



DESIGN OF A CELLULAR ASSEMBLY LINE FOR ELECTRICAL MOTORS

FÁBIO ANDRÉ LOPES ARAÚJO

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ISEP – School of Engineering

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Fábio André Lopes Araújo

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Dissertation presented to ISEP – School of Engineering to fulfill the requirements necessary to obtain a Master's degree in Mechanical Engineering, carried out under the guidance of Francisco José Gomes da Silva (PhD), and co-supervised by Jorge Manuel Teixeira Tavares (PhD), Adjunct Professors at ISEP – School of Engineering, Polytechnic of Porto.

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President

Luís Carlos Ramos Nunes Pinto Ferreira, PhD

Associate Professor, ISEP - School of Engineering, Polytechnic of Porto

Supervisor

Francisco José Gomes da Silva, PhD

Associate Professor, ISEP - School of Engineering, Polytechnic of Porto

Second supervisor

Jorge Manuel Teixeira Tavares, PhD

Adjunct Professor, ISEP - School of Engineering, Polytechnic of Porto

Examiner

Paulo Manuel Salgado Tavares de Castro, PhD

Full Professor, Faculty of Engineering, University of Porto

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KEYWORDS

Automobile industry, Electric motor, Automation, Cellular assembly line, Mechanical design

ABSTRACT

The automobile is a cornerstone of today's society. Its large usage for personal mobility or industrial cargo transportation creates a big demand for automobiles, making this industry one of the largest ones in the world. When there is a large demand for a product, the competitiveness to gain a market share is also very high, obligating the competitors in such industry to constantly improve and innovate in order to deliver the best product possible, while complying with high quality standards and short delivery times.

To survive in the automobile industry, companies and suppliers have to constantly invest in newer and more efficient technologies, and develop production methodologies capable of delivering products at high production rates, quality, and efficiency. This is where automation enters the equation, helping companies achieve these requirements through the design of dedicated or flexible systems capable of producing large quantities with great repeatability and quality, while reducing manual labor and the costs and inconsistencies associated with it.

It was in this context that the work present in this thesis was developed. A supplier for the automotive industry needed an assembly line to mass-produce a new model of an electric motor and introduce it in the market. The goal was to design a semi-automated cellular assembly line, where the operators would mainly perform load/unload operations and the automated systems would perform the majority of the assembly operations. The automation of the assembly operations allows the control of the production process at all times, ensuring a final product within the quality requirements and a much easier troubleshoot of eventual problems that can emerge during the production.

Due to the complexity and size of the assembly line, this thesis will have a main focus on stations 1 and 2 of the assembly line designed, which will be explained in deep detail, while the remaining stations will only be briefly explained.

In the end, the results of this project were extremely positive, the assembly line was concluded with success and delivered in time to the customer, complying with all the requirements imposed in terms of safety, quality, cycle time, and production traceability.

PALAVRAS CHAVE

Industrial automóvel, Motor elétrico, Automação, Linha de montagem celular, Projeto mecânico

RESUMO

O automóvel é um pilar da sociedade dos dias de hoje. O seu uso generalizado, para deslocações pessoais ou transporte de cargas industriais, cria uma grande procura por automóveis, fazendo desta indústria uma das principais a nível global. Quando há uma elevada procura para um produto, a competitividade para conquistar uma fatia desse mercado também é muito elevada, obrigando as empresas presentes na indústria automóvel a uma constante melhoria e inovação, de modo a fornecer o melhor produto possível, atendendo a elevados padrões de qualidade e prazos de entrega curtos.

Para sobreviver nesta indústria, as empresas e fornecedores tem de investir constantemente em novas e mais eficientes tecnologias, e desenvolver metodologias de produção capazes de elevada cadência de produção, com a qualidade e eficiência requeridas. A automação ajuda as empresas a cumprir estes requisitos através de sistemas dedicados ou flexíveis, capazes de produzir grandes quantidades com elevada repetibilidade e qualidade, ao mesmo tempo que reduzem a quantidade de trabalho manual, juntamente com os seus custos e inconsistências associadas

Foi neste contexto que o trabalho apresentado nesta dissertação foi desenvolvido. Um fornecedor da indústria automóvel precisava de uma linha de montagem para a produção em massa de um novo modelo de motor elétrico, o qual pretendia introduzir no mercado. O objectivo é desenvolver uma linha de montagem celular e semiautomática, onde os operadores realizariam maioritariamente as operações de carregamento e descarregamento, enquanto os sistemas automáticos executariam a maioria das operações de montagem. A automação dos processos de montagem permite monitorizar e controlar o sistema em qualquer instante, assegurando um produto final que cumpre com os requisitos de qualidade e uma resolução muito mais rápida e eficiente de eventuais problemas que possam surgir durante a produção.

Devido ao tamanho e complexidade da linha de produção projectada, esta tese irá focar-se nas duas primeiras estações, analisando-as a fundo, enquanto que as restantes estações serão apenas brevemente mencionadas. No final, os resultados deste projeto foram extremamente positivos, uma vez que a linha de montagem foi concluída com sucesso e entregue atempadamente ao cliente, cumprindo todos os requisitos impostos em termos de segurança, tempo de ciclo qualidade e rastreabilidade da produção.

LIST OF SYMBOLS AND ABBREVIATIONS

List of abbreviations

Term	Designation
ABEC	Annular Bearing Engineering Committee
AC	Alternating Current
AGV	Automated Guided Vehicles
ANSI	American National Standards Institute
CAD	Computer Aided Design
CE	<i>Conformité Européenne</i>
CNC	Computer Numerical Control
CPU	Central Processing Unit
DC	Direct current
ESD	Electrostatic Discharge
EU	European Union
FEM	Finite Element Method
FTS	First Tier Supplier
GDP	Gross Domestic Product
HMI	Human Machine Interface
ID	Internal Diameter; Identification.
IPTE	Integrated Production and Test Engineering
ISO	International Organization for Standardization
LED	Light Emission Diode
OD	Outer Diameter
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PEEK	Polyether Ether Ketone
PLC	Programmable Logic Controller
RTD	Research and Technological Development
SCARA	Selective Compliance Assembly Robot Arm
TS	Technical Specification

List of units

Term	Designation
bar	Bar
dB	Decibel
kg	Kilogram
kg·m ²	Kilogram square meter
kg·m ² /kg	Kilogram square meter per kilogram
kg·m ² /m	Kilogram square meter per meter
kg/m ³	Kilogram per cubic meter
kN/μm	Kilonewton per micrometer
kW	Kilowatt
m/s ²	Meter per square second
m ²	Square meter
m	Meter
MPa	Megapascal
mm/s	Millimeters per second
N	Newton
N·m	Newton meter
N/mm ²	Newton per square millimeter
rpm	Rotations per minute
s	Seconds
μm	Micrometer

List of symbols

Term	Designation
\$	Dollars
%	Percentage
€	Euro
Cr	Chemical element Chromium
g	Gravity acceleration
Mn	Chemical element Manganese
Mo	Chemical element Molybdenum
Ni	Chemical element Nickel
n°	Number
V	Vanadium
°	Degree
∅	Diameter

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INTRODUCTION

1.1 CONTEXTUALIZATION

1.2 GOALS

1.3 METHODOLOGY USED

1.4 THESIS STRUCTURE

1 INTRODUCTION

1.1 Contextualization

Automation consists of taking a task performed by a human and applying technology capable of executing the same task with none or reduced human intervention.

The automation industry started to evolve with the perfecting of the steam engine, which was invented around the XVII century, but only by the end of the XIX century was sufficiently improved to be applied in most of the industrial uses. This allowed the design of machines that were able to help workers perform their tasks better and faster. Nevertheless, the biggest development occurred when electricity started to be used around 1920, at the same time that the industry started to use feedback controllers and logic relay. Since then, the technology kept evolving and the digital controllers were the next boost to the evolution of automation. By the 80s this industry was sufficiently mature to make industrial engineers dream about “lights-out” manufacturing, which consists of having a factory floor working 100% without human intervention. This reality is still far away but nowadays is already possible to design and produce entire production lines fully automated, where humans only control the process without interacting directly with the process. Although these lines come at a higher initial cost, depending on the predicted lifetime of the machines, this investment can be reimbursed by the elimination of the human labor costs.

Automation is strongly present in the automotive industry, where quality and mass production are a must, so that vehicles can be produced under high safety standards and low production costs. This is a consequence of the high competitiveness between the different brands acting on this market.

1.2 Goals

This work emerged at IPTE (Integrated Production and Test Engineering) when one of its customers, a supplier for the automotive industry, needed to start the production of a new model of electric motors. The customer specializes in the development and production of electric motors, either for general applications or custom solutions required by his clients, such as the motor in question. In their facilities the customer already owns other assembly lines and, according to the production quantities demanded, they can either be manual, semi-automated, or fully automated.

For the product in question, the main goal of the project presented in this thesis is to develop and design a new semi-automated assembly line capable of producing this product with a cycle time of 40 s.

To successfully complete the design of this assembly line, a visit to the customer's factory was made and after a series of reunions the following goals were defined:

- Study the product and the production processes;
- Group the assembly steps into different stations;
- Automate the maximum amount of assembly processes, minimizing manual assembly operations;
- Ensure the safety of the operator at all times;
- Ensure an ergonomic design of the equipment;
- Ensure the traceability of the production history and associate with the part number of the product produced;
- Minimize the risk of product damage and dirt accumulation during production;
- Guarantee that the station possesses ESD (Electrostatic Discharge) properties;
- Comply with the cycle time of 40 s.

1.3 Methodology Used

To complete the objectives defined for this thesis, the following methodology was adopted:

- Analyze the electric motor components;
- Analyze the assembly sequence;
- Division and definition of the workload for each cell (definition of the stations);
- Definition of the layout;
- Brainstorm and compare possible solutions for each system to be designed;
- Budgeting;
- Develop and design the solution chosen from the brainstorm;
- Validation of the assembly line design with the customer;
- Perform all the dimensioning necessary to ensure the correct operation of the systems;
- Perform the pneumatic project;
- Identify all the purchase components necessary;
- Prepare all the custom parts for production;
- Manufacturing of the assembly line;
- Debugging and final validation with the customer;
- Writing of this thesis.

1.4 Thesis Structure

This thesis is organized into five main chapters, which are:

- 1 – Introduction: A global presentation of the work developed is given, presenting to the reader the context on which this thesis was developed, why it was developed, the goals and methodology used;
- 2 – Bibliographic work: The reader is presented with a theoretical summary of the themes present throughout the thesis, which are mainly referenced on books and scientific articles dedicated to such themes;
- 3 – Characterization of the company, product, and problem: In this chapter, the reader receives a deeper insight of the company, product, and production sequence, as well as a presentation of the predefined layout that emerged from discussions with the customer during the budgeting stage of the project;
- 4 – Thesis development: The project details are presented in this chapter, giving to the reader an insight of how the design choices were made as well as a detailed explanation of the equipment, operation sequence and component dimensioning;
- 5 – Conclusions: the final considerations, as the results of the project, are presented, as well as possible future improvements.

BIBLIOGRAPHIC WORK

2.1 AUTOMOTIVE INDUSTRY AND THE COMPONENTS INDUSTRY

2.2 AUTOMATION OF PRODUCTIVE SYSTEMS

2.3 AUTOMATION FOR INDUSTRIAL SOLUTIONS

2.4 RECENT STUDIES IN THE FIELD

2 BIBLIOGRAPHIC WORK

2.1 Automotive Industry and the Components Industry

The automobile has come a long way since the first self-propelled vehicle was created. The first step for the emergence of the car, as we know it today, was given by a French inventor, Nicolas-Joseph Cugnot, who created a Steam-powered Carriage, which was a very rudimental vehicle, but it was the first recorded device to convert the linear motion of a piston, into rotary motion and use it to propel a vehicle [1]. In 1885, the Motorwagen was created by Karl Benz. It was a tricycle powered by a single-cylinder internal combustion engine. It is considered to be the first-ever commercially available vehicle [2].

The commercialization of these vehicles gave birth to the Automotive Industry. Since then, the automotive industry has grown to be the industry of the industries, reaching a global level and becoming extremely competitive. Henry Ford was the first to thrive in this competitive industry, introducing the mass production assembly line. His goal was to reduce the production cost of the vehicle and make it affordable for the masses [2], [3]. This assembly line became a reference to all production methods.



Figure 1 – Automobile evolution: a) Joseph Cugnot's 1770 *Fardier à Vapeur* [4]; b) Benz Patent-Motorwagen [5]; c) Ford T-Model [3];

Nowadays, the automotive industry is no longer working under this mass-production model. The expectation and needs of the customer shifted, increasing the demand for variety, customization options, lower prices, and higher efficiency, and so, the automotive industry had to rearrange its structure. This new reality forced OEMs (Original Equipment Manufacturer) to offer customization options to the customers and work in a Just-in-Time Methodology so that it could be able to adapt to the market as it evolves [6].

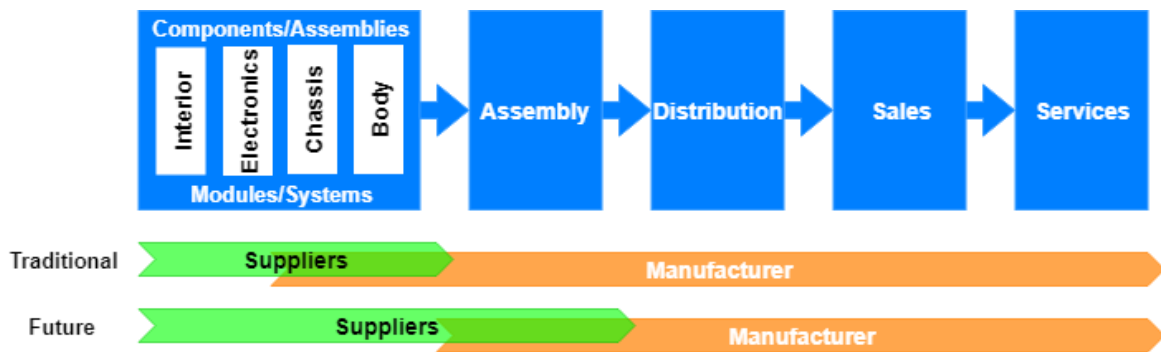


Figure 2 - Evolution and transfer of responsibilities, from the manufacturer to the suppliers, (Adapted from [7])

During this rearrangement of the Automotive Industry structure, the components industry started to emerge, becoming a keystone in the Automotive Industry [8]. A process of decentralization (as seen in Figure 2) and globalization started to occur within the OEMs, they were now working hand-in-hand with their suppliers to design and develop new car models, being the following actions the main ones adopted by OEMs [9]:

- The growth in outsourcing;
- The co-design;
- The design of shared platforms;
- The integration of systems and modularization;
- The concentration in the number of FTS (First Tier Supplier).

Outsourcing was the main action taken towards the decentralization. OEMs asked their FTSs to step up in the RTD (Research and Technological Development) of certain parts of a car model, working with them in a co-design relationship. The development process of a new component is now very different, meaning that the OEMs have a different relationship with their suppliers, depending on the type of part in question [9].

The type of part to be integrated into a car design can fit in one of three categories [9]:

- **Supply proprietary part:** the component used is from a standard item of the supplier's catalog;
- **Black box part:** the development and design of a certain component is of entire responsibility of the supplier; the car manufacturer only defines the functional features that the component must perform;
- **Co-design part:** A component that is developed based on the exchange of competences and information between the car manufacturer and the supplier.

Suppliers can also be divided into four different types [7]:

- **Components manufacturers:** specialists in a certain process, like plastic mold injection or metal casting;
- **Assembly manufacturers:** specialized in a certain process, with additional assembling capacities;
- **Systems manufacturers:** Suppliers with capacities to develop and manufacture complex systems;
- **System integrators:** Suppliers able to integrate components and systems into modules.

2.1.1 General Requirements of the Automotive Industry

The automotive industry has a vast number of OEMs and suppliers, which leads to high production standards and strong competition. For companies to survive in this market they need to constantly innovate their technologies, products, and production processes, as well as establish an attractive relation between quality, variety, and price. In short, it is possible to state that the automotive industry lies in three major cornerstones: competitiveness, quality, and delivery time.

Competitiveness

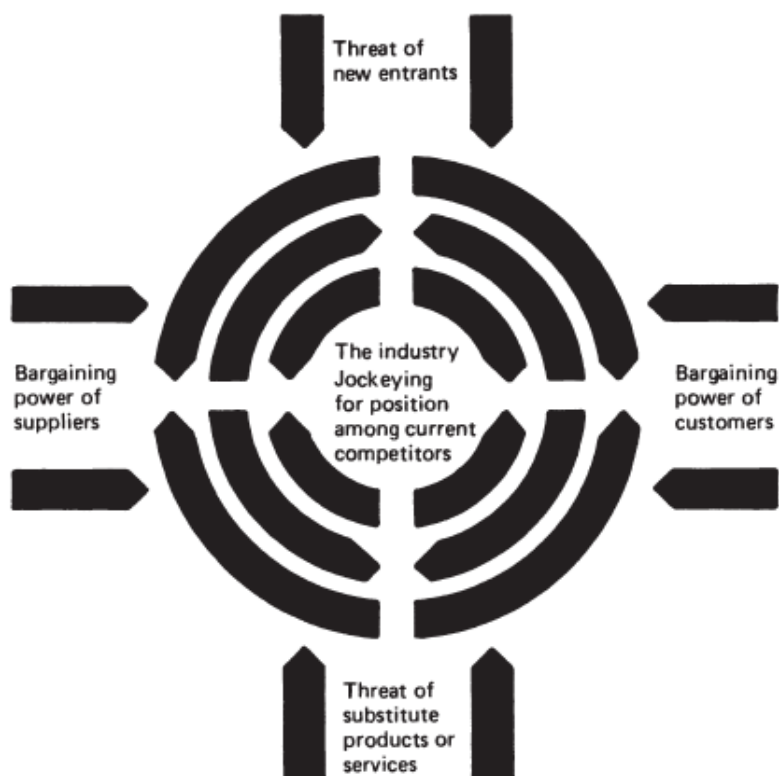


Figure 3 - Forces that influence the competition in an industry [10]

The competitiveness in the Automotive Industry depends on the market fluctuations. It is also influenced by pressures made by the costumers to the suppliers, regarding the relation between price and quality. Therefore, the Automotive Industry is in constant evolution, since a fast response to the necessities of the market is the way to ensure competitiveness. This evolution focuses on the creation of new technologies, in order to unlock the ability to produce better car models, more efficient and more attractive, as well as new production methods, while still maintaining the quality and reducing the production cost to the bare minimum [11].

A company is more or less competitive depending on its ability to maintain this balance. According to Porter, companies stay competitive as long as they keep constantly updating and innovating [12]. Moreover, in the article “How Competitive Forces Shape Strategy”, issued in 1979, Porter states the main forces that shape the competitive strategy, represented in Figure 3 [10]. A resume of Porter’s Matrix is presented in Table 1.

