummy variable, equal to 1 if the function selected in the study is the cost function and assumes 0 for other functions
TRANSLOG	Functional form	A dummy variable, equal to 1, if the functional form described in the study is the translog, and 0 for other functional forms
HALFNORMAL	Half normal distribution	A dummy variable, equal to 1, if the error component of the distribution that measures the technical inefficiency is half normal, and 0 for other distributions
PANEL	Panel data	A dummy variable, equal to 1, if the observations have a panel data structure, and 0, if they are cross-section

Using STATA, Table 2 presents the statistical description of the variables analysed. One thing to note from Table 2, is that the overall mean of MTEs is 0.819, which implies that the potential for efficiency improvement in the energy industry is approximately 18% on average for all the studies considered. The next section presents the model specification.

Table 2. Variables and descriptive statistics

Variable	Mean	Stand. Deviation	Min	Max
MTESCORE	0.8192	0.1288	0.3085	0.9992
TREND	12.8580	4.1864	1	20
TREND2	182.7469	100.5143	1	400
EPOLICYJOURNAL	0.3333	0.4729	0	1
EECONOMICSJOURNAL	0.1667	0.3738	0	1
NONPAR	0.7407	0.4396	0	1
SFARANDOM	0.1420	0.3501	0	1
DEACCR	0.3765	0.4860	0	1
INPUTORT	0.6173	0.4876	0	1
COSTFUNCTION	0.1358	0.3436	0	1
TRANSLOG	0.1914	0.3946	0	1
HALFNORMAL	0.1358	0.3436	0	1
PANEL	0.5617	0.4977	0	1

3 Model Specification

The efficient scores are truncated between zero and more infinite, and the Tobit model [9] is the best choice to estimate the model. The meta-model can be described as follows:

$$MTESCORE_i = \beta_j X_{ij} + \varepsilon_i \tag{1}$$

where $MTESCORE_i$ is a column vector, and their values represent the MTE of each study. The matrix X_{ij} represents all the specific characteristics of each study, and ε_i is a vector of the errors terms. The endogenous variable is the average of efficiency scores presented in the paper and the exogenous variables are displayed in Table 1. In our study, from the data described in the previous section, Eq. (1) can be described by Eq. (2):

$$\begin{aligned} MTESCORE_i =& \beta_0 + \beta_1 TREND_i + \beta_2 TREND_i^2 + \beta_3 EPOLICYJOURNAL_i \\ &+ \beta_4 EECONOMICSJOURNAL_i + \beta_5 NONPAR_i \\ &+ \beta_6 SFARANDOM_i + \beta_7 DEACCR_i + \beta_8 INPUTORT_i \\ &+ \beta_9 COSTFUNCTION_i + \beta_{10} TRANSLOG_i \\ &+ \beta_{11} HALFNORMAL_i + \beta_{12} PANEL_i + \varepsilon_i \end{aligned} \tag{2}$$

This meta-model can be transformed into a Tobit model, presented in Eq. (3):

$$MTESCORE_i \begin{cases} MTESCORE_i^* \ if \ 0 \leq TE_i^* \leq 1 \\ 0 \ if \ MTESCORE_i^* < 0 \ or \ MTESCORE_i^* > 1 \end{cases} \tag{3}$$

Two alternative models are estimated, the random effects Tobit, and the fixed effects Tobit. The fixed effects model assumes that the true effect size is identical for all studies

[10, 11] and it is similar to the methods that consider fixed effects. The variability between studies occurred only by chance, and it ignored the heterogeneity among them. By contrast, under the random effects model, we estimate the mean of the distribution of effects, and we consider the presence of heterogeneity across studies, using an error term that includes the stochastic disturbances and the fixed and random effects, as Eq. (4):

$$MTESCORE_i = \beta_j X_{ij} + v_{ij} \tag{4}$$

where $v_{ij} = \varepsilon_i + u_{ij}$ and u_{ij} is treated as a random variable.

In our model, the random effects Tobit can be described by the Eq. (5):

$$MTESCORE_i \begin{cases} MTESCORE_i^* = \beta_j X_{ij} + v_{ij} \\ \\ MTESCORE_i = max\left\{TE_i^*, 0\right\} \end{cases} \tag{5}$$

The fixed effect Tobit is estimated with dummies for each study, but the results for the dummies are not displayed, to permit the comparison of the results.

4 Results

The results for the fixed effects and the random effects Tobit models are presented in Table 3 below. The results for a statistical significance level of 5% shows that the random effects model is more significant when compared with the fixed effects model. So, the inference will be made in relation to the random effects model.

Table 3. Estimated results

Variable	Random Effects Tobit		Fixed Effects Tobit	
	Coeff	t-statistic	Coeff	t-statistic
CONSTANT	3.769	1.19	16.249	5.06
TREND	0.0006	0.05	0.076	4.19
SQTREND	−0.0002	0.47	−0.001	−2.97
EPOLICYJOURNAL	0.035	2.12	0.042	−3.34
EECONOMICSJOURNAL	0.059	2.08	0.148	−6.25
NONPAR	−0.119	−1.90	−0.038	−0.88
SFARANDOM	0.002	0.007	0.051	3.24
DEACCR	−0.065	−3.22	−0.054	−5.08
INPUTORT	−0.112	−2.56	−0.022	−1.08
COSTFUNCTION	0.086	−2,09	−0,217	−5,89
TRANSLOG	−0.035	−0.96	−0.099	−2.93

(*continued*)

Table 3. (*continued*)

Variable	Random Effects Tobit		Fixed Effects Tobit	
	Coeff	t-statistic	Coeff	t-statistic
HALFNORMAL	0.015	0.43	0.160	5.83
NUMBER OF OBSERVATIONS	162		162	
LR CHI2	40.80		511.26	
Prob > Chi2	0.0000		0.000	
Log Likelihood	126.125		358.325	
Pseudo R2	32.15		42.12	

In general, the estimated values for the coefficients of the regressors present results which were expected, but some contradict our assumptions. We did not expect that the coefficients of the variable SIZE would appear with a negative sign. TREND variable increases the estimated efficiency as the year of publication increases, and more recent years should thus have higher efficiency values. As the value of SQTREND coefficient is negative, the trend of this variable is decreasing.

Both the coefficient of the Energy Policy Journal and the Energy Economics Journal have positive values, although the former has a slightly lower value. This may indicate that the technical efficiency level of studies increases in articles published in the latter. However, this is a reserved conclusion, as the evidence is not clear for accepting this hypothesis for a 5% significance level, neither for the coefficient of the Energy Policy Journal. The NONPAR variable appears with a negative coefficient, but it is not statistically significant. This suggests that the empirical evidence did not show that the application of parametric techniques in studies leads to higher efficiency values. There is no clear-cut answer in the literature about which one should be preferred. Therefore, both methods end up without additional evidence of priority between them. The SFARANDOM coefficient implies that the choice of a random effects model increases the estimated value for the technical efficiency, compared with a fixed effects model. We expected a positive sign for this coefficient, as the random effects model allow heterogeneity and the breakdown of variables in heterogeneous and homogeneous. The results show, as expected, a negative value for the estimated coefficient for the DEACCR variable, but the result is statistically insignificant. Surprisingly, the coefficient of INPUTORT has a negative value, which was not expected, as the energy sector is conditional on the demand side, but this variable is not statistically significant. The value for the coefficient of the COSTFUNCTION variable is negative, which means that the use of the cost function has a negative impact on the estimated value of the efficiency, compared with the use of the production function; however, this result is not significant. The TRANSLOG variable has a negative coefficient, which means that the application of more flexible functional forms in this case does not produce the expected effect. We would expect a positive sign. This result can be associated with the inclusion of translog restrictions on functions which in some way cause a reduction of their flexibility. The HALFNORMAL variable, which represents the half-normal distribution for the error

term inefficiency component has a positive coefficient. This means that this distribution when compared to the others distributions has a positive impact on the estimated value of efficiency. Therefore, this suggests that other distributions, such as truncated and exponential ones, may have a tendency to decrease the value of the estimate of efficiency. Regarding the type of data, we expected that the use of panel data would cause an increase in the estimated value of efficiency and the value found for this coefficient is what we would expect. The results confirm that the use of panel data reduces the variance of the efficiency level of the observed units.

5 Conclusion

The main goal of this study is to explain the effects of specifying different models for efficiency estimate values in energy sector, and to be able to suggest adjustments that may contribute to the achievement of greater comparability on individual analytical results. There is no study of this nature in the literature for the energy sector. In this way, this work represents an innovation in the field of efficiency analysis for the energy sector, but on the other hand, it does not allow comparisons with other works.

The most important thing to conclude from this study is that none of the methods, DEA and SFA prove to be better than the other to estimate TE. This is important information for researchers.

A relevant piece of data is the fact that it appears that the energy sector can still improve its level of efficiency by around 18%, since the average level obtained for estimating efficiency is approximately 82%. This information is particularly important for the application of public policies in this sector.

Finally, it should be noted that this work constitutes an open field for future analyses. There is an open field to investigate what is not covered by the constant analysis of this study. For example, the model specification does not capture several aspects that might be useful for future specifications. It would be interesting to find out what effects the origins of the studies (geographically) may have on the estimation of efficiency. On the other hand, a specification that considers the mean, standard deviation, maximum and minimum values of output, input and control variables, would be valuable for obtaining the result of the effect it may have on estimates of efficiency scores. This would be laborious work, but it would be very interesting, although many studies do not have information about this data.

In conclusion, in the future, with more data available, it will be possible to specify the model so that it can capture the effects that the type of regulation applied in the various countries can have on the estimation of efficiency values.

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Study of Hysteresis Curves for Conformity Assessment in EGR Valves

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Abstract. The automotive industry is one of the most competitive branches of industry worldwide, due to its demand for a better product. The concept of quality and conformity is extremely important to get an edge over other competitors in the market, while continuous improvement is one of the keys to adapting and improving in an industry where costs are as important as innovation for new and better products. This paper presents a new End-of-Line (EOL) method developed to enhance the quality control of Exhaust Gas Recirculation (EGR) valve. The new method is based on Hysteresis Current loop with two primary settings (open and closed). Through the analysis of the hysteresis current loop, the new method identifies the existence of non-conformities that affect the mechanical functionality of the EGR valves. The method recently implemented at the company involved in this study is having a significant impact on improving its quality control at an irrelevant appraisal cost.

Keywords: Automotive Industry · Exhaust Gas Recirculation valve · Hysteresis Current loop · Quality assessment

1 Introduction

With the process of globalization, a lot of companies establish really high standards for products and services, and at this level of competition, it is necessary to take into consideration all areas of the processes that can be improved while establishing a culture that pursues continuous improvement and process optimization inside the respective organization to get an edge over the rest of the market competition.

The automotive industry is one of the biggest worldwide in sales as well as investment in research and development of better technologies. This development nowadays contributes to the increased usage of electronic components and software systems integrated into one vehicle. One of its primary focuses with this increase in technology is to ensure the safety of the vehicle's usage, which needs to take into account a wide range of factors.

In this scope, this paper focuses on the study of a method that allows the assessment of the functioning of Exhaust Gas Recirculation (EGR) valves, more specifically in their hysteresis current loop during operation. This evaluation method, put together with the diverse existing end-of-line (EOL) quality tests, will contribute to the reduction of type I

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and type II inspection errors and therefore allow the improvement of the quality control process.

This paper is organized as follows. The next section presents the description and assumptions of quality and conformity assessment in the automotive industry. Section 3 presents a description of the problem that will be treated in Sect. 4. Section 4 describes the proposed model and presents an analysis and discussion of the results obtained. The paper ends with conclusions and directions for future research.

2 Quality and Conformity Assessment

2.1 Quality and Safety in the Automotive Industry

Törner & Öhman [1] performed a qualitative study regarding the drivers, the safety cases, and issues regarding these last ones. Their goal is to explore the reasons for the introduction of new safety cases based on a sample of drivers with experience developing safety-related systems in the automotive industry, as well as the potential usage and potential issues of those same cases in the automotive context. It is vital for a product or service to get certified in terms of safety, and these cases pose an interesting approach to the study as they focus on the drivers in a way to introduce new safety cases and how the automotive industry perceives them. This can be interpreted step-by-step as, firstly, defining the safety objectives of a system, then establishing the connection between the evidence found to relate to the desired goals, and, lastly, collecting all the necessary data that needs to support the procedure. All this help in doing assessments of the risks and its usage provides potential support for system development and improvement.

Shahbazi, Delkhosh, Ghassemi, & Wiktorsson [2] evaluated the perceived risks associated with the potential disruptions in the automotive industry. Results indicate that selecting the right suppliers plays a vital role in the management of the supply chain, with supplier quality problems and failures being one of the most critical perceived risks.

The automotive industry is an ever-evolving industry. A few decades ago, most of the cars available had minimal technology in them, being mainly built on mechanical systems. Nowadays, cars have increasing amounts of technology, ranging from extensive software programming to sensors, cameras, navigation, etc. With this increase in technology, there is also an increase in the complexity of the systems, meaning that the risks associated with failures or faults also increase. There is a risk classification system in the automotive industry called Automotive Safety Integrity Level (ASIL), defined in the norm ISO 26262 [3], and depending on it, it might mean that an even more detailed Failure Mode and Effect Analysis (FMEA) is a better approach to preventing future defects.

Therefore, in the automotive industry, it is vital to ensure the functionality of the different systems and their conformity with customer specifications. Even a small valve poses a safety risk to the vehicle and, therefore, poses a safety risk for the driver and the rest of the passengers.

2.2 The Function of an EGR Valve

During the combustion process, the gases produced include a reactive gas named nitrogen oxides, or NOx, which is harmful. The EGR valve "*allows a precise quantity of exhaust*

gas to re-enter the intake the system, effectively changing the chemical makeup of the air entering the engine. With less oxygen, the now diluted mixture burns slower, lowering temperatures in the combustion chamber by almost 150 °C, and reducing NOx production for a cleaner, more efficient exhaust" [4].

The EGR valve's functioning varies between two primary settings: open and closed. When the engine is starting up, the valve is closed. At low speeds, the valve gradually opens. If more power is required, the valve closes to ensure as much oxygen enters the cylinder as possible. As well as reducing NOx, EGR valves can be used in downsized gasoline direct injection (GDi) engines to reduce pumping losses, improve the efficiency of the combustion, and improve knock tolerance. In diesel engines, the EGR valve can also help reduce diesel knock at low speeds [4].

2.3 The Hysteresis Loop

The word hysteresis translates the idea of a delay (lag behind) and is associated with different phenomena or fields of interest (for example, in physics, engineering, chemistry, biology, economics, and information technology, among others) [5–7]. Hysteresis is identified when, acting on a physical system with two variables continuously dependent on time, it does not immediately return to its initial state, presenting a delay or memory that can be visualized in a hysteresis loop (see Fig. 1). In the literature review, no studies were identified with the application of hysteresis currents as a control method in EGR valves.

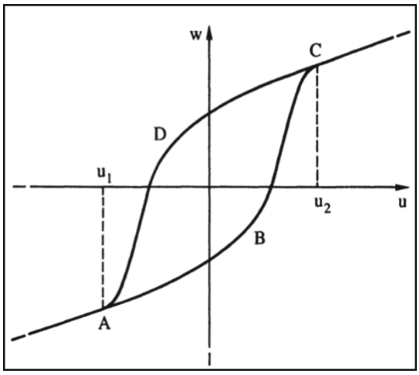

Fig. 1. The Hysteresis Loop [5]

There are several steps in this study, highlighting: (i) identification of the problem; (ii) collection of data on the hysteresis curves; (iii) statistical analysis of the data; (iv) presentation of the control method and parameters to be evaluated; (v) validation of the proposed method; (vi) implementation of the method at the End of Line (EOL) of the respective production line and validation of the results obtained.

3 Problem Description

For this paper, the hysteresis concept is incorporated into a control that is designed for a production line of EGR valves. As explained before, the EGR valve allows reusing the exhaust gas to lower the emissions by reintroducing this gas together with the air that goes into the combustion chamber. The quantity of gas reintroduced is controlled by a module that puts together an EGR valve, an EGR cooler, and an EGR tube [8] (see Fig. 2).

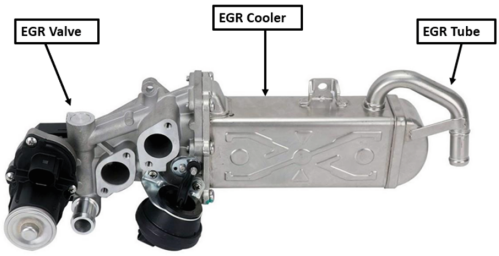

Fig. 2. Example of an EGR Module.

Even when inspecting 100% of the products, there is not a 100% reliable method to avoid errors at inspection, including error type I (faulty parts that are sent to the customer) and error type II (good parts for rework) [9]. Since it is a complex product and production process, certain defects are only detected in the customer application or directly in the end customer, thereby increasing the associated costs due to poor quality and requiring action plans to eliminate or mitigate the risks [10].

Regarding customer "0 km" and warranty complaints, in 2021, failures with EGR valves produced in this specific line represented approximately 0,052% of the company's production. A further analysis identified 37% of those failures as being quality complaint cases (failure identified at the B2B customer) and 63% as being warranty cases (failure identified during the warranty period at the final customer). In the cases in which the company was liable, the customer had to be compensated for their costs, which may include the valve cost, the labor cost, the cost of product not sold, the transportation cost, and the time the part was operating at fault, amongst many others.

To be noted that of the total percentage of cases for this year, 41% were related to failures that compromise the mechanical functioning of the valve by creating friction in the movement, having identified the following defects:

- Damages on the gears of the part of the gear of the motor;
- Damages on the intermediate pin creates friction between gears;
- Damages on the spring of the part;
- Damages on the flap or poppet, whether on its insertion or on the shaft.

The EOL tests consider the mechanical open-close functioning of the valve (OK or NOK). The B2B customers make the assembly of the EGR valve or module in the engine,

and their final test considers the real operating conditions with intensive electronic control. An error alert concerning the EGR module represents a further investigation of the causes in the supplier.

The historic analysis identified several causes, for instance, damages in the gears or damages in the insertion of the intermediate pin, whose effects were not monitored at the EOL of the production line. Based on an internal specification of hysteresis consumption for a customer of a different valve, it suggested an opportunity to study the hysteresis loop of these EGR valves.

4 Hysteresis Curves for Quality Control of EGR Valves

4.1 Collection of Data on the Hysteresis Loop

The functional electric test is a non-destructive test. The EGR valves are considered in this work as being electrically actuated through a torque motor incorporated in the valve. The function of the EGR valve is controlled by software in the EOL computer, which controls the power supply of the valve and varies the signal of the motor input voltage. Figure 3 presents, as an example, a bench for off-line electrical tests with similar equipment and EOL test software conditions.

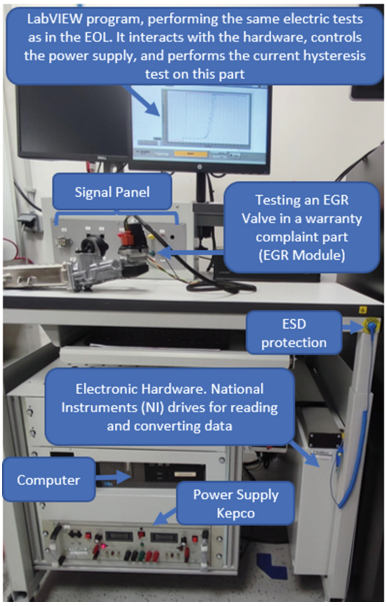

Fig. 3. Electric tests from EOL at a different test bench.

The test consists of applying a voltage profile to the torque motor in order to perform the valve opening-closing cycle. In this procedure, the current in the torque motor and the voltage of the sensor that are integrated in the valve are registered. An example of

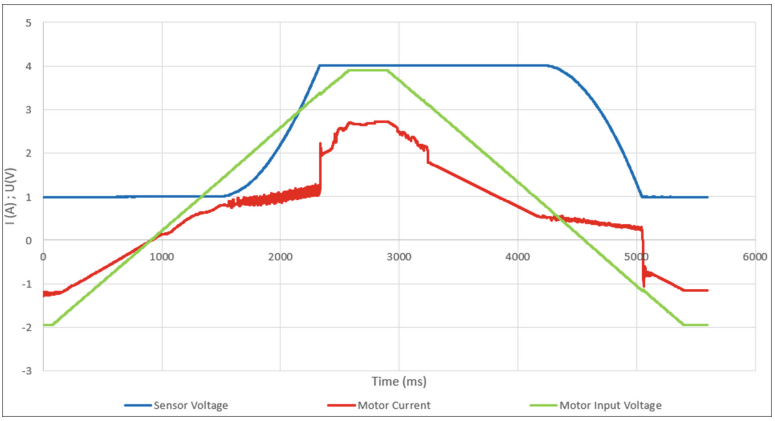

Fig. 4. Signals of an EGR valve.

the input (motor input voltage) and output signals (motor current and sensor voltage) can be seen in Fig. 4.

Each test cycle of open-close allows to measure and register around 6000 discrete value pairs of current and voltage values. Considering these output signals, a hysteresis loop for current and voltage is represented (see Fig. 5).

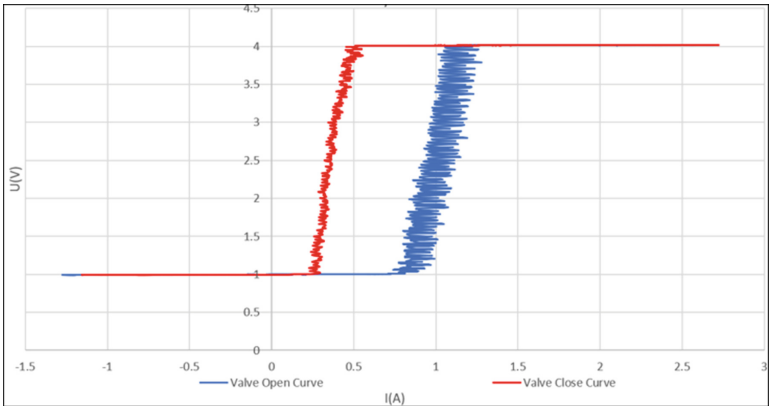

Fig. 5. Example of an EGR valve hysteresis loop.

The blue curve represents the valve opening, and the red curve represents the valve closing. The lag between the two curves is the hysteresis.

4.2 Procedure for the Hysteresis Current Evaluation

The procedure mentioned in the previous section was replicated for 50 valves considered compliant in the EOL, each one taken from a lot of N pieces. The information

obtained was stored in a database. Since the value of the sensor voltage is programmed and therefore controlled, its variation is negligible; only in the motor current is there variability. Using Excel, the values of the average motor current and the standard deviation are calculated for each valve of the 50. A trendline is determined from the average current values and its adjusted polynomial equation. Two other polynomial equations are established, spaced from the average by ±3 times the standard deviation, and their graphical representation is considered the upper and lower limits of control, respectively (Fig. 6).

