ESCOLA
SUPERIOR
DE TECNOLOGIA
E GESTÃO
POLITÉCNICO
DO PORTO

P.PORTO

M

MESTRADO
ENGENHARIA INFORMÁTICA

Multi-Agents System Approach to Industry 4.0: Enabling Collaboration Considering a Blockchain

Pedro Daniel Coelho Pinheiro

10/2020

ESCOLA
SUPERIOR
DE TECNOLOGIA
E GESTÃO
POLITÉCNICO
DO PORTO

M

MESTRADO
ENGENHARIA INFORMÁTICA

Multi-Agents System Approach to Industry 4.0: Enabling Collaboration Considering a Blockchain

Pedro Daniel Coelho Pinheiro

Doutor Ricardo Jorge da Silva Santos

Abstract

The evolution of existing technologies and the creation of new ones paved the way for a new revolution in the industrial sector. With the introduction of the existing and new technologies in the manufacturing environment, the industry is moving towards the fourth industrial revolution, called Industry 4.0. The fourth industrial revolution introduces many new components like 3D printing, Internet of things, artificial intelligence, and augmented reality. The automation of the traditional manufacturing processes and the use of smart technology are transforming industries in a more interconnected environment, where there is more transparent information and decentralised decisions.

The arrival of Industry 4.0 introduces industries to a new environment, where their manufacturing processes are more evolved, more agile, and with more efficiency. The principles of Industry 4.0 rely on the interconnection of machines, devices, sensors, and people to communicate and connect. The transparency of information guaranties that decision makers are provided with clear and correct information to make informed decisions and the decentralisation of decisions will create the ability for machines and systems to make decisions on their own and to perform tasks autonomously.

Industry 4.0 is making manufacturing processes more agile and efficient, but due to the fast pace of trends and the shift from the traditional mass production philosophy towards the mass customisation, following the Industry 4.0 guidelines might not be enough. The mass customisation paradigm was created from the desire that customers have in owning custom made products and services, tailor made to their needs. The idea to perform small tweaks in a product to face the needs of a consumer group, keeping the production costs like the ones from the mass production, without losing efficiency in the production. This paradigm poses great challenges to the industries, since they must be able to always have the capability to answer the demands that may arise from the preparation and production of personalised products and services. In the meantime, organisations will try to increasingly mark its position in the market, with competition getting less relevant and with different organisations worrying less with their performance on an individual level and worrying more about their role in a supply chain. The need for an improved collaboration with Industry 4.0 is the motivation for the model proposed in this work.

This model, that perceives a set of organisations as entities in a network that want to interact with each other, is divided into two parts, the knowledge representation and the reasoning and interactions. The

first part relies on the Blockchain technology to securely store and manage all the organisation transactions and data, guaranteeing the decentralisation of information and the transparency of the transactions. Each organisation has a public and private profile were the data is stored to allow each organisation to evaluate the others and to allow each organisation to be evaluated by the remainder of the organisations present in the network. Furthermore, this part of the model works as a ledger of the transactions made between the organisations, since that every time two organisations negotiate or interact in any way, the interaction is getting recorded. The ledger is public, meaning that every organisation in the network can view the data stored. Nevertheless, an organisation will have the possibility, in some situations, to keep transactions private to the organisations involved. Despite the idea behind the model is to promote transparency and collaboration, in some selected occasions organisations might want to keep transactions private from the other participants to have some form of competitive advantage. The knowledge representation part also wants to provide security and trust to the organisation that their data will be safe and tamper proof.

The second part, reasoning and interactions, uses a Multi-Agent System and has the objective to help improve decision-making. Imagining that one organisation needs a service that can be provided by two other organisations, also present in the network, this part of the model is going to work towards helping the organisations choose what is the best choice, given the scenario and data available. This part of the model is also responsible to represent every organisation present in the network and when organisations negotiate or interact, this component is also going to handle the transaction and communicate the data to the first part of the model.

Keywords: Industry 4.0, Collaboration, Blockchain, Multi-Agent System, Decision-Making

Resumo

A constante evolução de tecnologias atuais e a criação de novas tecnologias criou as condições necessárias para a existência de uma nova revolução industrial. Com a evolução de dispositivos móveis e com a chegada de novas tecnologias e ferramentas que começaram a ser introduzidas em ambiente industrial, como a impressão 3D, internet das coisas, inteligência artificial, realidade aumentada, entre outros, a industria conseguiu começar a explorar novas tecnologias e automatizar os seus processos de fabrico tradicionais, movendo as industrias para a quarta revolução industrial, conhecida por Industria 4.0.

A adoção dos princípios da Indústria 4.0 levam as indústrias a evoluir os seus processos e a ter uma maior e melhor capacidade de produção, uma vez que as mesmas se vão tornar mais ágeis e introduzir melhorias nos seus ambientes de produção. Uma dessas melhorias na questão da interoperabilidade, com máquinas, sensores, dispositivos e pessoas a comunicarem entre si. A transparência da informação vai levar a uma melhor interpretação dos dados para efetuar decisões informadas, com os sistemas a recolher cada vez mais dados e informação dos diferentes pontos do processo de manufatura. A descentralização das decisões vai sofrer alterações, uma vez que os sistemas vão tomar decisões por eles próprios, ao ponto de executarem as suas tarefas autonomamente.

Mas a evolução dos mercados e as mudanças nas necessidades dos clientes levaram à evolução do paradigma de produção em massa para o paradigma da personalização em massa. Este paradigma origina da vontade dos clientes de obter produtos feitos à medida, personalizando certos aspetos de um produto. A ideia passa por fazer alterações a um produto de forma a satisfazer um grupo de consumidores, mas garantindo que o fabricante mantém os custos iguais aos da produção em massa e não perde eficiência na produção. Este paradigma coloca desafios muito grandes às indústrias, pois obriga a que estas tenham sempre a capacidade de responder rapidamente às necessidades que possam surgir na preparação e produção de um conjunto de produtos personalizados. Ao mesmo tempo, com a evolução da Indústria 4.0, as indústrias vão procurar cada vez mais marcar a sua posição no mercado com a competição a ficar cada vez menos relevante e com as diferentes organizações a preocuparem-se cada vez menos com o seu desempenho a nível individual e cada vez mais a desempenhar um papel de colaboração numa cadeia de distribuição.

Face às mudanças e dificuldades da Indústria 4.0, esta dissertação propõe um modelo que pretende

melhorar a colaboração entre organizações. Este modelo aborda um conjunto de organizações como entidades que pertencem a uma rede, onde as mesmas podem colaborar entre elas e estabelecer parcerias e enfrentar os desafios que possam surgir. Este modelo está divido em duas partes: a representação do conhecimento e o raciocínio e interações.

A primeira parte, a representação do conhecimento, é focado nos dados e informações que vão ser gerados pela rede de entidades. Cada organização tem um perfil publico e um privado onde são registados dados que permitem a própria organização avaliar as outras e a mesma ser avaliada pelas outras organizações presentes na rede. Nestes perfis, cada organização vai ter a possibilidade de especificar aquilo que tem para oferecer aos restantes membros da rede, assim como ter uma classificação de todas as outras organizações presentes. Esta classificação é gerada com base nas interações que são estabelecidas. Em contrapartida, cada organização terá uma avaliação geral que é baseada na visão que as outras organizações vão ter sobre a mesma. Para além desta informação, esta parte do modelo vai funcionar como um registo de transações entre as organizações, uma vez que sempre que duas organizações negociarem entre si, esta interação vai ficar registada. Todos os dados presentes neste componente serão públicos, o que significa que qualquer organização pode consultar os dados que existem na rede, melhorando assim a transparência de informação. No entanto as entidades vão ter a possibilidade de, em certas circunstâncias, manter os dados e as transações privadas para as organizações envolvidas. Apesar de a ideia do modelo ser promover a colaboração, em certas ocasiões as organizações podem querer manter certas informações privadas de forma a obter uma vantagem competitiva na mesma posição de mercado. Neste modelo a representação do conhecimento tem também o papel de fornecer segurança e confiança às organizações para guardarem os seus dados, garantindo que, depois de guardados, ninguém os pode modificar.

A segunda parte, o raciocínio e interações, presente neste modelo tem como objetivo intervir e melhorar as tomadas de decisões no contexto em que o modelo se insere. Imaginando que uma organização precisa de um determinado serviço que pode ser fornecido por duas outras organizações presentes na rede, esta segunda parte intervém de forma a ajudar a entender qual a melhor escolha, dado o cenário criado e os dados disponíveis. Esta parte do modelo tem também a responsabilidade de virtualizar todas as organizações presentes na rede. Quando duas organizações estabelecer uma transação, esta parte do modelo vai ser a responsável por virtualizar também essa mesma transação e de comunicar os dados para a primeira parte do modelo.

Contents

List of Figures

List of Tables

Acronyms

BA Blockchain Agent.

BGP Byzantine Generals Problem.

CPPS Cyber Physical Production Systems.

DLT Distributed Ledger Technology.

DMA Decision Maker Agent.

EA Entity Agent.

FIPA Foundation for Intelligent Physical Agents.

HF Hyperledger Fabric.

MAS Multi-Agent System.

MSP Membership Service Provider.

PBFT Practical Byzantine Fault Tolerance.

PoS Proof of Stack.

PoW Proof of Work.

Chapter 1

Introduction

In a world where revolutions are what define the evolution and development of societies, the current information and technology era might have had the biggest impact in transforming the modern world. Today, the amount of data produced is far superior when compared to the past, while at the same time, software and hardware keep developing at a fast pace and keep getting better in terms of performance, applicability, and potential.

Some governments, to take advantage of the existing and emerging new technologies, saw a great applicability in the manufacturing environment and, as such, they have made a great effort in pushing these technologies into the manufacturing processes of several industries, in order to improve the performance, quality, and controllability of these processes [2]. These initiatives aimed at pushing forward digital transformation, driven by increased digitisation and the connection of products, value chains, and business processes. The manufacturing environment has been facing many changes in the recent years, but these initiatives started to guide industries into its fourth industrial revolution, called Industry 4.0 [3]. The fourth industrial revolution will fundamentally impact the way people work and live and has been coined by the World Economic Forum as a new chapter in human development, enabled by extraordinary technological advances, that will give continuation of the advances of the first, second, and third revolutions [4].

With the introduction of industry 4.0, manufacturing processes will increase its efficiency, meaning that industries will be able to produce more, better products, and faster. Industries will be able start innovating faster, developing new and more complex products. Overall, industry 4.0 enables new ways of creating value, novel business models, and help organisations have a better control over their production [5].

Industries will take advantage of the amount of data produced, to help guide their business models and production plans towards the products that their clients want. But if industries can gather more data to combine with the one that they already have, industries can improve manufacturing, assure quality, manage their supply chain, and evaluate any potential risks [6]. The problem starts when customers, driven by the social requirements and by the need to express themselves, start looking for customised products [5].

Due to globalisation as well as technological, economical, and political factors, market conditions change quickly [4]. Manufacturing companies need to focus on cost-effective manufacturing to be able to maintain their competitive position, while competition is starting to get less relevant on an individual level and moving towards companies competing as part of a supply chain [7]. At the same time collaboration related to manufacturing has started to see some increase because of organisations sharing resources and information. A collaboration between organisations is crucial for a great success in the fourth industrial revolution, and creates a possibility of industries being able to manufacture their original products as well the customised products required by their customers, without having to cause an impact in their production [8].

This work, titled ”Multi-Agents System Approach to Industry 4.0: Enabling Collaboration Considering a Blockchain”, is focused on providing a blueprint to enable industrial organisations to collaborate in the face of the fourth industrial organisations, taking as a premise the fact that customers will demand high availability of more complex and customised products, and only through collaboration industries will be able to answer this and other demands. This work does this by presenting a model that is mainly divided into two parts.

The model creates the idea that the organisations should be encapsulated in a network that allows for partners to identify themselves more easily and to discover new organisations to collaborate with. The first part of the model is supported by a blockchain and works as the knowledge representation unity of the model, where all the organisations present in the network will have their data, their transactions, and data that represents how one organisation perceives the others and how it's perceived by their partners securely stored. This knowledge representation is structured in a way that encourages collaboration, but also allows organisation to compete, since competition can't be fully removed, otherwise organisation would slow their individual development and innovation.

The second part of the model presents a multi-agent system, designed so that, based on the data stored in the blockchain, an organisation can decide which is the best organisation to partner with. This partnership can be to share resources, knowledge, and information or to perform a traditional business to business transaction. Taking advantage of this partnership and coordination of resources is a major form of collaboration that can enable organisations to thrive even further in the fourth industrial revolution.

1.1 Structure

After the introduction present on this chapter, this dissertation is structured as follows. Chapter two is focused on the concept of industry 4.0, from understanding its core concepts and its origins, to analysing how industries will integrate this concept and its technologies in their processes. Chapter three addresses multi-agent systems, making a distinction between agents and multi-agents systems and presenting some applications present in the literature. Chapter four takes an in depth look at blockchain and ledger technologies, presenting their core concepts, looking at blockchain's security mechanisms, addressing the different types of blockchains and their differences, and presenting some key features and concepts that make blockchain and ledger technology stand out. Chapter five is dedicated to the presentation of the proposed solution, starting by presenting an overall look at the proposed model and then divide the proposal into three smaller parts, with the first one being a presentation of the concept of the network of entities, the second one being the knowledge representation and how blockchain is integrated into this model, and the third part being focused on the reasoning and interaction, where the multi-agent system that is part of the solution is presented. Chapter six contains a series of theoretical scenarios to show the different applicability situations for the model. In the chapter eight, this dissertation ends, with an overall view of the work presented, an enumeration of the future work, and with the scientific contribution that resulted from the research for this dissertation.

Chapter 2

Industry 4.0

This chapter aims to provide an overall vision around the concept of industry 4.0, providing multiple definitions of concepts related to it. In a first instance, this chapter contains a introduction to I4.0, discussing how the industry evolved until reaching this point, as well making a definition of how this concept can be integrated into the multiple industrial dimensions. The Cyber Physical Systems are also explained on this chapter, and there is a description of how I4.0 can be applied to change factories, manufacturing, and products.

2.1 I4.0: From mass production to mass customisation

The constant search for improvements in life quality is something present in every society, and as a result, industries need to find ways to answer to society's requirements. To answer this requirements, industry has been advancing rapidly, and has experienced some revolutionary stages [9], while always trying to improve people's life quality through customised and high quality products.

After the first industrial revolution, consequent revolutions have followed and have introduced new ways to aid production, from water and steam powered machines to electrical and digital assisted production, resulting in dramatic changes in the manufacturing processes [10]. The first industrial revolution started in the eighteenth century and in the nineteenth century are introduced manufacturing systems that used water and steam power. The second revolution followed through nineteenth century and represented the introduction of mass production utilising electricity. The middle of the twentieth century marked the arrival of the third industrial revolution, that introduced electronic, information, and communication technology systems for automation. With the technological advances introduced, there was a major shift in the manufacturing paradigm, with industries having a widespread adoption of computer-aided manufacturing systems and computer-aided design systems [2].

With the mechanisation, electrification and automation of production equipment, manufacturing progressed from a basic set of rudimentary processes to the mass production of a demanding industrial society, with productivity and efficiency continuously improving [5]. The mass production paradigm provides low-cost products through large scale manufacturing, satisfying the basic needs of customers, however the number of varieties offered on the products resulting from this type of production can be very limited [11] and cannot provide and answer to the growing demand for personalised products. This lead to the development of mass customisation, a manufacturing paradigm that tries to provide customised and high quality items to the costumers. However, this production paradigm is not sustainable, since it contributes to the environmental disruption, consumes plenty of nonrenewable resources [9], and faces other problems such as a aging population and competition from developing countries [10].

Since the third industrial revolution, more and more technologies have been introduced to the industry and with the ever more increased use of sensors being applied in the manufacturing equipment, real time production data can be obtained, to facilitate decision making and to provide a better control over the production environment [12]. This is slowing been developing into a new paradigm, that is creating the fourth industrial revolution, the so-called Industry 4.0 [10]. The connection of the physical industrial equipment, and other devices that are constantly streaming real time data, over the internet, combined with the evolution of analytics and big data have created a way to integrate manufacturing and logistics systems in the form of Cyber Physical Production Systems (CPPS) [3, 12]. I4.0 can be viewed as a structure in which CPPS takes advantage of the immense volumes of data and communications network to produce automated exchanges of information in which production and business processes are matched [13], making production operate in a flexible, efficient, and green way with constant high quality and low cost [9]. Since the third industrial revolution was also focused on automation and the introduction of information systems, it is easy to question why such a big importance is being given to this fourth revolution, but i4.0 focuses much more on the digitisation of the entire industrial process and on the end-to-end integration of digital industrial ecosystems [2].

This digital industrial ecosystems are being created due to the introduction of new technologies, linked with the concept of i4.0, in the industrial environment. The manufacturing life cycle is becoming oriented towards the increased individualism of customer requirements and emphasises the idea of constant digitisation and linking of all productive units in an economy [13]. To achieve this, it relies in a series of new technologies [13, 3]:

- The Industrial Internet of Things: a network of interconnected and uniform devices, that communicate using standard protocols. This allows for devices to interact both with one another and with a centralised controller, while also allowing for real time data streaming;
- Cybersecurity: with the increase connectivity and use of standard communications, it is important for i4.0 to address the issue of cybersecurity, using identity and access management of machines and users;

- The cloud: in i4.0, organisations need increase data sharing across the sites and companies, deploying to the cloud more data-driven services for production systems;
- Big Data: the collection and processing of raw data into comprehensive information, that will be used to provide knowledge to different core business processes and to support in real time decision-making;
- Simulation: using real time data to mirror the physical world in a virtual model, allowing an operator to work and test machine settings without using a physical one, reducing production down time and improving quality;
- 3D Printing: with a faster and relatively cheaper way of manufacturing, this technology will be used to produce small batches of complex and customised products;
- Augmented reality: i4.0 will use this type of technology to provide workers with real time information to improve decision making and work processes, while supporting a variety of services, such as selecting parts in a warehouse or sending remote repair instructions;
- Robots: this technology is becoming more autonomous, flexible, and cooperative and eventually, in i4.0, robots will work and interact with one another and with humans, creating a symbiotic work environment.