Table 1 – Porter’s forces that govern competition [10]

The threat of new entrants	New competitors/companies trying to enter a market niche, surging with new ideas or lower prices, trying to conquer a portion of the market.
Bargaining\ power of costumers	Costumers are constantly searching for the best offers on the market, looking for the best relation between price and quality.
The threat of substitute products or services	The possibility of other companies creating similar products, or a new product, with a higher value than the existing ones.
Bargaining power of suppliers	Suppliers have a great influence on the quality and price of the final product. This is a power they take advantage of to bargain better deals for them.
The industry jockeying for position among current competitors	Represents the pressure that established companies apply to each other, with innovation and pricing, in order to conquer a bigger parcel of the market.

Quality

As established before, the companies taking part in the Automotive Industry have to deal with big requirements regarding quality. This obligates the companies to acquire systems capable of managing quality, aiming to continuously improve, preventing defects, reducing waste, and minimizing variations.

Regarding the automotive industry, the suppliers must obtain the certification IATF 16949:2016 [13]. A company that is certified with this standard is informing the customers of possessing the following competencies [14]:

- The fulfillment of pre-requirements to supply products/services to the car manufacturers;
- Competitive advantages for organizations wishing to establish lasting relationships with car manufacturers or their suppliers;
- Coherent, integrated, and systematic implementation of tools and procedures, focused on the specific needs of the automotive sector.

The standard IATF 16949:2016 goes hand-in-hand with the ISO 9001, respecting its structure and requirements. The ISO 9001 is not needed to possess IATF 16949:2016, although, a company that possesses IATF 16949:2016, also complies with certain sections of the ISO 9001 [14]. This is very important since ISO 9001 is highly respected across all industries.

It is also very recurring for certified companies to be subjected to quality audits, either from the costumers or from competent companies, to ensure the correct implementation of the processes and systems implied by the respective standards, and the inexistence of deviation from quality requirements [15].

Delivery Time

The delivery time is also an important aspect of the automotive industry. With car manufacturers drifting away from bulk production, it is important to ensure the shortest delivery time possible of components to produce, on time, the product for the final customer. This issue is more noticeable with custom parts, standard parts usually have a much smaller delivery time [16]. From this need, companies started to operate with a just-in-time philosophy. The goal is to produce only the necessary and on time, never compromising the quality of the final product. The correction of weak points presents at the manufacturing floor, identification of the bottlenecks, and their improvement, in order to reduce cycle time, takes a major role in this philosophy [17].

2.1.2 The Importance of This Industry on the Economy

Yearly, the World Travel & Tourism council executes a study to compare the influence of different sectors on the global GDP (Gross Domestic Product). The influence of the different sectors in 2018 is demonstrated within the graphic from Figure 4 [18].

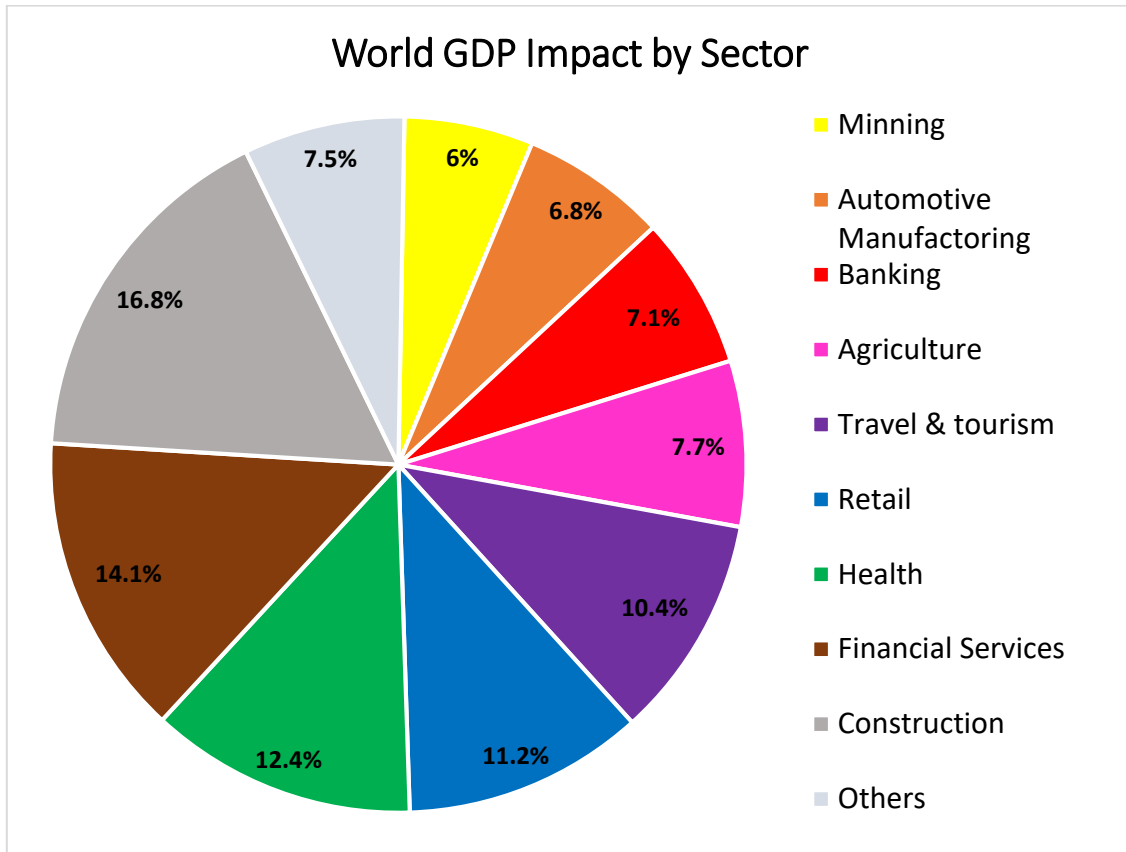


Figure 4 - World GDP impact by sector (Adapted from [18])

According to this study, the automotive manufacturing industry is responsible for 6,8% of the world's GDP. It is also estimated, in this study, that this percentage is equivalent to a contribution of 5,8 trillion dollars. Despite not being the biggest sector, automotive manufacturing is still a sector of major importance [18].

It is also important to take notice that, during the year 2018, the production of motorized vehicles reached the figure of 95,6 million units. It was the first time since 2009 that the production decreased. In the graphic from Figure 5, is possible to see the evolution of the production volume [19].

Regarding Europe, in 2018 the production of motorized vehicles reached 22,8 million units, which represents almost 24% of the global production, making it the second-largest motorized vehicles producer, falling only after the greater China [20].

To reach these numbers, Europe counts with a manufacturing workforce of 3,5 million employees, being responsible for 11,4% of Europe's employment in manufacturing. Indirectly, the automotive industry provides jobs for another 11,2 million employees, in works such as sales, maintenance, transport, construction, and many others. This means that a total of 13,8 million Europeans depend on the automotive industry to guarantee their jobs [20].

In Portugal the numbers also have great significance, for instance, in 2018, 306 679 vehicles were produced in Portuguese territory. A study in 2017 states that around 29000 companies work for the automotive industry, providing jobs for 124000 workers. This sector was responsible for 11% of the total exportation of the country and 21,6% of the total fiscal revenues in Portugal. The business volume was of 23,7 thousand million euros [21].

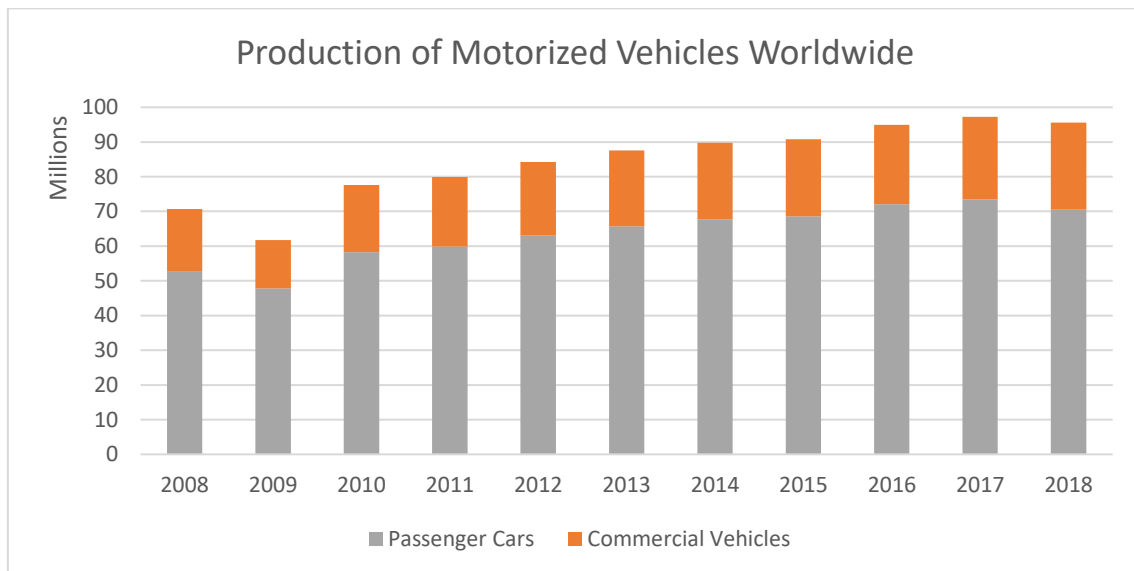


Figure 5 - Production of motorized vehicles worldwide (Adapted from [19])

2.2 Automation of Productive Systems

Nowadays, the industry consistently requires more and more production efficiency, while using the least amount of resources possible. Automation is the answer to these requirements, currently being a major cornerstone in the industry [22]. Automation is present within a diverse range of industries, however, the automotive industry is one of the main sectors that promote the research and development of automated systems, with the goal of increasing productivity and flexibility [11].

Component manufacturers have increasingly opted for the implementation of automated systems over the use of manual assembly processes. The intention is to optimize the production costs (higher profits and lower expenses), productivity, manufacturing time, while, at all times, assuring the quality and complying with the requirements of the customers. By applying these systems, the manufacturers ensure their flexibility and competitiveness. Furthermore, another factor that contributes to the use of automated systems is the safety of the employees, due to the fact that some production operations present a risk to the physical and mental wellbeing of the operator [23].

These are some of the main demands that come with the production of the large number of components that a motorized vehicle possesses. According to Groover [24], the key factors that lead companies to invest in the automation of manufacturing processes are listed in Table 2.

Table 2 - Factors that lead companies to invest in automation (Adapted from [24])

Increased productivity	The productivity of an automated process, compared to a non-automated version of itself, is usually higher. The cycle time tends to be lower, which implies a rise in the production output.
Reduced production costs	The implementation costs of an automated system can be justified by the exclusion of human labor. Operators are one of the major costs of production, so when they are eliminated, the production costs are considerably reduced.
Quality improvements	Automation increases the repeatability, and consistency of production, therefore increasing the quality of the final product.
Shorter delivery time	It is possible to reduce the delivery time through automation, since this method eliminates, almost completely, wasted time, between the production orders, to the time that the products are delivered. This is a keystone to assure competitiveness.
Executing tasks that cannot be performed manually	Some operations cannot be executed without the use of machinery. Some processes, such as manipulating very small components or with complex geometries, or even processes with a high precision requirement, are better off using automated systems.
Avoid the cost of non-automation	The benefits of automation are noticed across the most diverse areas of a company. For instance, the increase in quality, fast response, and the good work conditions provided to the employees contributes to the satisfaction of the final customer, and possibly increasing sales.
Reduction or even elimination of manual operations	The implementation of automated systems allows the extinction of repetitive and exhausting manual tasks, improving the work conditions for the workers.

The arguments presented in Table 2 are just some of the factors that can be stated. Another thing worth mentioning is the fact that automation provides new opportunities for the employees. It is usual to associate automation with the reduction of labor costs, by replacing factory operators, but, this is not necessarily true. When an operator is replaced by a machine it does not make him dispensable, the operator can be reintroduced on the factory floor with the job of maintaining and controlling the machine. This opens up new growth and learning opportunities while leaving behind a repetitive and monotonous job [7].

2.2.1 Automation Levels

The production process of a certain product with more than one component usually needs some kind of assembly. The evolution of the assembly processes is connected to the need to manufacture products in quantity. Therefore, the pioneers in batch production, or mass production, are also the pioneers in modern assembly techniques [25].

Generally in the industry, the assembly process can be executed in three different ways [24], [26]:

- Manual assembly;
- Semi-automated assembly;
- Fully automated assembly.

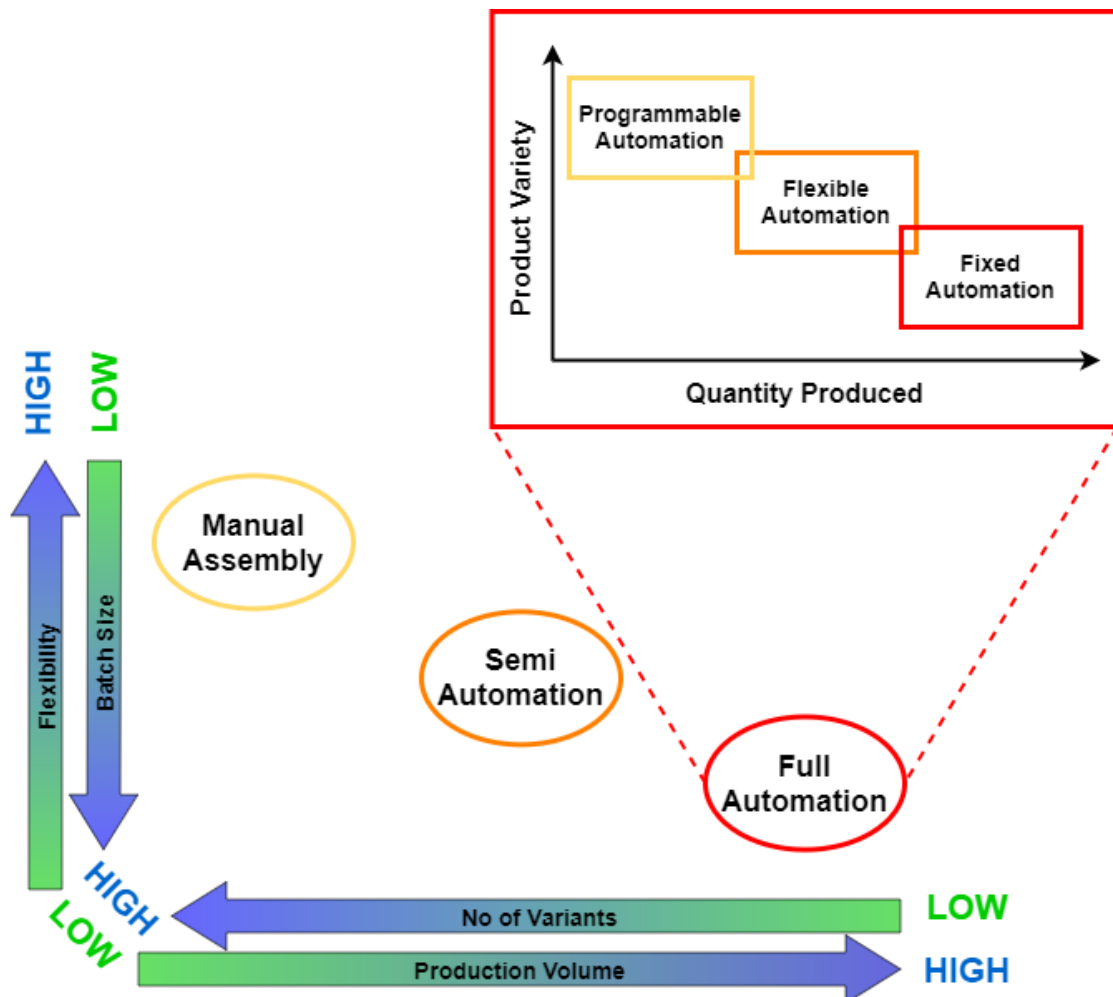


Figure 6 - Assembly process according to desired flexibility, batch size, number of variants, and production volume (Adapted from [24], [26])

Besides the parameters shown in Figure 6 (batch size, flexibility, number of variants, and production volume) that shape the assembly process, there are other variants of the product that need to be taken into consideration, such as:

- Product design;
- Production rate (cycle time);
- Manpower available;
- Time of permanence of the product in the market.

All of these factors allow the evaluation of the product and selection of the most suitable assembly process to implement [25].

2.2.1.1 Manual assembly (with auxiliary systems)

As seen within the subchapter 2.2.1, there are situations where manual work is still preferable. Furthermore, the implementation of automated machinery can be very expensive and unworthy in some cases. According to Groover [24], the reasons to adopt manual assembly production in certain situations are stated in Table 3.

Table 3 - Reasons to adopt manual assembly production (Adapted from [24])

Tasks with high automation complexity	Some tasks are technically and economically tough to automate. The coordination, dexterity, and sensitivity of human movements are factors to take into consideration regarding complex handlings and tasks.
Short market availability timespan	Products that will only be available on the market for a short time and with a restricted quantity, being produced in a single batch and without further productions.
Custom products	A unique product requested by the customer, with very specific functions, is better to be produced by hand thanks to the human production flexibility.
Demand variations	The demand for some products fluctuates. Unlike automated machinery, manual assemblies do not have a fixed cost of operation, since the number of workers on a production can be changed according to the market demand for the product.
Reduce the risk of a new product failure	Instead of a direct investment in automated machinery, companies like to start a small production to test the market, taking advantage of manual assembly.

2.2.1.2 Semi automation

The semi-automated assemblies consist of machinery that together with a human executes determined tasks. The level of automation of the assembly process is determined by evaluating the number of tasks that are executed by the machine and by the operator. Semi-automated machines are peculiar because some tasks are executed by automated equipment, leaving the remaining ones for the operator. On the other hand, fully automated assemblies do not require a human to execute the tasks, only to control and execute maintenance operations.

One of the most seen examples, within the automotive industry, are machines that have a manual load/unload process and automated execution of the remaining tasks (Figure 7).



Figure 7 - Semi-automated equipment from IVS [27]

2.2.1.3 Full automation (flexibility vs dedicated)

The fully automated systems are the ones that require the largest initial investment. To achieve full automation, with the smallest human intervention during operating, it is necessary the collaboration between different departments, namely, the mechanical, electronic, and programming department. This type of automation is preferred by companies whenever possible [28].

As seen in the subchapter 2.1.1, fully automated assemblies can be divided into three categories, programmable automation, flexible automation, and fixed automation. Within Figure 6 there is a smaller graph that shows the relation between the product variety and the quantity produced and where these types of full automation are located. In Table 4 a further explanation is given on these types of full automation.