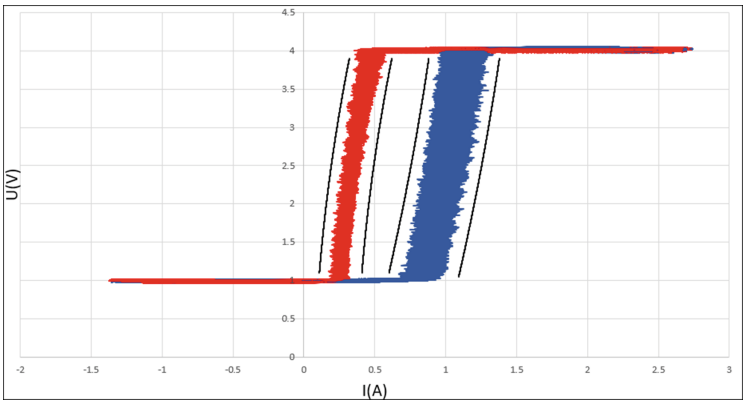

Fig. 6. Representation of upper and lower limits of control.

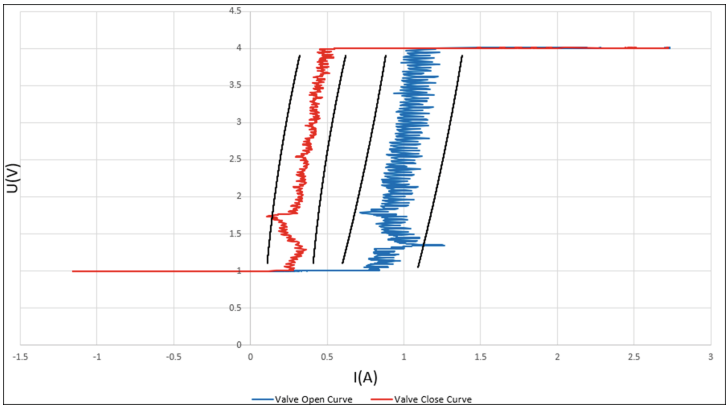

Fig. 7. Example of a NOK EGR valve.

According to Fig. 6, the limits are used in the desired interval of movement of the valve to identify product conformity through its hysteresis curves. If the measured values of a valve are between the limits, the valve is considered as OK; otherwise, the valve is

identified as NOK. This procedure is performed by the software in the EOL for 100% of the EGR valves produced in the production line.

Figure 7 presents an example of a valve with its hysteresis curves outside the limits and therefore considered NOK.

5 Final Considerations

This paper proposes a new method based on the hysteresis current loop to identify functional problems with mechanical origin in EGR valves and thus reduce type I and type II inspection errors associated with the control process in the EOL. The results indicate a positive impact of this new method on improving process control and reducing the number of "0 km" and warranty complaints from customers due to previously undetected mechanical defects. This method does not influence the cycle time, and the unit control cost is irrelevant (it represents 0.28% of the product value). Nevertheless, the use of the hysteresis current curve to monitor the valve operation has the disadvantage of being complex to implement, requiring a detailed study as well as the collection of real data for the definition of the control limits. Another limitation is related to the impossibility of identifying the failure mode associated with a non-conformity in this control. On the other hand, once the control limits are established, the entire process of controlling the hysteresis currents of the EGR valves is done automatically and can be applied to other types of valves.

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Analysis of Constructive Heuristics with Cuckoo Search Algorithm, Firefly Algorithm and Simulated Annealing in Scheduling Problems

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Abstract. Nowadays, decision making is one of the most important and influential aspects of everyday life, and the application of metaheuristics and heuristics facilitates the process. Thus, this paper presents a performance analysis of the combination of constructive heuristics used to generate initial solutions for metaheuristics applied to scheduling problems. Namely, Nawaz, Enscore, and Ham Heuristic (NEH), Palmer Heuristic and Campbell, Dudek, and Smith Heuristic (CDS) with Cuckoo Search, Firefly Algorithm and Simulated Annealing. The aim is to compare the performance of these combinations to analyse the efficiency, effectiveness and robustness of each. All combinations were analysed in an in-depth computational study and then subjected to a statistical study to support an accurate analysis of the results. The results of the analysis show that the Firefly Algorithm associated with NEH, despite having a high runtime, performs better than the other combinations. However, the best effectiveness-efficiency ratio corresponds to SA-Palmer and SA-CDS.

Keywords: Nawaz, Enscore, and Ham · Palmer · Campbell, Dudek, and Smith · Firefly Algorithm · Cuckoo Search Algorithm · Simulated Annealing

1 Introduction

The metaheuristics are nature-based, such as, for example, Firefly Algorithm, Cuckoo Search Algorithm and Simulated Annealing. In fact, a peculiarity of these types of metaheuristics is their ability to adapt to any problem. For example, they can be applied to flow scheduling problems, as in this paper, as well as any other difficult optimization problem. Furthermore, existing constructive heuristics, including CDS Campbell, Dudek, and Smith Heuristic (CDS), Palmer, and Nawaz, Enscore, and Ham Heuristic (NEH), are known to result in good solutions with minimal runtime. However, the effectiveness and efficiency of the results can be influenced by various surrounding factors, notably

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the initial solution/population. In this sense, the objective of this paper is to compare the performance of Cuckoo Search, and the Firefly Algorithm when associated with an initial constructive heuristic in order to analyse the efficiency, effectiveness and robustness of each their solutions.

The paper is divided into 6 sections. Sect. 2 presents the literature review of each algorithm. Section 3 develops the context of the problem and the parameterization. The following sections deal with the statistical analysis and the discussion of results.

2 Literature Review

This literature review will emphasize the constructive heuristics and metaheuristics used throughout the paper in order to solve the problems presented.

2.1 NEH Heuristic

The Nawaz, Enscore, and Ham Heuristic (NEH) has been known as one of the best constructive heuristics for the minimization of makespan in flow shops problems [1]. It is based on the idea that jobs with high processing time should be scheduled as early as possible in the sequence [2]. This has been proven effective and consists of two key steps [3]: a) jobs are sorted in descending order of total processing time, and a feasible initial schedule can be obtained and b) the jobs in the initial sequence are picked up one by one and are arranged corresponding to a minimum improbability value, to obtain an optimal schedule [4].

This process is repeated until all jobs are scheduled [5]. The pseudo-code of this heuristic is represented in Algorithm 1 [2].

Algorithm 1 - NEH heuristic

```
Rank jobs in decreasing order of total processing time
Remove first job of ranked list and insert it as first element
k=1
While (k ≤ number of jobs to schedule) do {
    Take the first job of ranked list
    Insert it in all of k+1 possible places of current partial sequence
    Evaluate all k+1 resulting partial sequences
    Keep the best sequence as new current partial sequence
    k=k+1}
```

2.2 Palmer Heuristic

Palmer Heuristic is based on slope indexes to arrange jobs in ascending or descending order of specified weights with the aim of minimizing makespan [6]. Palmer was the first to introduce the concept of a work slope index, and this algorithm is characterised by minimal computational effort [7]. In Eq. 1, job prioritization is done so that jobs with processing times that tend to increase from machine to machine receive higher priority;

while processing time of job that tend to decrease from machine to machine receive lower priority [8].

$$S_j = \sum_{k=1}^{M} \frac{2k - M - 1}{2} t_{jk} \tag{1}$$

where M = number of machines, S_j = Slope index in job j and t_{ijk} = processing time job j in machine k.

2.3 CDS Heuristic

The Campbell, Dudek, and Smith Heuristic (CDS) is a method expanded from Johnson's rule that is able to minimize makespan for more than two machines in series [9]. This heuristic builds *m-1* schedules by grouping the *m* machines into two virtual machines and solves the problem of *m-1* generated by repeatedly using Johnson's rule [2]. The best of these schedules is the solution to the problem [5]. So basically, it looks for the best priority sequence by combining the existing workstations into two groups of machines. The machines in both groups are ranked by priority based on the shortest processing time. Thus, the shorter processing machine is ranked to be first. However, the longest processing machine is ranked to be last [10]. Its formulation is described in Eq. 2 [11]:

$$\begin{array}{ccc} \underline{First\ sequence:} & \underline{Second\ sequence:} & \underline{K - sequence:} \\ t_{i,1} = t^*_{i,1} & t^*_{i,1} = t_{i,1} + t_{i,2} & t^*_{i,1} = \sum_{k=1}^{k} t_{i,k} \\ (first\ workstation) & t^*_{i,2} = t_{i,m} + t_{i,m-1} & \\ t^*_{i,2} = t_{i,m} & & t^*_{i,2} = \sum_{k=1}^{k} t_{i,m-k+1} \\ (last\ workstation) & & \end{array} \tag{2}$$

2.4 Simulated Annealing

Simulated annealing (SA) is a stochastic approach that aims to overcome the optimal by accepting solutions with a probability based on the annealing process [12]. In the practical application of the metaheuristic, the temperature gradually decreases as the algorithm progresses in order to reduce the probability of accepting worse solutions. In this way, worse solutions are rejected more often as the algorithm progresses. The probability of accepting a worse solution at each iteration is given by [13]:

$$p = e^{-\frac{\Delta}{T}} \tag{3}$$

where Δ is the difference between new and current solution and T is a parameter. The probability of a better solution being accepted is always one.

2.5 Cuckoo Search Algorithm

The Cuckoo Search Algorithm (CSA) uses the breeding behaviour of some cuckoo species and the Lévy flight behaviour of some birds and fruit flies [14]. This metaheuristic makes an analogy between the nests and the possible solutions of an optimization

problem. Cuckoo eggs are laid in host bird nests and if the bird discovers these eggs, it can destroy, abandon or rebuild the nest elsewhere [15]. Foraging and the route used by the cuckoo to search for food is defined as random by this algorithm, since the next step is based on the current location and the probability of moving to the next location [14]. Mathematically, the nest or the new solution X_i is generated by the Eq. 4 for the ith nest:

$$X_i^{n+1} = X_i^n + \alpha \oplus Lévy(\beta) \tag{4}$$

where α represents the step size and the random step length (β) follows the following Lévy Flight distribution as shown in Eq. 5 [16]:

$$Lévy(\beta) \sim s^{-\beta} \tag{5}$$

2.6 Firefly Algorithm

The Firefly Algorithm (FA) was developed based on the dynamic nature of fireflies and was introduced by Xin-She-Yang [17] in 2008. Decision making respects three rules: (1) attractiveness between fireflies is independent of gender, (2) brightness is proportional to attractiveness and inversely proportional to the distance, and (3) the quality of the solution is affected by the brightness of the fireflies [18].

The motion of the fireflies i, x_i, is defined by Eq. 6 (1):

$$x_i = x_i + \beta_0 e^{-\gamma r^2}\left(x_j - x_i\right) + \alpha(rand - 1/2), \tag{6}$$

where r is the distance between fireflies i and j, β_0 is the attractiveness at $r = 0$, α is the size of the random step and γ is the absorption coefficient. In this way, firefly i moves in the direction of the brighter firefly j. However, if the brightness of both fireflies is equal, a random movement is generated [19].

3 Flow Shop Sequencing Problems

By the definition, in a Flow Shop each job passes only once in each machine and each machine is only capable of executing one job at a time. The aforementioned metaheuristics are intended to continuous problems, and their solution were discretized [20].

3.1 Implementation and Parameterization of Metaheuristics

In order to improve the performance of the metaheuristics, Design of Experiments (DOE) was applied, in Table 1, to understand the effect of combining the various parameters of the metaheuristics, according to Shim, N. Shin, A. Stern et al. [21].

Table 1. Parameterization of metaheuristics

SA	T	L	α	IC		Study Bases
	9601	150	0.8	10000		E. Aarts and J. Korst [21], R. Kolisch and S. Hartmann [22]
FA	γ	U_γ	a_γ	n	IC	Study Bases
	0.1	1	0.1	40	250	Udaiyakumara and Chandrasekaran [18], Khadwilard et al. [23]
CSA	U	α	P(a)	n	IC	Study Bases
	0.4	1	07	40	250	J. García and B. Crawford [24] and D. Belbachir and F. Boumediene [25]

4 Statistical Analysis

After applying the combined algorithms and testing each combination 250 times for different data samples randomly generated, different results were obtained. To treat and understand them, a few iterations were performed. First, the results were summarized to means of Makespan and runtime (processing time) for further data analysis, in Table 2.

Although it is already possible to draw conclusions about the data, it is essential to perform a statistical evaluation of the results for more accuracy. Thus, in order to verify how the data were distributed, a histogram was created with the help of *Past Software*. With the information obtained by the histogram represented in Fig. 1, it would then be possible to select the statistical model for further statistical evaluation. After the histogram analysis, it was verified that the results do not follow a normal distribution and as such, for the statistical evaluation the Kruskal-Wallis and Dunn's Post Hoc tests were selected for their suitability and were run using the Past Software [26].

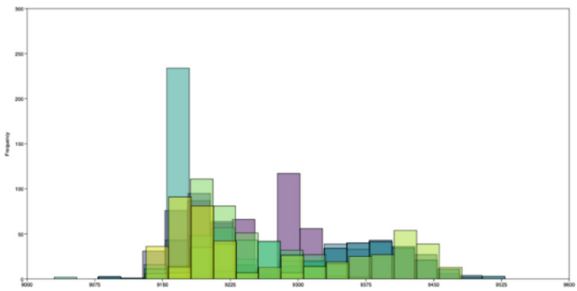

Fig. 1. Histogram of the makespan

In the Kruskal-Wallis test, the hypothesis of the twelve combinations having significant difference or not was tested. The hypotheses analysed were then:

$$H_0 = \textit{There is no significant difference among the twelve combinations}$$

$$H_1 = \textit{There is a significant difference among some of the twelve combinations}$$

Table 2. Results of combinations - Makespan and CPU

	SA		CSA		FA	
	Makespan	CPU	Makespan	CPU	Makespan	CPU
NEH	9279	00:03:06	9361	00:02:44	9167	00:03:14
Palmer	9195	00:01:10	9356	00:02:34	9203	00:01:33
CDS	9189	00:02:00	9361	00:01:22	9252	00:01:38
Random	9217	00:01:53	9365	00:02:16	9180	00:02:54

Kruskal-Wallis test for equal medians
$H(chi^2) = 2127$ H_c(tie corrected) $= 2129$ p (same) $= 0$
There is a significant difference between sample medians

Table 3. Result of Dunn's Post Hoc test

	SA-NEH	SA-Palmer	SA-CDS	CSA-NEH	CSA-Palmer	CSA-CDS	FA-NEH	FA-Palmer	FA-CDS	SA-Rand	CSA-Rand	FA-Rand
SA-NEH												
SA-Palmer												
SA-CDS												
CSA-NEH												
CSA-Palmer												
CSA-CDS												
FA-NEH												
FA-Palmer												
FA-CDS												
SA-Rand												
CSA-Rand												
FA-Rand												

Thus, since $p_{value} \leq 0.05$, the null hypothesis is rejected with 95% confidence, emphasizing that there is a statistically significant difference between the combinations. Although it is verified that there is a difference between some of the twelve combinations, it is not yet known which combinations are different from each other. For this, the Dunn's Post Hoc test was applied, obtaining the results shown in the Table 3. The above-mentioned table highlights, in blue, the combination pairs whose difference between them is statistically significant, that is, whose $p_{value} \leq 0.05$. Thus, it is possible to draw relations about the different combination pairs, and comparisons between them can be made.

5 Analysis of Results

In the interest of evaluating the performance of the different metaheuristics associated with initial constructive heuristics, the following graphs are presented in Fig. 2, which shows the solutions and average runtime time for the different instances.

From the graphs presented, it can be seen that FA - NEH is generally better than the others. However, with respect to execution time, it is the highest. In contrast, SA-Palmer and SA-CDS present solutions, on average with 51.03% lower execution time, although 0.27% worse than the best solution found. On average, it can be stated that metaheuristics

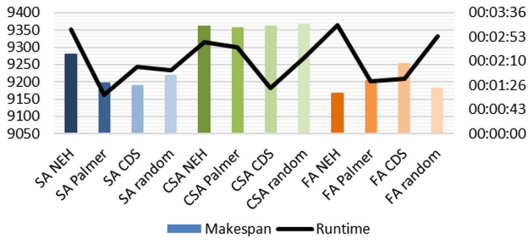

Fig. 2. Graph Makespan and Runtime of the 12 combinations

have a greater influence on makespan, while constructive heuristics impact the execution time more significantly. In this sense, the CSA proves to be less effective than the FA and SA, since the latter provide better solutions in comparable situations. On the other hand, Palmer, CDS and random, in this sequence, are much more efficient than NEH, in which they require less runtime. As for the robustness of the algorithms, the solutions obtained by FA and SA within each heuristic have a lower standard deviation compared to the other algorithms, which means that there is not a large discrepancy between the various solutions.

6 Conclusions

In this study, an attempt was made to reconcile metaheuristics and constructive heuristics in order to identify whether, with a better solution right from the start, the algorithm would become more efficient. Once developed, computationally implemented and tested, SA, FA and CSA associated with NEH, Palmer and CDS proved that they can be very useful in problem solving, in that they generally lead to satisfactory solutions quickly and efficiently.

The experimental analysis developed shows that FA-NEH provides better solutions regardless of its instance size, despite requiring more runtime. When it comes to the best effectiveness-efficiency ratio, SA-Palmer and SA-CDS are more valued.

As future work, improving the initial population should be considered, integrating not only one heuristic, but several in order to take advantage of the potential of each one, in addition to elaborating a new hybrid metaheuristic that combines the best aspects of the presented algorithms. On the other hand, it would also be interesting to expand the application of these algorithms to other decision-making contexts.

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Mapping of Newcomer Clients in Federated Learning Based on Activation Strength

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Abstract. Federated learning is a collaborative machine learning approach that allows multiple parties to train a model without exchanging sensitive data. In manufacturing, where different parties may have proprietary or sensitive data that cannot be shared, this is especially useful. However, traditional federated learning approaches (as proposed by McMahan et al.) do not consider the differences in data and computing resources across different parties, leading to sub-optimal model performance. Personalized federated learning addresses this issue by allowing each party to contribute to the model training according to its specific data and resources. Furthermore, most common approaches only consider a limited set of data and a short period of time, without considering the system's long-term usefulness. It is important to consider the integration of new clients and the continuous change of data, which could result in the addition of new classes. This paper will explore the potential of federated learning in manufacturing and present a flexible and expandable approach, focusing on mapping newcomer clients based on activation strength of weights.

Keywords: Federated Learning · Continual Learning · Multi-Headed Neural Networks

1 Introduction

Over the last few decades, the architectural approaches to technology have changed from centralized to decentralized approaches and back again: In the 1960s, local terminals did not have sufficient computing power, so the computing tasks were executed on central computing nodes. Centralized systems had lower management and operating costs, and their configurations were simpler than those of decentralized systems [1]. With the introduction of the personal computer (PC) and its increased computing power in the 1980s, computing tasks could be executed directly on local client computers, increasingly

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eliminating the need for centralized servers [2]. The development of increasingly resource-intensive applications and the availability of greater bandwidths of internet access resulted in the emergence of cloud computing technology in the 2000s, and therefore forcing an architectural shift towards centralized computing systems again.

While the pooling of resources in the cloud finds much application in the private sector or on non-critical data, there is a tendency towards edge computing in industry. Manufacturing is a data-intensive industry with many parties generating data from different sources such as outputs from production processes, quality control systems, and sensors [3]. Machine learning algorithms have the potential to analyze this data and improve manufacturing processes by predicting failures, optimizing production schedules, and improving quality [4]. However, data in manufacturing is often proprietary or sensitive, making it difficult to share and train a machine learning model on a common dataset [5].

This work attempts to combine the aspects of continual learning, especially the "Dynamic Architectures" approaches, with the efforts of federated learning to create a robust system that can use the advantages of FL but is extensible for future tasks. The theoretical concepts used for this purpose are described in more detail in the next section. This is followed by the assumptions and requirements arising from the production environment. The main concept is presented and a focus is placed on the reliable integration of new clients in this paper. After the description of the implementation and the results, we conclude with an outlook on the next steps.

2 State of the Art

One way to overcome the obstacle of data sharing is a decentralized approach, such as Federated Learning (FL), proposed by Google researchers (McMahan et al.) in 2016 [6]. The goal of FL is the use of a broad, heterogeneous database by collaboratively training a model without explicitly sharing information [7]. Unlike traditional centralized learning where models are trained using large datasets residing on a central server, here only data in the form of network weights is shared and no raw data such as production data or images [8]. This approach allows each participant to stay in control of their own data while benefiting from the advantages of collaborative learning, such as better generalizability and a higher stability of the solution. By indirectly increasing the samples of the dataset, it is further possible to access a wider variety of data and thus feature characteristics. The initial approach to FL is Federated Averaging (FedAvg), where a server distributes a model to clients. After local training on their data, the server collects the weights of participating clients, averages them, and distributes the resulting model to all clients, resulting in the next communication round (see Fig. 1).

Multi-Task Learning (MTL) attempts to imitate the ability of humans to transfer skills from one task to another [9]. On the one hand, limited available data can be used for several similar tasks and on the other hand, sharing knowledge between the models can even lead to performance improvement compared

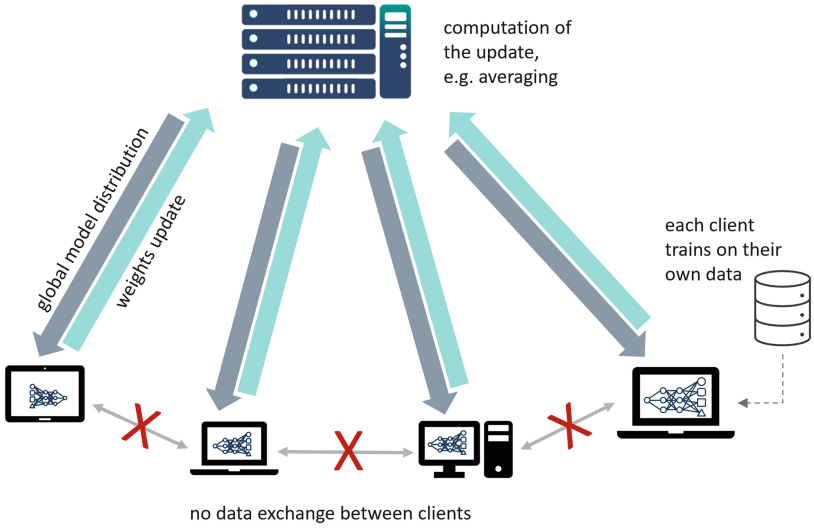

Fig. 1. Basic federated learning concept

to using individual models [10]. A related concept is multi-head or ensemble learning, where the main goal is to create a more robust model [11]. When done correctly, sharing a base model can reduce computational resources while increasing model accuracy [12].

Continual learning (CL), also referred to as lifelong, sequential or incremental learning is the problem of learning from an infinite stream of data, intending to preserve and extend the acquired knowledge [13]. In contrast to static artificial neural networks, which are incapable of adapting and expanding, the real world consists of continuous streams of information and constantly evolves [13]. Humans learn sequentially throughout their life. They gradually forget some old information, especially details, but without a complete loss of obtained knowledge [14]. The ability to integrate new knowledge and stability to preserve previous knowledge is called the "stability-plasticity" dilemma in both biological [15] and artificial neural systems [16]. Without a good balance, neural networks can suffer from "catastrophic forgetting", thus resulting in deterioration of performance in handling old classes when acquiring new data [17]. Although continual learning is a long-standing challenge [18,19], with the spread of AI applications into daily life, the ability to continuously learn and improve still gains importance.