With the introduction of these technologies, industry 4.0 aims at being able to provide mass customisation of manufactured products, while making an automatic and flexible adaptation of the production processes. I4.0 has the intention of facilitating communication between parts, products, and machines, apply human-machines paradigms, optimise the production and provide new types of services, business models to the value chain [14].

2.1.1 Information Integration

Integration and self-optimisation are the two major mechanisms used in industrial organisation and the paradigm of industry 4.0 is outlined by three dimensions of integration: the horizontal integration, the vertical integration and the end-to-end digital integration [3].

In horizontal integration, one cooperation should be able to compete and cooperate with many other related corporations. This way related corporations can form an efficient ecosystem, where information, finance, and material can flow fluently among them. Integrating various technological systems used in different stages of manufacturing and business planning, within a company and between several companies will create new value networks as well new business models [9, 2].

In vertical integration, there is a need of having an integration of products, equipment, and human needs with different aggregation levels of the value creation and manufacturing systems [14]. With vertical integration there is a necessity of having the different systems integrated at different levels, such as actuator and sensor, control, production management, manufacturing, and planning to enable a flexible and configurable manufacturing system. With this integration machines it can be dynamically configurable to adapt to different types of products, delivering an end-to-end solution [9].

The end-to-end digital integration refers to the integration throughout the entire engineering process, since in a product focused value creating process a chain of activities is involved. With this, the digital and real world are integrated across a product's entire value chain and across different companies, while also respecting customer requirements [9, 2].

Besides this three integrations, in i4.0 it is expected to also occur the integration of hardware, software, data, and information. With an efficient and real time flux of data, this integrations are crucial to support automation and production processes needs [3]. With multiple industries involved in industry 4.0, there will be a need to share and exchange data, making i4.0 systems interconnected and applications must work together [15].

2.2 Cyber Physical Systems

The recent developments in technology have provided an higher availability and affordability of sensors, data acquisition systems, and computer networks that combined with the competitive nature of today's industries have forced factories to move towards high-tech methodologies and adopting new technologies [16]. With the increased connectivity that comes with industry 4.0 combined with this new adoption of new forms of technologies, industries will have a strong connection between their physical and digital worlds improving the quality of information used for planning, optimisation, and production [3].

Cyber Physical Systems are defined as a transforming technology that provides innovative services to enable connection of the operations between its physical reality and computing and communication capabilities [16, 14]. Shafiq et al. [17] defines CPS as being "the convergence of the physical and digital worlds by establishing global networks for business that incorporate their machinery, warehousing systems and production facilities". Monostori et al [18] says that CPS "are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet". Unlike traditional embedded systems, which are designed as stand-alone devices, CPS focus on working with a network of devices, continuously interchanging data by linking this systems intelligently with the help of cloud systems in real time [3], which aligns with the trend of having information and services always available which is inevitable in the highly connected world of today. In industry 4.0, due to the growing use of sensors and network connected machines, there will be a continuous generation of data and CPS can be developed to manage this data and leverage the connectivity between the machines, creating smart-machines. Also applying the concept of CPS in production, logistics and services in the current state of industrial practices, it would transform today's factories into smart-factories with significant economical potential [16].

As an emerging and key technology for industry 4.0, cyber physical systems are expected to offer promising solutions to transform current state and influence of many industrial systems [14]. The evolution of this systems mainly depend on the adoption and reconfiguration of industry systems and because CPS combines information and materials, decentralisation and autonomy play important roles in improving overall industrial performance [19]. CPS are capable of increasing productivity, modify the workforce performance, and produce higher quality goods with lower costs via the continuous collection and analysis of data [20]. In order to introduce CPS into any industry, the 5C architecture serves as preset to illustrate the workflow of how to construct a CPS from the initial data acquisition, thought analytics, to the final value creation [18]. The 5C architecture is outlined as follows [16]:

1. Smart Connection Level: The first step is to acquire accurate and reliable data from machines and their components. It is important to consider various types of data and a way to transfer data to a central server is required. Also a proper selection of sensors is important.
2. Data-to-information Level: Using several tools and methodologies available, meaningfully information has to be inferred from data to calculate machine health, bringing self-awareness to the machines.
3. Cyber Level: With information being pushed from every connected machine, this level acts as a central information hub, gathering massive amounts of information so that specific analytics can be used. These analytics provide machines with self-comparison ability, where the performance of a single machine can be compared with the rest of the fleet. Also similarities between machines and historical information can be used to predict future behaviours.
4. Cognition Level: With the knowledge generated until this level a proper presentation of the acquired knowledge with info-graphics needs to be made to support correct decision making.
5. Configuration Level: this level is a feedback from the digital to the physical world and acts as a supervisory control to make machines self-configure and self-adapt. This works as a control system that applies corrective and preventive decisions, which has been made in the cognition level, to the system.

2.3 Industry 4.0 Applications

Industry 4.0 describes many changes in the manufacturing systems. These changes do not only have technological implications but also organisational. The approach and ideas in the context of industry 4.0 are situated at the interface of disciplines such as electrical engineering, computer science, business administration, information systems engineering, mechanical engineering, among others [21].

The adaptability, the resource efficiency, and the integration of supply and demand processes, therefore elements where industry 4.0 can be applied become smart. This is the case for factories, cities, equipment and products that will, eventually, start demonstrating intelligence and knowledge. According to Stock and Seliger [22] the main applications of industry 4.0 are smart factories and manufacturing, smart product, and smart city.

2.3.1 Smart Factory and Manufacturing

The development towards industry 4.0 has a huge influence on the manufacturing industry and it its based on the establishment of smart factories and manufacturing. This development also provides immense opportunities to increase the performance of manufacturing using the ubiquitous information and communication technology infrastructure [22].

Factories which are embedded in the flow of data will evolve to the so called smart factories. In an ideal scenario this factories will operate with a certain level of autonomy and are able to manufacture products using the power from smart grids. Smart factories are using CPS for value creation, enabling them to self-organise its manufacturing processes and its information flow throughout the factory, in a decentralised manner by interchanging smart data with the CPS [22]. Industry 4.0 makes factories more intelligent, flexible and dynamic by equipping manufacturing with sensors, actors, and autonomous systems. Machines and equipment inside the factories will achieve levels of self-optimisation and automation, while being able to improve manufacturing processes to fulfil more complex and qualified standards [14].

In industry 4.0, manufacturing systems should be designed to follow human needs and not the reverse [21]. The future of manufacturing will be based on an innovative platform that bundles intelligent products, data, and services, and makes them consistently used [21]. Advanced methodologies of analytics and CPS will be implemented in manufacturing creating a technology push that will require higher level mechanisation, digitisation and networking [14, 21], but also in industry 4.0 smart manufacturing systems need more autonomy as a key factor for a self organised system, capable of responding to the manufacturing needs and changes [3].

2.3.2 Smart Product

Benefiting from Industry 4.0 will be a new type of product generated from smart manufacturing, the so called smart products. These products have embedded sensors, identifiable components, and processors which carry information and knowledge to convey the functional guidance to the costumers and transmit use feedback to the manufacturing system [10]. The architecture of industry 4.0 will allow costumers to communicate with this smart products [14], but this products will also allow for an increase production development since the smart products hold information about its requirements for the manufacturing processes and manufacturing equipment [22].

With such technology and features embedded in this smart products, many functions can be added to the products such as measuring the state of the product or tracking a product. Also a full production information log can be embedded with product assisting product development to optimise the design and the maintenance [10]. Furthermore with smart products, costumers will not only be able to know the production information of the product but also receive advice in how to use the product depending on their own behaviours [10].

2.4 Conclusion

This chapter introduced the concept of industry 4.0 and showed how the current state of industry evolved until reaching this new revolution. It is clear to understand that industry 4.0 will allow a smart, efficient, effective, individualised and customised production that aligns with the trend of mass customisation that is taking effect.

The interest in industry 4.0 has increased due to the belief that this evolution is marking a major turning point in the industrial history. It is possible to conclude that with the proper integration of new or existing technologies and with more advanced technology, like CPS, an improvement in the quality of industry 4.0 can be accomplished. The adoption of industry 4.0 will demand an high effort to integrate all of the information and processes that exist in the current industry so that an increase in digitisation can be made and an environment where connected network of humans and machines coexist and work together with shared and constantly flowing data that can be analysed to support decision making processes.

Industry 4.0 will create smart factories and products, increasing cost and time efficiency and improving product quality, while being able to respond to a more demanding costumer, that is constantly searching for highly customised products. It is possible to also conclude that the adoption of industry 4.0 and all of it's key technologies, such as IoT, CPS, ICT, big data, and cloud computing, needs to be made in a progressive way to guaranty that all levels of the industrial organisation are correctly integrated and that all challenges that appear are correctly tackled.

Chapter 3

Multi-Agent Systems

This chapter is focused in explaining what are multi-agent systems (MAS), which is very important topic in scientific research and with great potential in terms of applying agent-based or multi-agent based technology to solve practical problems. This chapter contains an overall vision of agent based systems as well of multi-agent systems and they can be used to improve decision making. Some applications of this technology are also presented to better consolidate the understanding and the potential of this technology.

3.1 What is an Agent?

Agent-based technology is recognised as being one important approach for the twenty-first century manufacturing system. The suitability of agent technology is a unique factor to consider in the real-world applications, particularly in industry 4.0 since it can bring a major improvement in the decision-making processes and in the collaboration of different systems [23]. A lot of researches are on-going in the applications of agent technology for the manufacturing systems, as well in the production process planning and scheduling to create a re-configurable manufacturing system [23].

Literature offers a lot of definitions for agent technology, making it hard to provide a general definition that is accepted by every researcher, since there is no strict definition about what an agent is [24]. One general definition given by Russel et al. [25] states that an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors. This definition means that an agent is an entity, that can be either physical or virtual, that senses its environment and acts accordingly over it. A physical entity can be any controller that controls directly a particular component or part of a system, while a virtual entity is a software that receives inputs from an environment and produces outputs [24]. If the agent just responds to the inputs, transforming them into actions, the agent is known as reactive, meaning that it will not maintain an internal state and does not predict the effects of its actions [26]. On the other hand, if the agent maintains internal state, predicts the effects of its actions or is capable of some sort of reasoning that agent if called a deliberative agent [26].

But to this definition of agent some authors still add some key aspects that can transform its understanding. One more complete definition is given by Maes [27] that says that autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realise a set of goals or tasks for which they are designed. Another definition similar to this one is stated by Adeyeri et al. [23] that says that the term agent means an entity meant to perform a task continuously and autonomously in the non-determinacy environment where other processes and entities exist. One key aspect mentioned between these two definitions is autonomy. Autonomy means that agents operate without the direct intervention of another entity and operate with some kind of control over their actions [24]. Another key aspect is the fact that they act to perform a set of goals. This means that the agent will be acting to achieve a certain objective, exposing some sort of rational behaviour, that acts as a response to the inputs that it senses [24]. In addition to this, agents can have a knowledge base about a particular environment or problem to be solved, with that environment being either a physical system, an operating system, the internet, etc [23].

3.2 Multi-Agent Systems

Multi-agent Systems (MAS) aim to provide both principles for construction of complex systems involving multiple agents and mechanisms for coordination of independent agent's behaviour [28]. When a number of agents exist at the same time in a given environment, a set of interactions is created from one agent to the other, creating a multi-agent system, where each agent maximises its own utility by cooperating with other agents to achieve goals [23].

A MAS is defined by Stone et. al. [28] as being a loosely coupled network of problem-solving agents that work together to find answers to problems that are beyond the individual capabilities or knowledge of each agent. The fact that the agents in a MAS work together implies a certain level of cooperation among the agents involved. This cooperation can be explicit by design, if the system is designed so that the agents behave in a way that leads to an enabling environment for cooperation. It can also be adapted, if the agents learn to cooperate or by evolution if the agents behaviour evolves thought some kind of evolutionary process [24]. MAS differ from a single agent system since the agents in the MAS try to model each other's goals and actions. Furthermore, the environmental dynamics of the MAS can be determined by other agents, since other agents may affect the environment in unpredictable ways [28].

Multi-agent systems are a particular type of distributed intelligent systems in which autonomous agents inhabit a certain environment. This environment can be dynamic, unpredictable, and open, with no global control or consistent knowledge [29]. The agents in this system interact with each other by exchanging knowledge and by negotiating, to achieve their own goals or the global goal, with interactions being the core of a multi-agent system [29].

The wide use and research around agent technology is due to what it can offer to a system, since MAS provide many benefits such as parallelism, robustness, and scalability [24]. The parallelism can help with the limitations of time bounded reasoning requirements and can assign several independent tasks to be handled by multiple agents [22]. The robustness aspect means that if control and responsibilities are sufficiently shared among agents within a MAS, the system can tolerate failures of one or more agents [24]. This agent systems are also scalable, meaning, that since they are modular systems, it is relatively easy to add new agents to a multi-agent system. Furthermore, if a system needs to change its parameters over time or across agents can also benefit from this advantage [28].

3.3 Applications

In the last decade MAS appeared as a new software technology that offers an efficient and more natural alternative to build intelligent systems, thus giving a solution to the current complex real world problems that need to be solved [29]. Agent technology has found its useful application to multiple sectors such as defence, healthcare, and business services and it is recognised as a potent tool for the 21st century manufacturing system, being widely used in the field of production, system integration, simulation, modelling, assembling, planning and maintenance [23].

The application of MAS reported in the literature tend to focus on the field of automotive, logistics, planning, scheduling and manufacturing control. For instance, a MAS was created to schedule in real-time, cargo assignment to vessels in a large crude carrier fleet used to carry out transcontinental transportations of oil [26] and other agent based system was created to control the production of cylinder heads in the Daimler production with a reported increase of 20% in productivity [26]. The University of Castilla-La Mancha, using MAS, created a distributed decision support system for the airport ground handling management, where the agent based technology was responsible to address complex tasks of planning operations and allocate resources [30].

Besides the areas of production planning, supply chain, and logistics, where the previous examples fit, there has been reports of agent systems being used in other areas such as traffic control, to optimise the flow of traffic in complex environments, in energy and smart grids, to monitor and manage large-scale networks of energy producers and consumers. Furthermore, MAS have also been used in buildings and home automation, as well in the military to control and coordinate robots. Another area where MAS can be applied is in network security, to perform distributed network traffic analysis and to detect attacks [26].

The suitability of agent technology is a unique factor to consider in real world applications, especially in industry 4.0 since this is a revolution that is technology driven and there will be a need to address the market competitiveness for manufacturing enterprises, as well improve decision making, the use of services, communications, collaboration and other difficulties that will affect multiple systems [23].

3.4 Conclusion

Multi-agent systems offer an efficient alternative to build intelligent systems and are a potent tool for solving tough problems, and especially for solving manufacturing complex issues in the present age of technological evolution. Due to the features that MAS provides, such as reasoning, communication, coordination, learning and planning, they are also becoming an indispensable resource for the fourth industrial revolution, as shown by its vast application fields.

At the core of MAS are the agents, that can be active and responsive by their own activities, making this type of system, and the interactions between them, autonomous. This contributes to the adaptability of this type of systems, since the agents can adjust their activities to the dynamic environment they are in. It is also clear that the main advantages of multi-agent systems are their scalability, robustness, and parallelism, justifying the amount of research that is on-going in the application of this technology in various fields, and especially in the industrial environment where this can have a unique suitability and help solve many complex problems.

Chapter 4

The Blockchain Technology

In this chapter there is going to be made an explanation about one of the most relevant technologies of the current times, that is promised to disrupt many areas, the blockchain technology. This chapter contains a presentation of the concepts of this technology and some more in depth properties that become more relevant each day. This chapter ends with the enumeration of some real-world applications of blockchain and tries to understand what possible applications can be done and what the future holds for this technology.

4.1 The core concepts of blockchain

Blockchain is being praised as a technological advancement that allows societies to trade and interact in a revolutionary way [31]. This technology is marking the dawn of a new era in decentralised information technology [32], with a high praise reputation that is attributable to its properties by allow mistrusting entities to make exchanges and interact without relying on a trusted third party [31].

This technology was first introduced as part of Bitcoin's underlying infrastructure, but its potential applications reach far beyond digital currencies and financial assets [32], with this technology, finding its purpose in areas such as distributed cloud storage, smart property, IoT, supply chain management, ownership and royalty distribution [31], among others. Blockchain can act as a catalyst for growth and create a true collaborative global ecosystem, with shared goals and objectives, for the benefit of a wider community [33].

Blockchain is a peer-to-peer distributed ledger technology (DLT) that works as register of all the transactions that happened to all the participants of the network [34]. A DLT is a distributed data structure, that is spread across several computing devices [35]. Blockchain acts as a distributed database, maintaining records of all the transactions on a blockchain network, with this transaction being time stamped and bundled into blocks, where each block is identified by a cryptographic hash [35]. This technology is formed by a linear sequence of blocks, as can be seen in figure 1, creating a chain of blocks, where each one has a reference to the hash of the previous one, giving it the name of blockchain [1]. A block consists of the block header and the block body. The block header is where the hash of the previous block, *i. e.* its parent block, is stored [1]. The block body is composed of a transaction counter and transactions, with the maximum number of transactions that a block can contain depending on the block size and the size of each transaction [1].