Figure 8 - Examples of: a) Programmable automation [29]; b) Flexible automation [30]; c) Fixed automation [31];

Table 4 - Categories of fully automated assemblies (Adapted from [24])

<p>Programmable automation</p>	<p>These systems allow changing the sequence of an operation via program and tool changes, enabling it to work with different products. The tool changing operation can be done automatically or manually. These systems are usually seen working with batch productions. An example of a programmable automated system is seen in Figure 8.a), where a CNC (Computer Numerical Control) is being loaded and unloaded by a robot.</p>
<p>Flexible automation</p>	<p>Flexible automation allows the uninterrupted production of different products, and can even adapt to changes made to the product, only by changing the control program. Usually, the differences in the product are very small and the production rate is median. In Figure 8.b) it is possible to see an example of a flexible welding automated production line, which can simultaneously produce different car models without the need to change the welding tools attached to the robots.</p>
<p>Fixed automation</p>	<p>Fixed automation is very commonly used when the intention is to mass-produce a certain product to achieve very competitive prices. These systems are peculiar by their low, or inexistent, flexibility. The production operations are very focused and limited to the configuration of the machine. An example is the production of glass bottles (as seen in Figure 8.c)), which are mass-produced.</p>

2.2.2 Production and Assembly Lines

Usually, on the factory floor of a manufacturer, various products are being produced or assembled simultaneously. Because of this, the equipment is grouped in manufacturing systems and logically organized on the factory floor, creating the plant layout [32]. A well-designed layout contributes to improvements in productivity and cost reductions, by enabling the manufacturing system to be more efficient.

Depending on the variety of products and the production volume, certain layouts are more appropriate for each different case. Judging by the yearly production is possible to classify it as a low quantity production (1-100 units/year), medium quantity production (100-10000 units/year), or high quantity production (more than 10000 units/year) [32]. Within this classification, four types of plant layouts can be defined and applied in each case, as seen in Figure 9. In Table 5 a brief explanation is given to each type of layout.

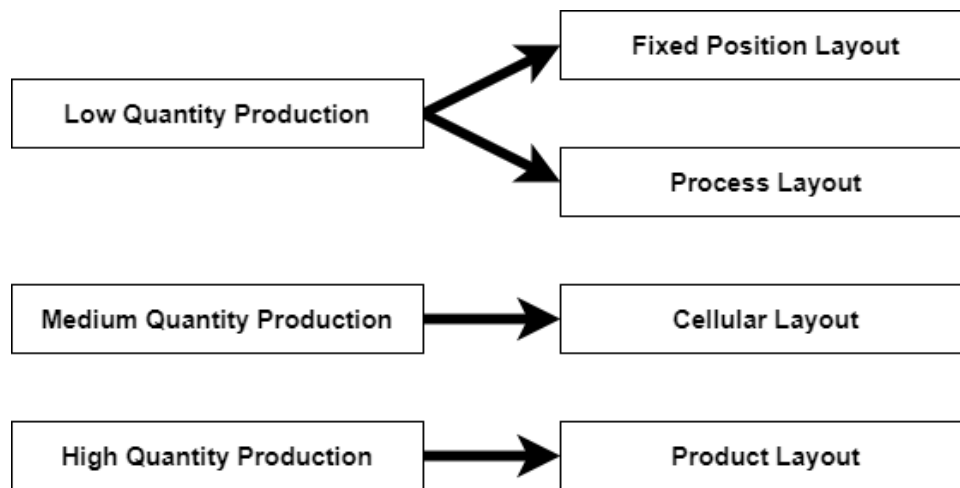


Figure 9 – Plant layouts according to production volume (Adapted from [32])

Table 5 - Types of plant layout (Adapted from [32])

Fixed-position layout	Products with large dimensions can be hard to handle and transport, so it is usual to use this type of layout, where the product stays stationary on the production floor and the operators and processing equipment move around it. Ships are an example of the use of this layout.
Process layout	In this layout the equipment and working stations are grouped according to their finality, creating process departments. Depending on what a part may or may not need, it moves around (usually in batches) within the departments until the processing has been completed.
Cellular layout	Consists of the creation of work cells, constituted by machinery and operators, which are dedicated to the production of a family of similar products with minimal setup changes needed. If there is a big dissimilarity between the products it is recommended to use a process layout.
Product layout	A product layout consists of grouping several machines that are dedicated to the production of a single product that has a very large demand rate (mass-produced). The machinery and/or workstations are organized in line with each other, where the product is shifted around and the operations are done according to the manufacturing sequence.

2.2.3 Manpower Associated and the Perception on Change

When automation started to emerge in the manufacturing industry the main goal was to replace human labor with machinery capable of executing the same task, with greater performance and efficiency, and at the same time reducing the costs associated with manpower. During this time, automation was only capable of executing standard and repetitive tasks, while, nowadays automation devices are more flexible and can take over non-standardized tasks [33].

It is still a common belief, that automation is a major enemy of the human workforce in manufacturing factories. It is also true that these statements do not match the trends in numbers of employment [34]. A study performed in 2018 at the United States of America, shows that 84% of employers want to maintain or increase the current workforce, and this is a trend that has been stable for the third year in a row, and it is expected to be maintained [35]. The fact is that automated systems require a large workforce to be achieved and maintained, so it can actually require a larger workforce than non-automated systems. The true threat is to low-skill jobs, because, these are the easiest to automate, and not only in manufacturing factories, jobs as transportation and logistics also have a tendency to be automated [36].

The true challenge is to make human skills and the know-how of the workforce, beat the rapid evolution of automation technology and artificial intelligence. Additionally, it is also important to state that the rate of technology evolution is entirely dependent on the innovative and creative capacities of the human beings involved. So, the answer to ensuring jobs in areas where automation has a great impact on the workforce is through education. It is important to promote capacities that will be in great demand in the future, as well as capacities that will resist the implementation of automated systems [37].

2.3 Automation for Industrial Solutions

2.3.1 Presses

Presses are massively used in the manufacturing industry. They can be used to process assembly operations, as well as shaping, bending, punching, and conforming operations. The most common use of presses, in assembly operations, is to press-fit components together, which consists of fixing two components together due to an interference in their dimensions. For instance, when press-fitting a bearing into a shaft, the diameter of the shaft is slightly larger than the internal diameter on the bearing. Pushing these two parts together to create a solid connection requires some load which is the purpose of a press [38].

Usually, in assembling operations, a press is characterized for having a body shape like a “C” or “H”. “H” type presses are more suitable for heavy-duty operation or with high accuracy

requirements, while “C” presses are more versatile, but bare smaller loads. In both cases, at the bottom, a nest is used to orient and secure the receiving part, and at the top, a tool will allow the installation of the element to be assembled. The orientation between the top tool and the nest is crucial for the correct execution of the operation [39], [40].

The linear pressing motion can be executed in various ways, and according to how it is performed, is possible to classify presses as manual, pneumatic, hydropneumatic, hydraulic, and electric. However, nowadays, the most used in the automotive industry are the servo-electric presses, as they allow for better movement control and register in all positions the load that is being applied, which is a great advantage in process and quality control [39].

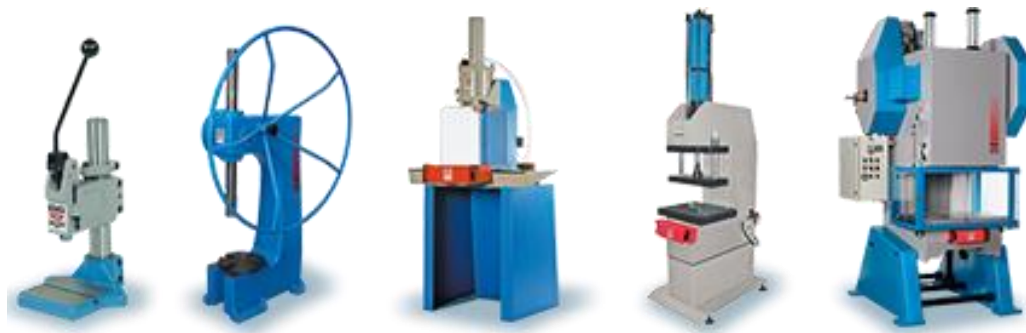


Figure 10 - Example of different types of presses [40]

2.3.2 Threaded Fasteners

One of the most common ways to assemble parts together is through threaded fasteners. The reason for their high usage is given to the fact that threaded fasteners (like screws, bolts, nuts, etc.) are fairly cheap and massively available in the market, in the most diverse forms and geometries, allowing for a very wide range of applications. Moreover, this type of assembly is also very flexible, allowing an easy assemble, disassemble (for maintenance), recycling, and repair [41].

To perform the tightening of these connections, screwdrivers are required. Such equipment can be powered manually, pneumatically, or electrically. Nowadays, like presses, electric screwdrivers are preferable, because of the ease to collect data from the screwing operation (for instance, torque and angle). When using power tools, most times the equipment can create great loads, that are not ergonomically safe for the operator [42]. To solve this, it is common to see powered screwdrivers attached to torque arms, which grant an easier way for the operator to position the tool while, at the same time, dampening and absorbing the resulting forces of the screwing operation. Another option is to fully automate these operations, for example, with a robot or gantry system, or to perform the operation manually using a hand-held tool.



Figure 11 - Positioning torque arm with an electric screwdriver [43]

2.3.3 Handling Systems

2.3.3.1 Overhead Cranes and Forklifts

A very common sight in manufacturing companies is the presence of overhead cranes and/or forklifts. These machines are essential for a company that will handle materials of larger dimensions and weight, either when they come to the factory, during logistics operations or expedition. Depending on the cargo that the companies are going to handle, both cranes and forklifts have their pros and cons. A comparison between the two can be seen in Table 6 [44].

Table 6 - Pros and cons of overhead cranes and forklifts [45], [46]

	Overhead cranes	Forklifts
Pros	<ul style="list-style-type: none"> • Capable of reaching higher spaces; • Longer lifespan; • Higher towing capacity; • More cost-efficient (low maintenance); • Single-man operation. 	<ul style="list-style-type: none"> • High flexibility; • Available in various sizes; • Low initial investment.
Cons	<ul style="list-style-type: none"> • High initial investment; • A large area of installation; • Fixed area of work. 	<ul style="list-style-type: none"> • Requires free paths to move around; • Can be a two-man job; • Frequent maintenance.
Illustration		

Regardless of the pros and cons presented, the use of an overhead crane or forklift, depends on the case. Cranes are more efficient, but forklifts are more flexible, and in other cases, companies require the use of both. In general, across the most various industries, forklifts are much more common on factory floors, due to their flexibility and cost.

2.3.3.2 Conveyors

Conveyors are very frequently used in manufacturing factories. They can be used within a production line or on logistics facilities. For instance, in assembly lines, conveyors are often used to transport the materials between work stations. They are useful in every place where there is a need to transport, or feed, goods from one point to another, making the process easier, efficient, and convenient.

These are mechanical devices that are available on the market in a big variety of constructions and can be powered manually, by gravity or a motor, making them very flexible and capable of conveying the most diverse types of products and materials [47].

These solutions are, in most cases, more efficient than manual transportations or other means, such as forklifts. They are also easily operated and safe for the workers, excluding the need for complicated safety systems and to train the workforce to operate the equipment.

As stated before, there are several designs of conveyors. In Figure 12 it is presented some of the most commonly used conveyors in the manufacturing industry.



Figure 12 - a) Roller conveyor [48]; b) Overhead conveyor [49]; c) Belt conveyor [50]; d) Chain conveyor [51];

2.3.3.3 AGV (Automated Guided Vehicles)

Automated guided vehicles are machines that autonomously follow a pre-established path. This equipment is commonly used in the industry to move materials around the factory floor, between pick-up and delivery points [52].

The typical AGV is composed of a body, drive system, guidance system, power system, safety system, power storage, and communication system. The drive system is installed in the two drive wheels and is composed of two individual motors, which propels the vehicle forward, or on turns, by adjusting the speed rates between the motors [53]. The guidance system identifies the path that the AGV must follow, which can be done in many ways, for instance, the AGV can be guided by an energized wire, magnetic path, laser, GPS, etc. There are also different types of AGV's, some are towing vehicles, others are designed for heavy-loads and some to replace man-operated forklifts [54].

In the beginning, AGVs were mainly used for logistic purposes, for example, feeding products to an assembly line and collecting the final product. Nowadays, with the evolution of the technology available, AGVs are more capable, efficient, and flexible and are also being implemented within the manufacturing lines, replacing conveyors or forklifts.



Figure 13 - Automated guided cars in assembly line application [55]

2.3.3.4 Actuators

Actuators can be described as transducers because they are capable of receiving a command signal (usually electric) and convert it into physical action, such as rotation, linear motion, load, etc. Typically, the command signal is given at a low level of energy, so it often requires an amplifier to allow the driving of the actuator.

Depending on the type of amplifier used, actuators can be classified as electric, pneumatic, or hydraulic. Out of these three categories, the most commonly used are electric actuators. Meanwhile, pneumatic and hydraulic actuators share a similar concept of operation, but hydraulic ones are capable of higher pressures and consequently higher loads [24].

In Table 7 it is presented the advantages and disadvantages of each category of actuators.



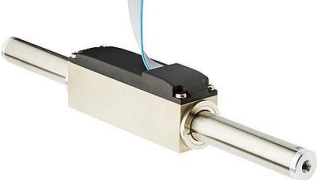
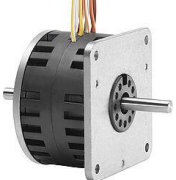


Table 7 - Comparison between pneumatic, hydraulic, and electric actuators [56]

	Advantages	Disadvantages
Pneumatic	<ul style="list-style-type: none"> • Available in the most various sizes and shapes; • Simple structure and operation; • Good repeatability; • Low cost; • High durability and often requires low maintenance. 	<ul style="list-style-type: none"> • The air is compressible, which may allow an unstable operation; • Pressure losses and air quality are critical and costly; • Requires regulators, valves, compressors, sensors, etc., to be controllable.
Hydraulic	<ul style="list-style-type: none"> • Suitable for heavy applications; • Hydraulic motors have a great horsepower-to-weight ratio; • Capable of holding a constant torque and load due to the incompressibility of the fluids. 	<ul style="list-style-type: none"> • Leaks create a lower efficient system and a cleanliness problem; • Require high maintenance; • Higher initial cost; • Like pneumatic actuators, it requires a lot of external equipment to be controllable.
Electric	<ul style="list-style-type: none"> • Highest precision in positioning and repeatability; • Can be easily reprogrammed and within the same controller it's possible to define all working parameters (speed, load, acceleration, etc.); • No risk of fluid leaks. 	<ul style="list-style-type: none"> • Higher initial cost; • Not suitable for all environments; • Usually require more installation space where the movement is needed; • Due to the more complex construction, the continuous running of the motor can lead to overheats and faster wear of the mechanical components.

Electric Actuators

Electric actuators are capable of converting electrical power into mechanical power. In the industry, they are largely used, because, this type of actuators are available in many different sizes and styles, which makes them very versatile. The different types of electric actuators are presented in Table 8.

Table 8 - Types of electric actuators (Adapted from [24]; images from [57]–[62])

	Illustration	Description
DC motor		DC (Direct Current) motors are powered by direct current and present a great torque-speed relationship, which makes them very attractive. They are often used as servomotors.
AC Motor		AC (Alternating Current) motors are powered by alternating current, which is the most accessible power source in factories. Compared to DC motors, they are easier and cheaper to build, but harder to control.
Induction linear motor		Capable of producing a linear motion without the need for external hardware, unlike rotary motors. This type of electric motor allows for great precision and long ranges. They work under the same principal as AC motors.
Stepper motor		These motors rotate a specific amount of degrees (step angle) per electrical pulse received, therefore, the motion is controlled by the number of pulses sent. Their torque and speed are lower when compared to DC motors.
Solenoid		These are devices with a stationary wire coil and a movable spring-loaded shaft inside. When a current passes through the coil, the shaft moves linearly and when the current is cut, the spring moves the shaft back.
Electromechanical relay		Operation wise, electromechanical relays are similar to solenoids, but instead of moving a shaft, they move a metal arm, opening or closing an electrical contact. With a low current, it is possible to control circuits with higher currents and/or voltages.

Typically, in industrial applications, the need to use linear motions is very common. Sometimes, the need to operate precisely through different positions excludes the possibility of using other types of actuators, such as pneumatic actuators. Thus, it is very usual in the industry to convert the rotary motion, of stepper motors or servomotors, into linear motion, allowing to maintain all the advantages of these actuators, but with linear movements [24]. In Table 9, the most common ways to achieve this conversion are presented.