3 Requirements and Assumptions

In order to derive the requirements for our system, we will first look at the requirements for flexible production, i.e. the environment in which we find ourselves in. Although possibly subject to variations depending on the industry, there are some important characteristics that can be summarized into:

A **modular** design allows the addition or removal of machines and production modules to adjust production capacity, allowing production to be easily adapted to new requirements [20]. Flexible production should be able to quickly and easily switch from small to large production scales. Such **scalability** enables quick response to changing market conditions and customer requirements [21]. Automation of production steps can increase **efficiency** and can also help to reduce error rates and improve or maintain quality. However, an evaluation of the suitability of processes for automation is essential, as some tasks that require special sensitivity may still be more efficiently performed by **humans** [22]. **Flexible** production should be able to respond quickly and effectively to customer needs, as well as be resiliently to unforeseen events [23]. To be able to react quickly to changes in production, data and information should be collected and analyzed, demanding a high degree of **digitalization and interconnectivity** [24]. By connecting production units to each other, problems can be discovered quickly and alternative action recommendations can be created [25]. The avoidance of waste, such as unnecessary process steps or too long transport routes, but also the production of rejects, helps to achieve **sustainable** production [26]. Consequently, we need a modular and scalable (and therefore flexible) system, that works efficiently and does not leave humans out of the loop.

The general applicability of federated learning in a manufacturing use case was shown in a previous publication [27], where each client got images of one type of USB-stick with unique errors for quality control. The global model could not only detect every error type, but was also significantly better at generalizing when given new products than any individual model. The purpose of the concept to be presented is to achieve greater flexibility when using federated learning approaches, especially with respect to expandability and heterogeneity in the network architectures. This paper introduces the basic concept and examines the assignment of new clients to existing classification modules.

Common Federated Learning assumptions apply:

- Client's data has some overlap and similarity.
- Other than the data required for FL, no meta information is exchanged between server and clients.

Additional constraints are added from the production environment:

- The conformity of labels for the same class cannot be ensured, especially in the case of cross-company cooperation.
- Not all clients participate in every communication round (due to connection loss, low performance in battery mode, ...).
- Dynamic and durable solution: The number of clients and also the amount and distribution of data can change over time.

We will assume two scenarios:

(1) Participants have similar data, but their definition of classes is not identical. This can be due to language differences, varying naming conventions in companies or industries, or the usage of different hierarchic levels. For example,

one participant defines only the umbrella term "surface defect" for errors, and another uses the more detailed subclasses "scratch", "blister" and so on.

(2) New classes need to be introduced during the lifetime of the solutions because new errors have occurred or new objects have to be detected.

4 Concept

Federated learning is limited in its adaptability as all clients must have the same architecture and definition of classes, otherwise the clients will work against each other on every update. To circumvent these restrictions, we purpose to use a multi-headed approach with an automated class mapping. Multi-headed neural networks can be combined with federated learning by training each head of the network on a different subset of the federated data or by having each head specialize in a different task. In our setup, each head can be seen as a sub-model that is trained for a specific classification problem, and the final prediction is made by combining the predictions of all relevant heads or classifiers. Except for the connection layer to the backbone, every classifier can have a different architecture. During training, loss functions known in ensemble learning can be used, where each head adapts strongly to its tasks, but the backbone stays also adaptive to changing data.

The proposed architecture as shown in Fig. 2 has a common feature extraction block and multiple classifier, similar to multi-task learning approaches with multiple heads or multi-headed models as mentioned in the state of the art section.

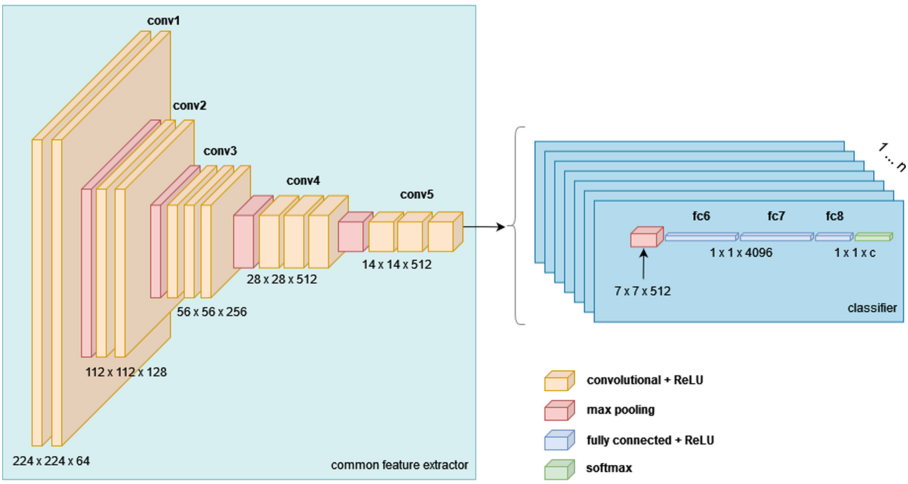

Fig. 2. Architecture with pretrained VGG16 used as common feature extractor. Diagram created with template from [28]

The federation is performed only for the necessary sub-models among themselves and only if all requirements are satisfied. These could be: Minimum number of new data points, enough free computing capacity for calculation, minimum elapsed time since last update and so on. The encapsulation of the classification has the further advantage that new classes can easily be added or whole modules can be replaced in the future because, for example, new guidelines defining what constitutes a defect are issued.

The solution should be independent of existing labels and work reliably without human intervention, but at the same time remain interpretable by a human. For the automated mapping of classes, we made the assumption that an input will activate the output neurons of the right class(es) the most.

5 Implementation and Results

For the common feature extractor the VGG16 [29] backbone with pretrained weights was used. As its original implementation is already divided into the modules features and classifier, we used the features module but defined our own classifiers with slightly different architectures, e.g. varied the number of layers and their sizes. This approach works easily with every network architecture, that is already split into features and classifier modules (e.g. tested on EfficientNetV2 [30]), and can also be applied to most other architectures. However, then the optimal transition point between features and classifiers must be determined first. Since we are still in the data acquisition process, we first experimented with a subset of the open available ImageNet images [31]. In its entirety, ImageNet is often used for benchmarks and is integrated into the major frameworks such as PyTorch and Tensorflow, for our analyses, however, the class hierarchies and their overlaps are significant (see [32] for a good presentation thereof). The chosen subset mimics our dataset well in terms of distribution and hierarchy levels, with every class containing 1.300 images. The same data was taken for each run, but the label list was changed (see Table 1).

Table 1. Distribution of Classes and Groups

Group	Class	Setup 1	Setup 2	Setup 3	Setup 4	Setup 5	Class Name	Superclass
a	A	0	9	0	0	0	scratch	not okay
	B	1	8	0	0	0	mechanical damage	not okay
b	C	2	7	1	2	1	product type 1	okay
	D	3	6	1	3	1	product type 2	okay
	E	4	5	1	4	1	product type 3	okay
c	F	5	4	2	5	0	rust	not okay
d	G	6	3	3	6	0	markings	not okay

For setup 1 and 2, each class corresponds to one label, but the order was reversed. In setup 3, the images are separated into the groups listed on the left.

Setup 4 keeps these groups, just classes from group "b" are treated individually. In our dataset setup 5 corresponds to a binary classification if a product is "okay" or "not okay", therefore grouping all other classes in class 0. Where we can divide "not okay" further into "scratch", "rust", "mechanical damage" and "markings". Although the first experiments were done with the ImageNet dataset and its classes, in order to provide a better access and understanding for readers in the mechanical engineering field, Table 1 shows class division of our dataset.

Our approach is based on the assumption that when the model is trained further with only data from one class, exactly the weights of the correct class are changed the most. To ensure that the appropriate error classes are suggested to each new client, it is sufficient to measure the activation of the output neurons (just the very last layer) with a few images (see Fig. 3). For this purpose, the training was continued with an increased learning rate of 0.01 (compared to 0.001 in normal training). These weights were stored and the differences from the weights of the normal training run were determined. Table 2 shows some exemplary results. The value in the table corresponds to the difference of the right class, as the differences for all other classes were so small that they could be approximated as zero.

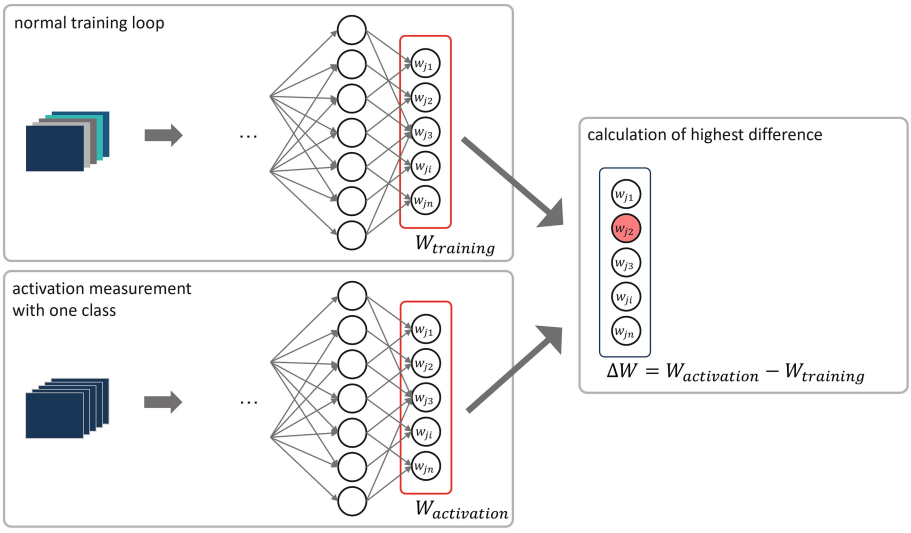

Fig. 3. Calculation of activation

Table 2. Exemplary Activation Strength Values

Batch Size	Epochs	Setup 1	Setup 2	Setup 3	Setup 4	Setup 5
8	10	0,0320	0,0036	0,5927	0,6440	0,0020
8	5	0,0295	0,0008	0,3720	0,3556	0,0006
8	1	0,0121	0,0002	0,0834	0,0859	3,90E−05
1	1	9,94E−05	5,07E−05	0,0078	0,1279	1,94E−07

In general, the activation became greater the more examples and epochs were used, but was already measurable with one image in the experimental setup. In our tests, which contained significantly more experiments than shown and were performed with different inputs, all mappings were correct. As the last layers with a few thousand values correspond to only a small percentage (<0,03%) of the trainable parameters, calculation takes only seconds.

It is even possible to determine several class mappings at the same time, if the distribution within the test batch is different enough, e.g. class A has 20 images, class B 10 and class C only 2. The ranking of the activation corresponds to this order, but is not to a linear function of it - so the activation for class A won't be necessarily twice as high. However, because the measurement runs do not need much computing power, the advantage compared to single runs is not large, but brings a degree of uncertainty with it.

The different setups showed that a mapping can be performed correctly, even if the data in the classes are heterogeneous (e.g. see class 0 in setup 5) or the data is distributed unevenly. If the activation strength is under a certain threshold, it can make sense to add a new classifier. The identification of the exact threshold and the number of minimum requests before a new classifier is created, still needs to be investigated, otherwise there is a risk of uncontrolled growth. Once the mapping is finished, it should be presented to a worker. On the one hand, to ensure that everything is correct, on the other hand, new errors may have been discovered that were previously unknown or irrelevant to the company. Afterwards, it can be saved locally at the client and used for all subsequent communication rounds.

6 Conclusion

This work showed that combining multi-headed neural networks with federated learning can provide a flexible and scalable solution for decentralized machine learning problems, where data privacy is of utmost importance. We proved that by calculating the activation strength, a good assignment of the prevailing problems of newcomer clients to existing classification modules is possible and thus a resource-intensive training or the setup of completely new networks can be avoided. Some aspects need to be further explored, such as the definition of a threshold for new classes and also the best way to bundle the outputs of different classifiers. Further, future work will focus on finding the optimal federation

parameters and dealing with clients who are online only very rarely and irregularly, and will address the question when it might make sense to split clients into clusters.

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An AI-Powered Network Intrusion Detection System in Industrial IoT Devices via Deep Learning

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Abstract. The widespread use of the internet, combined with the prevalence of cybersecurity threats such as botnets, has resulted in significant economic losses for manufacturing enterprises. An AI-powered network intrusion detection system is required to address the growing number of botnet attacks caused by increased machine-to-machine communication. Several Machine Learning (ML) and Deep Learning (DL) algorithms were used in this study to detect botnet attacks on seven IoT devices, with the goal of developing highly secure and accurate models for detecting security threats. After comparing its performance to other models, the proposed model was found to be highly performant, accurate, and robust for threat detection. After implementing different models, 2-CNN model demonstrated the highest accuracy level of 99.95% in DANMINI Video Door Phone Doorbell Hands-free Wireless Intercom. Furthermore, it was noted that the performance of the Deep Belief Network (DBN) model was inferior to that of other Deep Learning (DL) models in identifying Gafgyt botnet attacks.

Keywords: Deep Learning · Botnet Attacks · Detection Accuracy · Device Evaluation · IIoT Devices

1 Introduction

The incorporation of Industrial Internet of Things (IIoT) devices into manufacturing processes is accelerating the adoption of Smart Manufacturing, which uses sensors connected to a network to collect data. The data collected from such sensors can help improve operational efficiency [1]. Because of the increasing availability of low-cost sensors, advanced computing devices, and 5G networks, IoT devices have become commonplace in modern manufacturing systems [2, 3]. This reliance on networked and distributed control architectures raises concerns about the vulnerability of safety-critical systems to cyber-attacks, which can result in not only financial losses but also production

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delays and reputational harm [4]. Cyber-attacks, such as the Mirai bot in 2016, are constantly evolving and have become a pervasive threat, with one-third of all cyber-attacks targeting the manufacturing sector according to the U.S. Department of Homeland Security [5, 6]. It has been demonstrated that no month since 2013 has passed without a major online security breach exposing information for organizations or customers [7]. To combat these threats, effective protection and investigation countermeasures, such as network intrusion detection and forensic systems, are required [8, 9]. In this paper, we propose the use of novel, dependable, and effective Machine Learning (ML) and Deep Learning (DL) algorithms to compare and demonstrate how such methods can be used to improve the deterrence level of malicious attacks in industrial IoT devices.

2 Background

The recent surge in computing power and data collection has placed data analytics at the forefront of cyber-attack defense. Network security professionals leverage analytics for real-time threat detection and network traffic stream surveillance. Both machine learning (ML) and deep learning (DL) models are employed for malicious attack detection and are integrated with artificial intelligence (AI) to enhance analytics capabilities. DL, a subfield of ML, differs from ML in terms of learning mechanism and data/computing requirements. Figure 1 illustrates the relationship between DL, ML, and AI.

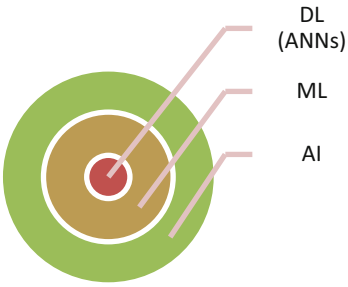

Fig. 1. Relationship between Deep Learning (DL), Machine Learning (ML), and Artificial Intelligence (AI).

In this study, a diverse set of models was utilized to predict IoT botnet attacks on seven sensors. To the best of our knowledge, these techniques have not been applied to the N-BaIoT dataset. The information related to the implemented models can be found in the methodology section.

3 Methodology

3.1 Preprocessing of the Dataset

In this study, the "N-BaIoT" dataset, a compilation of network traffic data collected from nine commercial IoT devices infected by botnets was analyzed. The dataset encompasses multiple sub-datasets that capture traffic flow patterns during botnet attacks or normal network traffic. The nine devices include: DANMINI Video Door Phone Doorbell,

Ecobee Smart Thermostats, Ennoi Monitor Video Doorbell Intercom System, Philips Baby Monitor, Provision PT737E and PT838 Security Cameras, Samsung SNH-1011N IP Wireless Smart CAM, and SimpleHome XCS71002 and XCS71003 Security Cameras. The data was generated by two notorious botnets: Mirai and Gafgyt. The 115 input features and one output feature were used to categorize the network traffic into three outcomes: Mirai and Gafgyt botnets, and benign network traffic, in which no attacks were observed. Further information about the dataset can be found in [10].

To ensure better classification accuracy, the data was downsampled to balance it prior to the application of our models. The numerical features, which had varying scales due to different units, were standardized using the SKlearn Standard Scaler. This involved subtracting the mean and scaling to unit variance by dividing all values by the standard deviation [11]. As both ML and DL models require numeric features, the data was preprocessed accordingly. An 80/20 split was employed to form the training and test datasets, considering the large scale of the dataset. The models used in this study were divided into two categories: ML models using Scikit-learn and DL models using TensorFlow.

3.2 DL Models with TensorFlow

DL models require all features to be numeric. For categorical features where no ordinal relationship is in existence, the integer encoding (assigning an integer to each category) can be misleading to the model and results in poor performance or unexpected results (predictions halfway between categories) as it allows the model to assume a natural ordering between categories. In this case, a one-hot encoding can be applied to the categorical representation [12].

3.3 Multilayer Perceptron (MLP)

Multi-Layer Perceptron (MLP) is introduced as a widely used class of feedforward Artificial Neural Network (ANN). MLP enables AI systems to perform data-based problem solving by allowing computers to program themselves based on input data. This architecture has the ability to be used for both supervised and unsupervised learning methods, and consists of an input, hidden, and output layer. The learning process of MLP resembles the development of a newborn's brain, as it transforms input variables into output variables through layers of neurons with randomly initialized weights. This mechanism has been extensively studied and documented in literature [13].

3.4 Recurrent Neural Networks (RNN)

The structure of neural networks can vary, with the two main types being Feed-Forward Neural Networks (FFNNs) and Back Propagation Neural Networks (BPNNs). FFNNs process data in a linear manner from input to output, whereas BPNNs process data in both forward and backward directions, enabling cyclic data flows. Recurrent Neural Networks (RNNs), which are a type of BPNN, have been used in applications such as natural language processing and speech recognition due to their ability to process data in cyclic flows. RNNs have been demonstrated to be effective in detecting malware based on network behavior, with high precision rates reported in previous studies [14, 15].

3.5 Long Short Term Memory (LSTM)

Long Short Term Memory (LSTM) refers to neural networks that have the capacity to learn order dependencies for sequence prediction by incorporating back propagation (BP) signals of previous neurons in the current processing. LSTM can be integrated with other neural network architectures, and its implementation can be seen in applications such as text prediction, machine translation, and speech recognition [15]. The use of LSTM mitigates the vanishing information problem in neural networks [16].

3.6 Attention-Based Long Short Term Memory (ALSTM)

The Attention-based Long Short-Term Memory (ALSTM) is a technique that enhances the capability of learning order dependencies in long sequence predictions. It merges the attention mechanism with the memory function of LSTM to address the issue of insufficient attention to critical features in intrusion detection [17]. ALSTM has been applied in detecting insider cybersecurity threats [17].

3.7 Fully Convolutional Neural Network (FCN)

The Fully Convolutional Network (FCN) is a variant of Convolutional Neural Network (CNN) that lacks dense layers and has a more lightweight structure [18]. The absence of dense layers leads to lower computational demands and improved efficiency in terms of processing power, runtime, and memory utilization compared to CNN. As a result, FCN has been adopted in biometric applications such as fake fingerprint detection due to its advantages over CNN and other neural network models [19].

3.8 Deep Belief Network (DBN)

DBN is a type of feed-forward network, where information flows from one layer to another without looping back. It is composed of multiple Restricted Boltzmann Machines (RBM), which are the simplest form of Multi-layer Perceptron (MLP) model in neural networks. RBM has been applied in real-life smartphone malware detection and has demonstrated high detection rates with low False Positive Rates (FPR) [20]. DBN has been used for intrusion detection using NSL-KDD and KDD 1999 datasets [21].

3.9 Probabilistic Neural Network (PNN)

PNN is a supervised learning approach based on Bayes theorem for pattern classification. The output layer selects the class with the highest probability. PNN is a good choice for the study as it decreases misclassification rate with increasing number of input variables and the output class in this case has only 3 classes [22].

3.10 Radial Basis Function Network (RBFN)

RBFN is a three-layer feed-forward NN, with input, hidden, and output layers. It is known for its non-linear activation functions and fast learning speeds. RBFN typically requires less time to reach the end of training compared to MLP. RBFN has been applied in various fields such as intrusion detection, medical field, and forecasting and demonstrated ability to detect novel attack types [23].

3.11 Learning Vector Quantization (LVQ)

LVQ is a type of Artificial Neural Network (ANN) that consists of an input layer and an output layer. It operates similarly to K-Nearest Neighbors (KNN) by dividing a large set of points into regions with approximately the same number of closest points. LVQ has been used in a variety of applications such as forecasting, prediction, and modeling [24].

4 Results and Discussion

Table 1 presents the average precision, recall, and accuracy values for the proposed DL models in the DANMINI Video Door Phone Doorbell Hands-free Wireless Intercom.

Table 1. Average accuracy, precision, and recall values for DANMINI doorbell for all DL models.

Model	Accuracy	Precision	Recall
RNN	90.39%	90.40%	90.38%
LSTM	94.76%	94.77%	94.73%
ALSTM	88.34%	88.34%	88.33%
MLP	99.31%	99.31%	99.31%
MLP-LSTM	95.28%	95.29%	95.28%
MLP-ALSTM	84.75%	84.75%	84.75%
CNN-LSTM	95.56%	95.57%	95.55%
CNN-ALSTM	95.06%	95.06%	95.06%
2-CNN	99.95%	99.95%	99.95%
2CNN-LSTM	88.98%	88.99%	88.98%
2CNN-ALSTM	94.74%	94.74%	94.73%
LSTM-FCN	90.92%	90.92%	90.92%
ALSTM-FCN	90.93%	90.92%	90.92%
DBN	48.90%	48.91%	48.89%
PNN	92.73%	92.74%	92.75%
RBFN	93.56%	93.52%	93.52%
LVQ	76.57%	76.55%	76.59%

The DBN model demonstrated subpar performance in the detection of Mirai botnet attacks across all devices, with the exception of the Philips Baby Monitor. The DL models displayed a lower detection accuracy for Mirai botnet attacks in the Doorbell and Philips Baby Monitor devices compared to other devices. The RNN model achieved a detection accuracy below 90% for Mirai botnet attacks in the Doorbell and Philips Baby Monitor devices, while achieving over 97.5% accuracy in other devices. The LVQ model displayed a Mirai botnet detection accuracy of 80% in both the Doorbell and Philips Baby Monitor devices, 85% in the PT737E Security Camera Device, 92.5% in the Simple Home 1002 Security Camera, 95% in the Simple Home 1003 Security Camera, and almost 98% in the remaining two devices. Variations in model performance across different devices can be observed in the CNN-LSTM models, while the CNN model

demonstrated 100% accuracy in the detection of Mirai botnet attacks in the Doorbell, Philips Baby Monitor, PT838 Security Camera, and Simple Home 1002 Security Camera. On the whole, DL models, excluding the underperforming models, displayed up to 99% accuracy in the detection of Mirai botnet attacks across several devices.