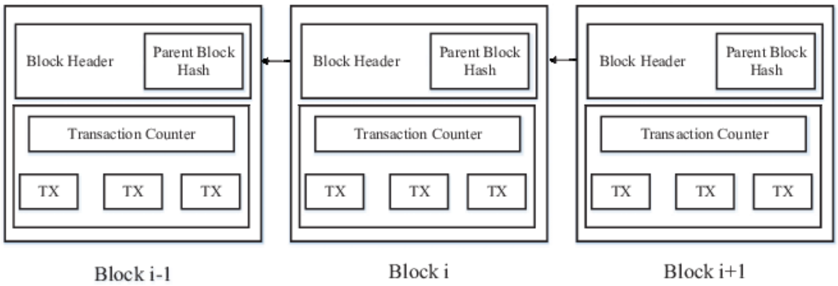

Figure 1: Example of a sequence of blocks, creating a blockchain [1]

Being a DLT, a blockchain is maintained by a network of nodes, where each node has a copy of the blockchain and each node executes and records the same transactions [35]. With this decentralised approach, there is no need for setting up a trusted centralised entity for managing the registry [34], which is a key feature of blockchain. Anyone can add data to the chain of blocks, by making a transaction, anyone can review the transaction, but no one can change it, making a blockchain a complete and immutable history of network activities [32].

To maintain the security of the network, blockchain uses cryptographic primitives such as hash function, digital signature and encryption [34]. The digital signature is used to validate the transactions, giving each user involved in the transaction a pair of private and public keys. The data, in the form of transactions, is digitally signed by the first user's private key and broadcasted by the participants in the transaction, so that the transaction can be grouped into the blocks in a chronological order and time stamped [34]. The second user involved in the transaction can validate the integrity of the transaction by using the first user's public key, easily checking if the data has been tempered or not [1]. A hash function is also applied to the content of the block, creating a unique block identifier to be stored in the next block [36]. Since the result of this function is deterministic and cannot be reversed, it is easy to verify if the content of the block was modified, by applying the function again, and comparing it to the identifier from the following block [34]. Any attempt to tamper information can be detected by the participants in the network, making the ledger immutable [34].

Besides security, blockchain has other key characteristics that allow it to find other applications outside the financial context. Another key characteristic is its decentralisation, that assures, in contrast to a centralised system, there is no need for a third party, like a bank, to validate and confirm a transaction [35].

Consensus algorithms are used to maintain data consistency in a distributed network [1]. Public verifiability of information [31] is another key property, that is achievable allowing each node to quickly validate transactions and verify that the state of the ledger was changed. Furthermore, because of the immutability of a blockchain, invalid transactions could be discovered immediately, guaranteeing the integrity and persistency of data [31], with information being protected from unauthorised modifications. Redundancy of data, is also a key property, that is inherently provided through replication of the blockchain across all nodes [31], while in a centralised system, this redundancy is only achieved creating replications of physical servers or creating backups. The information replicated on each node, and the need for each transaction to be publicly verified enables the transparency of data, even though that the amount of data that is transparent can differ from system to system [1].

4.1.1 Smart Contracts

Nick Szabo introduced this concept in 1994 and defined a smart contract as a computerised transaction protocol that executes the terms of a contract [37]. His idea was to translate contractual clauses into code, and embed it into hardware or software that can self-enforce them, to minimise the need for trusted intermediaries between transacting parties, and the occurrences of malicious or accidental exceptions [37].

In the context of blockchain, smart contracts are scripts stored in the blockchain, that represent a digital contract. Smart contracts are self enforcing and make it prohibitively expensive to break contracts, controlling blockchain participant's digital assets [38]. They work as software protocol that performs an action when certain conditions are met, reducing the amount of human involvement required to create, execute and enforce a contract [32]. Since contract partners do not usually fully trust each other, blockchain technology is suitable for this type of application, since in this distributed system, there is no need for a trusted third party, simplifying trustless protocols between multiple parties [31]. But besides allowing asset transfers between entities that do not trust each other, a blockchain that supports smart contracts allows for multi-step interactions to occur between these entities [37].

The entities involved in the transaction get to inspect the code and identify the outcomes before deciding to engage with the contract, have certainty of the execution, since the code is in the network and cannot be controlled fully by neither of the participants, have public verifiability over the process since all interactions are digitally signed [37].

Represented as a piece of code that resides on a blockchain, smart contracts encode certain conditions and outcomes, that are setup to only be available if the encoded conditions are met [39]. Smart contracts are stored in a block with a hash that identifies it, having a unique address, and can be triggered in a transaction by indicating the address in the blockchain [40]. Smart contracts include a set of executable functions and variables, with the functions being executed when transactions are made. Upon its execution, the variables in the contract change depending on the logic implemented in the function [35].

Once compiled, the contracts are uploaded to the blockchain network, which assigns a unique address to the contracts. When addressing a transaction to a contract, the contract is triggered, and the contract code is executed on each node participating in the network, as part of the verification of new blocks [35], in an independently and automatically manner, according to the date contained in the triggered transaction [40].

While Bitcoin supports a limited set of smart contracts, Ethereum, an open source blockchain platform [38], was the first blockchain to support arbitrary code execution on the blockchain, allowing any kind of smart contract [31]. The real potential for using smart contracts exists when they can be connected to other digital information and to the physical world in some way [31]. While some examples on how to connect smart contracts to other digital information already exists [35], the real potential is in connecting these contracts to physical assets, creating more use cases. But because practical smart contracts are relatively new technology, it is not clear yet to what extent these are legally binding, or how they should be interpreted [31].

Smart contracts allow to have general purpose computations occur on the blockchain. Where they excel, however is when they are tasked to manage data driven interactions between entities on the network [37], as they operate as autonomous actors, whose behaviour is predictable. As such, they can be trusted to drive any logic that can be expressed as a function of data inputs, provided that the data they need to manage is within their own reach [37].

4.1.2 Types of Blockchain

In a blockchain, to add a new block to the ledger a consensus protocol is employed and based on how the identity of a participant and its right to participate in the consensus are defined within the network: a distinction can be made between public, private, and consortium blockchain [34]. The taxonomy of blockchain systems can be defined according to how they handle a set of properties:

- Read and write permission: in a blockchain a participant can have a role as a writer and as a reader. As a writer, the participant is involved in the consensus protocol and can grow the blockchain by accumulating transactions within a block and append that block to the blockchain [31]. As a reader, the participation only concerns the transaction creation process, simply reading and analysing the blockchain [31], but, depending on the type of blockchain the reading permissions, regarding how visible transaction are, are also different [37].
- Consensus process: who can join this process can be different according to the type of blockchain.

- Consensus determination: depending on the type of blockchain, who can validate transactions can vary [35].
- Immutability: with a very distinct number of participants between the three types of blockchain system, how easy to tamper transactions will vary, since the records are being stored in every participant, making it hard to change records as the number of participants increases [1].
- Efficiency: just like immutability, efficiency is also affected by the number of participants, but in contrast to the previous property, the efficiency goes up as the number of participants is lower, since there are fewer nodes, taking less time to propagate transactions and blocks [1].
- Centralisation: the three types of blockchain mainly differ in how much centralised each system is [31].

A key difference between the three types of blockchain is how they handle the consensus process and what consensus algorithm they employee [35]. A consensus process makes sure that all nodes synchronise with each other, agreeing on which transactions are legitimate and added to the blockchain [37], therefore agreeing with the shared state of the system. In blockchain, how to reach consensus among the untrustworthy participants is a encapsulation of the Byzantine Generals Problem (BGP) [1]. This problem questioned how distributed computer systems could reach consensus without relying on a central authority, in such a way that the network of computers could resist an attack from ill-intentioned participants [41]. In BGP, the Byzantine army is camped outside an enemy city in hopes of conquering it. An independent general command each division, with some generals wanting to attack and others wanting to retreat, but an attack would fail if only part of the army attacked the city, forcing them to reach agreement to attack or retreat [1].

A blockchain solves this problem through a probabilistic approach [41], forcing information travelling over a network of computers to become more transparent and verifiable using mathematical problems that require some computational power to solve, making it harder for potential attackers to corrupt the network with false information [41]. To ensure the consistency of information, some consensus protocols are needed, with different approaches being adopted [1]. One of these approaches is the Proof of Work (PoW) consensus strategy used in the Bitcoin network [1]. PoW is based on a process that consists of looking for a nonce, a random number that is stored in every block, so that the resulting hash of a new valid block satisfies certain requirements [34], also called ”mining”. Its core idea is to allocate the accounting rights and rewards through the hashing power competition among the nodes. Based on the information of the previous block, the different nodes calculate a specific solution of a mathematical problem [42]. PoW takes the workload as a safeguard. The length of the chain is proportional to the amount of workload and all nodes trust the longest chain [42]. The problem with this approach is the amount of energy consumed, since 2013 the amount of energy consumed by Bitcoin mining had been already compared to the Irish national energy consumption [34]. To address this energy consumption issue, Proof of Stack (PoS) as been proposed as an energy saving alternative to PoW [1]. Compared to

PoW, PoS saves more energy and is more effective. But, as the mining cost is nearly zero, the attacks might come as a consequence [1].

Another consensus algorithm, the Practical byzantine fault tolerance (PBFT), is a replication algorithm to tolerate byzantine faults [1]. Byzantine Fault Tolerance can be a good method to solve transmission errors, but early systems required exponential operations and it was only in 1999 that PBFT system was proposed and the algorithm complexity was reduced to a polynomial level, with improved efficiency [42]. A new block is determined in a round. In each round, a primary block would be selected according to some rules. This block is responsible for ordering the transaction. The entire consensus process is divided in three phases (pre-prepared, prepared, and commit) and in each phase a node only enters the next phase if it has received votes from over 2/3 of all nodes. So, this consensus algorithm requires that every node is known to the network [1].

4.1.2.1 Public Blockchain

The public blockchain is open to the world, and they attract many users and active communities [1]. In this type of blockchain, everyone can check the transactions and verify it, allowing for all users to participate in the consensus determination process [38]. Besides everyone being allowed to participate in the consensus protocol for determining the valid state, public blockchains are coupled to a consensus protocol, such as PoW [34]. Furthermore, transactions in a public blockchain are visible to the public [1], and, such as in Bitcoin or Ethereum, anyone can join the network and can write to the shared state, invoking transactions [34]. The large number of participants in public blockchains ensures that records are stored in several nodes, making it nearly impossible to tamper transactions [1], but, this high number of participants also make it take plenty of time to propagate transactions and blocks. As a result transaction throughput is limited and latency is high [38], making this type of blockchain low on efficiency. The last property of public blockchains is that they are regarded as being fully decentralised [1].

4.1.2.2 Private Blockchain

A private blockchain, in contrast to public blockchains, has means to identify the nodes that can control and update the shared state, and often also have ways to control who can issue transactions [34]. This type of blockchain is fully controlled by one organisation, making it a centralised network, where the organisation can determine the final consensus and only those nodes that come from that specific organisation would be allowed to join the consensus process [1]. Here the permission to write data onto the blockchain is also controlled by one organisation, that may or may not allow users to have access to read the data [31]. This restriction on reading permissions can also provide a greater level of privacy to the users. Private blockchains are more efficient than public ones, since there are fewer participants and the transactions are quicker, but the records can be easily tampered with, since there are a more limited number of participants [1].

4.1.2.3 Consortium Blockchain

A consortium blockchain provides a middle ground between the low trust provided by the public blockchain and the 'single entity that rules everything' of the private blockchain [42]. In this type of blockchain, instead of allowing any person with an internet connection to participate in the transaction process or only allow a single organisation to have full control over what is done in the network, a few selected nodes are predetermined and they control the network [34]. Only this group of pre-selected nodes are able to participate in the consensus process, and since is formed by several organisations, the participants have the power to grant write/read permissions to other participants and only a small portion of the nodes in the network would be selected to determine the consensus, making this type of blockchain partially decentralised [1]. Consortium blockchains, are also very efficient, since there are few participants validating the transactions [31], but, as private blockchains, the limited number of participants makes it easier to tamper the blockchain [1].

4.2 Applications

Blockchain as seen a massive growth through various new innovative and technological concepts put forward. With the initial association of this technology with untraceable purchases on the dark net where users would use currencies to make anonymous purchases, blockchain gained a negative reputation [32]. But with the arrival of many large companies, such as IBM and JP Morgan, the investment and research in the technology increased, creating new possible applications and future paths for blockchain.

The more obvious and most well known application of this technology is for financial applications, with digital currencies, such as Bitcoin, being the first use case for blockchain [32]. This system offered a fully decentralised delivery of currency and traceable payments, while facilitating the exchange of digital currencies, or any other form of asset that can be registered with its own digital identity on a network [32].

Blockchain applications are far from being only financially related. Proof of ownership of intellectual property is often a proposed use case for blockchain [31]. The creator of a digital content can use a public blockchain as a time stamping service by making a transaction on the blockchain registering that asset, allowing for later to prove that the asset existed at a given time and was associated with the respective owner entity [31]. Blockchain can also be used to manage digital identities, with governments using blockchain to issue identities and passports to citizens, providing users with a decentralised service so that they can obtain their digital identity [32].

E-voting is another possible and studied application of blockchain [31]. In this system privacy is a major concern, as votes should be anonymous to prevent coercion, but on the other hand e-voting needs some sort of public verifiability, as there is a need to make sure that the creator of the system or someone who manages it does not change votes. So far no solution has been proposed that has been shown to be secure, verifiable, and private and there are many open challenges [31].

In the mobility sector, an example of an application is chasyr [43], a blockchain-based ride sharing platform that matches passengers and drivers, working as a uber-like service, in a decentralised architecture. Furthermore, in the sector DLT can be used to safely store car data, such as mileage and certificates, and to work in a decentralised transportation ecosystem, where people can use one token to ride on a bus or rent a bike, without any central authority to manage the operation [43].

Blockchain can be used to trace physical assets, allowing for a record of ownership to be maintained for each asset [32]. For example, Everledger tracks diamonds to ensure their authenticity, Provenence can track food origin to guarantee its sanitary safety [43]. Also this system can be used to develop applications to maintain records of manufacturing assets and inventory, keeping records of the asset identification and the transfer through the supply chain eliminating the need for manual paper records [35]. Blockchain can also be used for managing product certifications with the manufacturing information for a product, such as facility details, machine details, and dates, can be recorded on the blockchain. With this information recorded, the authenticity of a product can be provided, eliminating the need for a physical certificate which can be prone to tampering and forging [35].

With the rise of solar panels and other green sources of energy. the energy production is becoming more decentralised, offering a potential field for blockchain [43]. For example, blockchain can be used to certify the source of energy production, guaranteeing that it is environment-friendly, and can be used to trad energy between individual producers and consumers [43].

Currently, most blockchains are used for financial applications, to provide traceability, and to work as a prof of ownership, but more studies for different application in different fields are appearing, with traditional industries taking blockchain into consideration and thinking of applying blockchain into their fields to enhance their systems [1].

4.3 Conclusion

This chapter introduced the blockchain technology, its concepts, and applications that have been done or that are being studied. Blockchain has shown its potential to shape different fields and different industries, relying on its key characteristics like decentralisation, persistency, and anonymity.

Introducing a new way for people to exchange assets without having to fully trust the other participants and without having to rely on a trusted third party are the crucial beneficial points for the application of blockchain, and what inspires the search for real world applications, creating possibilities to disrupt the traditional way, and often bureaucratic, processes are handled.

This technology is recent but is evolving very rapidly, with commercialisation still a few years off but starting to take shape. As with many new technologies, different interpretations and necessities may originate several variations of the same concept, giving it an even more broad applicability and transformative concept, with companies looking at technologies to gain competitive advantage can not overlook blockchain.

The idea of a distributed ledger using blockchain has at its core some interesting approaches. The consensus process, how the state of the network is validated, and how permissions to read and write transactions to blockchain are handled give it a multiple array of configurations that can create the different types of blockchain. These different types can be implemented by different businesses or organisations, to suit their needs.

Chapter 5

Proposed Solution

The previous chapters addressed the study on the future of industrialisation, industry 4.0, introducing new concepts that hope to put industries in the next step of evolution. This chapter also touched a concept called mass customisation, that is forcing industries to move away from mass production, to meet costumer demands. In the other chapters, it was also introduced two technologies, MAS and blockchain, that have been targeted and proposed by many researchers as key pieces to be used in the future of i4.0.

This chapter is dedicated to the definition of the proposed solution that motivated this work, based on the premise of industry 4.0. The proposed solution present on this chapter is divided into three parts: first an overall presentation of the model, to present its structure and features; the second part is dedicated to explain how we can use blockchain in this model; the final part is referent to the Multi-agent system component, explaining how this component can be integrated with blockchain to create a model capable of supporting the future needs of industry 4.0

5.1 Improving collaboration in I4.0

As seen in previous chapters, industry 4.0 assumes its operations in a computerised and intelligent manufacturing environment, assuring flexibility and high production efficiency. Industry 4.0 also allows for a faster communication between costumer and producer, with costumers being much more demanding and requesting more personalised products. A study made by Deloitte on the rise of mass customisation [44] stated that 36 per cent of customers expressed interest in purchasing personalised products or services and that 46 per cent of customers are willing to wait longer for such products or services.

These displays of interests started moving production to what has been introduced in previous chapters as mass customisation, where industries lose the old paradigm of mass production and start looking at the individualisation of costumer's requirements. Now the goal is to deliver varied goods to fulfil small costumer groups with specific needs, while still trying to offer a reduced unit cost, moving the focus to variety through personalisation, flexibility, and responsiveness. In the context of industry 4.0, as can be seen in figure 2 [45], the manufacturing flexibility and the integration of different processes and activities are guarantied, due to the intelligent manufacturing environment where it operates. The problem is how, besides handling manufacturing and processes flexibility, industries will be able to fulfil personalised demands in the industry 4.0 context. Previously in a mass production environment, communication between industries and clients used to be unidirectional, but now with industry 4.0 and mass customisation this communication will need to be bidirectional.