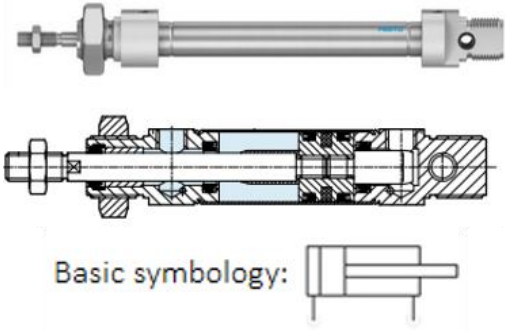
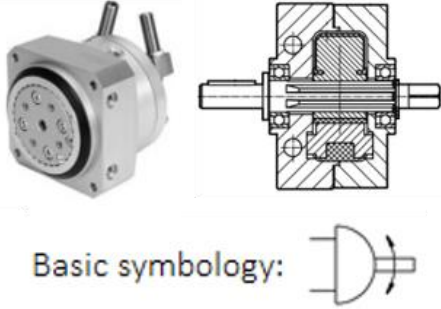
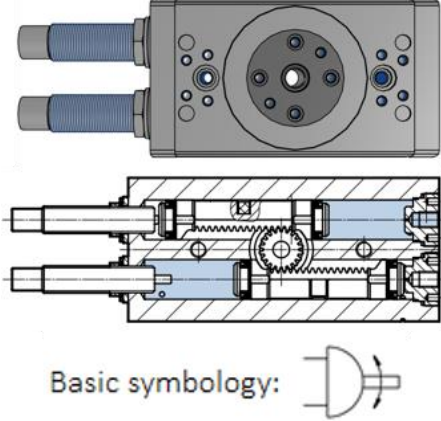
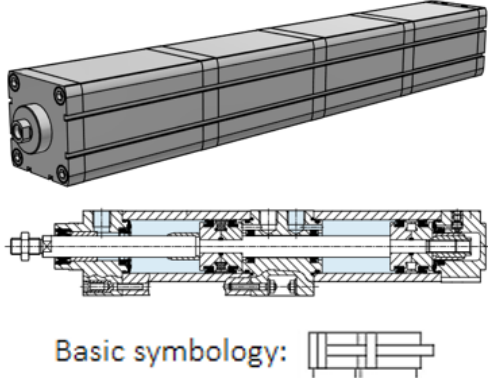
Table 9 - Different conversions of rotary motion into linear motion (Adapted from [24], [63]–[65])

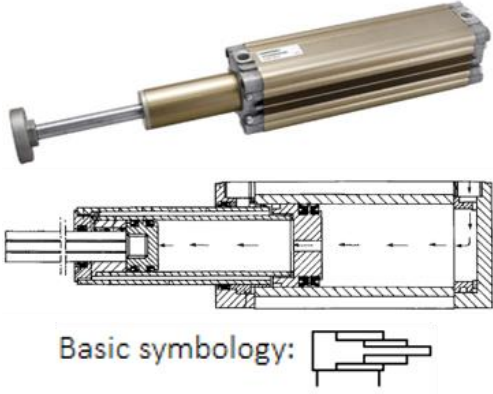
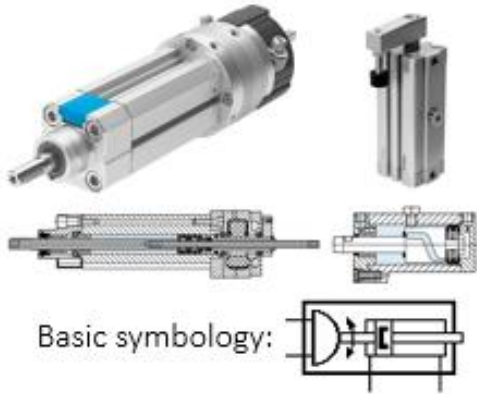

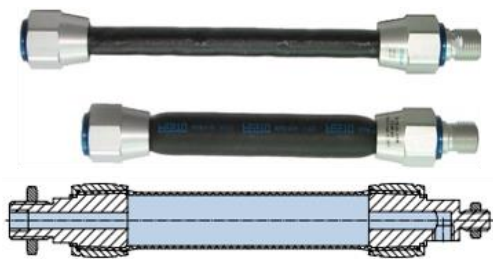
	Mechanism scheme	Example
Leadscrew and ball screw		
Pulley system		
Rack and Pinion		

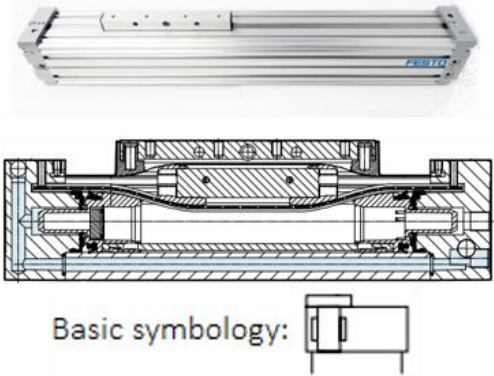
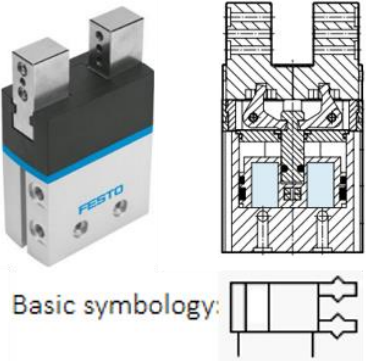
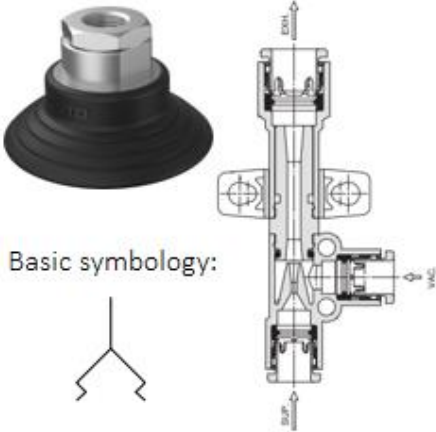
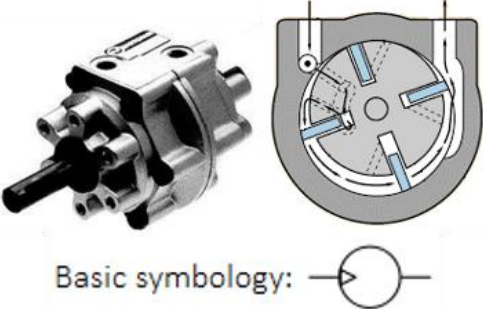
Pneumatic and Hydraulic Actuators

As established before in this subchapter, pneumatic and hydraulic actuators share the same working principle, but one is powered by compressible air and the other by non-compressible fluids. Thus, in order to present the different types of these actuators available on the market, Table 10 was created and both types of actuators are combined, but in the first column, under the actuator's designation, it will be indicated if the actuator is available in pneumatic type, hydraulic type or both.

Table 10 - Types of pneumatic and/or hydraulic actuators (Adapted from [66]–[68])

Actuator	Illustrations	Description
Cylinders with a piston rod (Pneumatic & hydraulic)	 <p>Basic symbology:</p>	<p>These are the most common pneumatic actuators. They are available in the most various sizes and shapes. These actuators perform linear motions and can work with a push or pull force, although in most cases the pushing force is larger. These cylinders also present different configurations, such as single-acting (return by spring), double-acting, double rod, with brake, etc.</p>
Semi-rotary drive with rotary vane (Pneumatic & hydraulic)	 <p>Basic symbology:</p>	<p>Inside these types of actuators exists a vane, which is attached to a shaft. When the chamber is pressurized the vane moves within it and transmits rotary motion to the shaft. They are called semi-rotary because they are usually only capable of performing rotations up to 270°.</p>
Semi-rotary drive with rack and pinion (Pneumatic & hydraulic)	 <p>Basic symbology:</p>	<p>Unlike the rotary vane actuators, these rotate by converting the linear motion of a piston with a rack, into rotation motion through a pinion. These actuators do not perform continuous turns, they usually only go up to 360° before having to move back. In most cases, they have a better size/torque ratio, compared to the semi-rotary vane actuators.</p>
Tandem, high-load, and multi-position cylinders (Pneumatic & hydraulic)	 <p>Basic symbology:</p>	<p>High-load and multi-position actuators are both tandem actuators, which consist of a set of multiple cylinders stacked in a line. The difference is that the high-load type are cylinders with equal strokes, multiplying the load, while multi-position ones are a set of different stroke cylinders, allowing multiple positions with the same actuator.</p>

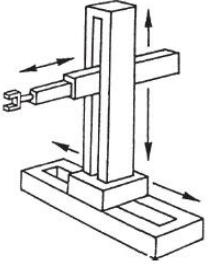
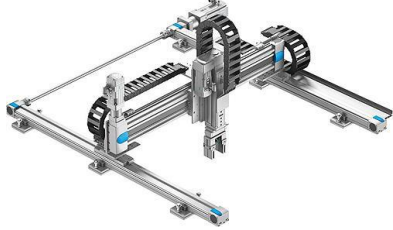
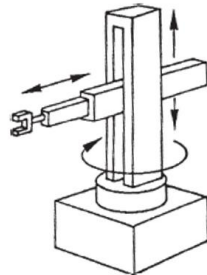

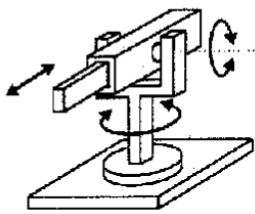

Actuator	Illustrations	Description
<p>Telescopic cylinders (Pneumatic & hydraulic)</p>	 <p>Basic symbology:</p>	<p>These actuators have the same working principle as the first ones mentioned in this table. They have the peculiarity of having multiple rods that slide inside each other. This allows for a very long stroke with a compact retracted length. A normal linear cylinder when is retracted has a length of approximately 110% of its stroke, while a telescopic cylinder has around 20% to 40% of the stroke.</p>
<p>Linear-swivel drive and clamp (Pneumatic)</p>	 <p>Basic symbology:</p>	<p>Linear-swivel actuators combine linear and rotary motion. There are two ways to achieve this, the first is combining a linear cylinder with a semi-rotary one and have individual control over the two movements. The other way is through a slot and a pin, but in this case, there is no individual control, the rotation starts and ends at a fixed point while the cylinder's rod is moving forward or backward.</p>
<p>Bellows cylinders (Pneumatic)</p>	 <p>Basic symbology:</p>	<p>Bellow cylinders are characterized for not having components sliding against each other, making them almost maintenance-free. When actuated, a rubber membrane expands, pushing the two mounting metal plates away from one another. These actuators have short strokes but can produce large loads. They can also adjust to angular and axial offsets. The stroke is adjustable according to the pressure.</p>
<p>Fluidic muscle (Pneumatic)</p>	 <p>Basic symbology:</p>	<p>The pneumatic muscle works with the same principle as the bellow actuator. Instead of moving parts, they also have a membrane that expands when the actuator is pressurized, but, rather than pushing the terminals away from each other, the pneumatic muscle pulls them closer.</p>

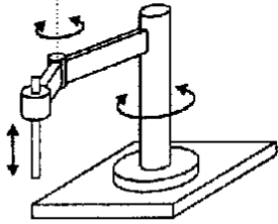

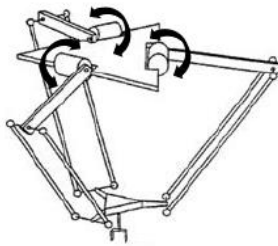

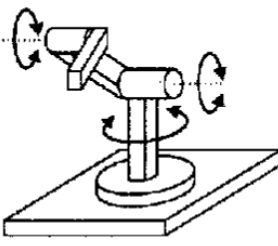

Actuator	Illustrations	Description
<p>Rodless cylinders (Pneumatic)</p>	 <p>Basic symbology:</p>	<p>In this actuator, there is a piston that moves inside a chamber but has no rod to the outside. Instead, the cylinder is attached to an external guided carrier that transfers the linear motion to the outside. In this type of actuators, the connection from the piston to the carrier can be done mechanically or magnetically. These are more compact, for the same stroke than cylinders with a rod.</p>
<p>Grippers (Pneumatic & hydraulic)</p>	 <p>Basic symbology:</p>	<p>Grippers are vastly used in the industry to manipulate an object or to lock them in place. These actuators usually have from two to four jaws, which are closed by a self-centering mechanism, ensuring a consistent grip. The claws can move linearly or by rotation, and the grippers are available in the single-acting or double-acting configuration.</p>
<p>Vacuum suction cups (Pneumatic)</p>	 <p>Basic symbology:</p>	<p>The vacuum, together with suction cups, are used to manipulate or fix objects. Suction cups are available in the most diverse sizes, shapes, and materials, making them able to adapt to various scenarios. The drawback is that they require smooth surfaces to operate and producing a vacuum can be quite expensive. The most common way to produce vacuum is through a Venturi tube.</p>
<p>Motors (Pneumatic & hydraulic)</p>	 <p>Basic symbology:</p>	<p>These devices transform the pneumatic or hydraulic energy, into a rotary motion. The direction of the movement can be fixed, or it can be controlled to produce rotation in both ways. These motors are very often used in the industry because the size/torque ratio is usually better when compared to equivalent electric powered motors.</p>

2.3.3.5 Robots

Robots are more and more a common sight in manufacturing companies. These handling systems are machines made from a set of simpler components, already mentioned in this subchapter, mainly servomotors. These manipulators can perform numerous types of tasks, from simple pick and place operations, up to complex automated actions, such as bin picking. These machines are also programmable and easily reprogrammable via their controllers and programming pendants, making them flexible and very powerful equipment for companies to own. In Table 11, different types of robots commonly used in the industry are presented [69], [70].

Table 11 - Types of robots commonly used in automation (Adapted from [71]–[75])

Robot classification	Example	Description
<p>Cartesian (Gantry)</p> 		<p>Main movement axes:</p> <ul style="list-style-type: none"> • 2 or 3 linear axes. <p>Applications:</p> <ul style="list-style-type: none"> • Large workspaces; • Feeding components; • Laser-cut.
<p>Cylindrical</p> 		<p>Main movement axes:</p> <ul style="list-style-type: none"> • 1 rotation axis; • 2 linear axes. <p>Applications:</p> <ul style="list-style-type: none"> • Handle heavy components; • Pallet moving; • Load/unload operations.
<p>Polar</p> 		<p>Main movement axes:</p> <ul style="list-style-type: none"> • 1 horizontal rotation axis; • 1 vertical rotation axis; • 1 linear axis. <p>Applications:</p> <ul style="list-style-type: none"> • Spot welding; • Load/unload operations.

Robot classification	Example	Description
<p>SCARA (Selective compliance assembly robot arm)</p> 		<p>Main movement axes:</p> <ul style="list-style-type: none"> • 2 horizontal rotation axes; • 1 linear axis. <p>Applications:</p> <ul style="list-style-type: none"> • Vertical assembly; • Spot welding; • Load/unload operations.
<p>Parallel (Delta)</p> 		<p>Main movement axes:</p> <ul style="list-style-type: none"> • 2 or 3 parallel rotation axes. <p>Applications:</p> <ul style="list-style-type: none"> • Vertical assembly; • 3D printing; • Load/unload operations.
<p>Articulated</p> 		<p>Main movement axes:</p> <ul style="list-style-type: none"> • 3 or more consecutive axes of rotation. <p>Applications:</p> <ul style="list-style-type: none"> • Handling operations; • Continuous welding lines; • Painting operations.

2.3.3.6 Vibratory Feeders

Vibratory feeders are one of the most common devices used to automatically feed small parts to assembly lines [76].

The most common configuration used in the industry is the bowl feeders, followed by linear feeders. The vibration created on the bowl produces a vertical movement and a twist motion about the vertical axis, which, through friction, pushes the part forward in the track. Along the way up, in the spiral track, the parts pass through different mechanical “traps”, which orient them to the correct position and reject the misaligned parts. When a part is rejected, it falls into the middle of the bowl and starts the journey back up again [77].

In theory, the working mechanics and the range of applications for vibratory feeders, make them appear as quite simple and reliable mechanisms, but, in truth, there are a lot of different variants involved in designing this equipment, making it a very complex task and highly dependent of trial and error experimenting after the design and fabrication process [76].

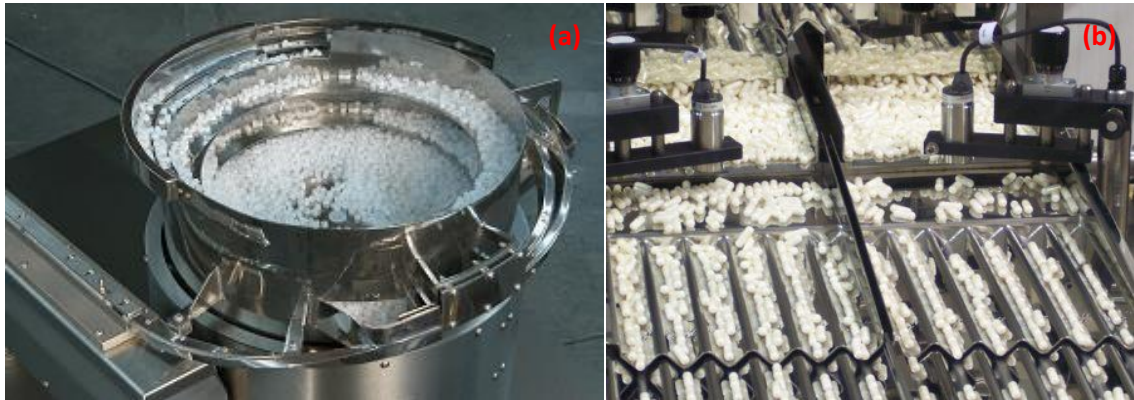


Figure 14 – Examples of vibratory feeders: a) Vibratory bowl feeder [78]; b) Vibratory linear feeder [78];

2.3.4 Industrial structures

When it comes to industrial structures, the skeleton of a machine comes down to two main options, welded steel structures or aluminum extrusion framing profiles. Welded steel structures have been around for longer than aluminum profile framings, which entered the market around the 1980s. Both methods of constructing structures have their place in the market [79].

Welded steel structures are superior to aluminum framings in strength and overall ruggedness. For welded structures, the construction options are infinite because steel is very customizable and the market offers a large variety of inexpensive standard profiles and sheets. These structures are also more affordable for larger productions, because, aluminum framing profiles are more expensive and they require specially designed fasteners that must be purchased from the supplier [80].

Aluminum framing profiles take the lead in terms of flexibility. These systems offer a very large variety of profiles sizes and components (such as hinges, handles, sliders, etc.), attached together by fasteners, to create modular structures. The production process is also much faster for aluminum framing and, unlike welded structures, does not require any specialized equipment. Additionally, in terms of eventual design errors, they can easily be corrected, while in welded structures the correction process can be quite expensive, involving operations such as cutting, rewelding, and repainting [80].

Thus, as established, welded structures and aluminum framings both have their advantages and disadvantages, hence it is also common to combine both methods together. For instance, a common sight in industrial assembly machines is for the structure to have a bottom welded structure and an aluminum framing on top. The welded structure supports all the weight of the workbench, all the components, and equipment, while the aluminum framing limits the work area and offers shelter from external debris and dust. An example of this can be seen in Figure 15.



Figure 15 - Machine example with a lower welded steel frame and an upper frame made with aluminum profile

2.3.5 Control Systems in Automation

Nowadays, in all types of industry, automated machine systems need electronic control, or computers, to command the operations and correctly execute the required tasks. Therefore, in order to obtain complex automated production systems, it is required the cooperation and know-how of different engineering areas, such as mechanical, electrical, and programming [81].

Previously, mechanical solutions to create and execute the movements needed to automate operations have been referred, now the control systems needed to achieve the automation of tasks will be briefly described.

2.3.5.1 Controllers

The controllers are responsible to logically connect the information provided by the sensors to the movements which the actuators must perform. Sensors inform the controller on what is the state of the machine, and after logically processing the information, the controller commands the actuators to achieve the required task [82].

A control system is achieved by implementing devices such as PLCs (Programmable Logic Controllers), microcontrollers, or microprocessors. In general, PLCs are made up of a power source, a CPU (Central Processing Unit), programming device, memory, and input and output modules (I/O modules), which can be digital or analogic. The I/O modules are the components used in the PLC to communicate with external devices, which can be sensors (inputs) or actuators (outputs) or even other systems that need information or take part in the control process of the operations [83]. In Figure 16 it can be seen a schematic representation of a PLC and an example of these devices.

It is clear that controllers are of major importance in an automated setting, but even so, these controllers are usually very compact and simple devices. Also, to achieve system control with these devices there is a need to program them, which can be done with the help of external software. Thus, this means that controllers are extremely modular and easily reprogrammable and repurposed, making them very versatile and able to adapt to any situation and also very susceptible to future improvements and optimizations after being installed [84].