It was also observed that the DBN model was the weakest performer in the detection of Gafgyt botnet attacks compared to other DL models. Upon closer inspection, the low accuracy of less than 1% for the DBN model in detecting Gafgyt attacks in the Philips Baby Monitor suggests a correlation between model accuracy and the type of botnet being detected. The LVQ model recorded a 60% detection accuracy for Mirai botnet attacks in the Doorbell and Philips Baby Monitor devices, 70% in the PT838 Security Camera Device, and closer to 90% in the remaining devices. Despite their underperformance in comparison to other DL models in detecting both Mirai and Gafgyt botnet attacks, the DBN and LVQ models demonstrated noticeable differences in accuracy per botnet type and across different devices. Overall, excluding the DBN model for some devices, DL models demonstrated better performance in the detection of Mirai botnet attacks compared to Gafgyt botnet attacks. Table 2 provides a summary of the average detection accuracy for Mirai and Gafgyt botnet attacks across all DL models per device.

Table 2. Average detection accuracy for Mirai and Gafgyt botnet attacks in each device.

	Doorbell	Philips Baby Monitor	PT737E Security Camera	PT838 Security Camera	Thermo-stat	SH 1002 Security Camera	SH1003 Security Camera
Mirai	85.13%	89.87%	96.73%	99.12%	98.84%	98.72%	98.85%
Gafgyt	85.70%	87.35%	97.18%	95.75%	97.57%	97.50%	96.91%

5 Conclusion

In this paper, an AI-driven network intrusion detection system was used to counter the escalating number of botnet attacks that arise from the growing machine-to-machine communication. Various Machine Learning (ML) and Deep Learning (DL) algorithms were employed to identify botnet attacks on multiple IoT devices, with the aim of creating models that are exceedingly secure and precise in detecting security threats. The results demonstrated that 2-CNN model was the accurate model in DANMINI Video Door Phone Doorbell Hands-free Wireless Intercom with the accuracy value of 99.95%.

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Automated Detection of Refilling Stations in Industry Using Unsupervised Learning

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Abstract. The manual monitoring of refilling stations in industrial environments can lead to inefficiencies and errors, which can impact the overall performance of the production line. In this paper, we present an unsupervised detection pipeline for identifying refilling stations in industrial environments. The proposed pipeline uses a combination of image processing, pattern recognition, and deep learning techniques to detect refilling stations in visual data. We evaluate our method on a set of industrial images, and the findings demonstrate that the pipeline is reliable at detecting refilling stations. Furthermore, the proposed pipeline can automate the monitoring of refilling stations, eliminating the need for manual monitoring and thus improving industrial operations' efficiency and responsiveness. This method is a versatile solution that can be applied to different industrial contexts without the need for labeled data or prior knowledge about the location of refilling stations.

Keywords: Industry 4.0 · Refilling Stations · Assembly Lines · Computer Vision · Artificial Intelligence

1 Introduction

Industrial Revolution refers to significant changes in industry or economy brought about by new technologies and methods. There have been four Industrial Revolutions, with the Fourth Industrial Revolution, also known as Industry 4.0, currently underway.

The term "Industry 4.0", describes the present trend of automation and data sharing in industrial technology, including advancements in Artificial Intelligence (AI), the Internet of Things (IoT), and big data analytics [1]. These technologies are being used to improve the efficiency, accuracy, and responsiveness of supply chain management, leading to significant improvements in productivity and profitability [2]. In addition, Industry 4.0 is often characterized by the integration of advanced technologies into traditional

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manufacturing and business processes, resulting in a more connected and intelligent system.

Assembly lines are a manufacturing process in which a product is assembled from components or sub-assemblies at various stations as it moves through the line, resulting in a high degree of standardization and specialization, which leads to increased efficiency and lower production costs [3]. As Industry 4.0 advances, companies seek ways to integrate new technologies into their operations to improve efficiency and responsiveness [4]. One of the areas where new technologies can be applied is in refilling stations, where manual labor is often needed to monitor and replenish materials, leading to potential production delays. However, one potential issue affecting assembly lines is the lack of incoming raw materials, which can occur due to a late notice of low supply at the refilling station.

A refilling station, illustrated in Fig. 1, is a point on the production line where materials or supplies are replenished to keep the production process going. It is typically located near the point of use on the production line. It may be equipped with storage areas, handling equipment, and automation technology to monitor and alert workers when materials need to be refilled.

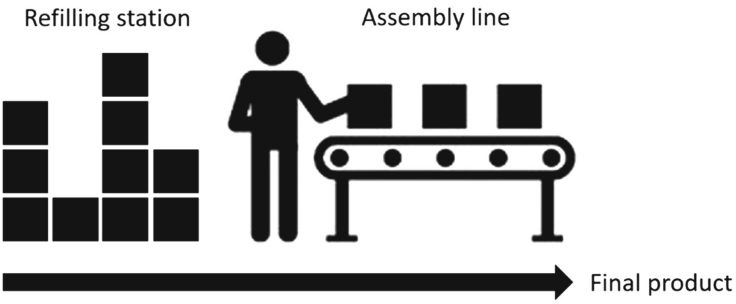

Fig. 1. Depiction of a refilling station within an assembly line.

Many assembly lines have a physical limit to how much space can be allocated for components due to workers' accessibility [5]. Besides that, in many industries, the refilling stations are located far from the main warehouse, and because of this, when they reach a low level, it will take some time before someone realizes the lack of supply and subsequently fill the needs. This waiting time in some companies has a huge impact: production stops without the necessary components in the right places. This situation can also be avoided by implementing a system that anticipates when resupply will be required based on previous consumption data, allowing businesses to prepare the supply in advance.

Human labor, such as laborious or repetitive jobs, which can slow production, is a challenge in Industry 4.0. To prevent such production setbacks, a potential solution is to use sensors that can detect the lack of materials and take some action when that happens. By removing this repetitive and boring task, the operators can focus on more important work. For example, the operator could only have to act after receiving a warning of a supply shortage and then take care of the contact with the provider, as opposed to having

to stop their work and frequently go to the refilling station and alert them as necessary (which can also be automated).

This paper aims to examine the operation and design of a system for automatically detecting refilling stations in industrial assembly lines. This study will concentrate on building and implementing a sensor-based neural network system that can automatically recognize refilling stations, minimizing the need for manual labor and improving efficiency.

The paper will examine how we can detect refilling stations with AI automatically without training the AI for that specific problem, discussing the technical details and requirements for its implementation. It will also provide valuable insights for managers and industry leaders on effectively implementing such a system in their operations.

2 Related Work

The filling level of resources in an industry is typically measured by monitoring the number of resources present at a given time. This can include raw materials, finished goods, or inventory items. The measurement can be done manually or through automated systems, such as sensors and software. The measurement data can be used to track trends, identify bottlenecks, optimize production processes, and forecast future demand.

Among the subfields of AI is CV, which enables machines to process and comprehend visual information from the world, such as images and videos. It involves utilizing techniques such as image processing, pattern recognition, and machine learning or deep learning to extract useful information from visual data [6]. The use of CV in industries can help reduce errors, improve quality control, and increase production speed. CV and AI algorithms can be trained to detect refilling stations using both supervised and unsupervised approaches. Supervised training relies on labeled data, while unsupervised training utilizes unlabeled data. Even though most CV applications use supervised training because of its better performance, labeling data requires time and resources that are not always available. Additionally, it can be challenging for a supervised model to detect an object that deviates slightly from the examples it was trained on. On the other hand, unsupervised learning allows the detection of various forms of the object in question. Still, its performance may vary depending on the specific task and implementation, and it should be evaluated case-by-case [7].

Although there has been limited research on monitoring refilling stations, the adoption of Industry 4.0 practices has led to a greater emphasis on the monitorization of assembly lines. Sensor-based approaches, like RFID, gyroscopes, and accelerometers, have been widely implemented in this field [8–10]. In addition, Computer Vision (CV) and AI techniques have also been applied in assembly line monitoring research [11–13]. While sensor-based approaches have been utilized for specific tasks such as tracking objects [8], counting objects [9], and risk management [10], the application of CV and AI in assembly line monitoring research has opened up new opportunities. These more advanced solutions, such as assembly line automation [11], stock assessment [12], and performance measurement [13], have been made possible with the use of CV and AI techniques.

3 Methodology

Unsupervised detection of refilling stations presents several challenges due to the dynamic nature of industrial environments. Supervised methods rely on labeled data and prior knowledge of the location of refilling stations, which may not be available in all scenarios. On the other hand, unsupervised detection does not rely on labeled data and can be applied to any industrial scenario, making it a more versatile solution.

One of the main challenges of unsupervised detection is identifying and distinguishing refilling stations from the background and other objects in the environment. This task is particularly difficult in industrial environments where lighting, noise, and other factors can affect visual data. Additionally, refilling stations may not always have a consistent appearance, making it difficult to develop a single model that can accurately detect them in distinct scenarios.

Our pipeline (Fig. 2) is designed to detect refilling stations by identifying changes within images captured by a stationary camera.

The idea behind this approach is that refilling stations will likely experience more changes than other areas within the camera's field of view. To accomplish this, we use a combination of image processing, pattern recognition, and machine learning techniques to extract useful information from visual data, which will be explained in detail. Furthermore, by using an unsupervised approach, we can detect refilling stations in an industrial scenario without the need for labeled data or prior knowledge of their location. This way, we can effectively address the challenges of unsupervised detection and detect refilling stations in a dynamic and versatile way.

The automatic and unsupervised detection of refilling stations is a challenging task. Our solution uses a pipeline of steps that includes image resizing, background generation and mask generation with changes, K-nearest neighbors classification, cumulative mask generation, and final mask creation to accurately identify refilling stations in visual data. These steps work together to effectively detect refilling stations and reduce the risk of errors or misclassifications.

The process starts by capturing all images using a stationary camera in an industrial facility in Vila Real, Portugal, and resizing them to a resolution of 320×240. These images are input into a deep learning model [14] entitled AE-NE by its authors. The model was developed to distinguish between foreground and background objects in sequences of images. It makes use of an autoencoder architecture, a class of neural networks that have been trained to recreate the input image. The model uses a technique called background reconstruction, in which the background is estimated using the current and previous frames. Another method employed is background noise estimation, which aids in determining the amount of background noise in a frame sequence. The model also uses an error threshold, calculated using the L1 error, which measures the difference between the estimated and actual backgrounds. Following that, a mask reflecting the alterations in the background is generated for each frame using this error threshold. The outcome is a mask for every frame that draws attention to where the background changes.

These masks are combined to create a cumulative mask, which will help eliminate areas with minimal changes and reduce noise and false detections.

In another pipeline branch, the dataset images' means calculated and fed into a KNN algorithm [15]. This algorithm classifies each pixel in an image based on the majority

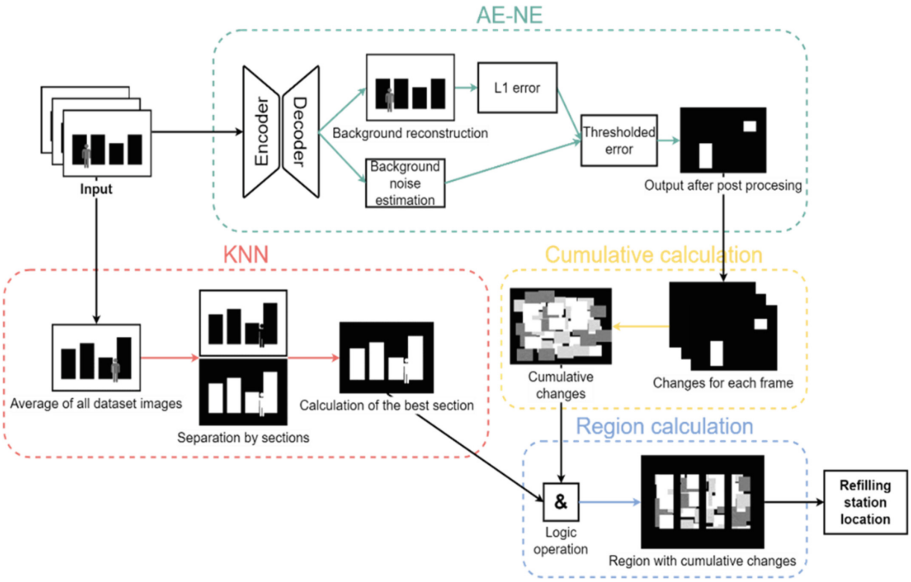

Fig. 2. Suggested pipeline for the unsupervised identification of refilling stations in an industrial scenario, comprising four key components: Autoencoder-based background reconstruction and fore-ground segmentation with background noise estimation (AE-NE), a K-nearest neighbors (KNN) algorithm, and cumulative mask and region computations.

class of its k closest training examples. Ultimately, it exports K images, each representing a section of the image. So, for example, if we want three sections (K = 3), we will get three binary images, each with its corresponding section in white and the rest in black. In this case, K = 3 was chosen because that allowed the algorithm to extract the floor, the wall, and the object of interest (refilling station).

Finally, the area in the cumulative mask that has experienced the greatest changes is calculated to determine the section with the most modifications. With this data, a final mask that only contains this region and the relevant alterations is produced. As a result, areas where changes are brought about by human movement, rather than changes at the refilling station, can be removed, and only the area with the most changes is shown.

4 Results and Discussion

Upon completion of the model's execution, the following results were obtained (Fig. 3):

As we can observe, the output obtained does not fully capture the filling station but depicts most of it. Some of the leftmost and rightmost portions of the refilling station are not detected; in this case, this can be due to how the refilling stations are operated since some columns are used more than others (as we can see in the cumulative mask). A bigger dataset with equal changes happening in all the rows could help resolve this problem. This issue can also be addressed by adjusting the threshold that selects the minimum intensity of white to be considered a refilling station. This threshold value

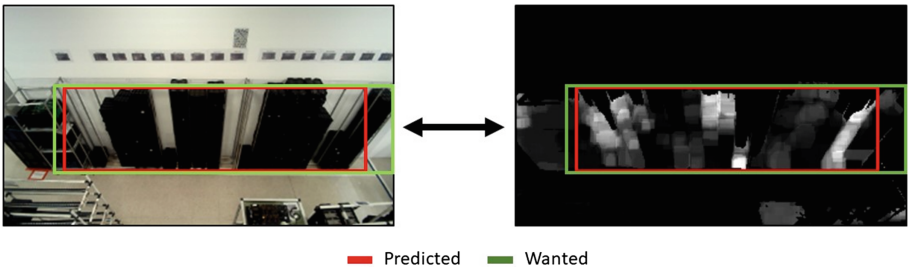

Fig. 3. Comparison of the input to the model with the resulting output. The red box represents the predicted location of the refilling station, while the green box indicates the actual location of the refilling station.

should be carefully selected because a small value could select areas not wanted, and a big value would not be able to surround the reffiling station entirely.

These results show that the unsupervised detection of refilling stations in an industrial context is a challenging task. Still, the proposed pipeline, which uses a combination of image resizing, background generation, and mask generation with changes, K-nearest neighbors classification, cumulative mask generation, and final mask creation, was able to detect refilling stations in visual data reliably.

Despite the challenges, the proposed pipeline has shown promising results in detecting refilling stations. It's crucial to remember that the model can still be improved, such as addressing the issue of capturing the entire refilling station and reducing noise. One way to achieve this could be to fine-tune the model's parameters and adjust the thresholds used in the pipeline. Additionally, incorporating more data and increasing the sample size could lead to more accurate and robust results.

It should also be noted that the suggested pipeline is flexible enough to be used in various industrial applications. It does not rely on labeled data or prior knowledge of the location of refilling stations, which makes it more adaptable to different environments. Additionally, applying unsupervised detection in refilling stations can help companies improve their efficiency and responsiveness by predicting when resupply will be needed based on past consumption data, allowing for advanced preparation of supplies.

5 Conclusion and Future Work

In this paper, we proposed an unsupervised detection pipeline for identifying refilling stations in an industrial context. The preliminary results showed that the proposed pipeline was able to detect refilling stations in visual data. However, it still has room for improvement, such as the use of techniques that could improve the performance of the methodology in the capture of the entire refilling station and reducing noise.

Besides that, in future work, it would be beneficial to test the proposed pipeline in different industrial environments and settings to evaluate its performance and adaptability in various scenarios. For example, this could include testing the pipeline in different lighting conditions with different types of cameras and refilling stations.

Lastly, another area of future work would be to develop the pipeline further to detect the filling level of each row in the refilling station. This could involve using additional sensors or image processing techniques to accurately measure the filling level. Once the filling level data is obtained, it could be used to implement anomaly detection or predictive models to detect when resupply is needed before the refilling station runs out.

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Simulation-Based Approach to Assess Impact of Increasing Skip Capacity for Underground Mining

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Abstract. Material excavated in underground mines must be hoisted to the surface level for processing and distribution. The capacity of these hoisting facilities, known as skips, can be a limiting factor that determines the rate at which excavated material can be removed to the surface. This paper presents the application of discrete event simulation to study the operations of an underground coal mining system to evaluate the impact of increasing skips capacity, together with adding buffers ahead of skips, and any bottlenecks that will be encountered. Different scenarios are considered to evaluate any variation in performance based on the area of the mine being excavated. The results reveal that adding a new skip facility can help increase monthly production output by more than 16% compared to the current levels, indicating a very favorable return on the investment. Findings also show that overall utilization of the skip facilities declines and that expected output is driven by the effective carrying capacity of the belt conveyors. Further research can be conducted to determine the effective buffer capacity and also the optimal effective belt conveyor carrying capacities to maximize production output.

Keywords: Simulation · mining · skips · belt conveyor

1 Introduction

Underground mining is one of the methods used for the extraction of various minerals from the ground. Material extraction from underground mines can be done either using discrete systems with trucks and loaders or continuous systems comprising of continuous excavation units and networks of belt conveyors. Underground mines also require mechanisms to transport the mined minerals to the surface. These also can be discrete units such as trucks and skips or belt conveyor-based continuous systems. Intermediate storage buffers or bunkers may also be used to temporarily hold material when it cannot be transported due to unplanned or scheduled downtime. The production throughput

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from such mining operations depends on many factors including rates at which material is extracted using the mining units, the types of transport systems used and their failure rates (relevant for continuous belt conveyor systems), distances from the mine faces to the location(s) where material is moved to the surface, etc.

Simulation is one of the techniques that can be used to study the performance of mining systems and for effective decision making related to system design and expansion, operations planning, performance improvement, and overall system optimization. Because most mining systems involve a combination of continuous excavation systems and discrete units interfaced with them, they can be modeled using discrete event simulation (DES) techniques. Early applications of DES to study mining operations are well documented [1, 2] and have been used to assess the impact of decisions related to mine design, operations planning, and optimizing overall performance [3–6]. In some more recent studies Yilmiz and Erkayaoglu [6] used DES to assess the daily performance of a longwall shearer taking into account the impact of several system elements such as belt conveyors, stage loader, and armored face conveyors. The influence of material production rate on profitability is investigated in Huerta et al. [8] to demonstrate that as investments in equipment fleet (i.e., costs) increase, profitability increases. Hou et al. [9] used DES to optimize the number of loaders and trucks required for an underground mine. They coupled DES with Monte Carlo simulation to address the uncertainties associated with transportation parameters.

This paper presents the application of DES to study the operations of an underground coal mining system to evaluate the impact of increasing the capacity for transporting material from the mine to the surface level and any bottlenecks that will be encountered. The system studied in this paper is a large-scale underground longwall mine in the Eastern US with capital equipment investment exceeding $150 million and an average output of 5 million tons/year. The mine uses one longwall shearer (LS) unit and five continuous miners (CMs). The system currently also comprises of three different conveyor belt systems, two intermediate bunkers, and one twin-skip system to transport coal to the surface (See Fig. 1). The conveyors are made up of multiple interconnected segments with the total distance of conveyance from excavation to extraction to the surface being as much as 20 miles.

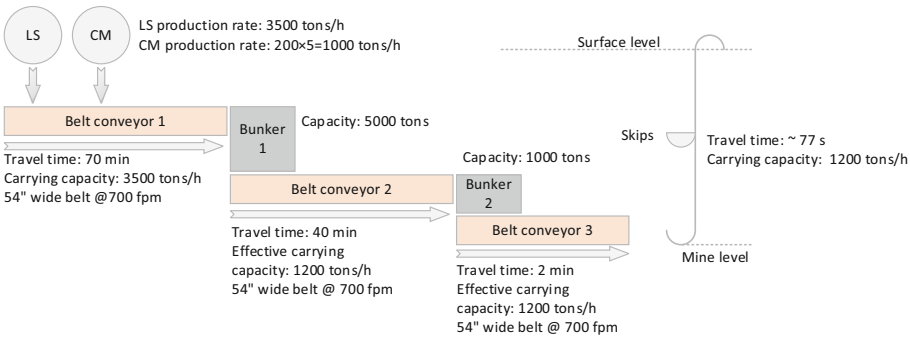

Fig. 1. Current configuration of mining units, conveyors, and bunkers with production and transfer rates and travel times (modified from Hong et al., [10])

The mine has been exploring different design improvements to increase coal throughout and overall revenue generated. Based on the findings of a previous study the mine management concluded that the investment required to increase the capacity of Bunker 2 was not justifiable based on the expected revenue increase [10].

This paper describes the application of DES to evaluate the impact of some new design changes in the underground mine intended to increase production output, the findings from the analysis and discussion of the results in comparison with the expected performance. Section 2 describes the system design changes, the methodology followed to develop the DES model and relevant mine system parameters. A discussion of results is presented in Sect. 3. Conclusions and future work are presented in the last section.

2 System Design Changes and Modeling Methodology

As an alternative to increasing the capacity of Bunker 2, mine management is now interested in evaluating the impact of installing an additional skip facility, i.e., another twin-skip system, with the same capacity as the existing unit together with small buffers (500 tons) ahead of each to increase production output. Simultaneously, the operation of Bunker 2, which has been experiencing more frequent breakdowns, is to be phased out. The distance to the new skip facility will be the same as the current one (i.e., 2-min travel time, see Fig. 1) and a new conveyor (belt conveyor 4) with the same carrying capacity will be installed. The effective carrying capacity of belt conveyor 2 (in Fig. 1) is currently limited to 1200 tons/h because that is the maximum capacity that can be accommodated with the existing skip facility. The addition of the second skip facility will increase this limit to 2400 tons/h. As such, the rate of flow on belt conveyor 2 can effectively be increased to 2400 tons/h. However, the capacity of each skip facility limits the effective carrying capacity of belt conveyors 3 and 4 to 1200 tons/h. The flow from belt conveyor 2 will be split equally between conveyors 3 and 4 at the point where Bunker 2 currently is placed but is to be removed in the future configuration.

The operations in the mine studied represent a hybrid system with continuous (LS) and discrete flow units. Shuttle cars are used to transport the material excavated by the CM units and therefore this conveyance can also be considered as a discrete flow of material. The skips used to hoist the material to the surface are also discrete flow units. Therefore, similar to the approach followed in previous studies with such combined systems, DES is used in this study to model and evaluate the system of interest. Material flow in DES is represented through discrete entities arriving in the system according to a specified inter-arrival rate. To model the continuous flow in DES the quantity of material to be represented per discrete unit must be established. Signifying a very small quantity of material per discrete unit increases the accuracy but requires significant computational effort and vice versa. Considering the accuracy desired, computational effort required, and the capacity of each skip (25 tons), it was decided that each entity in the DES simulation will represent 12.5 tons of raw coal. Thus, each skip system will hoist two entities to the surface in each cycle.