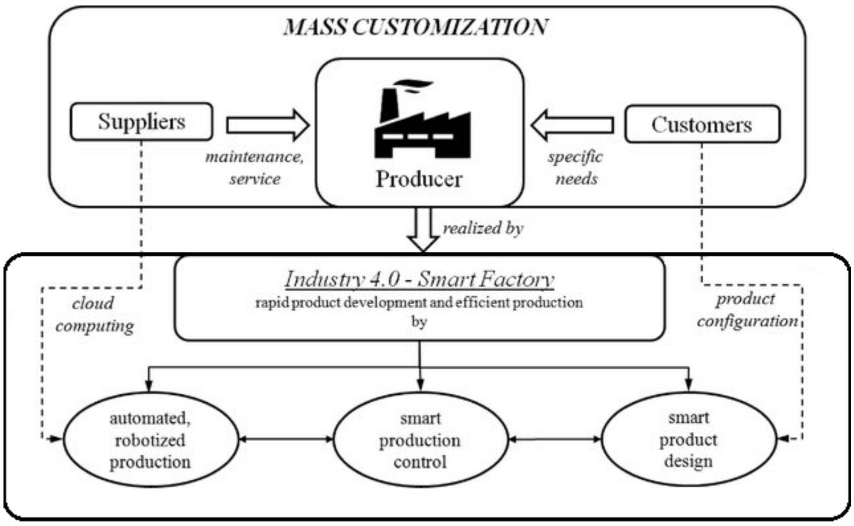

Figure 2: Mass customisation strategy in Industry 4.0 (adapted)

Customers will make requests with specific needs, directly to the producer or to an intermediary of the producer. By consequence the producer will need to use the services provided by its suppliers, to obtain the needed raw materials and other items to be able to fulfil the customer's requests. Once satisfied all the producers needs, it's up to a well configured industrial environment, called smart factory in the context of industry 4.0, to produce the desired products, using the CPS to automate and control the production, assuring the production of a quality item.

Furthermore, besides an effective communication with the clients, industries will have to work in continuous integration with their partners. These partners might be suppliers, service providers, shipping providers, and even other, competing, organisations. To obtain the resources and services needed to manufacture highly customised products, industries will need to quickly be able to interact with the right partner that can provide the needed resources. To achieve this, there needs to exists a better collaboration between industrial organisations and other businesses, even if they are competitors, to find success in the demanding environment of industry 4.0. Providing a model to improve collaboration in industry 4.0 is the goal of this proposal.

Usually, industries do not approach collaboration projects whit great hopes, mainly because they are used to only compete in the context of inter-organisational networks. Competition exists in situations in which a set of organisations are producing the same or related products and are thus striving to get first to market and to capture both the consumer and the supplier niches [46]. As presented in Turvey's (2018) work, competition is generally considered a key element in a well functioning economy, pushing businesses to be efficient, reducing costs, and investing to increase profitability. Competition is usually what keeps prices low for consumers, giving them more choices, and preventing one organisation for exercising market power. Organisations compete against each other, not only because they produce the same type of products or because they operate in the same markets, but also because they are influenced by each others work.

In pure competition context, the boundaries between the competing organisational systems are sharp and distinct, with competition springing from the tendency of organisations wanting to obtain the most value possible over their products, without having to rely on a partner to do so [46]. But, in the industry 4.0 context, the boundaries separating traditional industries are blurring [47]. Due to the introduction of the Cyber Physical Systems, the process of industry convergence is accelerating, making a gradual reduction in the distinction between goods and services, buyers and sellers, and individual firms [47], moving organisations to a collaboration context. As asserted by Hernandez et al. (2017) collaboration is at the heart of most challenges in industry 4.0, creating the necessity for a network to enable collaboration to solve such challenges [6].

Collaboration occurs when organisations work jointly on the development of products, where the distributed returns are sufficient for all the collaborating parties [46], witnessing a free flow of information between collaborating organisations, which in turn provides faster decision-making and can enhance the effectiveness of internal processes. Besides the flow of information, it is also important that collaboration brings organisations closer, enabling a faster assessment of their relations, to allow a organisation quickly decide on who to rely on to fulfil the services and materials that it needs for their manufacturing processes.

To improve collaboration in industry 4.0, this work proposes the combination of blockchain and multi-agent systems to be used in the same model. The model, presented in figure 3 [48], starts by creating a network as suggested by the work of Schuh et al. (2014), where entities can collaborate towards a stronger cooperation and each can achieve its targets. This collaborative network of entities aims at being an entry point for this model, allowing organisations, that already have some form of relationship established or are looking for new partners, to consolidate their goal and objectives.

The second part of this model is formed by a layer that uses multi-agent systems to handle the reasoning and the interactions between the entities, and by a blockchain to handle knowledge representation. With this two technologies combined we are able to provide empowerment for decision-makers in a decentralised system, which is also a key factor to promote collaboration in the context of industry 4.0 [8].

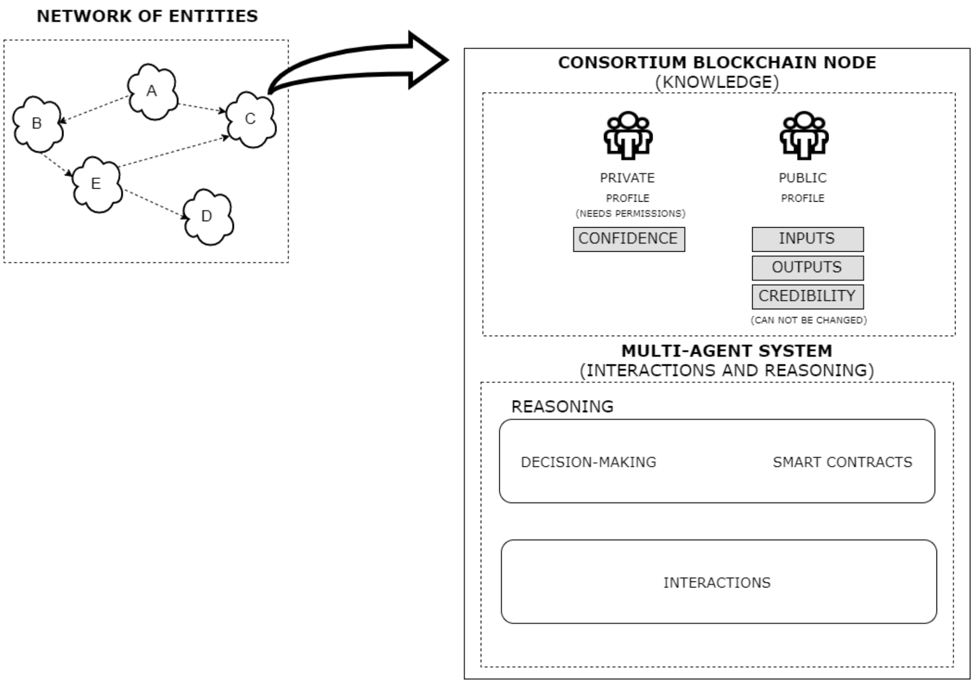

Figure 3: Proposed model that uses blockchain and MAS to improve collaboration in I4.0

The combination of MAS and blockchain is not new, as explained in the work of Calvaresi et al. (2018), some recent trends rely on the promising idea of integrating MAS and blockchain with the expectation of providing blockchain features in use cases where agent technology might require them. In the same work, the authors continue saying that the combination of MAS and blockchain can represent a solid solution if properly managed. The adoption of blockchain technology may fix the security limitations of agent systems and blockchain can provide features missing in some MAS scenarios, such as flexibility [34].

One example of the use of this technologies, applied to similar topics as this proposal, can be seen in the work of Casado-Vara et al. (2018) that presented a model that uses blockchain, smart contacts, and MAS to coordinate the tracking of food in the agriculture supply chain [40]. This model relies on blockchain to store all the transactions, with the authors pointing out security and decentralisation features as the main reasons why blockchain was applied. To coordinate all the members of the supply chain the authors use a MAS formed by several layers and agents. In this layers is where agents verify that if the participants of transactions are fulfilling the terms of the smart contracts and if not, they apply a penalty and the agents keep the money involved in the transaction until the conditions are satisfied. Another model applied to supply chain was proposed by Abeyratne et al. (2016) where the aim was to use blockchain based system to facilitate the vast amount of data to be collected about the products and users in manufacturing industry. This approach comprised of a decentralised distributed system that uses blockchains to collect, store, and manage this information throughout the products life cycle, claiming that this approach allows consumers to access product's information at any time, allowing them to make better buying decisions [32].

In the work of Ghadimi et al. (2017) it is proposed a multi-agent systems approach as a mean of automating and facilitating the process of sustainable supplier selection and order allocation, resulting in a more cooperative partnership [49]. The proposed model uses two sub models, a supplier evaluation sub-model and a order allocation sub-model. The first sub-model uses three types of agents, a data base agent, a supplier agent, a decision maker agent. The second sub-model uses a order allocator agent, a data base agent, and a supplier agent. The authors say that the model can improve order fulfilment rate, decrease demand uncertainty and eventually lead to better supply chain performance [49]. One last example in the literature, for applications of MAS and blockchain, is the work of Diogo et al. (2018) that aims to describe a new blockchain model, whose goal is to enable a gamified environment for a system comprised of a multitude of agents. A system where agents that work towards its intended goal provide good data and allow the potential to identify malicious ones [50]. The model considers three main entities: the agents that participate in building and maintaining the ledger, identified as ledger agents; the agents responsible for supplying ledger agents with processed data, known as slave agents; and data generating devices which may supply data to slave agents or directly to the ledger ones.

5.1.1 Network of entities

This model begins by creating a network of entities, where different organisations, firms, and industries are represented as generic entities. This network is a collection of autonomous organisations, with the entities that make up the network usually being legally independent entities. The objective of this network is not to create an idea that the entities belonging to the network appear and operate like a larger unique entity. Instead the point of the network is to encapsulate the different entities and their relationships in the same environment to allow the other components of the proposed model to be applied in an organised setup. Furthermore, organising the entities in a network type of representation allows to further understand what kind of dependencies and relationships are established between them.

Depending in what organisational context the model will be applied, the entities can represent different types of organisations. If the model is applied in the context of a large company, then the network of entities represents that same company but also its other units as separated profit centers. In this approach the network operates as a internal network allowing the different units of the same organisations to collaborate, interchanging processes, information and other resources. On the other hand, if the model is applied to a collection of different organisations that between them make trades and fall into a stable pattern of relationships that gradually becomes solidified, the network of entities will represent each one of this companies and their relationships. This is the more typical approach that the development of the model was based on, since in an industrial context most of the dependencies exist between different organisations, therefor the need to improve and to create a collaboration link is bigger in this situation.

In this virtual network of entities, each entity represents a physical organisation. This means that in this network, multiple industries that operate in a specific market or produce the same type of products can be represented, along side such entities as it's direct suppliers and service providers. Each one of this physical organisations has a relationship with one or more organisations, with this relationships being both complex, and multifaceted as well as highly dependent on the particular context in which they are embedded. Based on the work of Holmlund et al. this relationships can be categorised into two types [51]:

- Structural: if the relationship is represented by activity links, resource ties, connections, and institutional bonds. Links represent activities that the organisations perform and how these activities are interlinked. Ties refer to how organisations are resourced dependent. Relationships between actors in a business network are also connected to institutional actors and creating institutional bonds;
- Economical: if the relationships contain investments and financial adjustments that the organisations make. This investments may be made in monetary, technological, market and, in trust and commitment terms.

Independently of the relationship established between two or more entities, each one of the entities belonging in the network is dependent, at a certain level, of the others participants. As such, entities present in the network, have the necessity to collaborate with other entities to obtain materials, products, services, information, among other resources. But at the same time, each entity also has something to offer to the network, that in turn will fulfil the existing dependency of other entity.

5.1.2 Knowledge Representation

One of the layers of this model, handles the knowledge representation that supports the entire model. To do so, the model uses a blockchain to store the data of the entities and to store all the transactions, providing a shared, immutable, and transparent append-only register of all the actions that have happened to all the participants in the network. This layer is based on a Consortium blockchain, since it provides many of the benefits of a private blockchain, such as efficiency and transaction and data access privacy, without consolidating the power in one entity. The unique strategy of the consortium blockchain, that can be seen in figure 4, is highly beneficial for organisational collaboration, since it operates under a leaderships of a group instead of a single entity.

This group is the one that specifies who are the authorised transaction validators, and who has permission to participate in the consensus process. Transaction data and general data on the blockchain are also controlled using permissions, that are managed by this group. With this specifications, this partially decentralised distributed ledger can be applied to highly regulated businesses, since it has great efficiency in the transactions, with no transaction fees. The overall system rules are easier to manage and can achieve better protection against external disturbances.

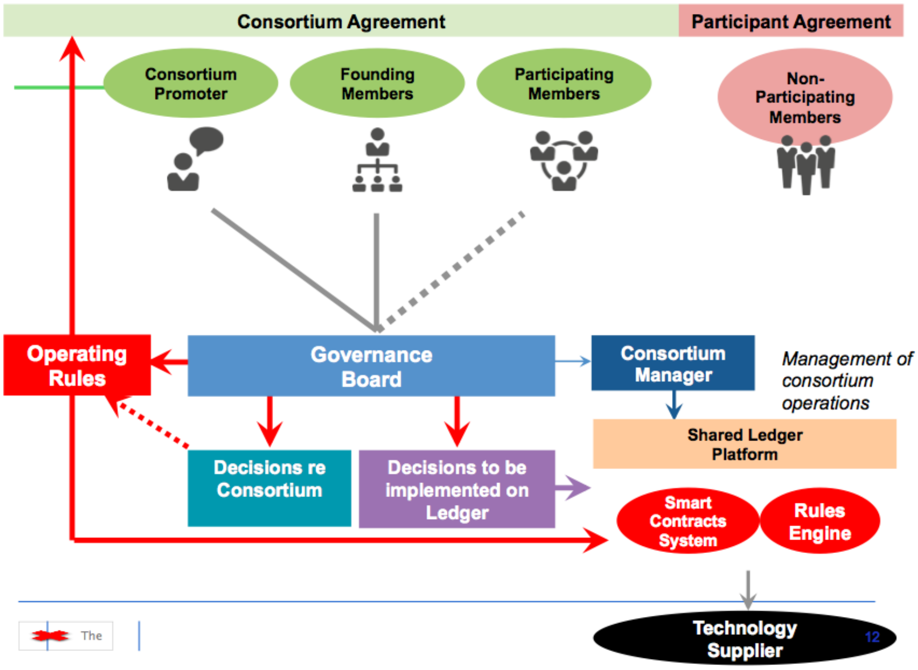

Figure 4: Consortium Blockchain Strategy

One of the pieces that are going to be stored in the blockchain is user related data. This data is created and registered for each entity belonging in the network, to create the possibility of identifying certain elements of the entities and to provide data to enable and ease the collaboration process. As such, an entity is represented by a public and a private profile. The public profile contains data that needs to be accessed by the network participants, to help validate and evaluate which entities should be approach to collaborate and help in specific processes needs. The private profile contains data that should help the entity to whom the profile belongs decide, together with the public profiles data, who is the best entity to collaborate with.

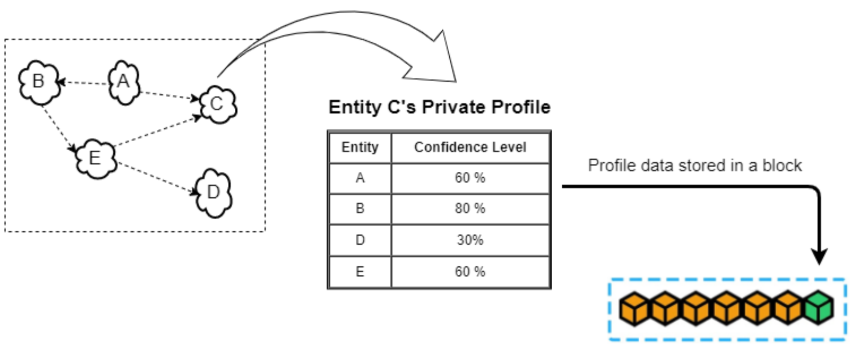

Figure 5: Private profile of an entity

The private profile contains data regarding the level of confidence that the entity has in every other entity (figure 5). Confidence is defined as being the feeling or belief that one can have faith in or rely on someone or something [52], meaning, in the context of this model, that one entity might have a certain level of confidence in other entity, despite what the level of confidence of the others entities is. This is represented by a percentage value ranging from zero to one hundred percent. Regarding accessibility, this data is only accessed by the entity that the profile belongs to, with the values for each entity being updated every time that the entity makes a transaction with other entity.

The public profile (figure 6) contains data that can help entities know the purpose of an entity in the network, such as, what is it looking for and what it has to offer to the network, helping the process of collaboration with the other entities, since this profile contains accessible information about the entity and what it represents to the network. This profile can be read by anyone in the network and stores the following values:

- Inputs - represents the needs of the entity, namely what it needs from the other entities in the network to fulfil it business processes. As an example, these inputs can be raw materials, maintenance needs, shipping services, among others. This value can be read by every one in the network, but only the entity can update this values.
- Outputs - this variable represents what an entity has to offer to the network. As it was previously described, each entity in the network has a set of needs that is looking to be fulfilled and has a set of outputs that it can offer that can be used as inputs by some other entity. So, ultimately, an output of an entity, might represent the input for some other.
- Credibility - this value is attached to the public profile of an entity and can be regarded as how this entity is perceived by each other entity in the network. Credibility is defined as being the quality of being trusted and believed in [53], meaning that this variable will hold a percentage value ranging from zero to one hundred, that will tell, based on previous interactions, how much the other entities trust a certain entity. Despite being stored in the public profile of an entity, the value can not be changed, even by the entity that owns the profile. This value is read only for the entities in the network.