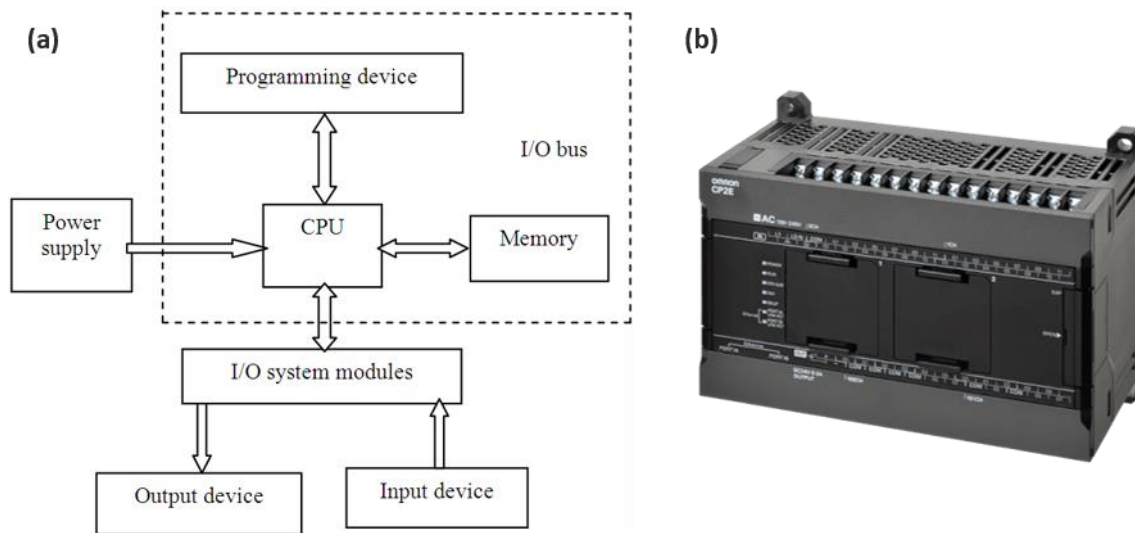




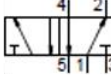
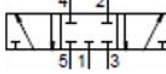
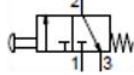

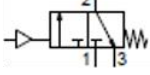
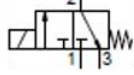







Figure 16 – PLC controllers: a) Simplified scheme of a PLC [85]; b) Omron's PLC series CP2E [86];

2.3.5.2 Pneumatic and hydraulic controllers

Like the actuators, pneumatic and hydraulic system controllers are very similar and share similar working principles, for this reason, they will be presented together as well. The controllers are responsible to redirect, control, and regulate the pressurized air or fluid. Without these controllers, it would be impossible to conceive functional and reliable pneumatic or hydraulic systems. In Table 12 the most commonly used controllers are presented.

Table 12 - types of pneumatic and hydraulic controllers [66]–[68]

Actuator	Illustrations	Description	
Directional control valves (Pneumatic & hydraulic)		The directional valves are the elements that redirect the airflow direction. These valves are used in many functions, such as commanding the actuator, air exhausting, on/off function, etc.	
	2/2 way valve:		They have two main variables that define their operation, the number of connections, and the number of positions. The valves are identified using the following configuration: n° of connections/number of positions. This identification is shown in the picture beside as well as an example of the most common configurations used: 2/2; 3/2; 4/2; 5/2 5/3. Another major aspect of the valves is the type of actuation used to change between positions. This actuation can be manual, mechanical, pneumatic, electric, combined, or spring load. In automation, the most common actuation used is a combination between an electric actuation and pneumatic pilotage, which means that the solenoid valve opens a small hole that allows air to flow and push the valve to another position. Although the main actuation is the combination mentioned, is also very common for these valves to also possess some type of manual actuation for maintenance or troubleshooting.
	3/2 way valve:		
	4/2 way valve:		
	5/2 way valve:		
	5/3 way valve:		
	Manual actuation:		
	Mechanical actuation:		
	Pneumatic actuation:		
	Electric actuation:		
Combined actuation:			

Actuator	Illustrations	Description
<p>Logic valves (Pneumatic & hydraulic)</p>	 <p>“OR” logic valve:</p> <p>“AND” logic valve:</p>	<p>There are many types of pneumatic logic components, such as timers, memories, “NOT”, etc. Nowadays, most of these components have been transferred from physical components to electronic control devices, such as the PLC. Still, the two most commonly used are the “AND” valves and “OR” valves. “AND” valves only send an output (port 2) when there is pressure in both entries of the valves (ports 12 and 14). “OR” valves send an output (port 2) when the pressure reaches either one of the inlets (ports 1 and 3).</p>
<p>Pressure control valves (Pneumatic & hydraulic)</p>		<p>This valves control, or are controlled, by the system pressure. They can either regulate the pressure by only allowing the air to enter the system when there is a pressure drop, or limit the system pressure by exhausting air when the pressure reaches a certain value.</p>
<p>Flow control valves (Pneumatic & hydraulic)</p>		<p>The flow control valves are used when there is a need to reduce the quantity of air flowing through the system. These valves are typically used to regulate the speed of an actuator or to time a pneumatic operation. The flow regulation can be fixed or variable and unidirectional or bidirectional. To regulate an actuator they are more efficient when controlling the air exhaust.</p>
<p>Non-return valves (Pneumatic & hydraulic)</p>		<p>Non-return valves, or check valves, only allow air to flow in one direction. Typically they only have two ports, entry and exit, but another common variation of these ports are the piloted non-return valves. These last ones can allow air to flow in the opposite direction but only when an air signal is given to the valve.</p>

2.3.5.3 Sensors

Sensors are mandatory components in automated systems. As established before, they are responsible to communicate to the controller the state in which the machine is currently on. In order to achieve this, sensors are capable of transforming a certain physical domain into another that can be more conveniently processed and, ideally, without information loss. For this reason, sensors are commonly considered transducers capable of converting a non-electrical signal (load, temperature, displacement, etc.) into an electrical signal (resistance, voltage, current, etc.) [87].

Depending on the type of signal and quantity of information that the sensors produce, they can be divided into analog sensors, discrete sensors (binary or digital sensors), and image sensors. In Table 13, it can be seen a brief explanation of each type of these sensors.

Table 13 - Types of sensors according to their communication signal (Adapted from [24], [87])

		Description
Analog sensors		The signal emitted by this type of sensor is a continuous analog signal, such as electrical voltage. The value of this signal fluctuates according to the measurand. For the signal to be used by a digital computer, the signal needs to be converted to digital by an analog-to-digital converter.
Discrete sensors	Binary sensors	Binary sensors convert an analog input to a one-bit output signal, either 1 or 0 (on/off). These types of sensors are very simple to work with and are very insensitive to electrical interference. These sensors can sometimes come with an adjustable threshold to control when the bit signal should be sent.
	Digital sensors	This type of sensors produce, such as binary sensors, one-bit output signal, but they can be in the form of a set of parallel status bits or as a series of pulses that can be counted. In short, these sensors produce digital signals that quantify the measurement being executed.
Image sensors		These sensors are used when it is necessary to harvest information related to the shape or structure of the measurand. To achieve this, the information obtained can be in the form of one, two, or three-dimensional images. The output signal of these sensors is packed with a large amount of information, which is more time consuming and complex to process.

There are other ways to categorize sensors, such as the quantities measured (pressure sensor, displacement sensor, proximity sensor, etc.) or by their main physical principle of operation (Resistive sensors, Capacitive sensors, Inductive sensors, etc.) [87].

The reason behind the categorization chosen in Table 13 lies in two factors, first, according to Regtien [87], it is possible that the market offers over 100 000 different types of sensors, which makes it impossible to summarize in this small theoretical approach. Second, the categorization regarding the physical principle of operation is too theoretical and extensive for the goal of this introduction. Thus, in order to keep it simple, a categorization regarding the output signal was adopted. Upfront, during the development of this thesis, some sensors will be explained in deeper detail to allow the reasoning of the choices made.

2.3.6 Machinery Directive

On 17 May 2006, the European Parliament adopted the directive 2006/42/EC on machinery, amending the Directive 95/16/EC [89]. The goal of this directive is to regulate the safety of machinery commercialized within the European market. The directive only defines the general requirements of health and safety and can, or must in some cases, be replaced by harmonized standards that cover more specifically certain types of hazard (as stated in Article 3).

This Directive obligates the Member States of the EU (European Union) to surveillance the market, in their territory, to ensure that machinery entering it, obeys to this directive and does not present any harm to the health and safety of humans when properly installed, used for its purpose and maintained correctly.

In Article 1, the directive specifies which products must be regulated, which are defined in Article 2, and also the products which are excluded from this Directive. The products mentioned, that must be regulated, are:

- Machinery;
- Interchangeable equipment;
- Safety components;
- Lifting accessories;
- Chains, ropes, and webbing;
- Removable mechanical transmission devices;
- Partly completed machinery.

The Directive states that the manufacturer, or authorized representative, is responsible to ensure that the machinery is compliant with requirements, before placing it on the market. The implementation of the Directive's requirements must be present in all design decisions and production stages. In short, the manufacturer must:

- Ensure that the machinery follows all the health and safety requirements;
- Issue the CE declaration of conformity and apply the CE (*Conformité Européenne*) marking to the machinery;
- The machinery specified in the Annex IV and machinery that does not fully comply with harmonized standards applicable, it must be submitted to a CE type-examination by a notified body;
- The instructions must be provided in the official language of the Member State where the final user is located.

The essential health and safety requirements are stated in annex I of the Directive, and the highlights can be found in Table 14. It is important to state that the table mentioned omits most of the information present in the Directive and does not replace its reading.

Table 14 - Highlights of annex I from the Machine Directive 2006/42/EC [89]

	Key points
Essential Health and safety requirements	<ul style="list-style-type: none"> • "Machinery must be designed and constructed so that it is fitted for its function, and can be operated, adjusted and maintained without putting persons at risk when these operations are carried out under the conditions foreseen"; • "The materials used to construct machinery or products used or created during its use must not endanger persons' safety or health"; • "Machinery must be supplied with integral lighting suitable for the operations concerned where the absence thereof is likely to cause a risk despite ambient lighting"; • "Under the intended conditions of use, the discomfort, fatigue, and physical and psychological stress faced by the operator must be reduced to the minimum possible, taking into account ergonomic principles".
Control systems	<ul style="list-style-type: none"> • "errors in the control system logic" and "a fault in the hardware or the software of the control system does not lead to hazardous situations"; • "the machinery must not start unexpectedly"; • "the machinery must not be prevented from stopping if the stop command has already been given"; • "The device must have clearly identifiable, clearly visible and quickly accessible control devices"; • "start machinery only by voluntary actuation of a control device"; • "Machinery must be fitted with one or more emergency stop devices to enable actual or impending danger to be averted".

	Key points
Protection against mechanical hazards	<ul style="list-style-type: none"> • "Machinery and its components and fittings must be stable enough to avoid overturning, falling or uncontrolled movements during transportation, assembly, dismantling and any other action involving the machinery"; • "The various parts of machinery and their linkages must be able to withstand the stresses to which they are subject when used"; • "The moving parts of machinery must be designed and constructed in such a way as to prevent risks of contact which could lead to accidents or must, where risks persist, be fitted with guards or protective devices".
Guards and protective devices	<ul style="list-style-type: none"> • "Must be of robust construction" and "be securely held in place"; • "Not give rise to any additional hazard" and "not be easy to by-pass or render non-operational"; • "Be located at an adequate distance from the danger zone"; • "Cause minimum obstruction to the view of the production process, and enable essential work to be carried out".
Risks due to other hazards	<ul style="list-style-type: none"> • The Directive adverts to protect against other risks in addition to the ones originated by mechanical hazards. The Risks Mentioned are: Electricity supply; Static electricity; Energy supply other than electricity; Errors of fitting; Extreme temperatures; Fire; Explosion; Noise; Vibrations; Radiation.
Maintenance	<ul style="list-style-type: none"> • "Adjustment and maintenance points must be located outside danger zones. It must be possible to carry out adjustment, maintenance, repair, cleaning, and servicing operations while machinery is at a standstill"; • "Machinery must be fitted with means to isolate it from all energy sources"; • "Machinery must be so designed, constructed and equipped that the need for operator intervention is limited"; • "The machinery must be designed and constructed in such a way that it is possible to clean internal parts which have contained dangerous substances or preparations without entering them".
Information	<ul style="list-style-type: none"> • "Information and warnings on the machinery should preferably be provided in the form of readily understandable symbols or pictograms"; • All machinery must be marked with "the business name and full address of the manufacturer", "designation of the machinery", "the CE Marking" and "the year of construction"; • "All machinery must be accompanied by instructions in the official Community language or languages of the Member State in which it is placed on the market and/or put into service".

2.3.6.1 Harmonized Standards

As mentioned before, in case of a harmonized standard exists for a specific hazard or type of machine, it must be preferred over the Machine Directive. Although it is not mandatory, the implementation of harmonized standards ensures that the Machine Directive is also being respected, meaning that the machine will be compliant with essential health and safety requirements. These standards are created to help designers and manufactures correctly integrate specialized equipment or design specific types of machinery. According to the standard ISO 12100:2010 [88], the standards respect a certain hierarchy, which is as follows:

- **Type-A:** “(basic safety standards) giving basic concepts, principles for design and general aspects that can be applied to machinery”;
- **Type-B:** “(generic safety standards) dealing with one safety aspect or one type of safeguard that can be used across a wide range of machinery”;
- **Type-B1:** “standards on particular safety aspects (for example, safety distances, surface temperature, noise)”;
- **Type-B2:** “standards on safeguards (for example, two-hand controls, interlocking devices, pressure-sensitive devices, guards)”;
- **Type-C:** “(machine safety standards) dealing with detailed safety requirements for a particular machine or group of machines”.

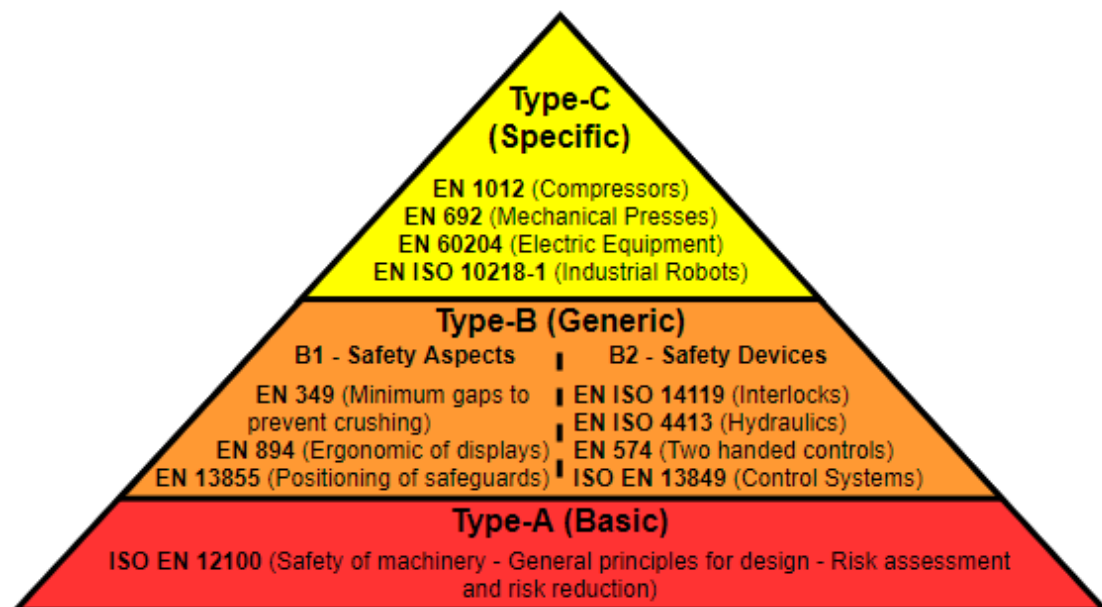
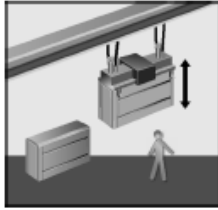

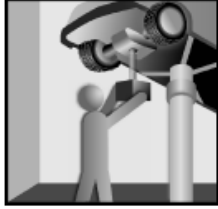
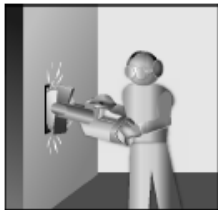





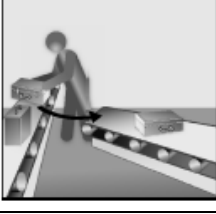
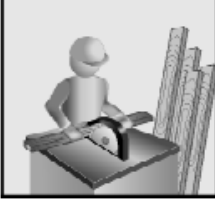
Figure 17 - Standards hierarchy (Own authorship)

2.3.6.2 Risks and Safety Systems


Although training, awareness, and coordination are extremely important to prevent accidents, additional safety systems and measures are always required to reduce risk. Safety requirements must be present since the design stage, aiming to eliminate the existing risks, with the implementation of safety measures, and informing the users of eventual residual risk that cannot be completely eliminated. A good way to identify the correct safety measures to implement is to execute risk assessments. The harmonized standard ISO EN 12100:2010 specifies basic terminology, principles, and a methodology to perform risk assessments and achieve safety in the design of machinery. In Table 15, it can be found a resume of hazard groups, which are stated in the standard previously mentioned, that should be taken into account during the execution of risk assessments.


Table 15 - Types of hazards (Adapted from [15], [88])

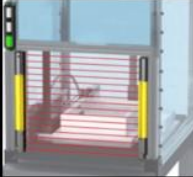
	Description		Example
Mechanical hazards	Usually related to moving parts from the machinery (translation, rotation, etc.) or their geometry (sharp edges, large dimensions, etc.).		<p>Origin: Object raised.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Crushing; • Impact.
Electrical hazards	The risk of a worker being electrocuted, indirectly or directly, by an electrically charged part of the machinery.		<p>Origin: Live electrical parts;</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Electrical shock; • Burn; • Puncture.
Thermal hazards	Injuries are commonly burns, associated to contact with flames, materials at extreme temperatures, etc.		<p>Origin: Object/materials at high or low temperatures.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Burns.
Noise hazards	Noise is present in all industries and when it exceeds 80 dB it can pose a danger to the worker, therefore, protection is necessary.		<p>Origin: Working machinery.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Hearing impairment; • Stress; • Fatigue.

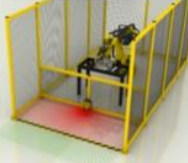
	Description	Example
Vibration hazards	When a machine is in operation, it can be a source of vibration that, when passed on to the worker, can cause injury.	 <p>Origin: Vibrating equipment.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Vascular disorder; • Osteo-articular disorder.
Radiation hazards	Depending on the machine in question, dangerous radiation may be present and, if so, safety measures must be applied.	 <p>Origin: Laser beam.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Burns; • Damage to the eyes.
Material hazard	Some machines can process or produce materials that can present hazards such as toxicity, flammability, irritation, and so on.	 <p>Origin: Combustion (fumes).</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Breathing difficulties; • Irritation; • Poisoning.
Ergonomic hazard	The design of machines must follow several dimensions and ergonomic principles that aim to prevent bad physiological effects.	 <p>Origin: Posture.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Discomfort; • Fatigue; • Musculoskeletal disorder.
Combination of hazards	Some hazards, when isolated, appear to be minor, but once combined with others can lead to greater levels of risk.	 <p>Origin: Cutting parts.</p> <p>Potential consequences:</p> <ul style="list-style-type: none"> • Noise; • Dust; • Severing.