Information feedback is critical to starting and stopping the mining operations upstream (at the LS and CM) depending on the fill levels at the intermediate storage bunkers. In addition, the operation of the belt conveyors must also be stopped/started

depending on the fill levels of the Bunker 1, Buffer 1 and Buffer 2 placed ahead of the skip facilities. The material and information flow between these different units in the mine is illustrated in Fig. 2. As indicated, the coal is routed to Buffer 1 and Buffer 2 alternatively. If both buffers are full then belt conveyor 2 will be stopped.

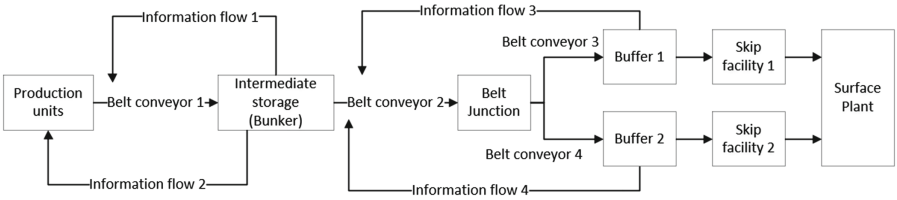

Fig. 2. Material and information flows in the mine simulation model.

Production rates for the mining units and data related to conveyors is shown in Table 1. The belt conveyor to the new skip facility is assumed to have the same performance as the existing one leading to the first skip facility.

Table 1. Production rates and conveyor data.

	Production Rates (tons/h)		Conveyor belt breakdown statistics		
	LS	CM (average/unit)	Belt 1	Belt 2	Belts 3 & 4
Minimum	960	57	0.3 times/h	0.12 times/h	0.27 times/h
Average	1480	97	110 min	60 min	48.8 min
Maximum	2167	214	48 min	26 min	58 min

Data related to the performance of skips is included in Table 2. It is assumed that the new skip facility to be installed will have performance identical to the existing unit.

Table 2. Skips performance data.

Skip operation		Skip breakdown	
Cycle time	77.5 s/cycle	Frequency	0.11 times/shift
Capacity	25 tons/skip	Average	80 min
Max. Skip rate	372 skip-loads/shift	Standard deviation	133.87 min
Avg. Skip rate	331 skip-loads/shift		

The values used for the key parameters in the simulation model are summarized in Table 3. For the simulation, the region from which coal is mined currently (which is much farther away) using one skip facility is used as the baseline (scenario 1). For

comparison purposes, the performance is also evaluated for the current mining region when two skip facilities are used (scenario 2). The underground excavation area of the mine spans a very large region. Thus, mining operations are periodically moved from one region to the next, once the coal has been excavated from that region. This shift affects the distance over which the mined material must be transported before it reaches Bunker 1. To account for the various regions from which coal will be mined in the future, three different scenarios (scenarios 3–5) are considered. Details for each of these scenarios is shown in Table 4.

Table 3. Simulation model parameters

Parameter	Description
One entity	12.5 tons of material
Interarrival time for LS	TRIA (20.88, 33.75, 46.88)
Interarrival time for CM	TRIA (42, 78, 158)
Warm-up period	2 h
Run length	720 h (30 days with three 8 h shift)
Replications	30

Table 4. Simulation scenarios analyzed.

Scenario	Description
1	One skip facility and the distance from production area to bunker is 40,500 ft
2	Two skip facilities and the distance from production area to bunker is 40,500 ft
3	Two skip facilities and the distance from production area to bunker is 3,800 ft
4	Two skip facilities and the distance from production area to bunker is 5,300 ft
5	Two skip facilities and the distance from production area to bunker is 6,800 ft

The mining system with the described characteristics is modeled using the Rockwell Arena® DES. System results are collected considering performance of the mine for 30 days (one month) with three, 8-h shifts/day. As indicated in Table 3, thirty replications were simulated for each scenario studied.

3 Results and Discussion

A screenshot of the simulation model animated interface is shown in Fig. 3. The results obtained from the simulation runs for the different scenarios are shown in Table 4. In addition to the average, the 95% confidence interval is shown for the monthly production rate, total skip loads/shift and the average level in bunker 1. The variation of monthly production rate and total skip-loads/shift are also visually presented in Fig. 4. Monthly

production data from the mine were used to validate the simulation results for the baseline scenario. The monthly output is comparable to the average monthly performance currently observed in the mine with the LS utilization reaching 53.8% producing 746,573 tons/month and material hoisted to the surface at an average rate of 332 skip-loads/shift.

The main difference between scenarios 1 & 2 is the addition of the second skip facility. As a result, the effective belt conveyor 2 capacity from Bunker 1 to the belt junction (when material gets split to flow to the two skip facilities) is now increased to 2400 tons/h. This is reflected in the increased production output and higher number of skip-loads/shift. Also noteworthy is the increase in the LS utilization rate. The findings also reveal a significant drop in the average level of material in Bunker 1 for scenario 2 indicating very little accumulation. This could be due to the fact that the effective carrying capacity of belt conveyor 2 has increased (to 2400 tons/h) and the total average production rates from the LS and CM combined (1480 + 5 x 97 = 1965 tons/h, based on data shown in Table 1) is below that value. Thus the need for material accumulation in Bunker 1 is now significantly low. While the capacity to hoist material to the surface has doubled with the addition of the second skip facility, the rate at which material is transported up to the buffers is limited by the effective carrying capacity set for belt conveyor 2. The skip utilization therefore drops to 52.4% with Scenario 2 compared to 89.2% for scenario 1.

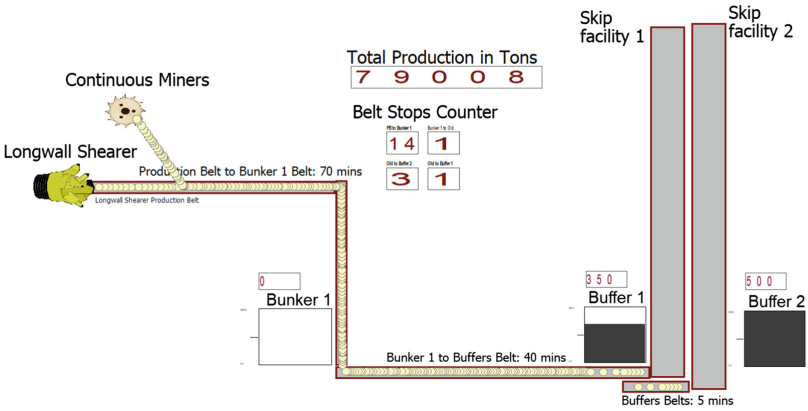

Fig. 3. Animation of coal transportation in the simulation model.

The variation of monthly production output, skip-loads/shift and other metrics for scenarios 3–5 are very much comparable to scenario 2. While the distances for the scenarios 3–5 are lower, under the current settings, the mine production is primarily driven by the effective carrying capacities for the belt conveyors and the rate at which material is hoisted by the skip facilities. Though the material transport distances for scenario 2 (40,500 ft.) and for scenarios 3–5 (average 5,300 ft.) are very different, the variation in the monthly production output between them (considering the average monthly production for scenarios 3–5) is only 1.1%.

The average increase in monthly production with two skip facilities for all future scenarios considered is greater than 120,000 tons/month, or by more than 16%, compared

Table 5. Simulation results.

Scenario	Monthly Production (tons)	Total Skip-loads/ shift	Skip Utilization (%)	LS Utilization (%)	Bunker 1 Average Level (tons)
1	746,573±5,118	332±2.27	89.2	53.8	1,533±27.75
2	877,403±8,483	390±3.99	52.4	68.1	54.6±7.88
3	867,506±9,938	385±4.57	51.7	67.2	53.7±1.25
4	867,115±12,141	384±4.43	51.6	67.2	52.9±1.25
5	868,184±8,037	386±3.90	51.9	67.3	57.9±8.34

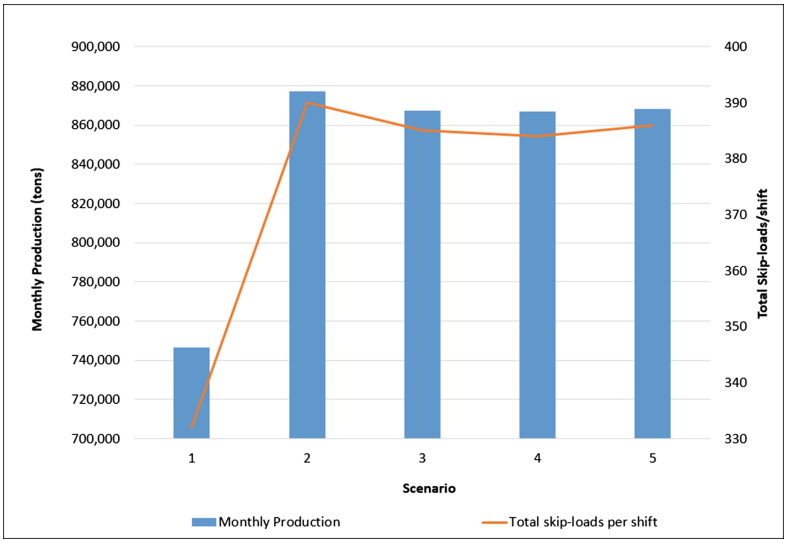

Fig. 4. Variation of monthly production and total number of skip-loads for different scenarios.

to current operations with one skip facility. Given the current market price of about $400 per sellable ton of coking coal [10] (the type produced by the mine), this will generate an additional revenue of over $20 million/month. These results provide the mine management the information necessary to evaluate the benefit of installing a second skip facility and to assess return on investment.

4 Conclusions and Future Work

This paper presented a simulation-based approach to evaluate the impact of installing additional capacity to hoist material from an underground coal mine. Different scenarios representing current and future operations were modeled using DES. The findings reveal that the addition of the second skip facility can increase monthly output by over 120,000 tons/month.

The results also indicate that the production output is limited by the effective belt conveyor carrying capacities. In the current studies they were limited based on the

maximum carrying capacity of the skip facilities. However, results indicate that the skip utilization rate is much lower after adding the second facility. In addition, the current analysis did not also assess whether increasing the size of the buffers ahead of the skip facilities can influence the monthly production output. Future studies will focus on more in-depth analyses of the skip facilities' performance. The feasibility to increase effective carrying capacities for the different belt segments without skip facilities reaching their maximum output will be investigated.

From an academic perspective, this work demonstrates how the discretization of continuous flow systems enables the modeling of hybrid discrete-continuous flow systems using DES. To the industrial community it shows the benefits of using simulation modeling to evaluate the impacts of major capital investments on mine operations, including production bottlenecks and equipment availability.

Acknowledgement. This work was partly supported by a grant from Coronado Global Resources.

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Others

The Potential of Digital Tools at the Service of the Mathematical Community

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Abstract. The success of digital technology in mathematics education includes the design of digital tools. In this article, we will describe two tools that are available for teaching and learning mathematics: the MathCityMap system, which includes the MathCityMap@home, and the ASYMPTOTE system. These systems consist of two components, namely a web portal for teachers and a smartphone App for students. We will feature the Digital Classroom which allows the teacher to monitor students' work and progress in real time. In addition, it allows students to interact not only with the teacher but also with each other. These systems meet the requirements of online and distance learning using smartphones.

MathCityMap and ASYMPTOTE systems were designed for the educational en-vironment, but they can be used in a variety of contexts. For example, in busi-nesses, decision-making.

Keywords: Mathematics · Digital tool · MathCityMap · ASYMPTOTE

MSC codes: 00A99 · 97U70

1 Introduction

Technological development is a reality today, and in the learning and teaching setting environment, technological progress is reflected in the development of the so-called information and communication technologies (ICT). Mobile technology – such as tablets and cell phones – has the potential to improve academic learning [1]. With mobile technologies, learning is accessible anytime and anywhere [2]. Combined with all aspects of learning, mobile learning will be a quality factor that will transform traditional learning. The advancement in mobile technology and generally portable devices slowly offsets the once relevant desktop computer [3].

In this article, we will describe two tools that are available for teaching and learning mathematics: the MathCityMap system (MCM - https://mathcitymap.eu/en/), which includes the MathCityMap@home, and the ASYMPTOTE system (https://www.asymptote-system.eu/en/portal-en/#!/). Both systems consist of two components, namely a web portal for teachers and a smartphone App for students. The Apps run on Android and iOS mobile devices.

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MathCityMap is a math trail management, where users can create tasks and trails and share them with each other or with the public through its App. It is a very important tool to be used by mathematics teachers, as it brings together an important recipe for the success of their students: outdoor education and technology. MathCityMap@home was an adaptation of MathCityMap during the Covid-19 pandemic.

The Covid-19 pandemic brought an increase in the digitization of materials and the use of learning software and platforms, there was a need to integrate technology in mathematics education. To cover the shortcomings of remote learning in mathematics education, the ASYMPTOTE system was born. ASYMPTOTE stands for "Adaptive Synchronous Mathematics learning Paths for Online Teaching in Europe" [4].

The paper is structured as follows: In the next section, we will describe these two tools that are available for teaching and learning mathematics: the MathCityMap system, which includes the MathCityMap@home, and the ASYMPTOTE system. We start by introducing and describing the MathCityMap system in Subsect. 2.1. In addition, we also refer to MathCityMap@home, in Subsect. 2.2. The aim of Subsect. 2.3 is to introduce and describe the ASYMPTOTE system. We end with some considerations and conclusions.

2 Mathematics Online Environments

2.1 The MathCityMap System

The MathCityMap system was created by Goethe University in 2012, and the final objective of this system is to develop a platform for the simplified creation and use of tasks that are part of mathematical trails. The system consists of two components: a web portal, as a tool to create and view tasks and trails, and an application for smartphones, as a tool to execute the trails (Fig. 1) [5].

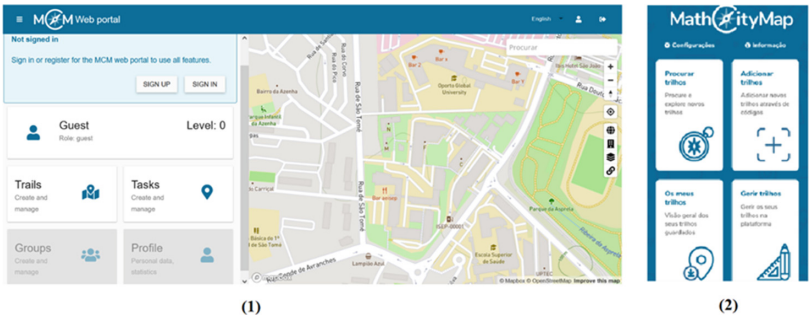

Fig. 1. (1) MCM Web Portal, (2) MCM App

The MathCityMap Web Portal (MCM) is designed for teachers and creative users who want to create their own tasks and trails and the MathCityMap App (MCM App) can be used by teachers, students, and anyone interested in experimenting math trails in the environment around them [6].

In the MCM Web Portal, there are several tasks grouped in different mathematical trails, and spread over different areas of mathematics. The trails are located in various

school spaces, city parks, historic buildings, markets, and tourist attractions, among other places (Fig. 2). The tasks are provided for all grade levels, with varying difficulty. The topics also vary, for example, there are tasks on geometry, statistics and probability, algebra, and arithmetic. In addition, the portal is equipped with guides and information about the mobile math trail system and with help for creating tasks [7].

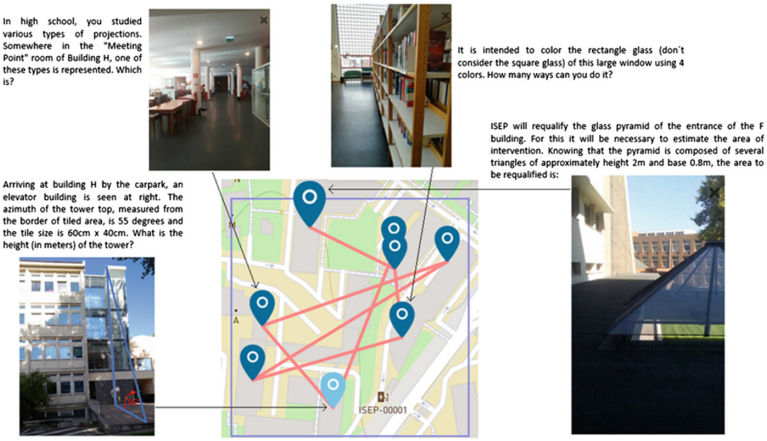

Fig. 2. An example of a trail in ISEP

A complete task includes an image of the object, the task description, suggestions that users can invoke when solving the problem, and an example of the solution. For an immediate validation of the solution, it is possible to choose different response formats [7]. In addition to creating original tasks, in the MCM portal, you can reuse public tasks to create your own trail. Each registered user can create their own tasks and publish them. To guarantee a certain quality in the public MCM tasks, some criteria that should be considered as a guide for the creation of tasks were defined [5]. Among the various criteria, it is worth highlighting the fact that the tasks must have a practical reference application and not be formulated in an excessively artificial way and that in order to solve a task, the user must be physically present at the place where the task will be performed. That is, the task data must be obtained only locally, which means that the image and description of a task should never be enough to arrive at the proposed task solution. Also, to solve a task, the user needs to have active participation, and do something (e.g., measure and count).

The MCM App is a navigation and feedback tool. After downloading the trail to your smartphone, no more internet connection is needed. Along the way, the App uses GPS to show you a map with the next task and its location. The application also provides immediate information about the introduced solution. In addition to solution navigation, and feedback the App offers up to three suggestions for each task [5].

The MathCityMap community is constantly growing, and all interested people can participate, creating and publishing their own tasks and trails. The basis for using the system is registration on the web portal and downloading the MathCityMap application onto the smartphone. The system is completely free and without advertising.

2.2 The MathCityMap@home System

Due to the Covid-19 pandemic, the educational situation has completely changed. Teaching moved from face-to-face to emergency remote teaching. With this change, students and teachers faced several difficulties that caused gaps in the quality of student learning. The MathCityMap@Home (MCM@home) system, based on the MCM system, was created to deal with these challenges. Thus, the MCM App - originally aimed at teaching math outdoors - is used here for distance education purposes. The workspace for teachers is still the MathCityMap Web portal. Here teachers can decide to use an existing learning trail or create their own tasks and learning trails [8].

MCM@home is technically based on the MCM system, but instead of using MCM for outdoor math learning, MCM@home uses the App for distance learning purposes. Students work independently and autonomously at home and, in the image or description of each task, all the necessary information for its resolution is given [9]. In MCM@home, as in MCM, students can invoke the formulation of tasks, hints, the sample solution and receive automatic feedback for their solution.

Users can easily transfer MathCityMap tasks to MCM@home in two steps: First, the MathCityMap task must be copied. Thus, all entries in the task form are kept. Second, the measurement data needed to solve the outdoor task is provided in the text or picture. By adding them, students can work on this task at home. To allow students to work autonomously, authors can optionally structure tasks into subtasks. Depending on their individual level, students can decide whether they want to work on the task as a whole or, if necessary, work on subtasks to solve the problem at hand. The MCM@home concept thus offers the possibility for underperforming students to work on the task at their own pace and receive stronger step-by-step guidance [9].

Both at MCM and MCM@Home, teachers can use the Digital Classroom feature, where all students work synchronously at a pre-defined schedule. Within the Digital Classroom, teachers can easily monitor the progress of students' work in real time. First, an overview of the class is provided, showing how the students solved the tasks in the learning trail created by the teacher for that class.

For each student, the number of tasks called, the quality of the solution entered per task, and each student's score are displayed. Students receive 100 points for each task correctly solved and lose points whenever they get an answer wrong or consult a suggestion (Fig. 3). Teachers also have the chance to view all interactions of each student with the App, such as the use of hints or sample solutions. In addition, in the Digital Classroom, a chat is implemented to allow direct student-teacher interaction, despite the spatial separation.

By using the chat function to send text or voice messages as well as images, teachers can directly support their students' task solving process [8]. To increase the motivation of students, the Digital Classroom feature can use some gamification elements, such as points or a leaderboard of points earned by different players or teams.

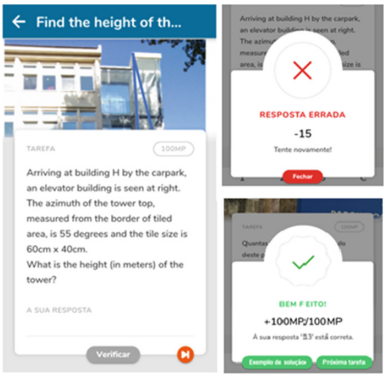

Fig. 3. An example of a task in the App

2.3 The ASYMPTOTE System

ASYMPTOTE was created to cover some deficiencies of remote teaching and learning in mathematics education [4].

The ASYMPTOTE system was adapted from MathCityMap (MCM) system. The concept of straight outdoor learning trails is transformed into a new concept, the concept of teaching and learning using learning graphs.

This new system also consists of a web portal and an App and allows teachers to conduct synchronous and adaptive online teaching and learning with a low barrier for students: only a smartphone is required.

ASYMPTOTE purpose

At the web portal, aimed at teachers, it is possible to elaborate or search and select tasks from a repository of tasks. The teacher can group together some tasks in a sequence with multiple levels of difficulty, for a specific or general topic of mathematics.

According to [10], a learning path is defined as a sequence of tasks that are designated to assist students in improving their knowledge or skill in a particular subject area. In ASYMPTOTE, task sequences are presented in the form of a learning graph, which is defined in [4] as follows: A learning graph is defined as a directed graph, where each vertex represents a learning activity (or task), based on a learning trajectory as the intended and expected way of learning.

In the application, aimed at students, it is possible to visualize the tasks or the learning graphs, solve them and obtain synchronous and systematic feedback.

ASYMPTOTE also provides a Digital Classroom mode that offers the possibility of direct communication between the teacher and the students or groups of students assigned by the teacher, i.e., offers a chat where valuable evaluative and explanatory comments [11, 12] are made by the teachers in a synchronous online environment.

The architecture of ASYMPTOTE learning graphs ensures that the entire learning process is self-guided and autonomous, following the self-determination theory [13] and it also aims gamification, where students receive points for a successful task-solving process [14, 15], motivating and stimulating them for learning.

To diversify and improve the teaching and learning process, ASYMPTOTE can be implemented in face-to-face, online and mixed educational contexts. Its contents can be used by teachers as support materials and as complementary resources adaptable to the teaching of mathematics. ASYMPTOTE can also be used as an online assessment tool, allowing one to choose between formative assessment, assessing student progress, or summative assessment, classifying the student as soon as he/she finishes a certain topic of instruction.

Tasks and learning graphs examples

In the ASYMPTOTE system, the teaching and learning process is based on tasks for primary, secondary, and university levels of mathematics, organized in learning graphs. Tasks in ASYMPTOTE are divided into three broad categories regarding their focus: training (includes mathematics and/or mathematical techniques), reasoning (requires the use of a mathematical argument, interpretation, or explanation), and modelling (real world modelling and problem solving).

Tasks are sequentially organized into learning graphs to guide students in improving their knowledge in different mathematics areas. The learning graphs format includes three main categories of tasks: main tasks, support tasks and challenge tasks (Fig. 4).