The confidence and credibility values are critical in the context of this model. Both of this values are important to categorise and to create a separation between entities, with confidence being linked only to the entity and with credibility being linked to all entities in the network, despite referencing only the entity owner of the profile. A recent study [54], introduced four main components for credibility: trustworthiness, expertise, reliability, and quality. The first two can be related to the credibility of the entity itself, while the last two relate to the credibility of the transactions performed. Credibility is used in the context of this model, to provide a way of an entity to be individually classified by all the others entities in the network. On the other hand, the confidence values have a more simple and direct approach, they are used to provide an entity a way of storing their evaluation for each entity, based on their previous interactions. This evaluation is portrayed in a confidence value that displays how much an entity should be willing to perform transactions with other entity, based on how much it trusts it. Both values can only

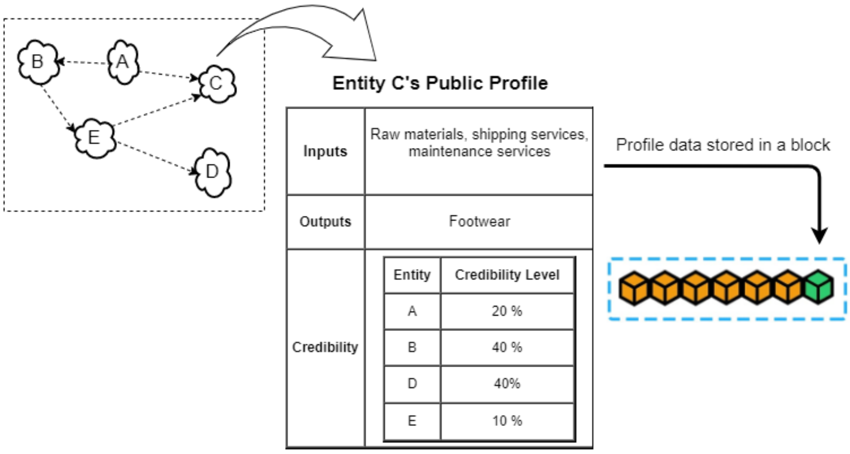

Figure 6: Public profile of an entity

be updated based on existing transactions and by the interactions between the blockchain and the multi-agent system. Furthermore, the way this profiles are setup allow for high level of flexibility between the relationships established between the entities, creating an environment that facilitates collaborations. For instance, if an entity A has a low level of credibility, but because previous collaborations with entity B were successful, this entity has a high level of confidence in entity A which enables it to rely on this entity to establish more transactions.

5.1.2.1 Hyperledger Fabric

The creation of the blockchain, that supports the knowledge representation layer for this model, demands some specific features. The fact that its holding information about organisations creates a necessity to balance the relation between transparency and privacy, while promoting the idea of collaboration. This creates the necessity for a special infrastructure that can provide such features. As such, for the creation of the blockchain, this work relies on Hyperledger Fabric (HF).

Like other blockchain technologies, HF has a ledger, uses smart contracts, and is a system where participants manage their transactions. But unlike other blockchain systems, Hyperledger Fabric is not an open system that allows unknown identities to participate in the network, the members need special authorisation and validation to enrol in the network [43]. HF is an implementation of a distributed ledger platform for running smart contracts, leveraging familiar and proven technologies, with a modular architecture allowing pluggable implementations of various functions [55]. Fabric is a consortium type of blockchain used in more than 400 prototypes, proofs-of-concept, and in production distributed ledger systems, across different industries and use cases, since it introduces a new blockchain architecture aimed at resiliency, flexibility, scalability, and confidentiality [56].

This new blockchain architecture introduced by Hyperledger Fabric is called *execute-order-validate*, and can be seen in figure 7. A distributed application for Fabric consists of two parts [56]:

- A smart contract, that in HF is called chaincode, which is the code that implements the program logic and runs during the *execution* phase. The chaincode is the central part of a distributed application in Fabric, with special chaincodes existing to manage the blockchain system and maintaining parameters. Chaincode is invoked by an application external to the blockchain, when that application needs to interact with the ledger.
- An endorsement policy that is evaluated in the the *validation* phase. This policy acts as a static library for transactions validation, which can only be parameterise by the chaincode. A typical endorsement policy lets the chaincode specify the endorsers for a transaction in the form of a set of peers. This set of peers are defined as the smallest set of organisations that are required to endorse a transaction in order for it to be valid. To endorse, an organisation's endorsing peer needs to run the smart contract associated with the transaction and sign its outcome.

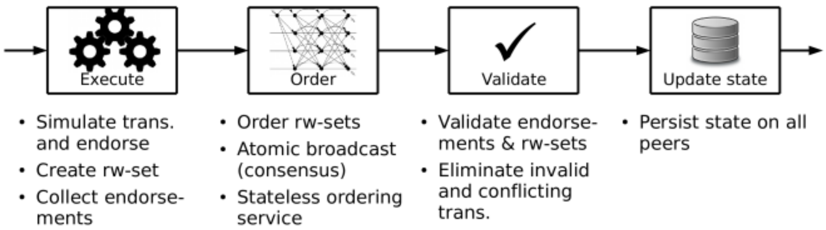

Figure 7: Execute-order-validate architecture of Hyperledger Fabric

Using this endorsement policy, transactions can be send to peers, with each transaction being executed by them with its output being recorded, during the *execution* phase. Then, following the architecture of Fabric, transactions enter the *ordering* phase. In this phase, consensus protocols are used to produce a totally ordered sequence of endorsed transactions grouped in blocks, that are then broadcasted to all peers. Then, in the *validation* phase, each peer validates, in the same order, the state changes from the endorsed transactions with respect to the endorsement policy and the consistency of the execution.

A Fabric blockchain consists of a set of nodes that form a network. As Fabric is permissioned, meaning that to access certain transactions data and to participate in the consensus process it is needed permissions, all nodes participating have an identity [56]. Nodes in a Fabric network take up on of three roles [55]:

- Non-validating nodes that submit transaction proposals for execution and functions as a proxy to connect issue transactions.
- Validating nodes that execute transactions and validate them. Not all nodes execute all transaction proposals, only a subset of them do, as specified by the policy of the chaincode to which the transaction belongs.

- Order service nodes are the nodes that form the ordering service. This service is responsible for establishing the total order of all transactions in Fabric. This nodes are unaware of the application state and do not participate in the execution or validation of transactions.

Hyperledger Fabric promises to be a comprehensive, yet customisable, enterprise blockchain solution due to its key design features [57]. Besides some previous explained features, like chaincode and endorsement policies, there are more that fully align with the intention of using HF in this model, like the case of the membership service provider (MSP). Due to the fact that in the network of an Hyperledger Fabric based system all participants are known, a public key infrastructure is used to generate cryptographic certificates, giving the possibility to control data access [57]. The MSP maintains the identities of all nodes in the system and is responsible for issuing node credentials that are used for authentication and authorisation [43]. Since in this model, there should be special authorisations for who can write and read specific data, for instance from the public and private profiles, this is a key feature that Fabric provides to apply in this scenario. This service comprises a component at each node, where it may authenticate transactions, verify the integrity of transactions, sign and validate endorsements, authenticate and block operations [43].

Furthermore, MSP allows for identity federation, when multiple organisations operate a blockchain network. Each organisation issues identities to its own members and every peer recognises members of all organisations, for example, by creating a mapping between each organisations and an MSP [56]. Hyperledger Fabric also offers the ability to create channels allowing a group of participants to create a separate ledger of transactions [57]. This can be specially useful in a network where participants are also competitors and don't want every transaction they made known for every participant. As an example related to this model, an entity can sell some products to some entities and not others. Additionally, when two or more entities create a channel, then only those entities have copies of that ledger.

5.1.2.2 Is Blockchain the right solution for this model?

Despite the use of blockchain and multi-agent systems being well documented in literature [50, 29, 32, 34], the use of blockchain, due to the fact of this technology still being recent and rarely used in real-world applications, a certain level of distrust is associated with it and quite often, with the use of blockchain, the question arises whether its use is just hype or is justified, as presented in the work of Wust et al. [31].

The use of blockchain here in question, more specific the use of Hyperledger Fabric, allows for a representation of multiple organisations, that can have multiple peers or nodes, and perform transactions through the channels. Since this blockchain operates in a type of business-to-business (B2B) network, the participants might be extremely sensitive about how much information they share. Therefor, Fabric supports networks, where privacy, using channels, is a key feature. There is also an access control, meaning that if an new organisation wants to join the network it has to enrol through the trusted membership service provider.

The usage of blockchain aligns with this proposal since there are multiple entities in the same network, that represent different organisations, which creates an opportunity to run a consortium blockchain among this set of known, identified participants [56]. A consortium blockchain provides a way to create interactions among a group of entities that exchange funds, goods, or information, while none are willing to agree on a trusted third party [31]. In this scenario, the usage of smart contracts can simplify trust-less protocols between multiple parties, while the details of the contract remain hidden and it only concerns a well-known number of participants. With the support of blockchain it is possible to create a system that allows for reliable interactions to be streamlined in an environment where there is a lack of trust [33] and therefor, provide opportunities for consumers and business, through improved collaboration.

In this proposal the usage of a blockchain allows the removal of a trusted mediator, since each entity might operate a node in the network, making sure that a single entity does not have a full control over the ledger [1], making this type of blockchain partially decentralised [38]. In addition to transactions, commitments and meta-commitments can be securely stored in the blockchain [34]. In this type of blockchain, participants know and identify each other [31], and anyone can join the network after suitable verification of their entity. Then a set of permissions are given to the entities to only allow them to perform a specific set of writing and reading operations [31]. This can guaranty that entities only have access to the appropriated sets of information about the other entities on the network, while controlling and updating the shared state of the network and issuing transactions [34]. For instance if entity A only makes transactions with B and C, there might be no need for the rest of the entities to have permission to read and share the data.

5.1.3 Reasoning and Interactions

The second layer of this model is based on a multi-agent system and its purpose is to provide a solution to handle the reasoning and the interactions between entities, achieving its end result that is to decide which are the best entities, from the network of entities, to interact with in each situation. This proposition meets another subject, the supplier selection problem, that is often referenced in the literature [58, 59, 60]. The supplier selection problem considers qualitative and quantitative criteria and influencing factors to perform the selection [49]. But when moving to an industry 4.0 manufacturing environment, organisations cannot rely on the typical entity selection process, since this will also be affected by industry 4.0 [59]. This process needs to be updated and its ideologies transferred into a more sustainable approach, where social measures and influencing factors are incorporated into the selection process [59].

Responding to the diverse customer demands requires the entities ability to link and work effectively and efficiently with each other, making the entity to entity relationship critical for each organisation [58]. Choosing the right partner for a business, enables the possibility of achieving a successful and profitable partnership, with less uncertainty and more information flow [60, 49]. Cooperation is an important element in characterising the future state of relationships between different manufacturing organisations. In contrast with what has happened in the past years, the future of manufacturing and overall business is deemed to be moving and focusing on much more collaborative interactions with a large amount of information exchange, creating joint efforts in value creation and total cost reduction [49].

The objective of this layer is working with a multi-agent system for entity selection, helping industries and decision-makers in manufacturing organisations to make better decisions, maintaining a long-term partnership among different industrial entities. Multi-agent systems can have a profound impact in large scale manufacturing and in industries [49] and because of that the research and development of these system need to be robust, reliable and fit to purpose. With such an important applicability, multi-agent systems have been studied and research intensely creating many publications that provide further insight into how these models can be developed and analysed [59].

Jennings et al. (1998) developed the "Gaia methodology", that provides a general analysis and design methodology to help design a detailed and easy to implement multi-agent system, from the requirements to the real system [61]. Adam et al. (2011) developed a framework called HoloMAS that focus on the notion of role in holonic MAS, providing and adaptive control system that can be applied on manufacturing systems [62]. Leitão and Restivo (2005) proposed and multi-agent system design architecture called ANACOR that is an agile and adaptive manufacturing control architecture that addresses the need for the fast reaction to disturbances, increasing the agility and flexibility of the enterprise, when it works in volatile environments. The adaptive control of this architecture can be balanced between a more centralised or a more decentralised structure [26].

For the multi-agent system in this work, the methodology presented by Nikraz et al. (2006) and the work of Ghadimi et al. (2018) have been followed. The methodology presented by Nikraz et al. focus on the key issues of analysing and designing a multi-agent system, with special emphasis on the analysis and design phases, that are based on the Foundation for Intelligent Physical Agents (FIPA) standards [63]. To design the system, an identification, categorisation, and refinements of agent types is performed during the analysis phase. First the methodology begins by making an initial agent type identification, where the main agent types are identified. To identify an agent the following rules should be applied [63]:

- Add one type of agent per user/device
- Add one type of agent per resource

Then the analysis moves on to the responsibilities identification, where from this step an initial list is made of each agent main responsibilities creating the responsibility table. Then the process moves on to the acquaintances identification, where the focus is on who needs to interact with whom [63]. Finally, the analysis ends with the agent refinement where a set of considerations is applied. These are related to: [63, 49]:

- Support - what supporting information agents need to accomplish with their responsibilities, and how, when and where is this information generated/stored
- Discovery - how agents linked by acquaintance relation discover each other
- Management and monitoring - is the system required to keep track of existing agents, or some agents need to be created on demand

The multi-agent system proposed in the reasoning and interaction layer is formed by several agents that represents many parties and functions. In this system three types of agents are defined: Blockchain Agent (BA), Entity Agent (EA), and the Decision Maker Agent (DMA). From this analysis results an agent diagram, that, as indicated in the methodology being followed, helps to identify the main agent types and what possible interactions there might exist [63]. As such, for this system the agent diagram can be seen in figure 8.

Following the methodology of [63], the functions and responsibilities of each agents need to be defined in a responsibility table, that can be seen in the table 1. With this information defined is possible to evaluate what the actual job of the agent is, i. e. it's behaviour. How each agent relates to another is defined in the form of communications and interactions, with messages being send between sender and receiver [49]. To perform a specification for the system interactions, Nikraz et al. advise that a interaction table should be created.

This interaction table takes into account every agent responsibility, defined in the responsibility table, that establishes a first contact type of relationship with other agent, and each row will include [63]:

- A description for the interaction
- The responsibility, identified by the number from the responsibility table
- An interaction protocol (IP) to implement the interaction, for instance, a Request.
- The role played by the agent. This role can either be a *Initiator* or a *Responder*
- The agent name of the complementary role
- A description for the trigger condition that initiates the interaction

The interaction table for the Decision Making Agent can be seen in table 2

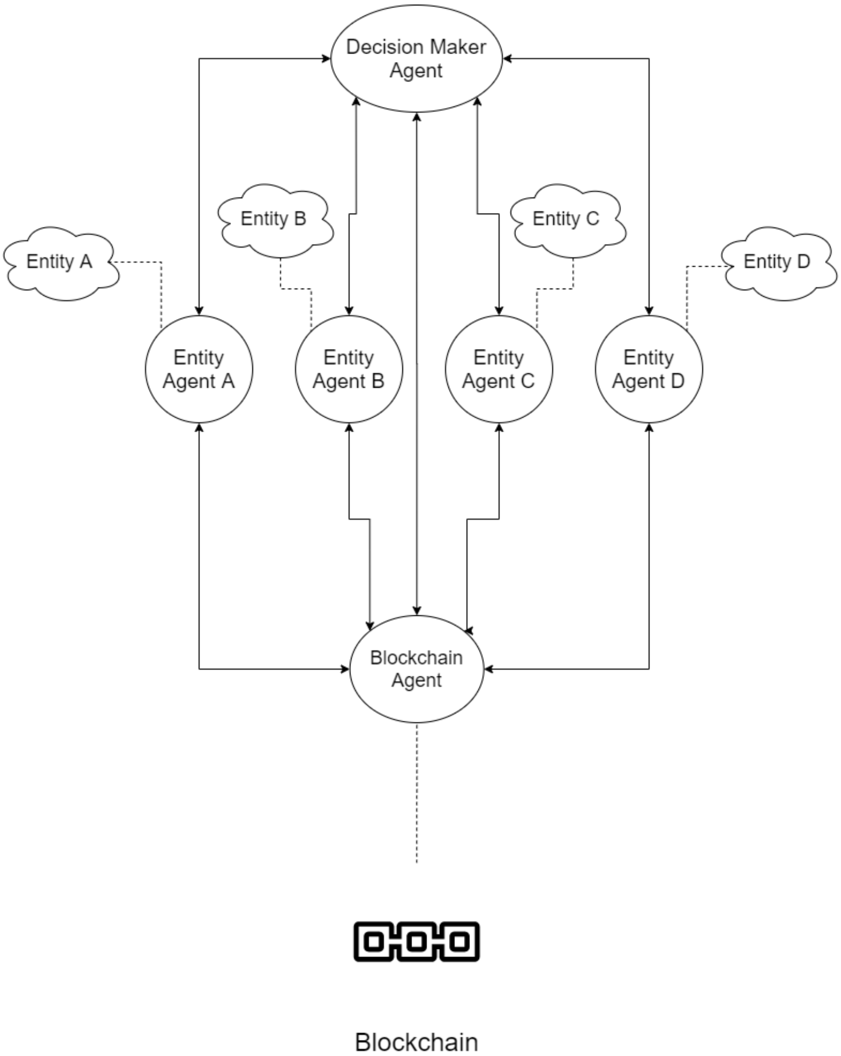

Figure 8: The network of agents

5.1.4 Interaction Between Model Components

The proposed model and its two main components, the multi-agent system and the blockchain perform multiple interactions between each other, either to access or create data. This model uses Hyperledger Fabric as its distributed ledger solution, and as such, this ledger stores important factual information about business objects, both the current values and the history of transactions that resulted in the current values. In Hyperledger Fabric, a ledger consists of two distinct parts, a world state and a blockchain. The world state is a database that holds the current values for the ledger state, making it easy to access them. The blockchain works as a transaction log that registers every change that lead to the current world state. The world state is implemented as a database, providing a rich set of operations for the efficient storage and retrieval of states. When a transaction that implies changes to the world state is submitted, by invoking a smart contract, ends up being committed to the blockchain, where a notification about the validity of the transaction is later sent to its committer.