After identifying the hazards that a certain machine can present, it is necessary to apply safety systems and devices capable of eliminating or largely reduce them. There are a vast number of solutions already available on the market. Choosing the best option depends on a large number of factors, such as the type of hazard in question, the frequency in which the zone needs to be accessed, the risk level, the available space, and so on. Regardless of the protections chosen, existing harmonized standards must be followed to ensure the correct implementation of the safety devices. Some of these standards were already mentioned in Figure 17, and they can define variables such as stopping times, safety distances, allowed velocity of movements, etc. Some examples of safety systems commonly used are exposed in Figure 18.


Emergency Stop	
Image	Description
	→ Allows the personnel to bring the machine to an emergency stop with the push of a button.


Two-hand Controls	
Image	Description
	→ Allows the machine to stop, or prevent start, if the operator removes one or both hands.


Light Curtains	
Image	Description
	→ Establishes a sensory barrier that surveillances access points, protecting the operator from injury.

Laser Scanners	
Image	Description
	→ Protects personnel by continuously scanning a user-defined area of up to 275° from the source.

Interlock Switches	
Image	Description
	→ Allows to monitor and lock doors or gates that separate the operator from a hazard.

Non-contact Switches	
Image	Description
	→ Similar function to the interlock switches, but without the capacity to lock movable guards

Physical Barriers	
Image	Description
	→ Physical guards that create a distance or block hazardous zones from being accessed.

Pressure Sensitive Mat	
Image	Description
	→ Detects the presence of personnel and signals the machine to prevent start or bring to a stop.


Warnings and Signs	
Image	Description
	→ Informs the personnel of residual risks or the need to use individual protection gear.

Figure 18 – Common safety systems (Own authorship; Images from [90]–[94])

2.3.6.3 Ergonomics applied to assembly lines

Inefficiency, fatigue, accidents, injuries, user difficulties, and demoralization are unwanted aspects in a production system that target high productivity and flexibility, by following a lean philosophy. However, too much emphasis on increasing productivity while dismissing the operator's well-being leads to the previously referred problems [95], [96].

A correctly designed workstation tries to mitigate working conditions responsible for stressful working environments. Work intensity, lack of human or material resources, overfilled working schedules, short cycle times, the substitution of absent workers, bad ergonomics, as well as the removal of all the waste through the implementation of lean methodologies, are factors that contribute to a stressful workspace [96]–[98]. Ergonomics studies the interaction between operator, equipment, and the dynamics that affect the interaction, increasing the performance of a production system by enhancing the human-machine interaction, which means, eliminating the negative aspects [96], [99]

One of the key points regarding ergonomics in the design of equipment is the proper dimensioning of parameters such as working height, reach zones, legroom, and range of vision. In the “Ergonomics Guidebook for Manual Production Systems” [100] a few guidelines are suggested to accomplish an ergonomic workspace, which are based on EN ISO 6385. A resume and adaption of these last two documents mentioned are given in Table 16.

Table 16 - Guidelines for the design of an ergonomic workspace (Adapted from [100], [101])


Illustration	Description
<div style="display: flex; align-items: center;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg); font-weight: bold; margin-right: 10px;">Reach zone and part presentation</div>  </div>	<p>Torso rotations and shoulder movements must be avoided especially when the operator has to carry masses equal or superior to 1 kg. Operating elements such as buttons, tools, knobs, containers, and so on, must be within the operator's anatomical reach, being that the reach distance should be shorter the heavier the component is, or the more frequently needed is. In short, having all the components easily accessible for the operator promotes motion fluidity and avoids unnecessary movements and/or efforts.</p> <p>Some standards define the operator's reach zone and dimensions for the design of ergonomic workstations. One of them is the ISO 14738, which, through anthropometric measurements, specifies the body's space requirements for workstations during normal operation in sitting and standing positions.</p>


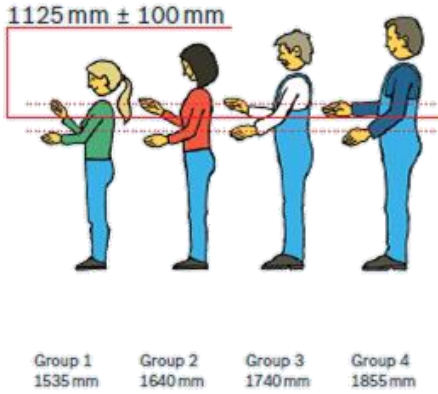
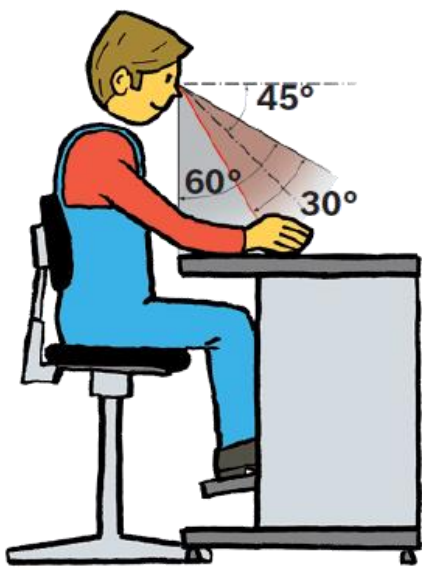
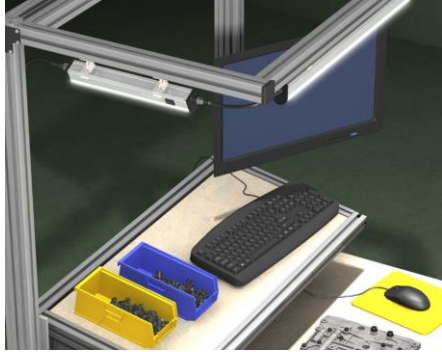
	Illustration	Description
Work area		<p>The work area height must be between 800 mm and 1500 mm. To improve performance and processing quality, the following guidelines are given:</p> <ul style="list-style-type: none"> • Avoidance of work above the heart (over 1500 mm): Otherwise, the supply of oxygen and blood circulation is restricted; • Promotion of dynamic activities: Stimulates the blood circulation and the oxygenation of the muscles; • Favor physical exertion variation: Job rotation varies the physical stimulation, which reduces the risk of stress accumulation; • Minimize effort: For instance, by using lighter materials, roller sections, or tool balancers.
Body height and working height		<p>The definition of the optimum working height is based on the type of activity performed and the body height of the operator. To accommodate the body height variation among the population, it must be taken into account the people to which the design is intended (target population). There are standards orientated to specific countries and regional requirements. These standards target individuals within 5 and 95% of the population characteristic. Usually, they cover at least 90% of the target population, with exception of safety-related tasks where wider intervals are used.</p>
Range of vision		<p>The operator's range of vision is an important factor to take into consideration when designing an ergonomic workstation. Ideally, the operator should have access to all the elements of an operation without moving his eyes or head, adjusting only the focusing depth if necessary. Unfortunately, head movements are inevitable in most cases, so it is recommended that the angle of view, from the horizontal plane, should be of $30^{\circ} \pm 15^{\circ}$ when standing, and $45^{\circ} \pm 15^{\circ}$ when sitting</p> <p>To improve productivity and reduce times losses during vision redirection and depth refocus, three aspects should be taken into account:</p> <ul style="list-style-type: none"> • Eye and head movements must be avoided; • Promotion of equidistant vision depths; • Avoid non-visible work locations to the worker.

	Illustration	Description
Lighting		<p>Another factor that must be regarded during the design of an ergonomic workstation is lighting. Defined by the performed activity, a correct light selection promotes high efficiency, concentration, and processing quality, while preventing premature fatigue and the risk of errors.</p> <p>The guidelines for the correct lighting strength, regarding the performed tasks, are:</p> <ul style="list-style-type: none"> • Average machining and assembly tasks: 300 Lux; • Fine machining tasks: 500 Lux; • Fine assembly tasks: 750 Lux; • Very fine assembly or precision work: 1000 Lux; • Work with extremely small parts: 1500 Lux.

2.4 Recent Studies in the Field

Other works were consulted and studied during the making of this dissertation, but not all were used as a reference in the bibliographic work. Thus, since these works can be useful to better understand some concepts, they will be identified and briefly presented in Table 17.

Table 17 - Recent studies in the field

Article	Description
<p>Araújo, W. et al. (2017) 'A novel concept of CNC machining center automatic feeder', <i>The International Journal of Advanced Manufacturing Technology</i>, 90, pp. 1539–1545. DOI: 10.1007/s00170-016-9475-6</p>	<p>This study aims to take a semi-automated machine, used to produce suspension mats for vehicle seats, and convert it to a fully automated version. The solution reached shows that it is possible to easily convert some equipment to be worker-free with low investments and great benefits in cycle time, material flow, and quality.</p>
<p>Castro, A. et al. (2017) 'Designing a robotic welding cell for bus body frame using a sustainable way', <i>Procedia Manufacturing</i>, 11, pp. 207–214. DOI: 10.1016/j.promfg.2017.07.225</p>	<p>This work had the goal of studying the possibility of reusing an out of service robot to produce welded body frames for buses. With very tight requirements regarding the space available for the machine, flexibility needed and quality, the study was concluded with optimistic results. The space occupied was reduced, the cycle time dropped by 51%, the quality was improved and the project had a payback time of 21 months for the investment.</p>

Article	Description
<p>Costa, R. et al. (2017) 'A novel concept of agile assembly machine for sets applied in the automotive industry', International Journal of Advanced Manufacturing Technology, 91, pp. 4043–4054. DOI: 10.1007/s00170-017-0109-4</p>	<p>This article relates the development of a fully automated equipment for the assembly of components to the automotive industry. The main challenge of the project was the flexibility required. The equipment needs to operate with twenty different variations and needs to be easily adapted for future iterations of new products.</p>
<p>Moreira, B. et al. (2017) 'A novel concept of production and assembly processes integration', Procedia Manufacturing, 11, pp. 1385–1395. DOI: 10.1016/j.promfg.2017.07.268</p>	<p>This study aims to present the advantages of assembly processes integration using automation. The study was made around an existing group of manufacturing and assembling operations of a given product, arranging them in a single cell to, mainly, improve the work management and material flow. The author concludes that by the means of proper mechanical design and automation it is possible to promote the integration of subassembly operations, improving productivity, flexibility, and eliminating quality concerns.</p>
<p>Barbosa, M. et al. (2018) 'A novel concept of CNC machining center automatic feeder', Procedia Manufacturing, 17, pp. 952–959. DOI: 10.1016/j.promfg.2018.10.111</p>	<p>The project aims to present a solution to extend the autonomy of machining centers using a 6-axes robot. The cell to develop must be able to connect to one or two machining centers, be easily personalized, and be able to be integrated into a system with AGVs. All this to prepare the cell to operate in a system capable of function in an industry 4.0 environment.</p>
<p>Correia, D. et al. (2018) 'Improving manual assembly lines devoted to complex electronic devices by applying Lean tools', Procedia Manufacturing, 17, pp. 663-671. DOI: 10.1016/j.promfg.2018.10.115</p>	<p>Nowadays a company needs to have an efficient production and to evaluate so, they use lean tools such as VSM, LLD, among others. This case study if it is possible to improve product quality, production rates, and reduce manufacturing lead time and production waste on a manual assembly line. Through a reorganization of the work methodology and modifying the workstations it was possible to increase by 10% the production rate without changing the manpower. After this, a new study needs to be done with 5S, SMED, and TPM methodologies to standardize and balance the work in each workstation.</p>

Article	Description
<p>Costa, M. et al. (2018) 'How to solve quality problems by advanced fully-automated manufacturing systems', The International Journal of Advanced Manufacturing Technology, 94, pp. 3041–3063. DOI: 10.1007/s00170-017-0158-8</p>	<p>This article relates the development of a fully automated equipment, created to solve quality problems that occurred on an existing semi-automated equipment. Before the redesign of the machine, the defect in one of the components of a windshield wiper transmission was only detected after being assembled, resulting in wasted products.</p>
<p>Rosa, C. et al. (2018) 'Establishing standard methodologies to improve the production rate of assembly lines used for low added-value products', Procedia Manufacturing, 17, pp. 555-562 DOI: 10.1016/j.promfg.2018.10.096</p>	<p>The goal of this article was to optimize the production process of an assembly line that manufactures control cables for the automotive industry. All the activities were mapped and timed in order to identify the existent inefficiencies and fix them through the implementation of Lean tools and methodologies. Translating in numbers, after the analysis and application of the methods, the author was able to improve the production line from 229parts/hour to 327parts/hour and reduce the occupancy rate by 30%, which meant activating the 2nd shift only partially. With these improvements, it is now possible to standardize this methodology and integrate it into other assembly lines.</p>
<p>Magalhães, A. et al. (2019) 'A novel concept of bent wires sorting operation between workstations in the production of automotive parts', Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41. DOI: 10.1007/s40430-018-1522-9</p>	<p>This work aims to show that automatic systems can be as good as robotic ones, with an advantage in cycle-time and initial investment, presenting a case study to back up this argument. The authors conclude that with a good workstation design, the application of a PLC, flexible orientation system, and an artificial visual camera is possible to solve the problem without the use of robotics. The author even presents some ideas to achieve the best production rate and workstation design, such as, taking advantage of gravity, apply anti-mistake systems or even install a feedback light system to warn the worker when to switch the final packaging.</p>

Article	Description
<p>Pinto, B. et al. (2019) 'A strategic model to take the first step towards Industry 4.0 in SMEs', <i>Procedia Manufacturing</i>, 38, pp. 637-645. DOI: 10.1016/j.promfg.2020.01.082</p>	<p>The main goal for this work is to define a gradual implementation plan for industry 4.0 in SMEs that work in a traditional way. To validate the plan/model, a case study was done in the implementation of the model in a components' cutting process for the automotive industry. The author concludes that with the implementation of this pilot model it will be easier to train the workers and help them evolve their cognitive capacities at the same pace of technological evolution. Additionally, this model, along with direct contact with more technologically advanced systems, allows SMEs to integrate other concepts of the industry 4.0 with the help of AGV's and robots on the factory floor.</p>
<p>Ribeiro, R. et al. (2019) 'Designing a Novel System for the Introduction of Lubricant in Control Cables for the Automotive Industry', <i>Procedia Manufacturing</i>, 38, pp. 715-725 DOI: 10.1016/j.promfg.2020.01.096</p>	<p>This work aimed to reduce the waste of lubricant during the introduction of grease into spiral command cables used in the automotive industry. A novel system was designed and implemented, which is capable of reducing the waste of grease by 70, also helping to decrease the environmental damage of the process. The solution achieved also redefined the logistics process of supplying the lubricating grease to the production line. This system can be applied not only to this kind of industry but to all industries that work with lubricants and aim to reduce waste and environmental damage.</p>
<p>Santos, P. et al. (2019) 'A novel concept of a conduit transport system', <i>Procedia Manufacturing</i>, 38, pp. 848-857. DOI: 10.1016/j.promfg.2020.01.166</p>	<p>The goal for this work was to develop a new solution for the transportation of conduits along an automated production line, by analyzing an existing system. Several operating gaps were identified and solved through simple and economic solutions. The new system designed demonstrated better performance, flexibility (capable of producing more models of the same family), and a drastic reduction of setup time (97%). Additionally, a vacuum cleaning system was added to eliminate the debris generated during production and good accessibility for maintenance was also a concern, reducing the number of stops and its duration.</p>

Article	Description
<p>Veiga, N. et al. (2019) 'Design of automated equipment for the assembly of automotive parts', <i>Procedia Manufacturing</i>, 38, pp. 1316–1323. DOI: 10.1016/j.promfg.2020.01.158</p>	<p>This project emerges from the need to automatically assemble three components to form a cable connector. The design was focused on the development of the concept, not paying big attention to mechanical and automation design details. The final result is a study of a machine regarding mechanical structure, pneumatics, electric project (GRAF CET), fabrication processes, assembly rate, economical study, and safety considerations.</p>
<p>Martins, N. et al. (2020) 'A novel concept of Bowden cables flexible and full-automated manufacturing process improving quality and productivity', approved for publishing in <i>Procedia Manufacturing</i>.</p>	<p>This work's goal is to develop a new concept of flexible equipment to produce Bowden cables for the automotive industry, based on a previously existing system. Some of the improvements consisted of the automation of four manual operations and the combination of all the production steps in the same equipment, avoiding external equipment and intermediate stocks. The equipment implementation reduced the cycle time by 25% and increased productivity by 30. Six workers were removed from the manual operations and redirected to functions with a higher value. The maintenance of the new design is easier and the quality of the final product is now higher.</p>
<p>Silva, F. et al. (2020) 'Robotized solution for handling complex automotive parts in inspection and packing', approved for publishing in <i>Procedia Manufacturing</i>.</p>	<p>This paper aims to design a piece of novel equipment for the inspection and packaging of suspension mats produced for the automotive industry. In the assembly line in question, these were the only non-automatic operations, and through a careful analysis of the possible solutions to automate these operations, a robotized solution was designed. The solution achieved was capable of reducing the cycle-time and, by eliminating the human factor from the inspection, increase the reliability and strictness of the inspection. This same concept can be applied to other types of products, thus improving productivity and providing real-time control of the quality of the products.</p>

CHARACTERIZATION OF THE COMPANY, PRODUCT, AND PROBLEM

3.1 WELCOMING COMPANY

3.2 PRODUCT PRESENTATION

3.3 SPECIFIC GOALS OF THIS WORK

3.4 PRELIMINARY DISCUSSIONS WITH THE CUSTOMER

3.5 ADOPTED METHODOLOGY

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3 CHARACTERIZATION OF THE COMPANY, PRODUCT, AND PROBLEM

3.1 Welcoming company

In 1992, five engineers founded a business for test automation (ITE) in Belgium, one of many companies and plants that constitute now the IPTE (Integrated Production and Test Engineering) Group.

Surpassing 25 years of existence, the IPTE Factory Automation group has grown by constantly investing in R&D (Research and Development), offering state-of-the-art solutions with cutting-edge technology, along with appropriate acquisitions, and is now a world-wide established supplier of industrial automated solutions for the electronics and mechanical industries, being the automotive industry the main focus.