The learning graph is represented visually by a kind of fishbone diagram which consists of: a central spine, where the main tasks (yellow, mandatory) lie and branches that connect it; on the right side there are the support tasks (green, provide related tasks of a lower level, which can help to solve the main task afterward); and on the left side there are challenge tasks (purple, with a higher difficulty than the latter, challenging those students who finish early or seek to dive even deeper into the topic).

Fig. 4. Example of a learning graph.

Tasks and learning graphs are created in the web ASYMPTOTE portal, by teachers.

The tasks must include some basic information, such as, its title and description and its author's information; core components, such as, the answer types, task type, sample solution, some hints, the assigned grade and tags. The answer type can be: exact value,

interval, multiple choice, fill in the blanks, vector (exact value), vector (interval), set, fractions and matrices.

The learning graph in the figure is named "Practice linear functions" and can be downloaded to the ASYMPTOTE APP by entering the corresponding code.

As the tasks are carried out, those that were answered correctly will be marked. If two attempts to answer a main task fail, the application directs the student to a support task to help them.

3 Conclusions

In this article, we describe two tools that are available for teaching and learning mathematics: the MathCityMap system, which includes the MathCityMap@home, and the ASYMPTOTE system. These systems consist of two components, namely a web portal for teachers and a smartphone App for students. Also, we feature the Digital Classroom which allows the teacher to monitor students' work and progress in real time. These systems were tested with the students and at the end of the experience an anonymous survey was given to try to understand how they felt. As we can see in Fig. 5, students considered the application ASYMPTOTE easy and challenging to use. The questions were evaluated using a Likert scale, with 1 being "I completely disagree" and 5 being "I completely agree".

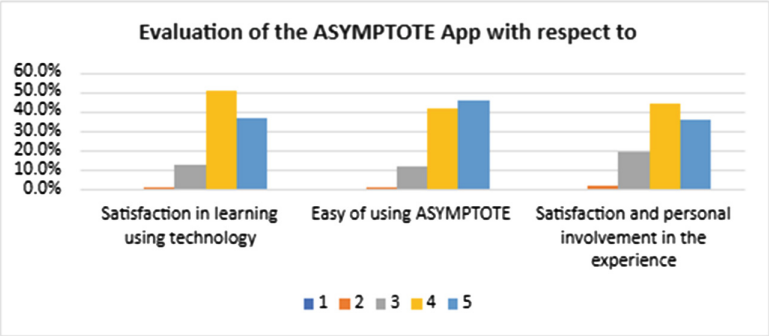

Fig. 5. Evaluation of the ASYMPTOTE App

Thus, although these systems were designed for the educational environment, the idea can be used in a variety of contexts. For example, critical thinking, engagement, teamwork and problem-solving activities can be developed with these applications. In businesses, decision-making often involves several participants with different views. In these cases, these systems can be used as mathematical models with a set of conditions to be met to help decision-making. Another use of these applications is to evaluate the performance of collaborators from an organization to measure their progress, knowing that, the progress may depend on the resources, facilities, and technology available in the organization and collaborators' motivation and ability.

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Power Consumption and Process Cost Prediction of Customized Products Using Explainable AI: A Case in the Steel Industry

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Abstract. Production shifted from a product-centered perspective (mass production of one article) to a customer-centered perspective (mass customization of product variants). It also happens in energy-intensive industries, such as steel production. Mass customization companies face a challenge in accurately estimating the total costs of an individual product. Furthermore, 20% to 40% of the costs related to steel products come from energy. Increasing the product variety can cause an inevitable loss of sustainability. This paper presents machine-learning approaches to improve the sustainability of the steel production industry. It is done by finding the most accurate way to predict the power consumption and the costs of customized products. Moreover, this research also finds the most energy-efficient machine mix based on the predictions. The method is validated in a steel manufacturing Small Medium Enterprise (SME). In this research, experiments were conducted with different machine learning models, and it was found that the most accurate results were achieved using regularization-based and random forest regression models. Explainable AI (XAI) is also used to clarify how product properties influence process costs and power consumption. This paper also discusses scenarios on how the prediction of costs and power consumption can assist production planners in performing workstation selection. This research improves the production planning of customized products by providing a trustable decision support system for machine selection based on explainable machine learning models for process time and power consumption predictions.

Keywords: Machine learning · sustainable manufacturing · mass customization · data-driven manufacturing · power consumption prediction · Explainable Artificial Intelligence (XAI)

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1 Introduction

The production industry is constantly evolving, and as a part of evolution, production shifted from a product-centered perspective (mass production of one article) to a customer-centered perspective (mass customization of product variants) [22]. Due to this shift, manufacturers must adapt to modern market characteristics like extreme product customization, short lead times, low volumes, and high mix cost-efficiently to compete in a contemporary Industry 4.0 environment [19]. This change affected many sectors, including the steel industry. The steel production industry consumes a lot of energy and accounts for 9% of Germany's industrial consumption and 4% of the country's total consumption [15]. In addition to this, 20% to 40% of the costs associated with steel production come from energy [27]. Moreover, various national policies restrict energy use due to carbon footprint and greenhouse gas emissions [5].

Another critical issue is that deciding on a reasonable price for a customized product is challenging [29]. Additionally, each product has a different production process and processing resources (i.e., machines), and for each resource, there are many other possibilities [26]. Therefore, finding the optimal processing method and choosing the best machines or workstations for customized products is challenging.

To address the problems, there is a need for a decision assistant tool that will predict the cost and power consumption of a product with customizable features systematically. Recent advancements in Artificial Intelligence (AI) which power the decision assistant tool, could improve production planning accuracy, time, and cost-efficiency. Companies could use the tool to calculate their customized products' costs efficiently, thus putting their products at a competitive price on the market. Without such tools, process planners must manually identify the decisive factors for workstation selection, process characteristics, and power consumption for each product's manufacturing process by analyzing the correlations in the data.

The emerging Explainable Artificial Intelligence (XAI) could improve transparency in predicting costs and power consumption because it can help determine the main influencing factors on power consumption and processing time. XAI may assist in ensuring legal compliance and ethical concerns by providing accountability and transparency in the decision-making procedures. As a consequence, the implementation of XAI in the manufacturing industry may result in manufacturing procedures that are more precise, efficient, and moral.

This research aims to identify the best ways to predict power consumption and production costs of customized products and reduce them throughout the production of steel products. The results of conventional machine learning and XAI were compared, and how the predictions can be used to determine the optimal production process sequence is shown.

This paper is organized as follows: related works in the application of machine learning and XAI in the production of customized products are presented in Sect. 2. Section 3 elaborates on the data collection and experiment setup. Section 4 discusses the experimental results. Section 5 gives an example

of a prediction scenario and the implications of the solution. There, limitations and further research are discussed. Section 6 shows the paper's conclusion.

2 Literature Review

Customized products are demanded not only in manual assembly or manufacturing processes in general, but they are also popular in food production and many other industries. However, little research has been done on optimizing customized product production. Most current works focus on optimizing manufacturing processes and less considering products, such as estimating machine changeover time [16], counting objects in manual assembly [19], identifying assembly constraints [22], improving 3D printing quality [28], and predicting wearing behavior of production line components [9]. There is a scarcity of research done to optimize customized product manufacturing. In the energy domain, most of the related works predict the energy consumption of only specific facilities, such as the energy consumption of machine tools [3,8,24], electric arc furnace (EAF) [5,6], heat, ventilation, and air conditioning (HVAC) systems [18]. This paper tries to fill the present research gap by finding the best methods to predict power consumption and the cost of customized products in the steel industry.

In recent years, Explainable Artificial Intelligence (XAI) has gained popularity as a manufacturing industry application. A predictive maintenance case study was carried out to show how XAI may aid in predicting maintenance activities, which used a very effective gradient boosting decision tree model to forecast tool and machine failures [14]. Similarly, STARdom's planned architecture combines XAI, active learning, and simulated reality to improve forecasts and offer guidance on making decisions for human-centered industrial systems [23]. Using "glass box" models that are understandable to humans and generate value-based explanations for data scientists, data engineers, and business experts, the XMANAI strategy focuses on explainable AI models and processes, revolutionizing the industrial value chain [17]. These studies demonstrate the potential for XAI to improve decision-making in manufacturing, reinforce trust, and provide insights into the workings of AI-enabled systems. However, research in employing XAI to predict power consumption and costs in processing customized products and to explain the influencing factors is still lacking. This research addresses this gap by developing multiple machine-learning regression models (cf. Table 1), employing SHAP and LIME XAI methods, and conducting experiments on multiple machines in a stainless steel production shop floor.

3 Data Collection and Prediction Model Building

This research collected data from a medium-sized European make-to-order stainless steel ring manufacturer. Customers can customize the product's material, heat treatment, and dimensions, including the steel rings' height and inner and outer diameters.

As shown in Fig. 3, the raw material must undergo several production processes on multiple workstations to transform it into the finished product. Firstly, raw materials are sawed to get the rough dimension of the final product. A forging process follows it to obtain the rough shape of the final product. Rings are rolled before heat treatment. After the material has been heat-treated, it must undergo a machining process. The last two processes are quality assurance and finalizing. In each step, there are several machine choices to process the materials.

The process duration must be predicted to calculate the processing costs obtained by multiplying the hourly workstation costs and process duration. The process duration was extracted from process log data obtained from a production process logger, and power data was collected using power meters installed on the machines.

Nine regression models were developed for process duration prediction and ten for power consumption prediction for each workstation. (see Table 1). Root mean squared error (RMSE) was measured for each developed model, as higher weights were aimed to be put on significant errors and have the same unit as the variables' values. In this way, the models for each workstation were compared, and the best predictive model, i.e., the one with the lowest RMSE value, was obtained.

After obtaining the best predictive model, SHAP (SHapley Additive exPlanations) is utilized to interpret machine learning prediction outcomes, as it aids in providing a clear understanding of the value and relevance of each feature in the model's output. [7]. In addition to SHAP, LIME (Local Interpretable Model-Agnostic Explanations) is applied to explain the outcomes of the predictions and to what extent the features influence the prediction [2]. LIME provides local explanations by building understandable models around each prediction, whereas SHAP gives global explanations by allocating feature importance to each input feature across the whole dataset.

4 Results and Discussions

After calculating the RMSE of the machine learning models for all workstations, it is shown that obtained errors vary drastically from workstation to workstation. Table 1 gives examples of the regression models and their RMSEs of duration prediction on 1000t Press and power consumption prediction on 3500t Press.

As shown in Table 2, 1000t Press and 3500t Press have low RMSE. It is because presses have a more stable machining duration. On the other hand, drop hammers depend on the product characteristics since they have to complete a certain number of blows to forge the material. The Elastic Net and Random Forest Regression models tend to predict the duration of most operations best. Elastic Net Regression performs better than other regularization-based regressions (i.e., Lasso and Ridge Regression) and much better than ordinary least squares (OLS) based regressions (i.e., Polynomial and Linear Regression). Unlike other regularization-based regressions, Elastic Net Regression can avoid overfitting by still including all features as predictors and controlling each predictor's

Table 1. Examples of duration and power consumption prediction error metrics

(a) Duration prediction error metrics for 1000t Press

Model	RMSE
Random Forest Regression [4]	1170.39
Gradient Boosting Regression [12]	1227.33
Elastic Net Regression [30]	1245.17
Ridge Regression [13]	1249.32
Lasso Regression [25]	1253.19
Linear Regression [10]	1264.29
Polynomial Regression [11]	1264.29
KNN Regression [1]	1328.82
Decision Tree Regression [20]	1341.39

(b) Power consumption prediction error metrics for 3500t Press

Model	RMSE
Random Forest Regression [4]	94.24
Gradient Boosting Regression [12]	94.69
Decision Tree Regression [20]	96.50
KNN Regression [1]	102.59
M5P Regression [21]	102.59
Ridge Regression [13]	133.10
Lasso Regression [25]	134.35
Elastic Net Regression [30]	162.13
Linear Regression [10]	249.36
Polynomial Regression [11]	249.36

impact on the duration value. Random Forest Regression performs better than the other decision tree-based models (i.e., Decision Tree and Gradient Boosting). Although building the Random Forest Regression Model required more computation time, it can avoid overfitting with more straightforward parameter tuning than Gradient Boosting Regression.

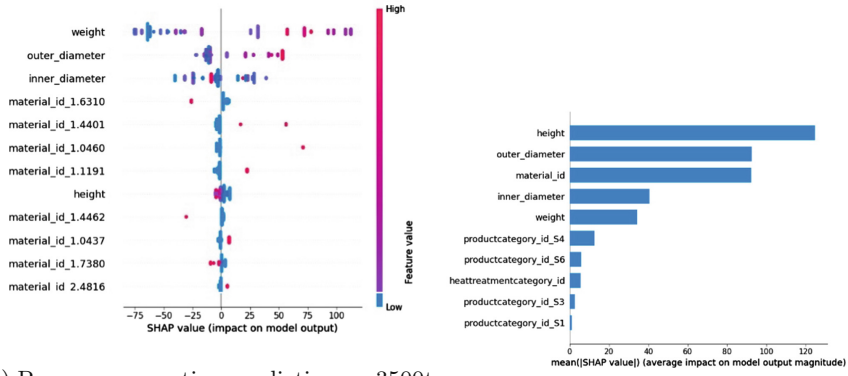
The volatility and product reliance on machining (Small Conventional Machine, Big Conventional Machine, and Hankook) and sawing processes may cause the high RMSE. The best RMSE was found in machining processes, making Random Forest Regression better suited for data that is prone to volatility. The low number of machine entries and the machining processes' insensitivity to the size of the product are factors causing the high RMSE.

Given that all workstations had a sufficient number of entries, likely, the system would accurately predict the power consumption of a customizable product. It is, however, critical to go through each operation step in detail. Similar to the duration prediction case, Random Forest Regression obtains the lowest RMSE for highly volatile data. 3500t Press (XX516) has the highest volatility power consumption data; thus, Random Forest Regression performs the best (see Table 2).

The variables with the most significant impact on the model predicting power consumption have been identified using the SHAP values. Each variable's SHAP value can be seen in Fig. 1a, which represents how significantly that variable contributes to the model's overall output. The SHAP values indicate that weight, followed by outer and inner diameters, is the factor with the most significant influence. The estimated power consumption is thus most affected by changes in weight, followed by changes in outer diameter and inner diameter. More energy is needed to process the product as its weight increases. The product's outer and inner diameters considerably impact power usage. This is because a larger product needs more material and power to mold it into the correct shape.

Table 2. Summary of the best models for each workstation.

Workstation	Duration/cost prediction		Power consumption prediction	
	Best Model	RMSE	Best Model	RMSE
Sawing	Elastic Net Regression	8591.85	n.a	n.a
Small Drop Hammer	Random Forest Regression	1170.39	n.a	n.a
1000t Press	Random Forest Regression	424.40	Lasso Regression	35.40
Old Ring Roller	Elastic Net Regression	933.10	Ridge Regression	16.12
New Ring Roller	Elastic Net Regression	777.46	Lasso Regression	63.51
800t Press	Elastic Net Regression	1549.56	n.a	n.a
3500t Press	Elastic Net Regression	794.29	Random Forest Regression	102.59
Small Conventional Machine	Random Forest Regression	5636.51	n.a	n.a
Big Conventional Machine	Random Forest Regression	3688.16	n.a	n.a
Hankok	Random Forest Regression	5158.04	n.a	n.a



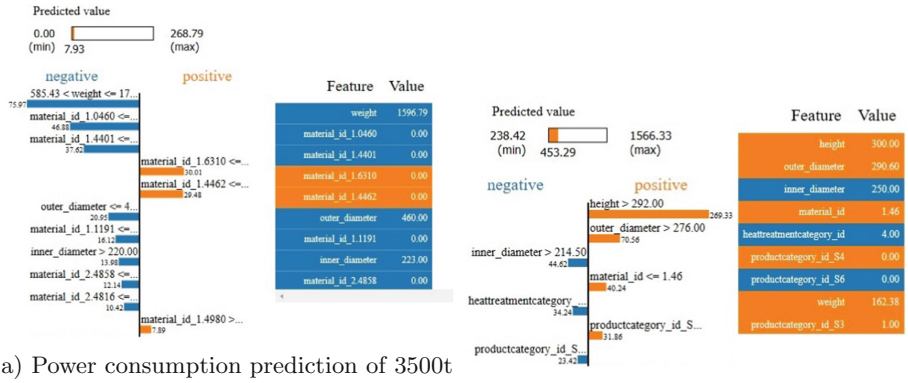
(a) Power consumption prediction on 3500t Press

(b) Process time prediction on 1000t Press

Fig. 1. SHAP values of random forest models for duration and power consumption prediction

It is discovered in Fig. 1b that height is the most important factor, followed by outer diameter, material id, inner diameter, and weight, to predict power consumption. Height has the highest positive SHAP value, meaning that having a longer product causes the manufacturing process to take noticeably more time. Like the inner diameter, the outer diameter has a positive SHAP value, suggesting that longer process times are similarly associated with bigger outside diameters. On the other hand, Material id has a mixed effect, with some materials having a positive impact and others a negative one on the model's predictions. Nonetheless, inner diameter generally has a negative effect on process time, indicating that bigger inner diameters result in faster process times. Lastly, weight has a somewhat negative effect, suggesting heavier products can be processed more quickly.

The random forest model predicts it will require a power of 7.93 to produce the product specified in Fig. 2a. According to the LIME explanation depicted in Fig. 2a, weight appears to have the highest impact on anticipated power usage, with values between 585.43 and 1703.47 (1596.79) having a negative effect. It implies that producing heavier products needs more power. The type of material is another element that adversely affects power consumption, with some materials, including 1.0460, 1.4401, and 1.6310, having a significant negative effect. On the other hand, some materials, like 1.4462 and 1.4980, have a favorable effect on power usage. Moreover, the product's outer diameter affects power usage negatively.



(a) Power consumption prediction of 3500t Press

(b) Duration prediction of 1000t Press

Fig. 2. LIME explanation for a single sample of prediction

Based on the given data test that can be seen in Fig. 2b, the LIME explanation demonstrates that height, outer diameter, inner diameter, material id, heat treatment category, product category S4, and weight are the factors that have the most significant impact on the prediction. The product height positively impacts the estimated processing time, showing that lengthening a product's height can lengthen its process time. Also, the outer diameter has a substantial positive influence of 70.56, showing that increasing the product's outer diameter may lengthen the duration. However, the inner diameter has a negative impact of −44.62, showing that shortening the processing time can be achieved by enlarging the inner diameter. The material ID of 1.46 has a positive value of 40.24, indicating that it strongly influences the process duration.

5 Example of Prediction Scenario

The prediction scenario was carried out in the following way: first, the manufacturer receives an order for a customized product. The given product characteristics are then inputted into the system. Power consumption and duration

are predicted using the best regression model (see Table 2) for each workstation. The optimal machine for each operation step is then highlighted regarding power consumption, duration, and cost. The process planner can choose the machine mix that will (1) minimize power consumption or (2) minimize process duration or production cost. It is essential to give the process planner the flexibility to decide the priorities, for example, whether time or power consumption is more important. Finally, the costs of all workstations are summed, resulting in the total cost to produce the product. Figure 3 presents an example of such a recommendation outputted by the developed system. The left figure shows the workstation selection that would use the least power during production, and the right one highlights the workstations that will result in the lowest duration and production cost. Process planners can analyze the information and select the solution that best fits the company's objective.

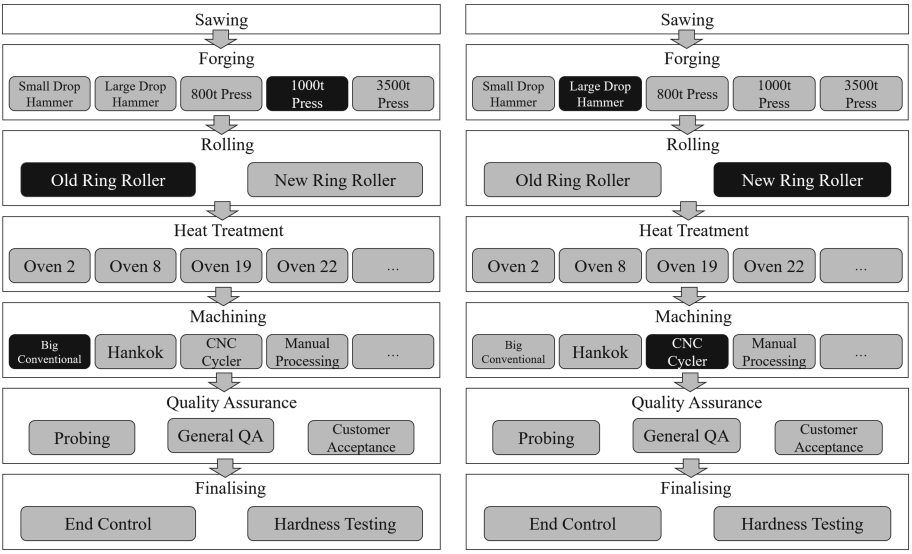


Fig. 3. Best workstation selection (cost and power consumption)

According to LIME Explanation, the three most crucial variables to take into account while attempting to decrease power consumption in the manufacturing process are weight, material type, and outer diameter. Manufacturers can utilize this information to inform their choices of materials and product requirements, lowering energy use and enhancing sustainability. Overall, the Lime explanation provides valuable insights into the factors that can influence the duration of the product.

The SHAP values of the input variables draw attention to the elements that affect the manufacturing process's length. The process duration is primarily influenced by height and outer diameter, although material id, inner diameter,

and weight are also important. Researchers and manufacturers can optimize the process and reduce its length by better understanding these elements' proportional influence. Manufacturers may create more effective and simplified manufacturing processes, cutting production times and costs while raising total productivity by concentrating on the essential variables. Further research focused on manufacturing process optimization and creating more complicated prediction models that can better represent the process's complexity can benefit from the insights gained from the SHAP values.

The company that was studied is a growing and innovative manufacturing SME, and in the first phase of the digital transformation, research was conducted to optimize production planning. Due to the company's limited sensor and software infrastructure, only partial shop floor data could be captured. As a result, a complete prediction of all machines' costs and power consumption cannot be achieved by the system. However, this research provides a foundation for optimizing machine selection in the company and generally in manufacturing customized products. Several steps are required to implement the developed system in an industrial setting, such as installing a power meter and production data acquisition system on each machine, deploying the machine learning in a cloud, and system testing.

6 Conclusions

Mass customization is demanded in more industries daily, and its successful implementation is crucial. An inevitable loss of efficiency accompanies mass customization and complicates the production process planning. A tool that predicts the energy consumption and cost of customizable products on various machines and finds the best machine mix will increase the efficiency and cost-effectiveness of many factories worldwide. Previous research on energy prediction did not focus on customizable products and used a small variety of prediction models. This paper shows that machine learning models can predict customized products' energy consumption and costs. They operate much faster than humans and give process planners valuable insights to select the best workstation. Random Forest Regression performs best for the predictions on volatile data. In contrast, regularization-based regressions such as Elastic Net, Lasso, and Ridge Regression show the best results for the less volatile data. XAI can provide useful information about the variables that affect power consumption and process costs. LIME focuses on local explanations around each prediction, and SHAP gives global explanations by allocating feature importance across the whole dataset. Manufacturers can decide how to optimize their production processes to lower energy usage and boost efficiency by being aware of these aspects.