One crucial part of this model is the interaction between the multi-agent system and the ledger. This

Agent	Responsibilities
BA	1. Receives the entity data from the EA 2. Save the data from the EA in a blockchain transaction 3. Informs EA that data was saved 4. Receives data request from EA 5. Returns data results to EA 6. Receives data request from DMA 7. Returns results to DMA
EA	1. Requests data from the BA 2. Send data to the BA to add to its public profile 3. Send data to the BA to add to its private profile 4. Receive data from the BA 5. Request DMA about results 6. Receives results from DMA
DMA	1. Starts decision making process 2. Requests data from BA 3. Receives data 4. Evaluate entities involved 5. Sends data to the BA 6. Informs EAs involved

Table 1: Responsibility Table

interaction is mostly unidirectional, since only part of the multi-agent system interacts with the ledger. This component is the Blockchain Agent, that as previously introduced, is the agent that connects to the blockchain and relays information to and from the other agents. Having this agent as the unique point of interaction with the blockchain, transforms the BA into a gateway of information and requests, that has the responsibility of knowing where to get the current request values and how to perform updates to the

Interaction	Resp.	IP	Role	With	When
Get necessary data from BA	2	Request	I	BA	A decision making process in initiated
Responds with decision data	5	Inform	R	BA	All necessary data has been received and the decision making process has ended
Responds with decision	6	Inform	R	EA	The decision making process has ended

Table 2: Interaction table for DMA

world state. Looking at each agent responsibilities, present in the table 1, it is clear that the BA is the agent that in fact needs to interact with the blockchain. These interactions can be justified by the need to respond to the data requests of the EA and DMA, as well to store new data in the blockchain. To do so, the BA needs to be able to access the world state, that holds the current value of the attributes of a business object as a unique ledger state, and needs to access the blockchain which immutably records the history of all transactions.

To achieve this, the BA needs to use simple ledger APIs to invoke smart contracts. Smart contracts define the different states of a business object, so they help define the key business processes and data that are shared across the different organisations collaborating in the network [56]. A smart contract programmatically can access the two distinct pieces of the ledger needed by the BA, the world state and the blockchain, and they primarily put, get, and delete states in the world state and can also query the immutable records of transactions [55]:

- get - represents a query to retrieve information about the current state of a business object
- put - creates a new object or modifies an existing one in the world state
- delete - removes an object from the current world state, but not its history

The interaction between the multi-agent system and the blockchain can be seen, as an example, in the figure 9. Assuming that in the collaborative network that are multiple organisations that sell products, each organisation has a corresponding entity agent. If one entity wants to add one more product to its inventory, the corresponding entity agent would gather all the necessary data and communicate to the blockchain agent that a new product needs to be added. This means that the blockchain agent needs to submit a transaction which implies changes to the world state, with this transaction ended up being committed to the blockchain.

To do so, the blockchain agent invokes a smart contract, that needs to be signed by the required set of

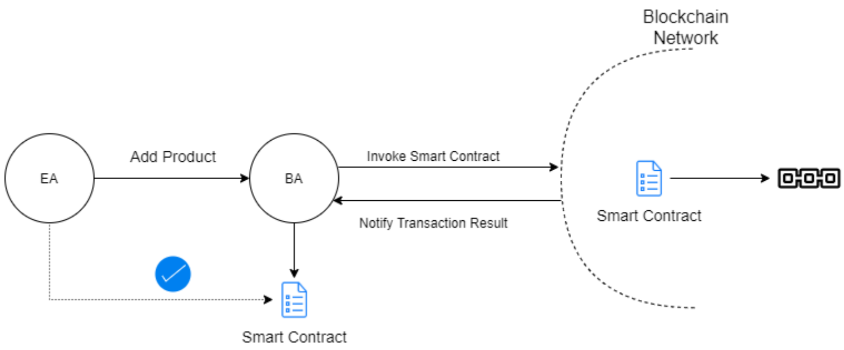

Figure 9: Interaction between the MAS and blockchain

organisations participating in the transaction. Then after running the smart contract the blockchain agent will be notified when the transaction has been included in the blockchain, whether valid or invalid. In the end, if the transaction was valid, the world state should be updated, and the organisation should see the new product added to its inventory. When the world state is updated, Hyperledger Fabric, attributes a version number, that is only used internally, to make sure that when any transaction is issued the world state is the correct for each node in the ledger network [55].

5.2 Limitations

The use of a different type of blockchain could have a potential impact on the overall model. The model presented uses Hyperledger Fabric as its ledger solution, since it is a type of blockchain technology that breaks away from the typically public and private types. The adoption of a different type of blockchain technology, such as R3 Corda and Ethereum, could potentially impact the overall model, since this technologies can bring different features and operating methods. This dilemma could potential be solved by developing a in dept comparison between this distinct technologies.

In addition to this, the multi-agent system developed in this model, still lacks maturity in some areas, namely when it comes to the actions of the agents. In this area, a subject that can potential affect the operation of the model is the DMA's behaviour and actions that is very important to the model. For the role that this agent plays, its is important to consider what decision making model framework/algorithm, such has the Markov decision process and a fuzzy inference system, should be used and how it could affect the model. This would enable to develop the model even further.

Is is also important to note that, since the applicability of this model is target at a network of organisations, where sensitive data is going to be available, privacy and security concerns need to be noted. This work relies on the underlining concepts of privacy that come attached to the blockchain technology, to provide an expected level security and confinement of information. Furthermore, Hyperledger Fabric provides even more support to security concerns, providing a public key infrastructure that is used to generate cryptographic certificates which are tied to organisations and applications, controlling data access and manipulation [56]. This notions coupled with the notion of channels, help target privacy and confidentiality concerns.

5.3 Conclusion

This chapter introduced the proposal to improve collaboration in a industry 4.0 scenario, aggregating the concepts introduced and addressed by previous chapters.

The presented proposal targets an improvement in collaboration between different organisations, without removing the competition factor, that still remains important to increase innovation and development. This is done by the presented solution, that enables the organisations to trust each other via a system impartial to all. The encapsulation of the organisations as entities, creates a network that enables connections and partnerships to be formed.

The model in this proposal is divided into two main parts. The first part, the knowledge representation, handles all the data generated by the entities and needs to work as a public registry of all the transactions and connections established. With the introduction of a ledger technology with the features of Hyperledger Fabric, the collaboration between entities becomes much more simplified for the organisations, while still enabling the possibility of entities competing with each other, using channels to register transitions without them appearing in the main ledger. The second part, the reasoning and interactions, introduces a multi-agent system with the end goal of helping each organisation which are the best organisations to make transactions with, based on the necessary requirements for that specific transaction and the overall status of the organisation in the network, as perceived by the remaining entities.

Chapter 6

Use Cases

The previous chapter introduced a model focused on improving collaboration between different organisations in an industry 4.0 environment. The way the model is designed, relies heavily on a solid multi-organisational structure, in order to process all the data provided by the organisations and use the different parts that constitute the model. Since the aim of the model is to provide an improvement in collaboration in I4.0, it is designed to be applied on a organisational perspective. As such, this chapter contains some theoretical use cases, that have the intent of providing some scenarios that demonstrate the applicability and potential impact when applying this model, demonstrating the potential for the use of the blockchain and the multi-agent system.

6.1 Use Cases for Organisations

Product manufacturing and industrial processes in general face great challenges regularly, either how to achieve a cost effective manufacturing of a product or how to adapt to respond to a new trend or a new business process. With the introduction of industry 4.0, many standardised business processes have changed, but with a more demanding customer and with new difficulties appearing constantly, organisations will need to find new way to answer some questions. Organisations need to collaborate and share resources and knowledge, as well improve their decision making to improve their manufacturing capabilities, answer requests of customers, and more easily and faster adapt to new challenges that may arise.

The following use cases demonstrate theoretical applications of the proposed model, that can provide a means for organisations to collaborate, sharing information and resources. As well as helping organisations in the decision-making process, when it comes to choosing another organisation to collaborate with, based on how the organisations are perceived and how they respond to the partnership need of other organisations.

6.1.1 Use Case A

For any organisation that aims at delivering some kind of product or service to a customer, the supply chain in which it operates is one of the critical elements of any business operation. This network that is created between a company and its suppliers to produce and distribute products to the final customer, includes different people, activities, entities, information, and resources. Industry 4.0 is seen by many manufacturers as an opportunity to improve coordination across the supply chain, with many hoping to be able to resolve many issues that occur in complex supply chains. The more complex the supply chain, more problems are likely to happen.

Industry 4.0 introduces changes and requires companies to rethink their supply chain and how their business operations are integrated with it. With the new technologies that are altering the way of working, associated with new trends and customer expectations, the base for the supply chain operations are changing. Furthermore, not only there is a need for organisations to adapt the supply chains, there is also an opportunity to improve the effectiveness of the operations taking advantage of the new technologies and moving supply chain into digital supply chains.

To achieve this, the technological integration of systems and data is not enough. Collaboration and cooperation between the manufacturers, their suppliers, and their supplier's suppliers is going to be needed, creating more value and improving the success of the business operations. Independently of the sector, collaboration between the different parties involved in the supply chain is needed, but depending on the type of business, the function of the parties can be different, with integration and collaboration of all the processes in the supply chain being crucial to match supply and demand.

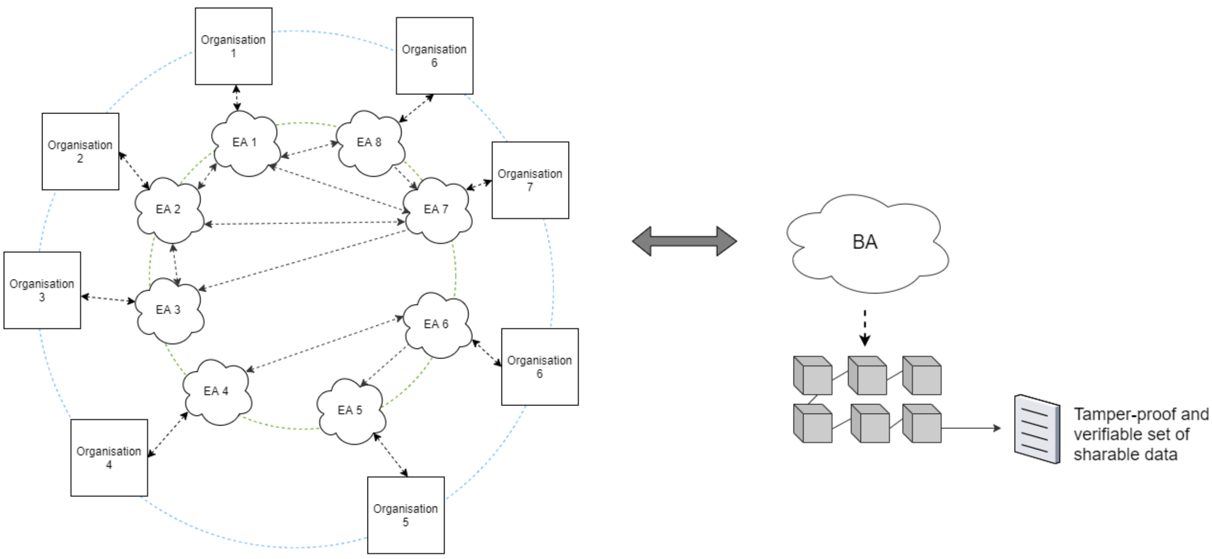

Figure 10: Representation of use case A

To help improve collaboration, all the organisations, business, and entities associated with a supply chain can be placed in a network of entities, just like the one presented in the model, creating a value network, where data can be shared between entities, decisions and information can be shared across the network, and data sources are integrated across systems. This will allow all the information being stored in the blockchain. Furthermore, this would allow for transparent and controlled transactions, with prearranged payment conditions so that they can only be visible to authorised participants. Every operation can have parameters pre-set, using smart contracts, making sure that certain conditions are guaranteed and agreed between all the entities involved. Also, product traceability would be vastly improved, since all the information about the products would be stored in an immutable ledger, customers could gain further insights about their product's origins.

As the business operations would go on, entities would evaluate each other's, setting each other's confidence and credibility levels, that would later be used when organisations need help in their decision making process, regarding which supplier to use or which service provider to use.

This use case is represented in figure 10. In this representation, many organisations are placed in a network of entities, where for each a corresponding Entity Agent is assigned. When organisations interact between them, the assigned entity agents mediate the interactions and register all the data that might be created. This data is then structured by the entity agents evolved and committed to the Blockchain. This data can be linked with a smart contract that can specify many details regarding data access, from imitating who can view the data to specifying a price to access it. To do so, the entity agents communicate with the Blockchain Agent, that will handle the Blockchain and data ledger management. Once the Blockchain Agent receives a message from one the entity agents, the Blockchain Agent will commit the data from the interaction to the Blockchain. When an organisation needs to access some data shared by another organisation, the data flow works the other way around. The Entity Agent communicates with the Blockchain Agent, that then gathers all the requested data, and sends it to the Entity Agent. The information is then presented to the organisation user through an interface. With this approach, organisations can create an environment where data and knowledge can be shared securely and in a decentralised way, making valuable information accessible to others and easing collaboration between them.

6.1.2 Use Case B

The exchange of data is essential for a connected industrial environment, with data being shared alongside a factory's manufacturing processes, different manufacturing sectors, and even shared between different factories. These data flows work as a digital representation of the manufacturing processes, needs, and products and enable the increase in productivity efficiency, problems awareness and tracing. Furthermore, this data flow allows for a new data-driven way of handling services and business models.

The problem with data sharing in industry 4.0 is that the data cannot be treated in the same way that current business to consumers online platforms handle user and platform data. This means that industrial data should not be commercialised, for advertising purposes, for instance, since the real value of the data relies on the application with the domain know-how and the application of the data in the creation of services and product-services combinations. Furthermore, there is a need to protect sensitive data, that may contain industry based secrets, safety information, or personal data. Industries also need to be able to compete, to drive innovation, and save the data related to the products and services that are storing the know-how of the innovations.

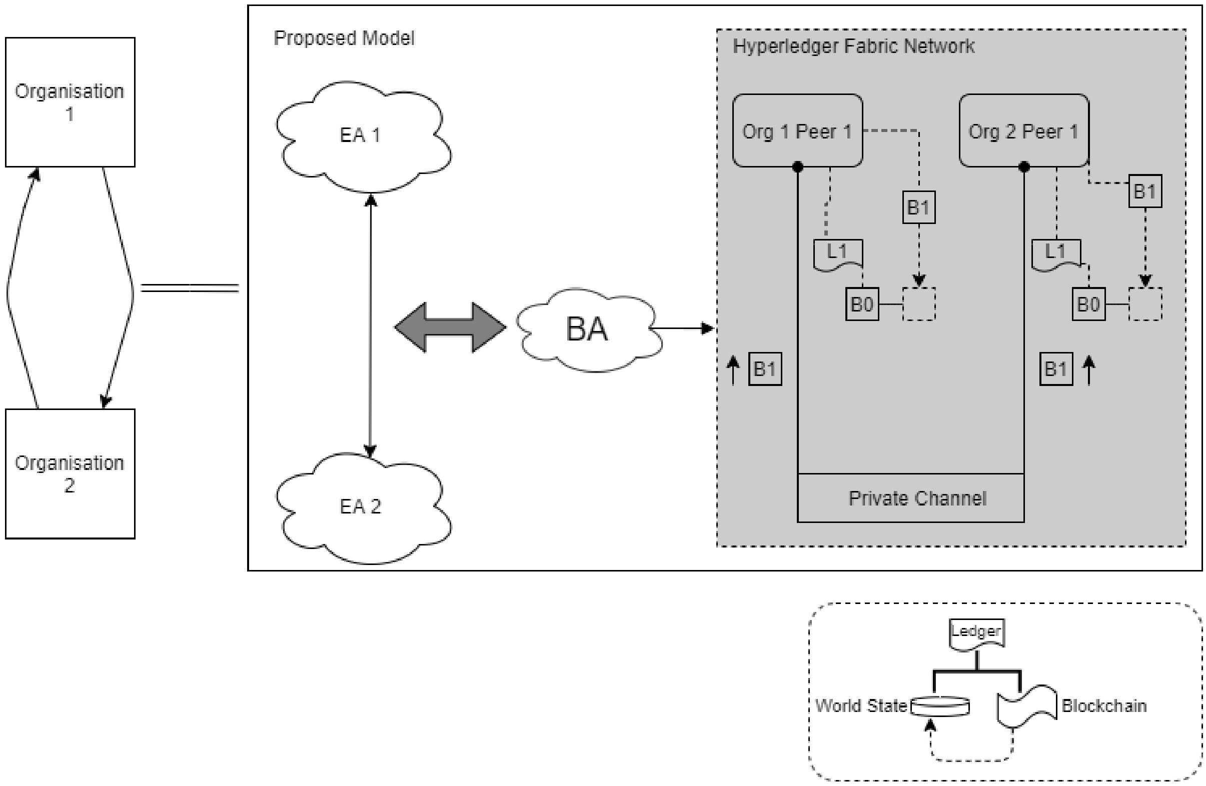

Figure 11: Representation of use case b

The model proposed in this work, especially the knowledge representation part, could play an important role in unifying the flow of data and information inside an industry and between industries in an industry 4.0 scenario. With the different organisations and industries represented as entities in a network, creating value, their information would be stored in the blockchain, assuring the immutability of the stored records. When two or more entities performed a transaction, such transaction would be stored in the blockchain. Any time an organisation wants to share any information in the network it can by creating a transaction with that information. In this scenario, if an organisation only wants certain entities to have access to the information, it can control that by using smart contracts. With the smart contacts is also possible to create a set of conditions that demand that when an organisation uses or accesses a certain shared piece of data, the publishing organisation can be notified. With the model, competition between entities could still thrive, with entities using Hyperledger Fabric channels to store transactions separated from the main ledger (figure 11), meaning that the transactions would still be stored in the blockchain, would still have all the properties of the other transactions, but they would only be accessible by the entities that have access to the channel, or the ones involved in the transaction that happened using a channel. Another problem that the model would help solve, is the data ownership/producer's rights dilemma. With transaction being stored in the blockchain, it would be easy to trace the origin of the information. With smart contracts it is possible to specify who can access the data, when, for how long, and at what price. Any transaction can be traced and the data owner can benefit in real-time.