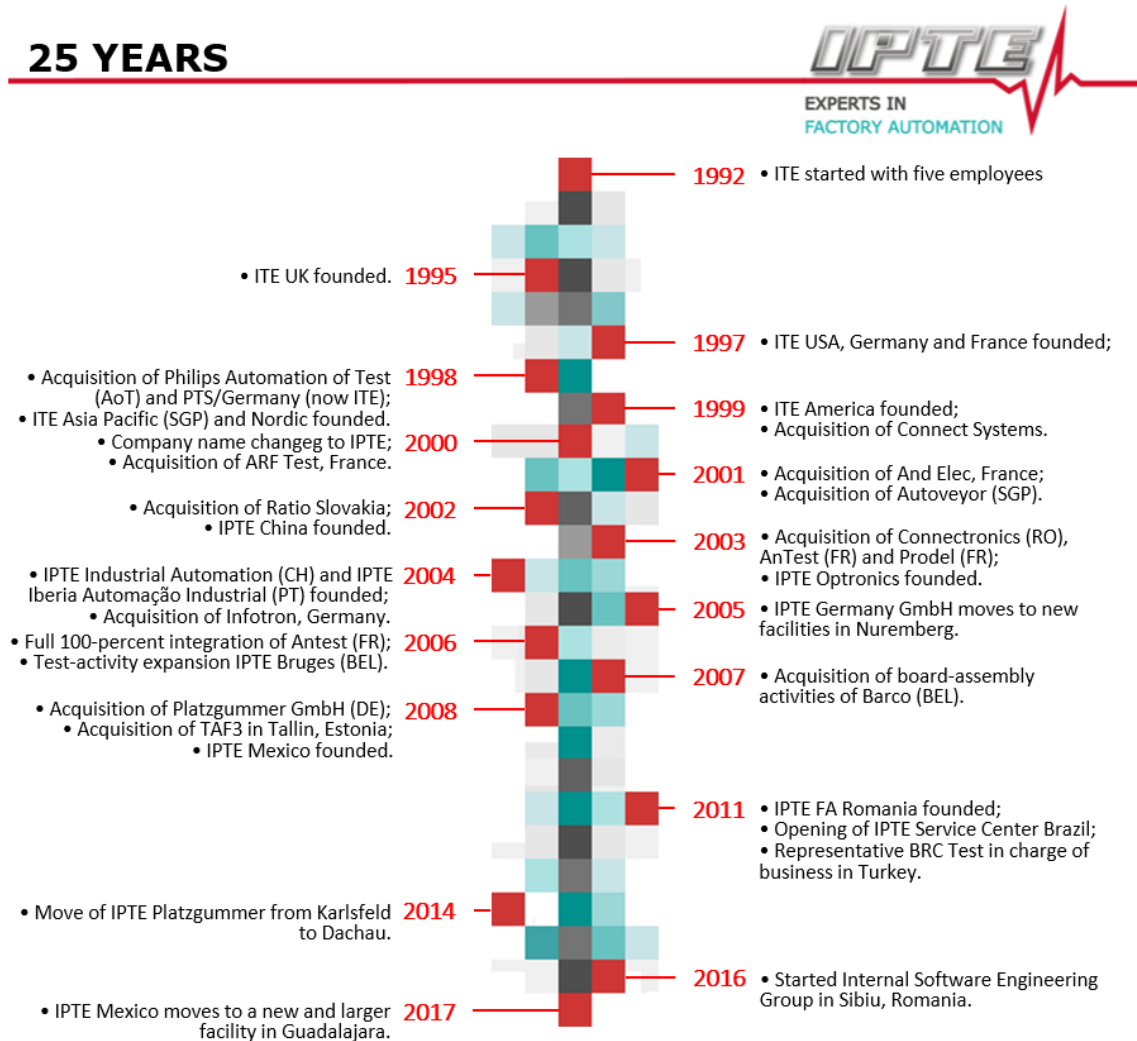


Figure 19 - Relevant dates in 25 years of IPTE

Nowadays IPTE Factory Automation is present in eleven countries (Belgium, China, Estonia, France, Germany, Mexico, Portugal, Romania, Singapore, Spain, and The United States of America) spread across three continents and has a workforce of around 900 employees.



Figure 20 - IPTE worldwide production locations

The IPTE Factory Automation Group offers services in three main categories:

- **Testing systems:** IPTE specializes in testing systems, ranging from In-circuit tests, flash programming, vision test, functional test, etc. To test PCBs (Printed Circuit Board), IPTE offers standard test handlers with customizable fixtures, which can be easily swapped to accommodate different products;
- **Standardized equipment:** the group has an offer of standard machinery that covers common process steps in electronic production, such as PCBs conveying, depaneling, selective wire soldering, laser plastic welding, etc;
- **Assembly systems:** IPTE offers personalized solutions for the assembly needs of the customer in the most diverse application areas. Solutions can range from in-line processes with pallets, offline processes with rotary tables, individual workstations, and so on.

IPTE's mission statement:

"We will perform as the leading independent global automation partner for the electronics and mechanics industry, whereby we escort and support our customers worldwide at their company sites."

3.1.1 IPTE Iberia - Portugal

Within the IPTE group, the company that welcomed the project is located in Ovar, Portugal.

IPTE started its activity in Portugal in 1999 with the creation of an office space. Later, in 2004, IPTE Iberia was founded, opening a manufacturing plant in Ovar. Since then, an office space was opened in Spain in 2006, and in 2008 a factory was also created in Spain.

In Portugal, over the 16 years of its existence, the company has relocated to newer installations (2008), which have already been expanded twice, first in 2014, and more recently in 2019. Today the area includes 4,500m² for production and 1000 m² for offices.

In Ovar, along with the services already mentioned, IPTE offers machining services with the company PMS 724 (for internal use and external costumers) with a fleet of 16 machines and 37 employees. The remaining activities of this factory count with a personnel of 64 people, making in total a team of 101 members working at this location, a team that was capable of generating a turnover of 17 million Euros in 2019.



Figure 21 - IPTE Iberia factory in Ovar

3.2 Product Presentation

The product that gave origin to the project developed in this thesis is an electric motor, which is going to be used within the automotive industry. Due to confidentiality issues regarding the product and the customer, information such as dimensions and the final application will be omitted and the product will be treated as a generic electric servo motor. Adding to this, the overall design of the product has been slightly changed, in such a way that details from the original product have been omitted, while the assembly process and the design of the assembling equipment have not been affected.

In Figure 22, a 3D CAD (Computer Aided Design) representation of the motor is given, as well as an exploded view of the motor, where all the components are identified and named. From this moment onwards, the components of the motor will be referred by the denominations given in the mentioned figure.

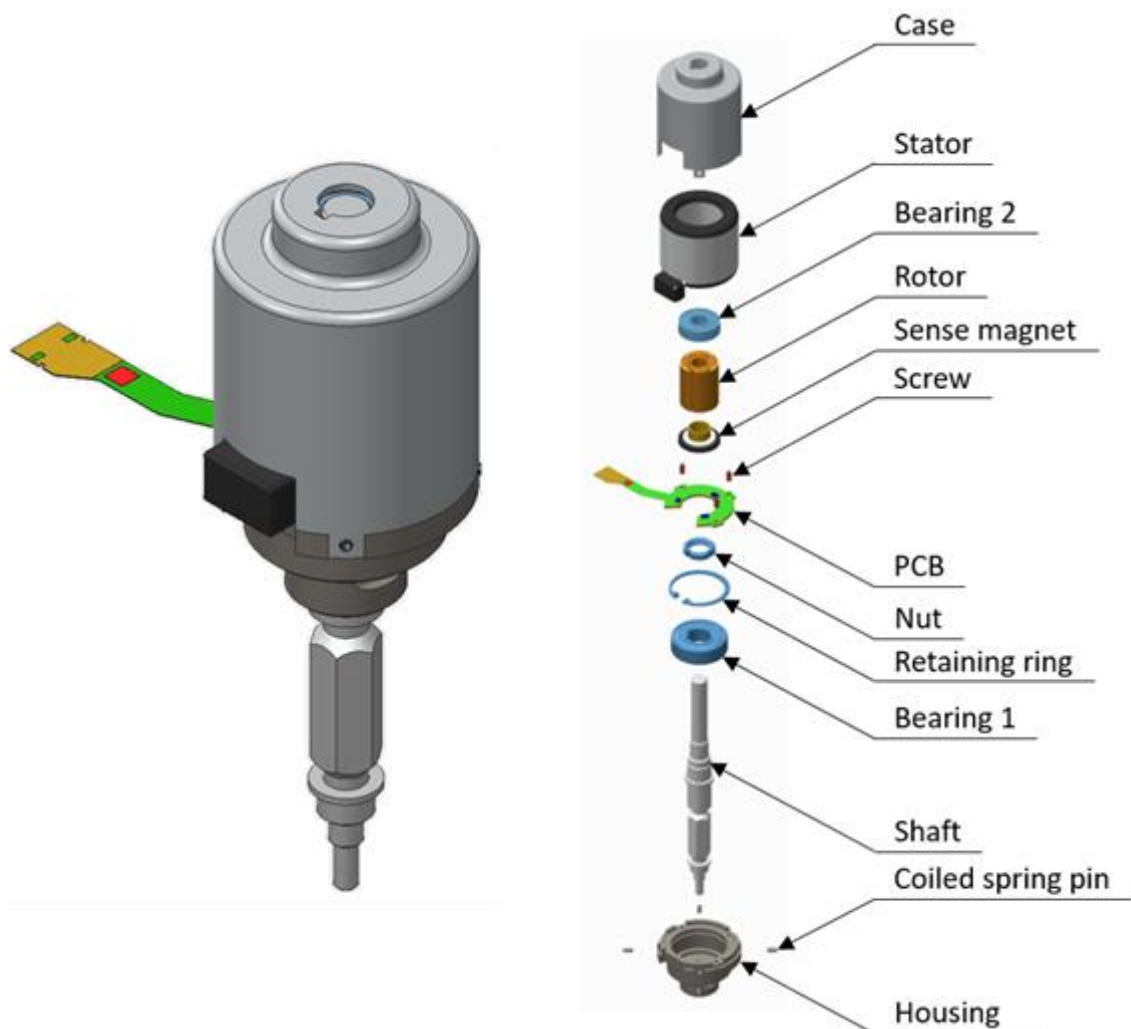


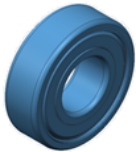
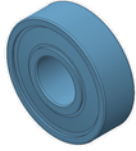


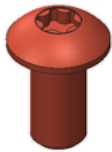
Figure 22 – Electric motor representation and its components

Table 18 – Electric motor components

Standard components	Custom components
<ul style="list-style-type: none"> • Bearing 1; • Bearing 2; • Coiled spring pin; • Retaining Ring; • Screw. 	<ul style="list-style-type: none"> • Case; • Housing; • Nut; • PCB; • Rotor; • Sense Magnet; • Shaft; • Stator.

As it can be seen in Table 18 and Figure 22, this motor is made up of 13 components, 5 market standard components and 8 custom manufactured components. Regarding the standard components, in Table 19 additional information is provided. The remaining components, as well as those present in Table 19, will be mentioned multiple times along the development of this thesis and consequently analyzed in deeper detail.

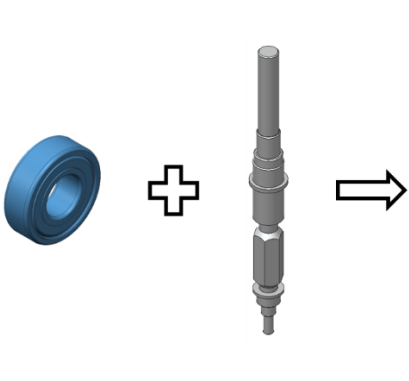
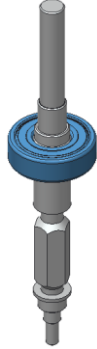
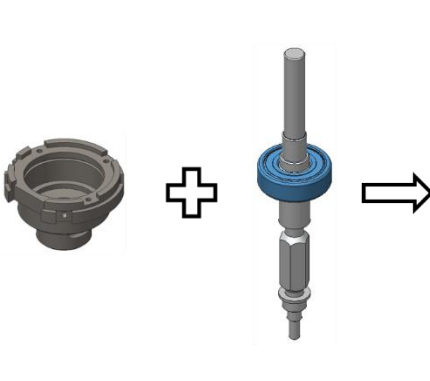

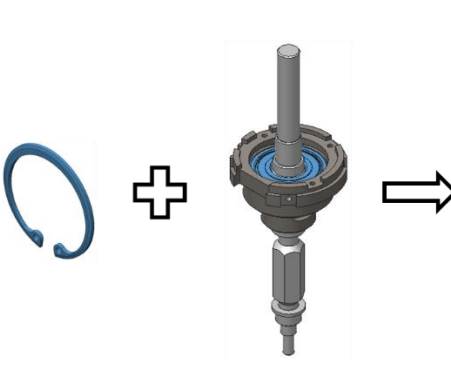

Table 19 - Standard components and relevant information

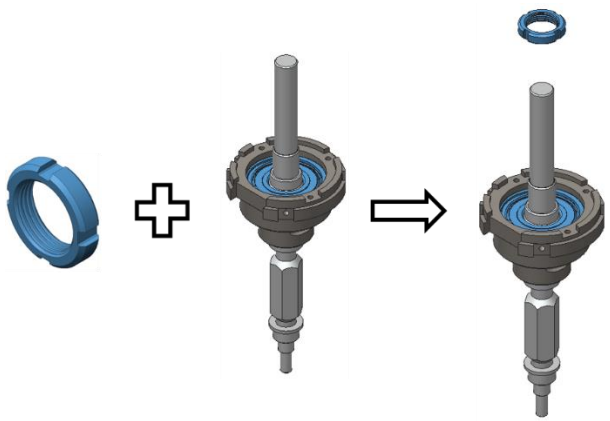

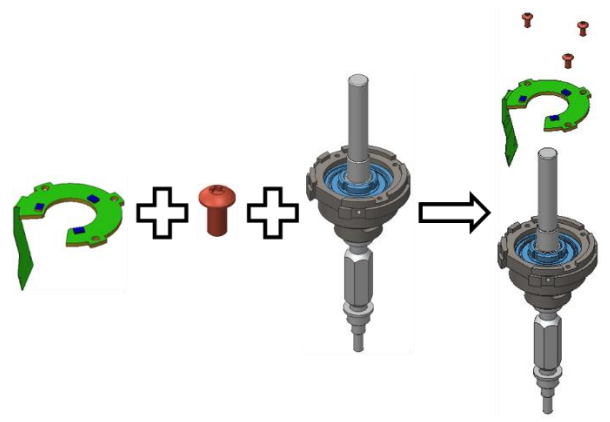

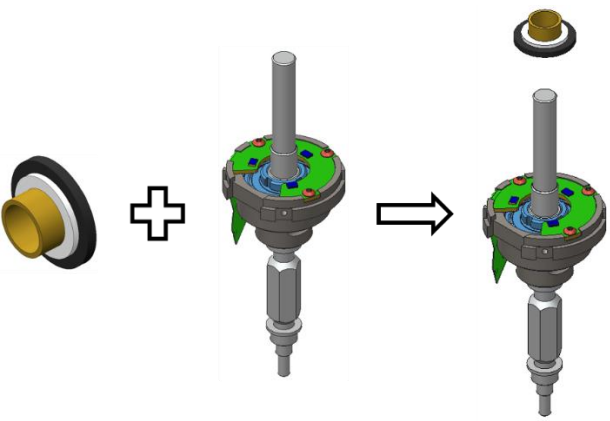

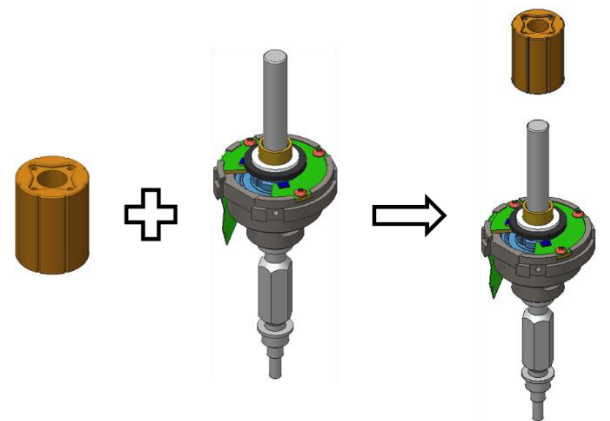

	Illustration	Information
Bearing 1		<ul style="list-style-type: none"> • Four-point contact ball bearing; • Double shielded; • Precision class: ABEC 1.
Bearing 2		<ul style="list-style-type: none"> • Deep groove ball bearing; • Double shielded; • Precision class: ABEC 1.
Coiled spring pin		<ul style="list-style-type: none"> • Heavy-duty coiled pin ISO 8748; • Material: High carbon steel; • Finish: Plain, oiled.
Retaining Ring		<ul style="list-style-type: none"> • Manufacturer: Rotor clip; • Type: VHO; • 15° chamfered outer edge to eliminate endplay.
Screw		<ul style="list-style-type: none"> • Pan head size and shape per ANSI B18.6.3; • Torx plus recess for key; • Screws provided with NYLOK 2510 adhesive.

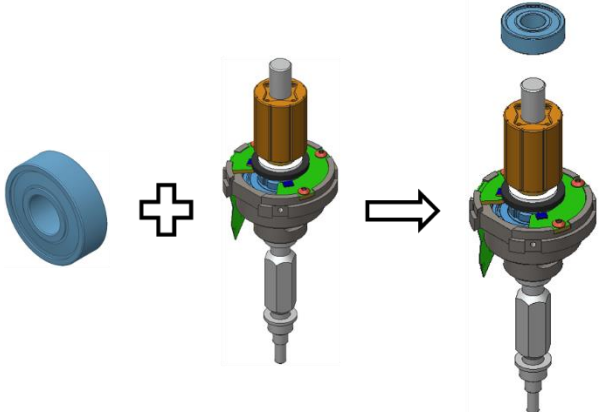

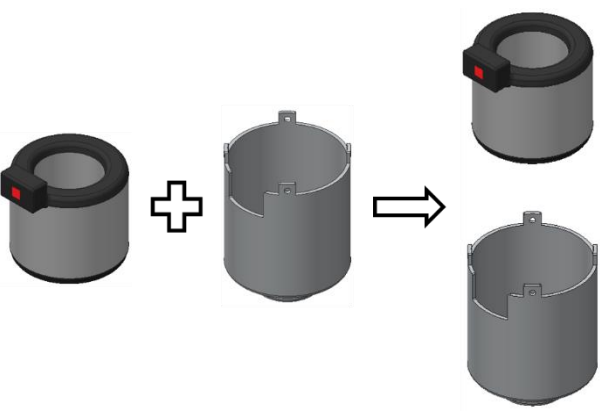

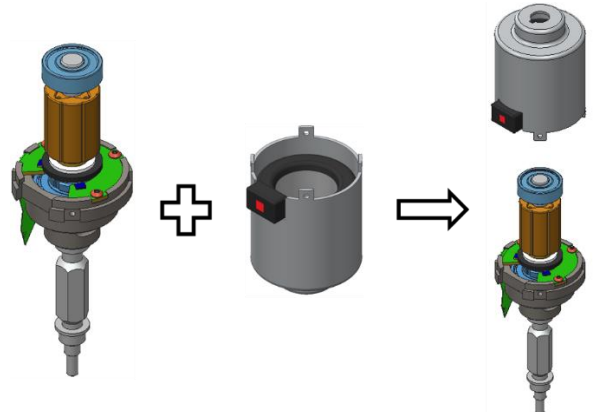

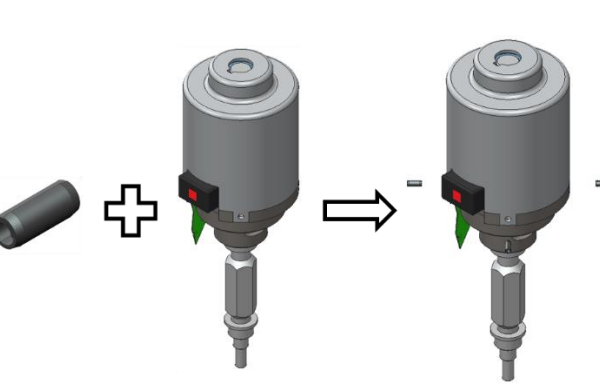

3.2.1 Assembly Sequence

To better understand the problem, it is important to know the components of the product, as well as the sequence in which they must be assembled. The assembly sequence is rigid, meaning that the components must be assembled in a specific order. Failing to do so would impede the assembly of all the components and compromise the overall integrity of the subassemblies produced. Thus, the assembly sequence was given by the customer and a schematic representation is provided in Table 20.