The key contribution of this research is to improve the production planning of customized products by providing a decision support system for machine selection based on trustable machine learning models for process time and power consumption predictions. The developed system can select the best machines to minimize power consumption and costs for each operation step. With more

training data and predictors, the system can predict more accurately and save time and costs in production planning.

Future research will employ deep learning models to predict cost and power consumption. In the project's second phase, more sensors will be installed to capture more data and improve the quality of the prediction models. Additionally, more predictors, such as features extracted from product drawings, are planned. An optimization model will also be developed to find optimal process sequences automatically.

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A Knowledge Graph Approach for State-of-the-Art Implementation of Industrial Factory Movement Tracking System

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Abstract. Digital sensing technologies are essential for realizing Industry 4.0, as they enhance productivity, assist with real-time decision-making, and provide flexibility and agility in manufacturing factories. However, implementing these technologies can be a significant challenge due to the need to consider various factors in manufacturing factories, such as heterogeneous equipment, fragmented knowledge, customization requirements, multiple alternative technologies, and the substantial costs involved in the trial-and-error process. A Knowledge Graph (KG) approach is proposed to streamline the implementation of the factory movement tracking system. The KG approach utilizes a knowledge representation reference model that integrates manufacturing objective, activity, resource, environment, factory movement, data, infrastructure, and decision support system. This reference model aids in classifying key phrases extracted from research abstracts and establishing knowledge relationships among them. A synthesized KG, created by analyzing thirty research abstracts, has correctly answered search queries about implementing the factory movement tracking system. This approach establishes a pathway for developing a software system to support movement tracking implementation through automatic interpretation, reasoning, and suggestions.

Keywords: Factory movement · Industry implementation · Knowledge Graph · Knowledge representation

1 Introduction

Manufacturing companies are transitioning from one technology revolution to the next to enhance productivity, agility, and flexibility in their production processes. In this context, Industry 4.0 is revolutionizing the manufacturing environment by integrating multiple new technologies, such as the Internet of Things (IoT), big data, cloud computing, analytics, and artificial intelligence, to create a smart manufacturing environment.

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For example, advanced sensors facilitate the collection and analysis of factory data in real time, enabling rapid decision-making, automation, process and quality improvements, improving production capacity, and minimizing downtime through efficient maintenance. In other words, the technologies have the potential to give a high level of visibility of the state of all processes across a factory.

However, implementing Industry 4.0 technology can be complex due to the need to consider various factors within a manufacturing factory, such as heterogeneous equipment, isolated and fragmented knowledge, customization requirements, multiple alternative technologies, and the significant costs involved in the trial-and-error process. These factors can make it challenging to successfully implement Industry 4.0 technology and fully realize its potential benefits. Ing et al. [1] identified seven important challenges in implementing Industry 4.0: data management and integration, knowledge-driven, process, security, capital, workforce, and education. Moktadir et al. [2] pointed out that the lack of technological infrastructure is the biggest issue in Industry 4.0 implementation. The studies within German manufacturing companies show that the competitiveness, future viability, and organizational and production fit impede the implementation of Industry 4.0 [3]. Veile et al. [4] observed that educating employees with new competencies and knowledge, necessary organizational and cultural changes, openness and trust, and integration into the existing machinery and production systems play essential roles in implementation. The challenges associated with implementing Industry 4.0 technology underscore the importance of systematically considering multiple aspects of the manufacturing factory and having up-to-date domain knowledge to overcome these challenges.

As new technologies and methods for Industry 4.0 are proposed and evaluated in the literature, it is necessary to systematically accumulate this knowledge so it can be stored, organized, and shared within organizations or external stakeholders. Therefore, the challenge is to encode and represent the knowledge reported in the literature to facilitate progression as the field matures. Since Industry 4.0 is a large subject, this research focuses on creating a Knowledge Graph (KG) approach for implementing an industrial factory movement tracking system.

The paper is organized as follows: First, it reviews existing approaches for implementing support. Then, it presents the research aim and methodology. Next, it explains the proposed knowledge representation reference model and KG generation approach, including an example. The paper then discusses the assessment and validation of the generated KG, and concludes with the findings and suggestions for future work.

2 Literature on Existing Industry 4.0 Implementation Support Approaches

The section reviews the reference architectures, observed patterns and ontologies (with any associated standards) used to support the implementation of Industry 4.0 technologies and identifies research gaps.

A **Reference architecture** is a high-level, abstract document that outlines the overall structure and organization of a system. In the context of Industry 4.0, reference architectures can provide the overall structure for systems and support the selection

and integration of their hardware and software components. Multiple literature sources have reviewed the existing reference architectures [5–7]. The common reference architectures highlighted are: IIRA (Industrial Internet Reference Architecture), RAMI 4.0 (Reference Architectural Model Industrie 4.0), SITAM (Stuttgart IT-Architecture for Manufacturing), LASFA (LAsim Smart FActory), NIST Smart Manufacturing architecture, and IBM Industry 4.0. These Industry 4.0 reference architectures are primarily represented in layers/levels, building blocks, and communication among them.

These architectures cover broad topics of smart factories from the business to the shop floor levels, such as business structure, operation, prognostics, optimization, information analytics, and monitoring/control of devices. Commonly these architectures were compared across the following five levels of automation architecture: (i) field (represents physical entities on the production floor); (ii) control (control a physical entity primarily using a PLC (Programmable Logic Controller) and a PID (Proportional–Integral–Derivative controller); (iii) system/process (controls multiple PLCs, e.g. SCADA (Supervisory Control and Data Acquisition)); (iv) operation (systems that monitor the entire manufacturing process - MES (Manufacturing Execution System)); and (v) enterprise (systems for integrated management; ERP (Enterprise Resource Planning)). Although the reference architectures tend to increase interoperability among systems/subsystems, reduce development costs/time, enable effective knowledge reuse, and adopt best practices, the following challenges in utilizing reference architectures are observed:

- High abstraction leads to difficulty in instantiating them to real-world Industry 4.0 projects.
- Difficulties in mapping terminologies used across reference architectures for representing similar concepts.
- The literature on architecture implementation lacks detailedness, particularly in analyzing architecture's internal structure, components, communication, data exchanges and types, and decision-making capabilities.
- Updating the evolving nature of the scope, technologies and systems involved is challenging.
- Drawbacks to apply in customized use cases for varying industrial requirements.

IoT patterns can be understood as a collection of problems and solutions within specific contexts. Bloom et al. [8] identify common input-output design patterns to understand data flow semantics in IoT applications: Closed-Loop, Cloud-in-the-Loop, Open-Loop, Cloud-on-the-Loop, and Device-to-Device. Washizaki et al. [9] observed 61 IoT design patterns such as 'Entity-Component-Attribute', 'Actuation-Actuator-Effect', 'Operator-Controller-Module' in published research articles. They noted that these patterns are not referenced frequently except 'Operator-Controller-Module'. These patterns are not well classified, varied in abstraction levels, and their application adoption is low.

Several **ontologies** have been proposed to describe resources, processes and location navigation. Some of the established ontologies are: Semantic Sensor Network (SSN) ontology [10], manufacturing resources and integration - IEC / ISO 62264 [11], and Process Specification Language (PSL) [12]. These ontologies provide detailed specifications in a particular domain by establishing terminologies and relationship definitions. Although these ontologies are well defined, integrating these ontologies to a common purpose of structuring knowledge progression through published literature is

not created yet. This paper aims to address these limitations observed by developing a Knowledge Graph (KG) based approach for systematically learning technology progression in factory movement tracking systems. This approach should support and drive the implementation of Industry 4.0 systems for realizing smart factories.

3 Research Aim and Methodology

This research aims to develop a support tool that systematically captures the knowledge generated in implementing Industry 4.0 processes and technologies. Structuring and reusing learnt knowledge will facilitate effective and streamlined industrial implementation and prevent costly trial-and-error procedures. This paper presents a Knowledge Graph (KG) approach for organizing and structuring abstracts from published literature about implementing a factory movement tracking system. This approach requires both a knowledge representation reference model and a process for creating the KG from the abstracts of research papers. Figure 1 details the process of creating and assessing a KG. Thirty research papers have been chosen based on the keyword search term 'factory movement data' in Google Scholar and analyzed using the described steps. Studying the first 30 relevant articles provided sufficient breadth and depth to validate the proposed KG approach for the movement tracking system. Protégé software was used to input the structured KG and assess it through SPARQL search queries. The following sections detail the steps mentioned in Fig. 1.

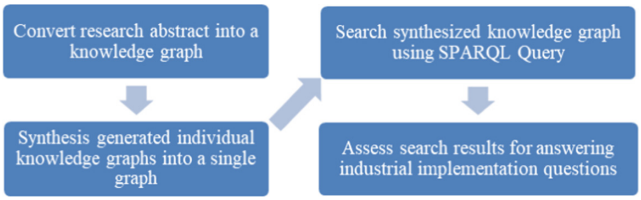

Fig. 1. Methodology to generate and assess synthesized Knowledge Graph

4 Knowledge Representation Reference Model

The proposed knowledge representation reference model provides overarching framework elements to consider when implementing factory movement tracking systems. The developed Knowledge Graph (KG) approach was based on this reference model that integrates manufacturing objectives (e.g. improve efficiency, productivity reliability, and quality), activity (manufacturing processes and workflows), resource (e.g. machines, tools, consumables, controllers, and workers), environment (e.g. factory layout, safety, working conditions), factory movement (e.g. location, direction of movement, velocity, time), data (e.g. data types, format, secure), infrastructure (e.g. sensors, data collection, storage, transfer) and decision support system (e.g. feedback systems, descriptive, prescriptive, predictive). The reference model facilitates mapping the research abstracts into

these entities and transforming them into the KG. Figure 2 describes the structure and possible influences on these entities. The figure also includes the subcategories within these entities.

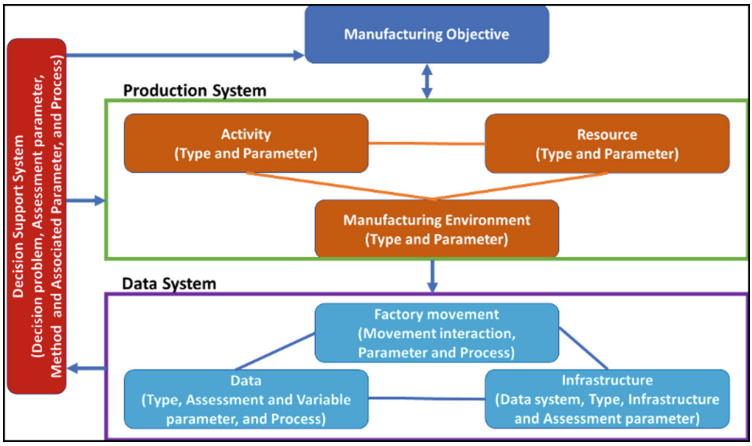

Fig. 2. Knowledge representation reference model

5 Knowledge Graph Generation Approach

The Knowledge Graph (KG) aims to create a semantic network by interlinking concepts, entities, and relationships related to factory movement system implementation. Four steps are structured to convert a research abstract into a KG:

Step 1: Keywords/phrases extraction from the research abstract.
Step 2: Mapping keywords to established entities in the reference model.
Step 3: Mapping keyword relationships based on object properties.
Step 4: Overall coherence check in the KG development.

Since accurate interpretation and consistent development are vital, these steps were conducted manually. However, once a significant labelled dataset is available, it will facilitate the development of an automated approach. The significance of the labelled dataset will be established by assessing the performance of the KG in answering queries correctly and comprehensively. Validating and updating labelled datasets regularly will improve the robust development of the KG. The following paragraphs detail each step using the below mentioned research abstract from Addison and Macleod [13]:

> "We describe a new tracking algorithm for the direction of arrival estimation problem where both the locations of the sensors in the array and the directions of arrival are nonstationary. The approach taken is Bayesian. The algorithm assumes that the filtering distribution is approximately Gaussian and maintains the mean and covariance of this approximation by fitting a quadratic surface to the log

posterior around the location where the log posterior is maximized. In the case where the sensor locations are stationary, the algorithm is shown to have similar performance to particle filter-based algorithms but at a reduced computational cost. In the case where the sensor locations are non-stationary particle filtering is unsuccessful and the new algorithm performs significantly better than currently existing algorithms."

Step 1: Keywords/phrases extraction: A keyword, or phrase, is a single word or a set of words that provide meaningful scientific content. It could be a subject or object in the sentence description. The predicate (i.e., properties/characterizing the keyword/phrases) was ignored at this step (e.g. 'reduced' was not included in 'reduced computational cost'). Key phrases were redefined to provide compact representation (e.g., 'locations of the sensors' into 'sensor location'). Some key phrases were maintained as they were if that's how the scientific community termed it (e.g. direction of arrival (DoA)). All extracted keywords/phrases were represented as singular (Table 1). Acronyms were expanded, and repeated keywords/phrases and synonyms were ignored. Also, generic words (such as performance) were not included.

Table 1. Extracted Keywords/phrases from the abstract

Extracted Keywords/phrases		
Tracking algorithm	Filtering distribution	Covariance
Bayesian approach	Gaussian	Stationary
Computational cost	Mean	Particle filter-based algorithm
Direction of arrival location	Direction of arrival estimation problem	Log posterior maximized location
Nonstationary	Fitting Quadratic surface	Sensor location in the array

Step 2: Mapping keywords to established entities in the reference model. In this step, the extracted keywords were mapped to the entities represented in the reference model (Table 2). The subcategories within the reference entities were considered and mapped.

Step 3: Mapping keyword relationships based on object properties. The relationships used in this abstract are *'apply to', 'assume', 'characterized by, 'has type', 'is better than', 'maintain by', 'reduce', 'same performance', 'near by'*, and *'utilize'*. Identifying the subject, predicate, and object in a sentence help to find appropriate relationships between keywords. For example, the relationships identified from the first sentence in the abstract are:

"We describe a new tracking algorithm for the direction of arrival estimation problem where both the locations of the sensors in the array and the directions of arrival are nonstationary."

Table 2. Mapping keywords/phrases to Reference entities

Keywords/phrases	Mapped Reference model entity	Keywords/phrases	Mapped Reference model entity
Tracking algorithm	Decision method	Filtering distribution	Decision process
Direction of arrival estimation problem	Decision problem	Nonstationary	Infrastructure parameter
Sensor location in the array	Infrastructure parameter	Direction of arrival location	Movement parameter
Computational cost	Decision Assessment parameter	Gaussian	Data variable parameter
Mean	Data type	Covariance	Data type
Stationary	Infrastructure parameter	Fitting Quadratic surface	Decision process
Log posterior maximized location	Decision associated parameter	Particle filter based algorithm	Decision method
Bayesian approach	Decision method		

Tracking algorithm → (apply to) → Direction of arrival estimation problem → (characterize by) → Sensor location in the array and direction of arrival location → (has type) → Non-stationary.

The above example utilized the predefined object properties for consistent KG development. New object properties could be added if the existing properties do not represent that object relationship. Class expressions describe relationships between key phrases using the identified object properties. The class expression syntaxes utilized in Protégé are: *some, value, only, min, max, exactly, and, or, and not*. Complex class expressions could describe the intricate relationships between key phrases and object properties. The representation of the complex abstract statement by the reference model entities is shown below:

> "In the case where the sensor locations are stationary, the algorithm is shown to have similar performance to particle filter-based algorithms but at a reduced computational cost."

In KG definitions, the Tracking algorithm included the following Sub-Class relationship entities:

(same_performance some Particle_Filter_based_Algorithm) and (has_type only Stationary).

(is_better_than some Particle_Filter_based_Algorithm) and (reduce some Computational_Cost).

The above example effectively demonstrates the building of complex class expressions representing key phrases and object relationships. In addition, class expressions can be nested to any required depths to build up detailed descriptions.

Step 4: Overall coherence check in the KG development. Although sentence-based analysis establishes explicit relationships between key phrases, implicit relationships (not directly represented in the abstract) should also be identified. The following implicit object relationships have been added for completion in the example abstract.

Particle Filter-based algorithm → (apply to) → Direction of Arrival Estimation.

Sensor location in the array → (has type) → Stationary.

The coherence check will ensure all keywords/phrases are related to appropriate object relationships. No keyword should be unconnected. Finally, the identified keywords and relationships are visualized in OntoGraf within Protégé software, which logically facilitates checking the KG structure. Figure 3 illustrates the KG developed from the example abstract. The first three rows define the direction of arrival estimation problem, the fourth row describes the methods used and assessment parameters, and the rest describes the proposed method. Following the same KG generation approach, 30 further research abstracts related to the factory movement tracking system were analyzed, mapped and synthesized into a single Protégé ontological file. This OWL protégé file can be accessed from this link[1]. This file could be used to visualize the complete KG in WebVOWL[2].

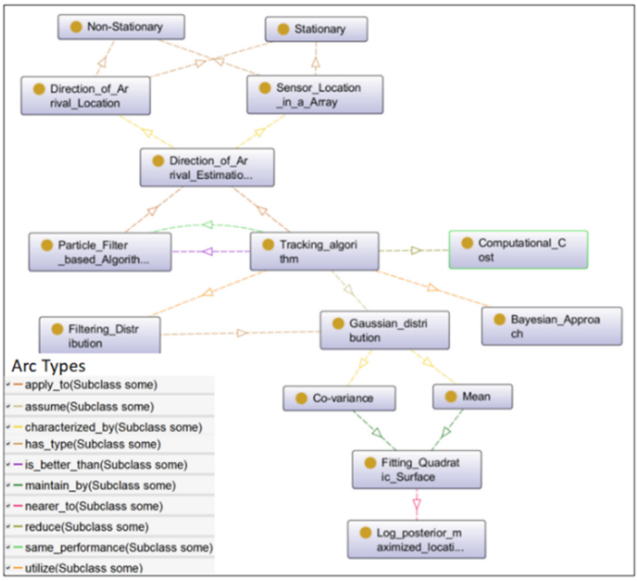

Fig. 3. KG representation of the example abstract using OntoGraf[3]

[1] https://tinyurl.com/kmf6fduf.

[2] Http://vowl.visualdataweb.org/webvowl

[3] https://protegewiki.stanford.edu/wiki/OntoGraf.

6 Knowledge Graph Assessment and Validation

This Knowledge Graph (KG) can help answer questions about implementing a factory movement tracking system, whether general or specific to technical details. Several query tools are available in Protégé software, such as DLQuery and SPARQL, that can be used to extract information from the KG. Some examples of queries and their results are presented in this section.

Specific Queries:

- What are the applications of the Affine Iterative Closest Point Method?
- What parameters does Affine Iterative Closest Point Method utilize?
- Do the Affine Iterative Closest Point Method better than the other method?
- Which article mentioned Affine Iterative Closest Point Method?
- How was the Affine Iterative Closest Point Method assessed?

The SPARQL Query for answering all these questions is:

PREFIX rdfs: < http://www.w3.org/2000/01/rdf-schema# >

PREFIX ss: < http://www.semanticweb.org/40013116/ontologies/2022/5/untitled-ontology-11# >

SELECT ?object.

WHERE {ss:Affine_Iterative_Closest_Point_Method rdfs:subClassOf ?object};

Figure 4 depicts the results obtained for the above query answering all the above-mentioned specific queries. The search query results are correct and will be useful in exploring methods and tools for implementing the movement tracking system.

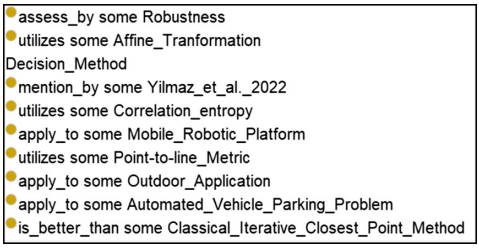

Fig. 4. SPARQL query results

A researcher tasked with evaluating the resulting KG for factory movement tracking systems made the following remarks:

- The KG was beneficial for understanding the state-of-the-art and quickly revealed the domain by viewing key entities such as decision problems and manufacturing objectives.
- The classification structures were appropriate for the entities. However, the researcher observed that overlaps between different classes are inevitable.
- The notable feature mentioned is that the KG provides a range of knowledge-based relationships between entities that are not necessarily hierarchic.
- The researcher noted that exploring object relationships supports identifying research gaps in the manufacturing factory movement tracking domain.

7 Discussion and Conclusion

This research presents a KG approach for the state-of-the-art implementation of an industrial factory movement tracking system. A knowledge representation reference model was proposed to support generating the KG. The resulting KG, which was created based on the analysis of 30 research abstracts, offers several advantages, including fast search and question answering, improved understanding of the current state-of-the-art in the movement tracking domain, identification of research gaps, and the ability to explore a wide range of knowledge-based relationships. Although the manual approach accurately applies the KG generation steps, the process is time-consuming to generate, validate, and update the structured KG. Also, analyzing only the research abstracts has limitations in covering overall knowledge comprehensively.

Further, the KG developer requires an understanding of the movement tracking system for correctly mapping keywords/phrases to the proposed reference entities. Significant progress has been made in automated knowledge discovery, such as Amazon AutoKnow [14], which built KGs for product descriptions. However, compared to known structured data description, creating KGs for a specific research domain is a challenging process for the following reasons: the sparsity/new terminologies used across varying research articles; a multitude of interpretations of reported findings; context understanding, complex and evolving nature of knowledge relationships; broader scope of synonym check, and extracting implicit relationships between entities. Therefore, the authors believe that manual and automated approaches should co-evolve, where annotated texts by the manual process could be helpful to train and develop an automated method for generating research-specific KGs. The ongoing research is to develop the KG comprehensively by analyzing more research abstracts and evaluating the efficiency of automated computing approaches in developing this knowledge graph.

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A Case Study of Standardization of a Project Management Tool in an Automotive Company

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Abstract. This paper presents a project in the automotive company whose aim was to standardize processes inherent to the use of a project management tool. This tool was developed internally with the purpose of spreading throughout the organization a methodology based on their own philosophy of lean thinking. During a deep analysis of the current procedures, some problems were identified regarding the lack of adequate use of the tool and its potentialities for project management, due to its complexity, specificity, and lack of training by the project managers. This project's main goal was to ensure that all project managers in the logistics area use this tool in a standardized way. To accomplish this, a checklist, a training plan, work instructions and a responsibility matrix were developed. An assessment was conducted in three different projects to assess the impact of these solutions. This assessment was created by the company to evaluate the way that projects were managed according to the company's philosophy on a scale of 1 to 4 and is composed of some criteria. The results indicate an improvement in several of these criteria, consequently improving the level from 2 to 3, because of the implementation of standardized procedures for the use of the tool and taking advantage of all its potentialities for project management.

Keywords: Standard work · Standardization · Project management · Logistics

1 Introduction

The world is becoming more competitive, and volatile changes in demand are increasing the complexity and competitiveness of the automotive sector [1]. Nowadays, logistics is being molded by globalization, there's always goods being transported across the planet, and new technologies are being used in order to ensure that logistics processes are safer and more secure [2]. Project management is a set of practices that are useful for the efficiency and evolution of the logistic chain. Projects in this area can benefit different areas, like fulfillment and production, quality control, transport, warehousing, distribution, and sales. These can include the management of the entire chain or just some parts and specific processes [3].