Figure 11 displays a transaction being made between two organisations, that want to keep the transaction private. To do so, their corresponding Entity Agents would behave and take actions towards completing the transaction, with the Blockchain Agent of the entity's network being responsible for executing the transaction in the Blockchain. But since the organisations want to keep the transaction private, the Blockchain Agent can't execute the transaction in the public ledger, but instead it needs to execute it in a channel. For that to happen a channel is created, where the organisations that belong to the channel are added to it as members (peers), creating a private network, where the BA will execute the transaction. After executing the transaction, the resulting block is added to the channel ledger, that is stored in each peer on the channel. This is represented by the block 1 (B1) being added to the channel ledger, that already contains one block (B0), with every peer having an exact copy of the same ledger. Integrating the designed Multi-Agent System with these features of Hyperledger Fabric enables organisations to automate pipelines to privately store transactions. Nevertheless, the use of channels needs to have some restrictions/limitations, otherwise the organisation would abuse this type of transactions, defeating the overall objective of the model, that is to make data transparent and available to everyone in the network.

6.1.3 Use Case C

Organisations are constantly trying to find ways of maximising the efficiency of their operations, looking to minimise the waste of resource utilisation, improve the operational capabilities, so that profits can be maximised, and the economy of the organisation thrives. Modern technologies and solutions available in the fourth industrial revolution mean that the increasing pace and quality of information transmissions will cause changes to the different economies. This means that with the digitisation of industries, owned resources cease to be the kind of assets that represent the bigger value to an organisation. Instead, the resources that an organisation can share or provide to others have a much bigger value and importance.

As a result, organisations are starting to adapt a new business model that relies on the exchange of resources. Unlike the previous model of production, the mass production model, where the customer had no real input into the production of a product, with the mass customisation model the customer almost entirely decides how the final product is going to be like. This means that the market where organisations operate need to be flexible, in order to ensure that no organisations has all the resources needed to achieve the final production objectives of a set of organisations. This idea of sharing resources with other organisations, allows using products or services without owning them, enabling organisations to reduce costs. Companies like Uber, Lyft, and Airbnb are examples of this approach where a need is met by linking someone or something with the resources to the people or organisations who needs them.

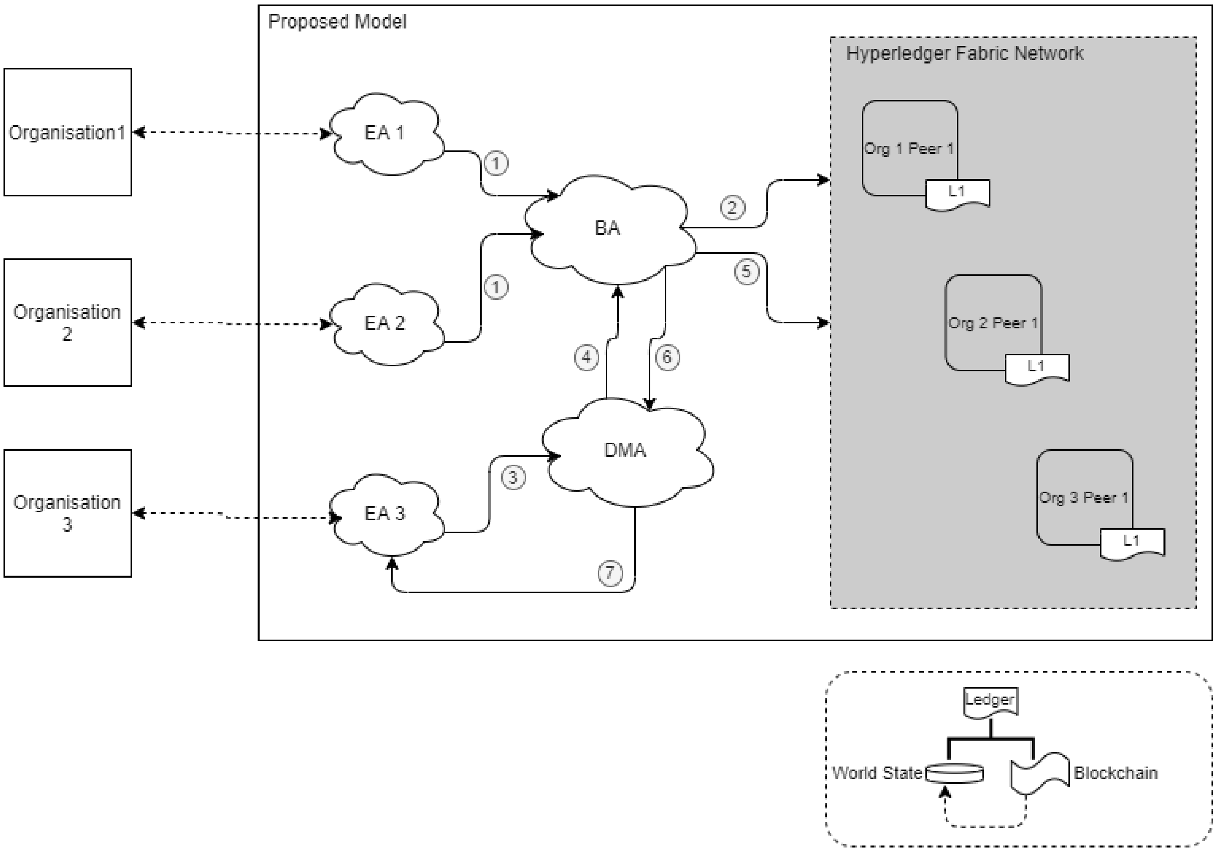

Figure 12: Representation of use case c

The model presented can enable organisations to share between them unused resources that might meet the needs of each other. Using the network of entities is possible to connect organisations and with information sharing obtain an increase in the efficiency in the business processes. The transaction from mass production to mass customisation demands the exchange of resources between organisations, by linking them together. But unlike the examples enumerated before, with the proposed model, there is no need for a third party to regulate the connection. With a service like Uber, there is someone that needs a ride and someone that works as a driver, and to link these two entities together there is the company, that mediates the transactions established. Using the model applied in a similar industrial scenario, it doesn't exist a need for a third party regulating the resources or services exchange, since with blockchain all transactions would be registered in a ledger, making this information immutable. Furthermore, since the model uses Hyperledger Fabric, the blockchain network is operated by a governance model that uses legal agreements and consensus protocols that builds trust in the system. Entities in the network can write smart contracts to ensure that the necessary set of conditions is met before making the transactions that makes the sharing of the resources. Besides this advantage, with the information already flowing in the network of entities, organisations can use the multi-agent system to help in the decision making process when it comes to select the entity to get the shared resources from. Organisations will need to evaluate the other entities present in the network to find which one has the shared resources needed and how they typically perform, taking input from the credibility and confidence values.

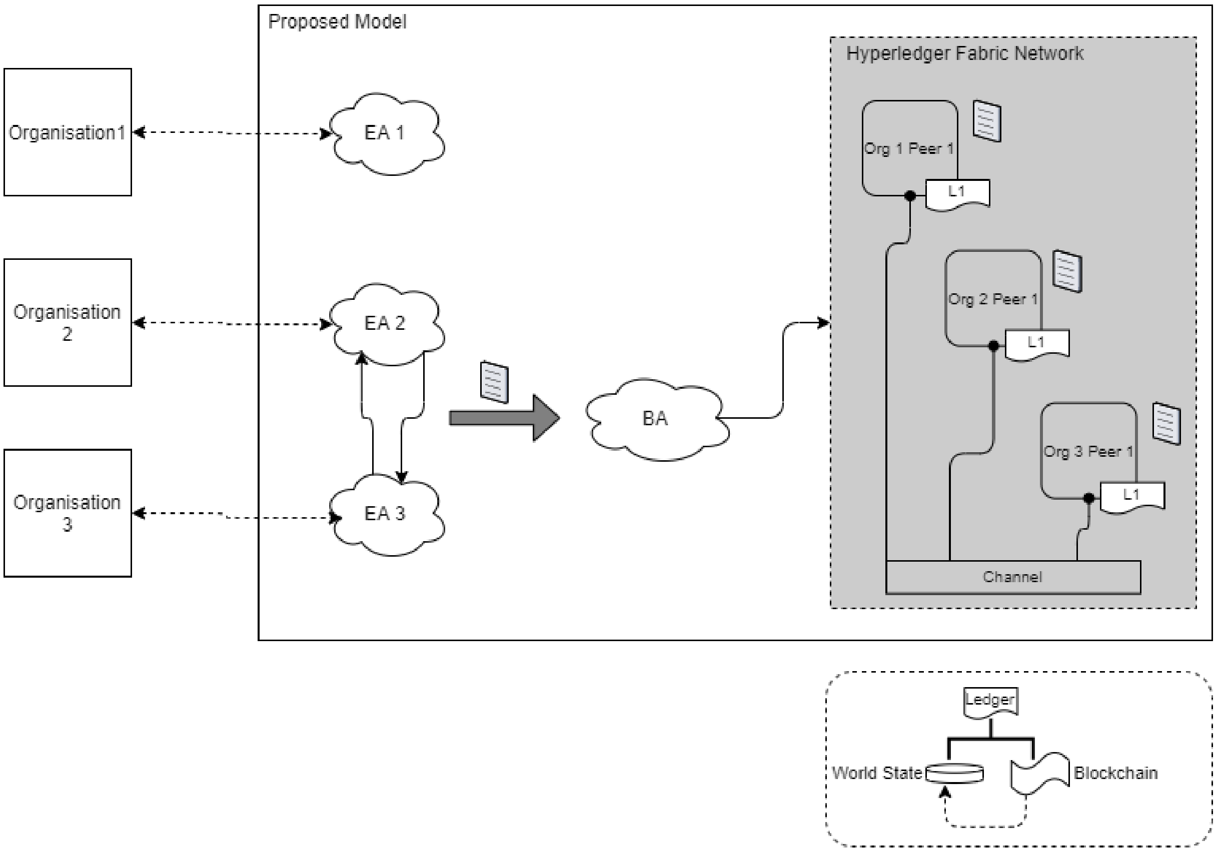

Figure 13: Representation of use case c (second part)

Figure 12 displays the first part of this use case, where all three types of agents are used to achieve the objective. The figure describes the flow of the process that the model would be able to represent in a situation similar to the one described above. The process would happen as follow:

1. Organisation 1 and Organisation 2 would want to share the availability of manufacturing resources. For that, their corresponding Entity Agents would build the data structure and communicate with the Blockchain Agent to pass on the information to the ledger (1)

2. The Blockchain agent would execute a transaction adding another block to the blockchain and updating the world state of all the organisation peers created in the Fabric network (2)

3. Supposing that Organisation 3 wants to outsource part of its production, the Entity Agent 3 would query the Decision Making Agent about what other organisations are interested or available to outsource their manufacturing resources (3)

4. The DMA would then request the Blockchain Agent the information about the other organisations and their corresponding profiles, available in the world state (4)
5. The BA would gather the information and send it to the DMA (5,6)
6. Once the Decision Making Agent has the requested information, it would take actions and behave in, based on each organisation information and profile, recommend which organisation should Organisation 3 outsource its production (7)

When Organisation 3 has the suggested entity to make a transaction with, the organisation can decide to move forward with the transaction (figure 13). Assuming that Organisation 3 wants to outsource the manufacturing capabilities of the Organisation 2, their corresponding Entity Agents will engage in an initial communication to form the initial conditions of the transaction. From this the information will be sent to the Blockchain agent, alongside with a smart contract that outlines the conditions of a valid agreement. The transaction and the smart contract will be executed on a channel in the Fabric network, creating a block that represents the transaction that will be added to the ledgers of the organisation peers. Note that despite Organisation 1 not being involved in the transaction, it will also have the exact same ledger that the other two organisations that originated the transaction. This happens because the peer of the Organisation 1 belongs to the same channel as the peers of the other two organisations, meaning that the transaction block will be added to all three ledger's blockchain and the corresponding world status will also be updated. If Organisation 2 and 3 wanted to keep the transaction private from other participants, a separated channel needed to be created where only peers from Organisation 2 and Organisation 3 would be added has members, just like in the previous use case.

6.2 Conclusion

The use cases presented show some applications and give more insights into how the proposed model works and what impact it might have. Despite the scenarios being similar in some aspects, they showcase different parts and approaches to the model, all with the same premise that the organisations involved need to be able to improve their collaboration, meaning that needs to exist a better way for the organisations to link with each other and to coexist in the same environment. Part of how they coexist in the same environment is related to how they share information between them and how transparent they are, and that's what the model applied to the use case A tries to demonstrate.

Use case A shows that the information produced by the organisations in the network will be converted to blockchain transactions, being available for anyone to read. The transactions contain structured information that can be the result of an exchange between two organisations or some data that an organisation wants to make publicly available. With this, information can be shared, and every transaction is registered. But there are going to exist situations where two organisations might want to make a transaction and keep it private, to hide it from its direct competitors for instance. On the use case B, this situation is translated to a scenario where the model operation is the same, but it relies on native Hyperledger Fabric features to keep transactions private for the organisations involved. When organisations use private channels to keep their transactions private, only the organisations involved have access to the block of information created from the executed transaction. Because of this, this feature needs to be restricted, otherwise on a real-world scenario all the organisations would constantly use private channels to make their transactions. This first two use cases also show that when two organisations want to collaborate in the real work, their corresponding Entity Agents will communicate, in order to mirror such real world interaction. Also one of the Entity Agents (the one related to the organisations that initiates the transaction) will communicate with the Blockchain Agent that will execute the transaction on the Blockchain with the instructions and information received.

The last use case, use case C, shows the full application of the model with all its elements being used. In this case, the Decision-Making Agent is used to help an organisation to better identify who they should collaborate with, given a specific situation or need. The Decision-Making Agent will use the information available from the ledger, that will be retrieved by the Blockchain Agent. That information may be the result from previous interactions between organisations, their profiles, and smart contracts. No more information is given regarding the Decision-Making Agent, because as it was mentioned in the limitations of the model, the DMA actions need further development. Nevertheless, this use case shows the interactions between the reasoning and interaction part of the model with the knowledge representations, that will lead to a model that will be able to help organisations with their decision making and eventually improve their collaboration. With improved collaboration, organisations can improve their business models and advance into industry 4.0 standards.

Chapter 7

Conclusion and Future Work

7.1 Summary

The work presented in this dissertation contains a model proposal to improve collaboration and cooperation between industries and organisations in an Industry 4.0 environment.

With the introduction of I4.0, industries are starting to evolve their manufacturing processes, taking advantage of the amount of data produced and the digitalisation of manufacturing pipelines, improving their business and manufacturing processes. The technologies and changes introduced by the fourth industrial revolution, are pushing industries to quickly adapt to these changes in order to continue achieving profits from their businesses and to stay relevant in an ever-growing competitive environment. Industry 4.0 will enable new ways of industries creating value, while having a better control over their production, making better products, faster, and developing products that meet general consumer expectations and needs. Besides responding to the basic customer needs, industries will need to face new challenges that origin from trends that keep on growing. One of these challenges, as viewed from the literature review, is the evolution of mass production to mass customisation [45, 44, 11, 5]. This will force industries to adapt their manufacturing process to be able to produce multiple products or the same product but with different variations, without having to make many changes to their production lines and while minimising their downtime. Furthermore, organisations need to make sure that they have all the necessary materials and services to respond to the manufacturing needs. Besides the production of personalised products, industries will also need to gather the conditions to quickly adapt to a changing environment, that is inherent to Industry 4.0. Both scenarios have a constant need for collaboration between organisations, as the answer to the challenges of the fourth industrial revolution.

By collaborating with each other, industries will be able to grow and to more quickly face the challenges and assess risks that might appear. Collaborating in an open and transparent environment where information is shared can help industries make better decisions and evolve in the Industry 4.0, as concluded in this dissertation. To do so, the model proposed in this work, represents each industry and organisation as an entity in a collaborative network. The model has two parts, the knowledge representation and the reasoning and interactions section.

The knowledge representation uses Hyperledger Fabric and is the entry point for all the information in the network. By creating a solid way of structuring and saving the data, creates the possibility that for each entity and its interactions, the data is stored and shared with all the entities, while keeping the information secure and making sure that stored information cannot be tempered with. Entities information contains data that helps create each organisation's profile and helps in the decision-making process, creating a way for network participants to evaluate and classify each other's performance when collaborating. The second part of the model, the decision making fraction, relies on a multi-agent system that interacts with the Hyperledger Fabric blockchain in order to gather the necessary data to handle decision making processes regarding choosing the right entity to collaborate. This is crucial, to help stakeholders and decision makers streamline their decision-making process, that can be the difference between acting in a useful time and solving a problem or failing.

In Industry 4.0, collaborating means sharing resources, knowledge, and information, and with the use of this model industries can better reach each other, and more easily collaborate, in order to continue thriving in the fourth industrial revolution, adapt to new situations, and answer effectively customer demands.

7.2 Scientific Contribution

During the elaboration and development of this dissertation, some scientific contributions were made, namely:

- ”Multi-agent Systems Approach to Industry 4.0: Enabling Collaboration Considering a Blockchain for Knowledge Representation” presented on the 2018 International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS) [48]. This contribution presented an initial overview of the entities profile, the importance of a multi-agent system in a industry 4.0 environment, and identified collaboration as a booster for success in I4.0.
- ”Industry 4.0 Multi-agent System based knowledge representation through blockchain” presented in the 2018 International Symposium on Ambient Intelligence (ISAMI) [64]. This work explored the application of blockchain as a way of improving information storing and, most importantly, as a better approach of representing an organisation, it's information, and it's needs.
- ”Improving Collaboration in Industry 4.0: The Usage of Blockchain for Knowledge Representation” in publication and to be presented at the 2020 International Conference on Practical Applications of

Agents and Multi-Agent Systems (PAAMS) [65]. This contribution explored the representation of a set of entities, in a collaborative network, and how blockchain and a distributed ledger could enable a collaboration between the entities, helping them achieve better results and face challenges in the face of the fourth industrial revolution.