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The Toyota Production System (TPS), a philosophy developed by Toyota, aims to create more value with more quality and fewer resources, time, and waste [4, 5] and as a consequence of the good results obtained by Toyota Motor Company with the application of this philosophy in a production environment, many other companies have identified it as an example to follow [6, 7].

Lean production, which has its origins in TPS, is defined as a collection of frameworks and techniques used to manage a company's process, with a focus on eliminating any task that adds no value and generates waste [8–10]. The application of the Lean philosophy has had a great impact on the industrial environment and has spread to other industries besides the automotive sector [11, 12]. Some of the more known lean frameworks are value stream mapping, standard work, the A3 report, the plan-do-check-act (PDCA) cycle, the Ishikawa diagram, and the checklist. Their primary goal is to continuously improve [12–17].

In this paper, a project developed by the logistics department of a multinational automotive company is presented. The aim is to standardize the process related to the usage of a project management tool. This tool was developed internally with the goal of spreading and making uniform across the company their way of managing projects based on their own philosophy, which is sustained by lean thinking. To accomplish this, the action-research methodology was used, beginning with a diagnostic of the current situation and identification of the main problems, then developing solutions to overcome them, and finally analyzing the results obtained.

2 Project Context and Diagnostic

The company developed its own philosophy, like Toyota did. This philosophy is also focused on removing any waste and promoting only tasks that aggregate value to the product. In order to spread this philosophy across the company, in every department, some principles, guidelines, and frameworks were created so it was easier for everyone to follow the company's philosophy and have uniform behavior in all areas.

In the area of project management, it was developed internally as a digital tool to facilitate and guarantee that projects are managed following the company's philosophy. This tool integrates other concepts like the PDCA cycle, the A3 report and the fishbone diagram. It allows the definition and tracking of Key Performance Indicators (KPI), the identification of root causes, project temporal planning, and many other important project management functions. When using this tool, project managers guarantee that all the relevant information for understanding and monitoring the project is centralized and exists in congruence across the company.

To evaluate how the philosophy is being followed in each area, there is a group of annual assessments that rank them on a scale of 1 to 4 based on criteria that are different from area to area. In the project management area, these criteria are related to the definition of KPI, creation of support documentation, follow-up of the project, regular meetings, duration of the project, and others. The criteria are divided into two groups: concept, which verifies the theoretical concepts of the philosophy of the project, and execution, which represents what is measurable. These assessments are carried out in every factory using the same criteria.

The most recent assessment realized on the factory where this study was conducted yielded a level 2 on both concept and execution. In this factory, the assessment is based on the information placed on the tool. Comparing these results with the company's average, which reveals a level 3 on concept and a level 3,8 on execution, the factory ones are a little behind.

During the diagnosis of the current situation in the logistics department, it was possible to identify two main problems regarding project management and the usage of the tool. The first was the lack of usage of the tool on some projects, caused by insufficient information on the criteria that tell if the project should or shouldn't be managed with the tool and by ignorance about this tool and the benefits of its usage. The second was an inefficient usage of the tool by some project managers on their projects, caused by the high specificity and complexity of the concepts and the philosophy behind the tool and the nonexistence of standard procedures for the usage of the tool. These problems were causing a huge inconsistency in the way that projects are being managed in the logistics department, a misalignment with the company's philosophy, and poor performance on the assessments.

3 Improvement Proposals

Through the problems identified, it's possible to understand the negative impact the lack of standard processes has on the usage of this tool by project managers. With this in mind, the standardization of processes was the main objective in the creation and implementation of improvement proposals.

In order to promote transparency across the logistics department on the criteria that tell which projects should or shouldn't be managed with the toll and to increase consistency on how the projects are managed, a checklist was created (Table 1).

Table 1. Checklist to manage a project with the tool.

Checklist	Description
Project responsible	Responsibility to manage the project already designated
Impact area of the project	Definition of the impact on any of the processes or tasks performed during contact with suppliers, order management, inventory, material reception and other operations related to the inbound
Maximum estimated duration	Finishing the project in an estimated time of 6 months maximum
Impact on one of the logistics' KPIs	Result of the project reflected, in at least, one of the following KPIs: • Logistics Costs; • Logistic quality; • Days of stock in warehouse; • Relationship between suppliers and clients

This checklist, which was created based on feedback from previous project managers and their leads, includes all of the criteria so that any project manager can independently determine whether the project is supposed to be managed with the tool and thus eligible for the assessment.

To facilitate the use of the tool and extract all the benefits from it, a manual was developed that centralized every piece of information and provided guidelines. This manual is composed of three main components: a training plan, work instructions, and a responsibility matrix.

The training plan (Table 2) is formed by some selected courses that were already designed by the company. This selection was based on the skills focused on and developed by each course and their importance to these tasks. With this training plan, project managers can develop their skills and knowledge in project management, the company's philosophy and concepts, and the tool itself. In this way, it is possible to solve the high specificity and complexity of the concepts and the philosophy behind the tool and promote knowledge about the tool and its benefits.

Table 2. Training plan.

Training	Skills
Training 1	Project management; PDCA cycle; Company's concepts and philosophy
Training 2	Quality management; Problem solving; Project management; Quality tools
Training 3	Quality management; Problem solving; Project management; 8D methodology
Training 4	Project management; Company's concepts and philosophy; A3 report; Company tool
Training 5	Project management; Company's concepts and philosophy; PDCA cycle; Company tool

Together, these courses represent around of 26 h training splintered across different approaches: web-based trainings, webinars, and seminars.

As a result of the identification of the lack of standard procedures for the usage of the tool, a work instruction was developed with the purpose of standardizing and creating some consistency in the way that this tool is used and extracting its maximum potential in

project management. The work instruction covers every functionality in detail, including in which phase of the project which should be used, how they should be used, and how they can impact the performance of the assessment.

To complete the manual, a responsibility matrix (Fig. 1) which depicts the relationship between all the general activities that must occur during the development of a project and the individuals who are responsible for them. As an example, the fulfillment of the checklist created should be done by the mentor of the project, and the usage of the tool is the responsibility of the project manager. This matrix allows every person who is or will be part of a project to have transparency and easy access to the information referring to her and others' responsibilities.

Label: **R** – Responsible **A** – Approver **S** – Supporter **I** – Informed **C** – Consultant	Project Manager	Project Mentor	Logistics Responsible for the Company's philosophy	Logistics General Coordinator	Company's Philosophy Department
Fulfilment of the checklist for the eligibility of projects to be managed in the tool		R		R	
Contextualization of the problem, current situation and project		R	S	R	
Enrolment in training and provision of support material		R	R		
Parameterization of project creation fields	R			A	
Fulfilment of the project info on the tool	R	S	C		
Alignment of the project development with company's philosophy	R	C	R	C	S
Progression of the PDCA cycle phases and project closure	R	S		A	
Election of the projects to be presented on the assessment	C	C	R	R	R
Project preparation for the assessment	R	R	R	S	S

Fig. 1. Responsibility Matrix

4 Results and Discussions

The standard work developed will tackle the problems identified before and consequently improve the results. To measure this improvement and the efficiency of the standardization implemented, the assessment was simulated in three different projects (Table 3) using the same criteria and scale as the official one.

Comparing the current levels performed on the most recent assessment with the ones obtained, it's possible to see a general increase in the results, as presented on Table 4.

These results show an increase of one level in terms of concept, which represents 25%, on the three projects, equalizing the company average. In terms of execution, just

Table 3. List of the simulated projects.

Project	Name
Project 1	VMI multisource implementation
Project 2	Commercial data confirmation
Project 3	Pendant control

Table 4. Assessments' results.

	Assessment 2022	Company average 2022	Project 1	Project 2	Project 3
Concept	2	3	3	3	3
Execution	2	3,8	3	2	3

one project does not achieved level 3, and despite the general picture being better, the results continue to lag behind the company average. The reason why project 2 performed level is behind the other ones is due to some delays on the project that comprise its duration, once this is one of the criteria evaluated, it consequently impacts the assessment made.

The standard work implemented is improving the way that the tool is used by project managers and how projects are following the company's philosophy, which is reflected in the results obtained. However, it's clear that achieving the highest level was impossible in none of the projects, neither in concept nor execution. A deeper examination revealed that this was one criterion, related to the extrapolation of the project's information and lessons learned to other factories within the company, that was never verified in any project and was identified as a tool limitation.

5 Conclusion

This paper describes a project developed at a multinational automotive company with the goal of standardizing a project management tool. A complete and detailed analysis of the current procedures in the logistics area allowed to identify problems regarding the inappropriate usage of the tool and the wastefulness of their advantages, which is reflected negatively in the last assessment. The implementation of standard work in order to overcome these problems has a positive impact that is proven by the results obtained, allowing one to conclude that standardization can improve the way that projects are managed and how project managers are following the company's philosophy.

Despite the improved results obtained after the application of standard work, there is still more to be done regarding the tool's evolution in order to overcome the barriers preventing access to the highest degree of the assessment. The emphasis should be on the scalability of this project management tool, which will allow extrapolation of the project's information and lessons learned to other factories within the company, thereby overcoming this limitation.

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Analysis of Evacuation Strategies for a 4-Star Hotel Using Simulation

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Abstract. Total evacuation time constitutes an important factor in the safety of any building. It is thus essential to devise an emergency evacuation plan, which will enable the safe evacuation of all the occupants in the shortest possible time. The main objective of this article was to examine and improve the evacuation process of a 4-star hotel located in the city of Porto, Portugal. To this end, one looked into 6 scenarios, by means of PathFinder simulation software, so as to determine the shortest total evacuation time and identify possible bottlenecks and congestion. The simulation model developed was tested to analyze the evacuation of 429 people from the hotel, based on the availability of the 3 accessible exit doors (central exit, side exit, spa exit) and elevators. Strategy 4 presented the shortest total evacuation time, with 536.0 s. Two other strategies which showed very similar times were 5 and 6, with 537.0 s and 537.5 s, respectively.

Keywords: Evacuation · Computational Simulation · Total Evacuation Time · PathFinder Software

1 Introduction

Evacuation constitutes one of the main solutions to reduce the impact of natural threats, or those caused by humans, on people located in buildings [1]. Evacuation in the context of an emergency is a crucial problem in large premises (e.g. skyscrapers) due to the presence of a great number of people within a limited area [2]. Simulation allows for the imitation of the behavior of a system through a computer-developed model. As such, it is an extremely useful decision-making support tool, which enables one to analyze the performance of the system under study without compromising resources [3–6]. Simulation is used in the prevention and reduction of disasters, making it possible

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to analyze and evaluate evacuation scenarios, strategies and priorities, with a view to decreasing evacuation time, as well as identifying limiting factors in the process, and possible bottlenecks [7]. The main objective of evacuation strategies is to ensure the best possible process for the safe evacuation of people. This requires varied approaches for the different types of occupants and buildings [8]. Evacuation time is an important concept in the evacuation process, indicating the time it takes for people to move from an area considered as dangerous to a safe location [9]. Incident analyses have demonstrated that there is a connection between a delay in the start of evacuation and the high number of deaths and injuries, especially in the case of fires in residential buildings and hotels. Pre-movement time and pre-movement behaviors currently constitute key aspects in the evacuation process [10].

This study aims to analyze and enhance the evacuation process of a 4-star hotel, located in the city of Porto (Portugal) by means of PathFinder simulation software in order to find the shortest total evacuation time and identify possible bottlenecks and congestion. Such a study enables the enlargement of literature review on the subject, since, at the present moment, there are no significant studies related to the evacuation processes in Hospitality. The available literature review on evacuation processes does not present strong references on the importance of evacuation processes' best practices in hotels.

The article is organized in 4 sections. Section 2 presents a review of literature that addresses some practical cases in the field. Subsequently, Sect. 3 describes the practical work undertaken, which includes topics such as the hotel layout, a study of the simulation undertaken, the validation of the evacuation support system, the different strategies analyzed, as well as the presentation of results. In Sect. 4, the conclusions drawn from the study are presented.

2 Literature Review

When compared to the performance of experiments in a real system, simulation models allow for experiments to be conducted at a reduced cost, within a shorter time period and with fewer associated risks [11, 12]. There are many practical cases that point to the importance and contribution of the simulation tool in the process of supporting decision-making in the context of the evacuation of buildings.

In a case study undertaken at the Hotel Radon in Niška Banja (Serbia), the objective was to conduct and analyze the simulation of a potential evacuation. In order to perform the study, a simulation model was developed by using *PathFinder* software, which led to the conclusion that, for the presumed evacuation conditions, it was possible to carry out the evacuation of all the people successfully and without congestion [13].

Using simulation, another case study addressed the evacuation of pedestrians from the Western Beijing railway station (China) by means of *PTV Vissim* software. Supported by the module *PTV Viswalk*, a simulation model was developed to reflect the interaction between pedestrians and their surroundings. It was thus possible to observe real evacuation processes and identify possible congestion [14].

In the case study of evacuation in the context of fire for the subway station Wenze Road in Hangzhou, China, the risk levels of congestion during the evacuation process

of passengers were assessed. In order to perform simulation, the model was developed through *Anylogic* software. It was subsequently concluded that congestion risk levels were higher when a fire occurred and, as such, recommendations were made to optimize possible emergency evacuations [15].

A case study undertook a real simulation of emergency evacuation, in the context of fire, in the BB Rusunami building, located in Bandung, Indonesia, which involved 33 people, as well as computational simulation through *FDS-EVAC* software. It was concluded that the time required to accomplish a safe evacuation of the building was longer than the time available to carry out such an evacuation. It was, therefore, concluded that the building needs additional fire protection systems if it is to ensure the safety of its residents [16].

In another study, and through the implementation of *PathFinder* software, the objective was to simulate the evacuation of people, in the case of fire, from the subway station Haicang Avenue in Xiamen (China). Based on four scenarios, it was concluded that crowd dispersion extends evacuation time; additionally, some congestion was also detected next to the staircases leading to exits 2 and 4, since these exits are close to the access control of the platform [17].

Also supported by *PathFinder* software, one more case study sought to analyze different evacuation strategies for an Airbus A330–300 aircraft. The researchers concluded that, if one of the exit doors is unavailable, evacuation time is longer when compared to the evacuation scenario where all the exit doors are available [18].

A study addressed an evacuation simulation of people from a subway station of the Mashhad Urban Railway in Iran, using *Pedestrian Dynamics* software. The simulation results made it possible to detect the congestion points along the evacuation routes and thus test new solutions to improve evacuation time. These indicated that evacuation time could be reduced by approximately 19.5% [19].

3 Practical Work

3.1 Hotel Layout

The hotel selected for this case study is situated in the city of Porto. The hotel area covers 10 floors (including floor 0). The 145 rooms consist of: 16 Junior suites, 4 Superior suites and 1 Presidential suite, a *spa* with 3 massage and treatment rooms, a dynamic swimming pool, sauna, Turkish bath, a sensory shower, 1 restaurant which seats 120 people, and 4 meeting rooms. The hotel is equipped with two elevators for guests, each with a capacity for 8 people. However, in the event of an emergency and consequent need to evacuate the building, these elevators move down to level 0, thus becoming unavailable. As was previously mentioned, this hotel comprises 10 floors, with the rooms located between the 2nd and 9th floors. The *spa* and meeting rooms are found on floor 1; the reception area, restaurant and bar are situated on Floor 0. From floor 2 to floor 9, there are three types of layouts for each level:

- Floor 2 to floor 6 – consist of 19 rooms, two of which are Junior suites;
- Floor 7 and floor 8 – consist of 17 rooms, four of which are suites (two Junior suites and two normal suites);

- Floor 9 – consists of 16 rooms, three of which are suites (two Junior suites and a Presidential suite).

3.2 Simulation Study

In order to construct the simulation model using *PathFinder* software, measurements had to be taken of the various areas in the hotel. One also had to include the available emergency plans in the process, so that the simulation model would present the correct architecture and dimensions. Figure 1 shows the simulation model developed for the hotel in 3D viewing mode.

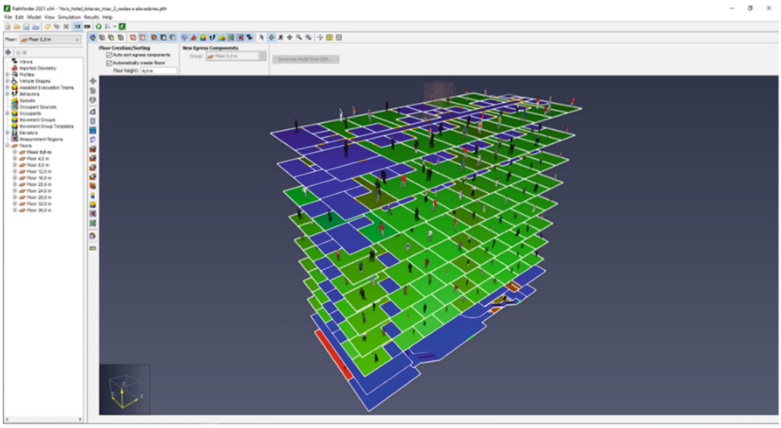

Fig. 1. 3D view of hotel simulation model

Figure 2 shows floor 0 of the hotel simulation model from a 2D perspective. The direction of the arrows on the stairs indicates the upward direction of the stairways.

Fig. 2. 2D view of floor 0 of the hotel simulation model

3.3 Validation of the Evacuation Support System

In order to validate the simulation model developed, one had to compare the time of a real evacuation procedure with that of evacuation resulting from the simulation of the model on *PathFinder* software. To this end, and in a real context, one measured the time that a hotel occupant would need to move from a certain location to a specific hotel exit. This time period was then compared with the time obtained for the same trip, using *PathFinder* software. This set of measured times is presented in Table 1. Through an analysis of these, one found that there is no significant dispersion of the times, having obtained an average percentage error of approximately 5.1%.

Table 1. Comparison of evacuation times.

Initial location of the hotel occupant	Real Simulation (Evacuation time in seconds)	Computer simulation (Evacuation time in seconds)	Approximate Percentage Error
Floor 9 (Without elevator)	127.0 s	123.0 s	3.1%
Floor 9 (With elevator)	86.0 s	90.0 s	4.6%
Floor 7 (Without elevator)	102.0 s	101,0 s	1%
Floor 5 (Without elevator)	83.0 s	81.0 s	2.4%
Floor 5 (With elevator)	75.0 s	69.0 s	8%
Floor 4 (Without elevator)	65.0 s	67.0 s	3%
Floor 3 (Without elevator)	58.0 s	54.0 s	6.9%
Floor 1 (*spa*)	18.0 s	19.0 s	5.5%
Floor 0 (Restaurant)	17.0 s	19.0 s	11.7%

3.4 Analysis of Evacuation Strategies

In order to analyze and enhance the hotel evacuation process, a simulation study of different evacuation strategies was carried out for a total of 429 hotel occupants. These strategies are based on the use of specific evacuation exits, the orientation of occupants towards the emergency exits and the operative status of the lifts. Each strategy allows occupants to evacuate by means of an established number of exits (one, two or three exits). This evacuation can include or exclude guidance; namely, hotel occupants may be directed to certain evacuation paths or elevators or, alternatively, occupants are not

provided with any type of orientation, and evacuate by taking the shortest route to an emergency exit.

Strategy 1: Scenario with 3 Available Hotel Exits, Unguided (with and Without Elevators)
Strategy 1 allows for the evacuation of the 429 occupants through the three exit doors of the hotel (central, side and *spa*), without any type of guidance. As such, occupants do not have to follow a specific evacuation path, thus doing so by taking the shortest route towards an exit. In this strategy, one simulated scenarios with and without the use of elevators in order to perceive their impact on the evacuation of occupants.

Strategy 2: Scenario with 2 Available Hotel Exits, Unguided (with and Without Elevators)
As in the strategy described above, strategy 2 enables the evacuation of the 429 occupants. However, in this context, only two of the three hotel exit doors are available. Occupants leave the building by using the exits, without any kind of guidance, taking the shortest path towards one of these. The scenarios created cover all the possible exit combinations.

Strategy 3: Scenario with 1 Available Hotel Exit, Unguided (with and Without Elevators)
Strategy 3 allows for the evacuation of the 429 occupants; however, only one of the three hotel exit doors is available. The occupants egress without any kind of guidance, making their way towards the exits by following the shortest path thereto. As in the previously mentioned strategies, one simulated scenarios for this strategy with and without the use of elevators, thus gaining an understanding of their impact on the evacuation of occupants.

Strategy 4: Scenario with 3 Available Hotel Exits, Guided (with and Without Elevators)
Strategy 4 allows for the evacuation of the 429 occupants by means of the three hotel exit doors (central, side and *spa* exits). The evacuation of the occupants from floors 2 to 9 is guided, in this case; namely, occupants of these floors are directed to the exits via a certain path or form of evacuation. As such, for the scenario in which the elevators are not available, one determined a number of occupants for each floor (from floor 2 to 9) who would only use the side staircase.

Strategy 5: Scenario with 2 Available Hotel Exits, Guided (with and Without Elevators)
Similar to strategy 4, strategy 5 allows for the evacuation of the 429 occupants, using the same type of orientation towards the exits. However, in this case, only two of the three hotel exit doors are available. The scenarios developed cover all the possible exit combinations.

Strategy 6: Scenario with 1 Available Hotel Exit, Guided (with and Without Elevators)
Like strategies 4 and 5, strategy 6 allows for the evacuation of the 429 occupants, who

are guided to the exits. However, in this context, only one of the three hotel exit doors is available.

3.5 Analysis of Results

Once an analysis of the simulation results for each strategy was completed, one was able to conclude that all the strategies studied led to a total evacuation time of under 1800 s (maximum total evacuation time suggested by literature for the evacuation of a building) [20]. One then proceeded to determine which of the strategies comprises the ideal setting, presenting the shortest total evacuation time. Accordingly, for each of the six strategies considered, Table 2 shows the values of total evacuation time for the best-case scenario.

Table 2. Total evacuation time for each strategy's best-case scenario

Strategies	Scenarios	Total evacuation time
1	Without elevators	664.0 s
2	Side and *spa* exits available (without elevators)	610.3 s
3	Side exit available (without elevators)	628.5 s
4	With elevators	536.0 s
5	Central and *spa* exits available (with elevators)	537.0 s
6	Central exit available (with elevators)	537.5 s

In sum, based on the content of Table 2, one is able to observe that the best scenarios for strategies 4, 5 and 6 present very similar total evacuation times. However, of all strategies studied, the scenario for strategy 4 - with three available exits and access to all the elevators - is that which presents the shortest total evacuation time.

4 Conclusions and Future Research Work

The theme for this study was that of developing a simulation model to analyze and enhance the evacuation process of a hotel. Several evacuation strategies were examined with the purpose of verifying their impact on the evacuation process, as well as determining the scenario which presents the shortest total evacuation time. As was previously described, the manner in which the elevators are used, the choice of evacuation routes by occupants, the number of exit doors available to leave the premises and their location, are all factors which influence the total time required to evacuate the building.

It is thus concluded that the shortest total evacuation time is to be found in strategy 4, in the scenario where the elevators are in operation and with three available exits. The time required is, at most, a second and a half less than strategies 5 and 6.

Regarding future research, one intends to implement the simulation model to examine the impact on the evacuation process caused by different speeds in the movement of

occupants during the process, as well as that of the existence of occupants with reduced mobility and social distancing.

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