7.3 Future Work

Despite the current contributions, further work can be done in order to improve the current model and to resolve some of the limitations identified and previously stated.

- The use of a multi-agent system in this work aims at helping the decision-making process. As such, the MAS needs further development, with the objective of better defining all the agents and structuring clear actions that will lead them to achieving the overall goal. The Decision Making Agent, defined in this model, is a major target in the future work, with effort needed to be done in order to develop the decision-making capabilities of this agent. A framework or algorithm, as the likes of the Markov decision process or a fuzzy inference system, are possibilities that need to be studied to further understand the impact that they will bring to the model. With the actions of the DMA defined, the MAS moves to a more complete status, pushing the overall model forward.
- There is a necessity to define some clear base rules when it comes to entities permissions to access data and boundaries in interactions, as well as data sharing. The numbers of times two entities can use channels to make a transactions will also be controlled, to prevent entities abusing the use of this feature and to make sure there are public transactions stored in the blockchain and in the world state, assuring transparency.
- As the entities need to have access to the information of other entities available products or services, a structure that represents these assets needs to be defined. Through this structure an entity must be able to properly showcase and configure its assets and the remaining entities must be able to easily understand it and evaluate it as an answer their needs. This structure should also describe constraints that the entity might setup in order to establish a transaction. These constraints would later appear in a smart contract, alongside other rules that might have been established between the entities, to ensure a valid transaction.
- A crucial future task is to develop an application using Hyperledger Fabric. This will enable to experience the development life cycle of Fabric and cover all major technical activities to develop an application and smart contracts. This, despite being a demo application, should allow the creation of entities with their assets, enable them to perform simple transactions and create smart contracts. On a later phase, there should be an integration with the MAS, creating a real representation of the model.

Bibliography

[1] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends," *Proceedings - 2017 IEEE 6th International Congress on Big Data, BigData Congress 2017*, no. June, pp. 557–564, 2017.

[2] L. Da Xu, E. L. Xu, and L. Li, "Industry 4.0: state of the art and future trends," *International Journal of Production Research*, vol. 56, no. 8, pp. 2941–2962, 2018. [Online]. Available: https://www.tandfonline.com/action/journalInformation?journalCode=tprs20

[3] S. Vaidya, P. Ambad, and S. Bhosle, "Industry 4.0 - A Glimpse," *Procedia Manufacturing*, vol. 20, pp. 233–238, Jan. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2351978918300672

[4] S. Pfeiffer, "The Vision of BIndustrie 4.0 in the Making-a Case of Future Told, Tamed, and Traded," 2017.

[5] X. Shang, Z. Shen, G. Xiong, F. Y. Wang, S. Liu, T. R. Nyberg, H. Wu, and C. Guo, "Moving from mass customization to social manufacturing: a footwear industry case study," *International Journal of Computer Integrated Manufacturing*, vol. 32, no. 2, pp. 194–205, 2019. [Online]. Available: https://doi.org/10.1080/0951192X.2018.1550675

[6] J. E. Hernandez, J. Kacprzyk, H. Panetto, and M. De-angelis, "Collaboration in a Data-Rich World," vol. 506, no. September, pp. 761–774, 2017. [Online]. Available: http://link.springer.com/10.1007/978-3-319-65151-4

[7] D. Turvey, "Competition or collaboration : from which well does innovation spring ?" no. May, pp. 1–14, 2018.

[8] G. Schuh, T. Potente, C. Wesch-Potente, A. R. Weber, and J.-P. Prote, "Collaboration Mechanisms to Increase Productivity in the Context of Industrie 4.0," *Procedia CIRP*, vol. 19, pp. 51–56, 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2212827114006453

[9] S. Wang, J. Wan, D. Li, and C. Zhang, "Implementing Smart Factory of Industrie 4.0: An Outlook," *International Journal of Distributed Sensor Networks*, vol. 12, no. 1, p. 3159805, Jan. 2016. [Online]. Available: http://journals.sagepub.com/doi/10.1155/2016/3159805

[10] J. Qin, Y. Liu, and R. Grosvenor, "A Categorical Framework of Manufacturing for Industry 4.0 and Beyond," *Procedia CIRP*, vol. 52, pp. 173–178, Jan. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S221282711630854X?via{%}3Dihub

[11] S. J. Hu, "Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization," *Procedia CIRP*, vol. 7, pp. 3–8, Jan. 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827113002096

[12] P. Zheng, H. Wang, Z. Sang, R. Y. Zhong, Y. Liu, C. Liu, K. Mubarok, S. Yu, and X. Xu, "Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives," *Frontiers of Mechanical Engineering*, 2018. [Online]. Available: https://doi.org/10.1007/s11465-018-0499-5

[13] M. A. K. Bahrin, M. F. Othman, N. H. N. Azli, and M. F. Talib, "Industry 4.0: A review on industrial automation and robotic," *Jurnal Teknologi*, vol. 78, no. 6-13, pp. 137–143, 2016.

[14] Y. Lu, "Industry 4.0: A survey on technologies, applications and open research issues," *Journal of Industrial Information Integration*, vol. 6, pp. 1–10, Jun. 2017. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2452414X17300043

[15] J. Lee, H.-A. Kao, and S. Yang, "Service Innovation and Smart Analytics for Industry 4.0 and Big Data Environment," *Procedia CIRP*, vol. 16, pp. 3–8, Jan. 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2212827114000857

[16] J. Lee, B. Bagheri, and H.-A. Kao, "A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems," *MANUFACTURING LETTERS*, vol. 3, pp. 18–23, 2015. [Online]. Available: https://ac.els-cdn.com/S221384631400025X/1-s2.0-S221384631400025X-main.pdf?{_}tid=f7791ef6-e69a-11e7-936e-00000aab0f6c{&}acdnat=1513894071{_}9c6ee4aba07cf562f0f69ff60c522f5e

[17] S. I. Shafiq, C. Sanin, C. Toro, and E. Szczerbicki, "Virtual Engineering Object (VEO): Toward Experience-Based Design and Manufacturing for Industry 4.0," *Cybernetics and Systems*, vol. 46, no. 1-2, pp. 35–50, Feb. 2015. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/01969722.2015.1007734

[18] L. Monostori, B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumara, G. Reinhart, O. Sauer, G. Schuh, W. Sihn, and K. Ueda, "Cyber-physical systems in manufacturing," *CIRP Annals*, vol. 65, no. 2, pp. 621–641, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0007850616301974

[19] D. Ivanov, B. Sokolov, and M. Ivanova, "Schedule coordination in cyber-physical supply networks Industry 4.0," *IFAC-PapersOnLine*, vol. 49, no. 12, pp. 839–844, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S240589631631165X

[20] M. Rüßmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, and M. Harnisch, "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries," Tech. Rep., 2015. [Online]. Available: http://www.inovasyon.org/pdf/bcg.perspectives{_}Industry.4.0{_}2015.pdf

[21] H. Lasi, H.-G. Kemper, D.-I. T. Feld, and D.-H. M. Hoffmann, "Industry 4.0," *Business & Information Systems Engineering*, 2014.

[22] T. Stock and G. Seliger, "Opportunities of Sustainable Manufacturing in Industry 4.0," *Procedia CIRP*, vol. 40, pp. 536–541, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S221282711600144X

[23] M. K. Adeyeri, K. Mpofu, and T. Adenuga Olukorede, "Integration of agent technology into manufacturing enterprise: A review and platform for industry 4.0," *IEOM 2015 - 5th International Conference on Industrial Engineering and Operations Management, Proceeding*, 2015.

[24] M. Glavic, "Agents and Multi-Agent Systems : A Short Introduction for Power Engineers," pp. 1–21, 2006.

[25] S. J. Russell, P. Norvig, J. F. Canny, J. M. Malik, and D. D. Edwards, "Artificial Intelligence A Modern Approach," Tech. Rep., 1995. [Online]. Available: https://www.cin.ufpe.br/{~}tfl2/artificial-intelligence-modern-approach.9780131038059.25368.pdf

[26] P. Leitão, V. Mařík, and P. Vrba, "Past, present, and future of industrial agent applications," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 4, pp. 2360–2372, 2013.

[27] P. Maes, "Artificial Life Meets Entertainment: Lifelike Autonomous Agents," MIT Media Lab, Cambridge, MA, Tech. Rep., 1995. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.471.5463{&}rep=rep1{&}type=pdf

[28] P. Stone and M. Veloso, "Multiagent Systems : A Survey from a Machine Learning Perspective 1 Introduction 2 Multiagent Systems," *Autonomous Robots*, vol. 8, no. 3, pp. 345–383, 1997.

[29] M. Oprea, "Applications of Multi-Agent Systems," *Information Technology*, pp. 239–270, 2004. [Online]. Available: http://link.springer.com/10.1007/1-4020-8159-6{_}9

[30] P. García Ansola, J. de las Morenas, A. García, and J. Otamendi, "Distributed decision support system for airport ground handling management using WSN and MAS," *Engineering Applications of Artificial Intelligence*, vol. 25, no. 3, pp. 544–553, Apr. 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0952197611002168

[31] K. Wust and A. Gervais, "Do you Need a Blockchain?" *2018 Crypto Valley Conference on Blockchain Technology (CVCBT)*, no. i, pp. 45–54, 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8525392/

[32] S. A. Abeyratne and R. P. Monfared, "Blockchain Ready Manufacturing Supply Chain Using Distributed Ledger," *International Journal of Research in Engineering and Technology*,

vol. 05, no. 09, pp. 1–10, 2016. [Online]. Available: http://esatjournals.net/ijret/2016v05/i09/IJRET20160509001.pdf

[33] B. Buchanan and N. Naqvi, "Building the Future of EU: Moving Forward with International Collaboration on Blockchain," *The JBBA*, vol. 1, no. 1, pp. 1–4, 2018.

[34] D. Calvaresi, A. Dubovitskaya, J. P. Calbimonte, K. Taveter, and M. Schumacher, "Multi-Agent Systems and Blockchain : Results from a Systematic Literature Review," no. April, 2018.

[35] A. Bahga and V. K. Madisetti, "Blockchain Platform for Industrial Internet of Things," *Journal of Software Engineering and Applications*, vol. 9, pp. 533–546, 2016. [Online]. Available: http://www.scirp.org/journal/jsea

[36] M. Vukolic, "Rethinking Permissioned Blockchains." [Online]. Available: http://dx.doi.org/10.1145/3055518.3055526

[37] K. Christidis and M. Devetsikiotis, "Blockchains and Smart Contracts for the Internet of Things," *IEEE Access*, vol. 4, pp. 2292–2303, 2016.

[38] I.-C. Lin and T.-C. Liao, "A Survey of Blockchain Security Issues and Challenges," *International Journal of Network Security*, vol. 19, no. 5, pp. 653–659, 2017. [Online]. Available: https://pdfs.semanticscholar.org/f61e/db500c023c4c4ef665bd7ed2423170773340.pdf

[39] K. Rabah, "Overview of Blockchain as the Engine of the 4th Industrial Revolution," *The Africa Premier Research Publishing Hub www.mrjournals.org Mara Research Journals MR Journal of Business & Management. Mara Research Journal of Business and Management*, vol. 1, no. 1, pp. 125–135, 2016.

[40] R. Casado-Vara, J. Prieto, F. D. la Prieta, and J. M. Corchado, "How blockchain improves the supply chain: case study alimentary supply chain," *Procedia Computer Science*, vol. 134, pp. 393–398, 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S187705091831158X

[41] A. Wright and P. De Filippi, "Decentralized Blockchain Technology and the Rise of Lex Cryptographia," *SSRN Electronic Journal*, 2015. [Online]. Available: http://www.ssrn.com/abstract=2580664

[42] D. Mingxiao, M. Xiaofeng, Z. Zhe, W. Xiangwei, and C. Qijun, "A review on consensus algorithm of blockchain," *2017 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2017*, vol. 2017-January, pp. 2567–2572, 2017.

[43] O. Dib, K.-L. Brousmiche, A. Durand, E. Thea, and B. Hamida, "Consortium Blockchains: Overview, Applications and Challenges," *International Journal on Advances in Telecommunications*, vol. 11, no. 1&2, pp. 51–64, 2018.

[44] C. Fenech and B. Perkins, "the Rise of Mass Personalisation." Deloitte, Tech. Rep., 2016. [Online]. Available: http://search.ebscohost.com/login.aspx?direct=true{&}db=buh{&}AN=114272069{&}site=eds-live

[45] P. Zawadzki and K. Zywicki, “Smart product design and production control for effective mass customization in the industry 4.0 concept,” *Management and Production Engineering Review*, vol. 7, no. 3, pp. 105–112, 2016.

[46] A. L. Oliver, “On the duality of competition and collaboration: Network-based knowledge relations in the biotechnology industry,” *Scandinavian Journal of Management*, vol. 20, no. 1-2, pp. 151–171, 2004.

[47] F. Ancarani and V. Shankar, “Symbian: Customer interaction through collaboration and competition in a convergent industry,” *Journal of Interactive Marketing*, vol. 17, no. 1, pp. 56–76, 2003.

[48] P. Pinheiro, M. Macedo, R. Barbosa, R. Santos, and P. Novais, “Multi-agent systems approach to industry 4.0: Enabling collaboration considering a blockchain for knowledge representation,” in *Highlights of Practical Applications of Agents, Multi-Agent Systems, and Complexity: The PAAMS Collection*. Cham: Springer International Publishing, 2018, pp. 149–160.

[49] P. Ghadimi, F. Ghassemi Toosi, and C. Heavey, “A multi-agent systems approach for sustainable supplier selection and order allocation in a partnership supply chain,” *European Journal of Operational Research*, vol. 269, no. 1, pp. 286–301, Aug. 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0377221717306410

[50] A. Diogo, B. Fernandes, A. Silva, J. Faria, J. Neves, and C. Analide, “A Multi-Agent System Blockchain for a Smart City,” *The Third International Conference on Cyber-Technologies and Cyber-Systems (CYBER 2018)*, no. Figure 1, pp. 68–73, 2018.

[51] M. Holmlund and J. Å. Törnroos, “What are relationships in business networks?” *Management Decision*, vol. 35, no. 4, pp. 304–309, 1997.

[52] “CONFIDENCE — meaning in the Cambridge English Dictionary.” [Online]. Available: https://dictionary.cambridge.org/dictionary/english/confidence

[53] “CREDIBILITY — meaning in the Cambridge English Dictionary.” [Online]. Available: https://dictionary.cambridge.org/dictionary/english/credibility

[54] A. L. Ginsca, A. Popescu, and M. Lupu, “Credibility in information retrieval,” *Foundations and Trends in Information Retrieval*, vol. 9, no. 5, pp. 355–475, 2015.

[55] C. Cachin, “Architecture of the Hyperledger Blockchain Fabric,” Tech. Rep., 2016. [Online]. Available: www.hyperledger.org

[56] E. Androulaki, A. Barger, V. Bortnikov, C. Cachin, K. Christidis, A. De Caro, D. Enyeart, C. Ferris, G. Laventman, Y. Manevich, S. Muralidharan, C. Murthy, B. Nguyen, M. Sethi, G. Singh, K. Smith, A. Sorniotti, C. Stathakopoulou, M. Vukolić, S. W. Cocco, and J. Yellick, “Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains,” 2018.

[57] “Introduction — hyperledger-fabricdocs master documentation.” [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-1.4/blockchain.html

[58] T. Mettler and P. Rohner, “Supplier relationship management: A case study in the context of health care,” *Journal of Theoretical and Applied Electronic Commerce Research*, vol. 4, no. 3, pp. 58–71, 2009.

[59] A. H. Azadnia, M. Z. M. Saman, and K. Y. Wong, “Sustainable supplier selection and order lot-sizing: An integrated multi-objective decision-making process,” *International Journal of Production Research*, vol. 53, no. 2, pp. 383–408, 2015. [Online]. Available: http://dx.doi.org/10.1080/00207543.2014.935827

[60] P. Fiala, “Information sharing in supply chains,” *Omega*, vol. 33, no. 5, pp. 419–423, Oct. 2005.

[61] N. Jennings, K. Sycara, and M. Wooldridge, “A roadmap of agent research and development,” *Autonomous Agents and Multi-Agent Systems*, vol. 1, pp. 7–38, 03 1998.

[62] E. Adam, T. Berger, Y. Sallez, and D. Trentesaux, “Role-based manufacturing control in a holonic multi-agent system,” *International Journal of Production Research*, vol. 49, pp. 1455–1468, 03 2011.

[63] M. Nikraz, G. Caire, and P. A. Bahri, “A Methodology for the Analysis and Design of Multi-Agent Systems using JADE,” Tech. Rep., 2006.

[64] P. Pinheiro, R. Santos, and R. Barbosa, “Industry 4.0 multi-agent system based knowledge representation through blockchain,” *Ambient Intelligence – Software and Applications –, 9th International Symposium on Ambient*, pp. 331–337, 01 2019.

[65] ——, “Improving collaboration in industry 4.0: The usage of blockchain for knowledge representation,” in *Highlights in Practical Applications of Agents, Multi-Agent Systems, and Trust-worthiness. The PAAMS Collection*, F. De La Prieta, P. Mathieu, J. A. Rincón Arango, A. El Bolock, E. Del Val, J. Jordán Prunera, J. Carneiro, R. Fuentes, F. Lopes, and V. Julian, Eds. Cham: Springer International Publishing, 2020, pp. 226–237.

ESCOLA
SUPERIOR
DE TECNOLOGIA
E GESTÃO
POLITÉCNICO
DO PORTO

P.PORTO

M

MESTRADO
ENGENHARIA INFORMÁTICA

Multi-Agents System Approach to Industry 4.0: Enabling Collaboration Considering a Blockchain

Pedro Daniel Coelho Pinheiro