Table 20 - Assembly sequence of the motor

Operation	Components	Subassembly
<p>Operation 1: Press bearing onto the shaft (Bearing 1 + Shaft)</p>		<p>Subassembly 1</p> 
<p>Operation 2: Subassembly 1 install into housing (Subassembly 1 + Housing)</p>		<p>Subassembly 2</p> 
<p>Operation 3: Retaining ring installation (Subassembly 2 + Retaining ring)</p>		<p>Subassembly 3</p> 

Operation	Components	Subassembly
<p>Operation 4: Screwing the nut onto the shaft (Subassembly 3 + Nut)</p>		<p>Subassembly 4</p> 
<p>Operation 5: PCB mounting (Subassembly 4 + PCB + Screws)</p>		<p>Subassembly 5</p> 
<p>Operation 6: Press sense magnet onto the shaft (Subassembly 5 + Sense magnet)</p>		<p>Subassembly 6</p> 
<p>Operation 7: Press the rotor onto the shaft (Subassembly 6 + Rotor)</p>		<p>Subassembly 7</p> 

Operation	Components	Subassembly
<p>Operation 8: Press bearing 2 onto the shaft (Subassembly 7 + bearing 2)</p>		<p>Subassembly 8</p> 
<p>Operation 9: Stator press into the case (Case + stator)</p>		<p>Subassembly 9</p> 
<p>Operation 10: Engine close (Subassembly 8 + Subassembly 9)</p>		<p>Subassembly 10</p> 
<p>Operation 11: Engine seal (press four spring pins) (Subassembly 9 + Coiled spring pins)</p>		<p>Final Assembly</p> 

3.3 Specific goals of this work

The project developed in this thesis was proposed to IPTE by one of its customers, which was going to manufacture a new model of an electric motor. The customer contracted IPTE to design and develop a semi-automated assembly line in order to mass-produce this electric motor.

The line to be designed will be dedicated to producing a single model with no variations, however, it should be designed in such a way that allows alterations, or repurposing of the equipment, due to improvements in the product or newer similar versions of the electric motor.

Thus, the goal is to design and develop an assembly line consisting of different cells, connected by a conveying system. Each cell will be responsible to execute at least one of the assembly steps mentioned in Table 20 and the overall cycle time is of 40 seconds. As mentioned before, the assembly line will work in a semi-automated configuration, which in this case means that the cells will be loaded and unloaded manually, and the execution of the assembly processes will be done automatically. All the cells will have to communicate with each other, tracing all the information and relating it to the unit being produced, in order to ensure traceability in quality control and ease troubleshooting. Even so, all cells must still be able to work standalone if needed. All of this must be achieved ensuring the safety of the workers, the quality of the final product, and with a simple and user-friendly setup.

It is also relevant to inform that this thesis, being developed for a master's degree in Mechanical Engineering, will have a greater focus on the mechanical design of the assembly line, mentioning some aspects of the electrical project and programming but with low depth. Moreover, the original assembly line had four additional cells for testing the motors, which will be disregarded in this thesis due to their greater focus in specialty areas outside the mechanical realm.

Chapter 4 will have a focus on station 1 and station 2, since explaining all the stations would be extremely extensive and unnecessary for the purpose of this dissertation. The reasons for the selection of these two stations will be better explained in subchapter 4.1.

3.4 Preliminary discussions with the customer

During the quotation stage of this project, the layout and the basic structural design of the individual cells were discussed with the customer. Both parts cooperated to reach an agreement on what would be the starting point for the design and development of the assembly line in question.

In this subchapter, a small introduction will be given about the general structural design of the cells as well as the different configurations that will be used, followed by the layout which the assembly line must follow. The distribution of the assembly steps through the cells will also be presented.

3.4.1 Cells

Through all the working years of IPTE Ovar, a vast spectrum of machinery has been designed and produced, including semi-automated assembly systems. Furthermore, at the customer’s factory, examples of this type of equipment are also present. The construction and disposition of some cells previously produced by IPTE are similar to some of the machines that the customer already owns, thus, the design to adopt will follow this path. An example (previously produced by IPTE) of the design and construction to follow is presented in Figure 23.

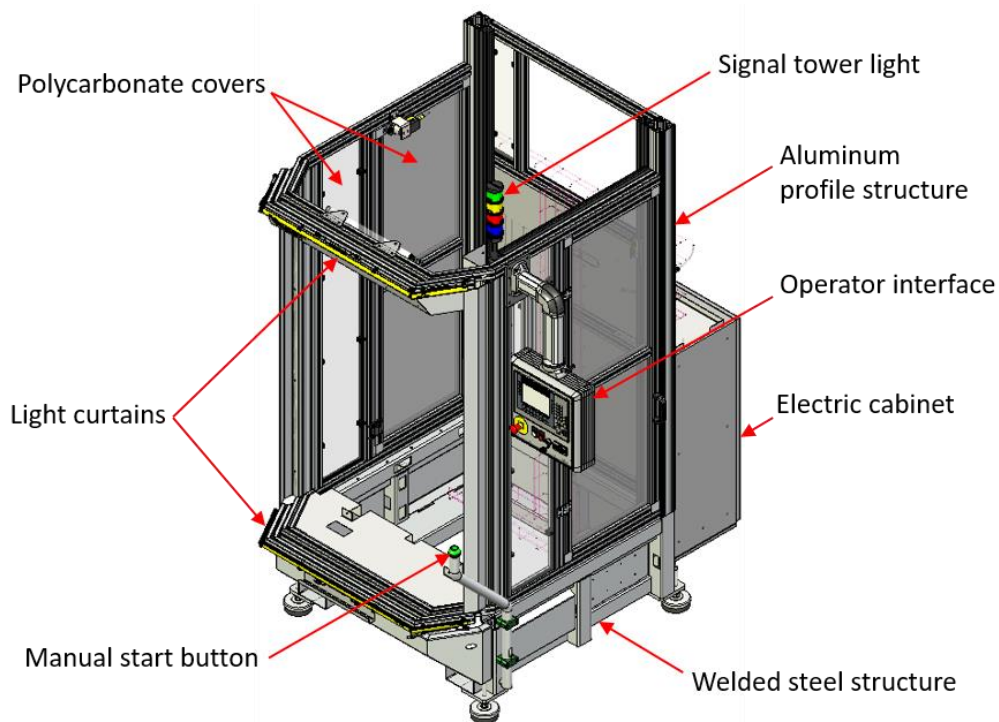


Figure 23 - Cell layout and construction

As seen in the figure above, the cells will have two different types of frames. A welded steel structure will be the base of the cell and accommodate all the parts (tabletop, assembly systems, top aluminum profile structure, etc.), while on top, the machine will be enclosed by an aluminum profile structure and polycarbonate sheets. The operator will be protected from the moving parts of the assembly system by safety light curtains at the front and polycarbonate sheets at the sides. An HMI (human-machine interface) and a signal light tower will be provided to control and display the state of the machinery. Additionally, at the front of the cell a palm switch to signal “start” will be installed, while on the back of the cell is where the electric cabinet and the pneumatic controls (air treatment unit and valves) will be installed.

During the definition of the layout, it was necessary to organize and combine the eleven assembly steps present in Table 20, since creating a cell for each one would result in an

extremely large plant for the assembly line, occupying unnecessary space. To prevent this, when possible different assembly steps will be executed in just one cell. It was also decided that the screwing operations of the nut and PCB would be done manually, as automating these operations would not create any relevant advantage and it would be more expensive and complicated to design.

Thus, it was then concluded that the cells would be divided into three different configurations, multiple operation cells, single operation cells, and manual assembly cell. More information about the different cells is presented in Table 21.

Table 21 - Different cell configurations

	Top view illustration	Description
Multiple operation cell		<p>Dimensions:</p> <ul style="list-style-type: none"> • Depth: 1200 mm; • Width: 1200 mm. <p>Workbench load capacity:</p> <ul style="list-style-type: none"> • 1000 kg. <p>These cells will be divided into two sides to host multiple assembly steps. The light curtains will be mounted in an “E” configuration to allow an alternating operation of the assembly process A and B.</p>
Single operation cell		<p>Dimensions:</p> <ul style="list-style-type: none"> • Depth: 1200 mm; • Width: 800 mm. <p>Workbench load capacity:</p> <ul style="list-style-type: none"> • 750 kg. <p>Single operation cells will only host one assembly operation so the dimensions are smaller. The safety light curtains are mounted in a “C” configuration, guarding three sides.</p>
Manual assembly cell		<p>Dimensions:</p> <ul style="list-style-type: none"> • Depth: 1200 mm; • Width: 800 mm. <p>Workbench load capacity:</p> <ul style="list-style-type: none"> • 750 kg. <p>There will only be one manual assembly cell, and it will follow the same dimensions and construction as the single operation ones, but there will be no light curtains in this cell.</p>

3.4.2 Layout

Table 22 presents the distribution of the assembly steps throughout the cells. This division was carefully planned in collaboration with the customer, in order to optimize the layout footprint. A schematic representation of the layout is presented in Figure 24.

Table 22 - Layout explanation

		Assembled Components	Description
Station 1 (Operator 1)	Station 1.A	<ul style="list-style-type: none"> • Shaft; • Bearing 1. 	The operator will manually load the shaft and the bearing 1 to a press and indicate the start of the operation.
	Station 1.B	<ul style="list-style-type: none"> • Subassembly 1; • Housing; • Retaining ring. 	The operator picks the subassembly from station 1.A and places it in the nest of station 1.B. Subassembly 1 will be installed into the housing followed by the retaining ring.
Station 2 (Operator 1)		<ul style="list-style-type: none"> • Subassembly 3; • Nut; • PCB + 3 Screws. 	The operator picks the subassembly from station 1.B and places it in the nest, tightens the nut, installs the PCB, and screws it in place. In the end, the product goes on a pallet.
Station 3 (Operator 2)		<ul style="list-style-type: none"> • Subassembly 5; • Sense magnet. 	The operator picks the subassembly from the pallet and places it in the press, where the sense magnet will be installed. The operator signals the start of the operation.
Station 4 (Operator 2)	Station 4.A	<ul style="list-style-type: none"> • Rotor. 	The operator places a raw rotor onto the magnetizer and indicates the start of the operation. After the operation ends, the rotor’s magnetization is manually checked.
	Station 4.B	<ul style="list-style-type: none"> • Subassembly 6; • Magnetized Rotor; • Bearing 2. 	The subassembly 6, the magnetized rotor, and a bearing 2 are placed in the press. The operator indicates the start and, in the end, puts the subassembly on the pallet.
Station 5 (Operator 3)		<ul style="list-style-type: none"> • Stator; • Case. 	The operator takes a stator and a case and loads them into the press. The operator signals start and will only pick up the resulting subassembly after the cool down sequence.
Station 6 (Operator 3)		<ul style="list-style-type: none"> • Subassembly 8; • Subassembly 9. 	The operator picks the subassemblies 8 and 9 from the pallet and station 5, loads them into the press and signals start. In the end, the subassembly goes onto the pallet.
Station 7 (Operator 4)		<ul style="list-style-type: none"> • Subassembly 10; • 4 Coiled spring pins. 	The operator picks the subassembly 10 from the pallet and loads it in the nest. The operator indicates the start and, in the end, packages the product for delivery.
Conveying system		(Not applicable)	The conveying system will work with pallets and connect all the cells. It will also be responsible to hold buffers and remove the products that failed the quality checks.

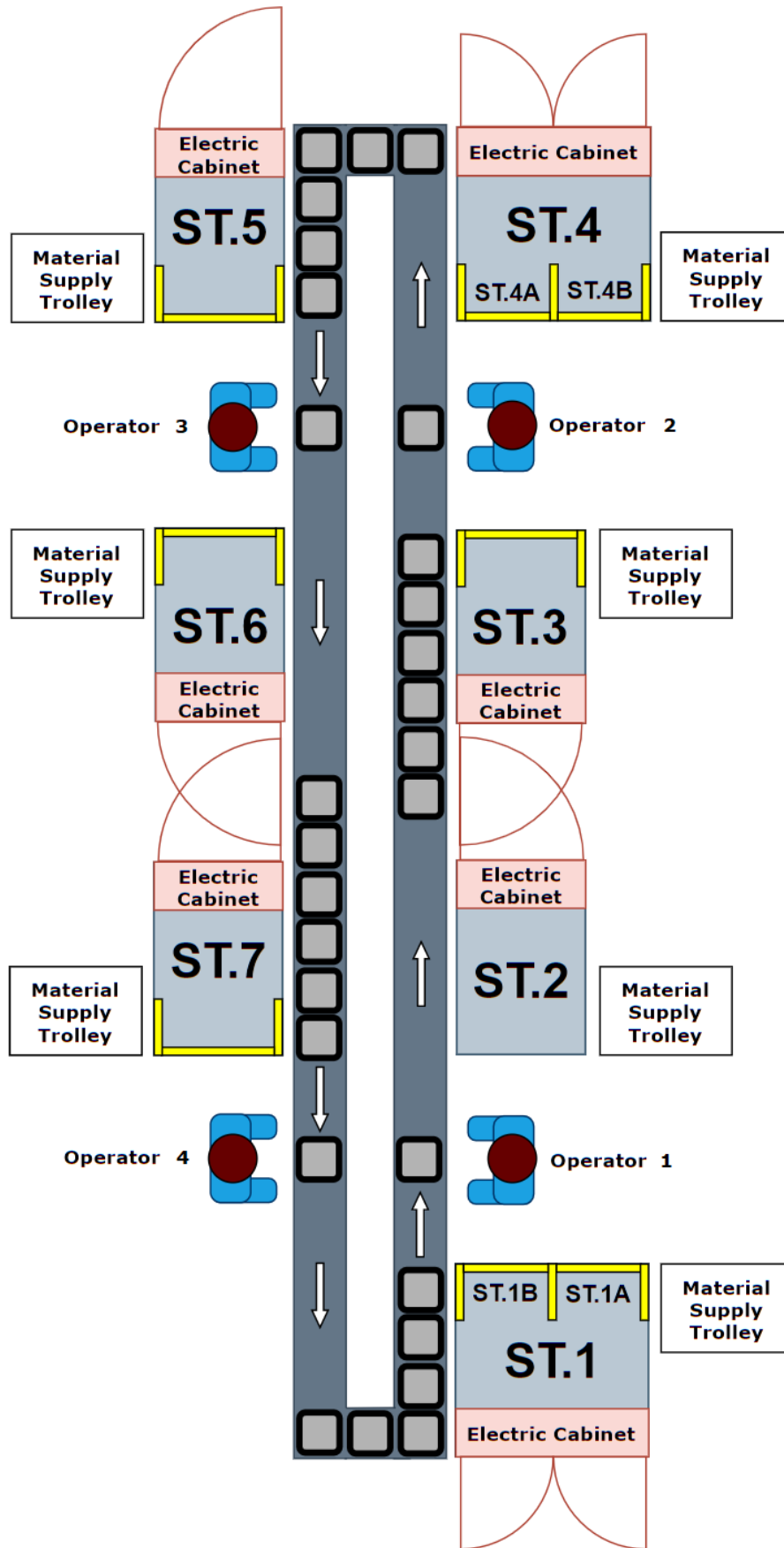


Figure 24 - Intended layout representation

3.4.3 Equipment specifications

The specifications for the equipment must be provided by the customer together with the request for a quotation. These specifications can include subjects such as dimensions, specific brands for specific components, work sequence, etc. Some requirements were already mentioned before, such as the overall dimensions of the cells, and others, which are more specific to a certain station, will be mentioned later. In this subchapter, it will only be stated the general specifications that all cells must follow. These specifications are present in Table 23.

Table 23 – Equipment’s specification

	Subject	Specification
General	2D scanners	All cells must be equipped with manual and fixed 2D scanners.
	Anti-static properties	All the standard and custom made components must possess anti-static properties.
	Air treatment unit	An independent air treatment unit must be mounted in every cell
	Lighting	All stations must be appropriately illuminated.
	Operator interface	The HMI must be placed on the lateral of the cells facing the conveyor and shall be provided one in each cell.
	Painted components	The paint used must be RAL7032 ESD.
	PLC	All stations will be equipped with a PLC.
	Safety	Operations that present potential danger to the operator must be protected on three sides by safety light curtains.
	Vacuum system	All stations must be prepared to receive a vacuum system to remove particles and debris, but the system will only be provided at the stations specified.
	Workbench	The workbench must be produced in steel with a thickness between 30 and 40 mm and treated with a hard chrome plating.
	Antistatic wristband	All operator must wear an antistatic wristband with monitoring;
Specified brands	PLC HMI (Human Machine Interface) Electronic components Servo motors	Allen-Bradley
	Displacement sensors	Keyence
	Load transducers	Kistler
	Pneumatic parts	SMC
	Fixed 2D Scanners	IFM
	Manual 2D scanners	Motorola
	Conveying system Aluminum profiles	Bosch Rexroth

	Subject	Specification
Process	Automatic 2D Scanners	These scanners will be fixed and used to read the 2D codes located in the PLC and the stator. These codes will be used to trace the condition of subassemblies and store the production history of the motor.
	Cycle time	Part-to-part cycle time of 40 seconds.
	Manual 2D scanners	A manual 2D scanner must be included in all the cells to read the batch and quantities of the components being used.
	Operation	All stations must be able to work standalone and will be connected to a central database to allow communication with each other and information storage.
	Operator interface	The operator interface should contain the HMI, the illuminated (white) push buttons (power on and function "A" and "B"), emergency stop, and a supervisor key switch.
	Part presence	The presence of all parts and their correct placement must be verified at the beginning of all operations.
	Pass and rejection process	After the finish of each operation, the tag "PASS" or "FAIL" must be related to the part being processed. The 2D code must be scanned at the beginning of the operation, and if the tag "FAIL" appears, the operation must be prevented from starting. When an operation results in a "FAIL" a message must appear in the HMI and the operator must acknowledge the message.
	Vacuum system	In stations where the vacuum system is applied, the pressure must be checked and maintained under 0,15 bar. The access to the vacuum line must be controlled and only opened when necessary.

3.5 Adopted methodology

As already explained, the assembly line is organized in stations, and during the project phase, each station was treated individually. Particular attention was given to standardize as much as possible the systems designed and use them in multiple stations, if applicable. This allows time savings during the design and assembly stage, which consequently reduces manufacturing costs. Therefore, the project will be presented, first by breaking down important common elements present in more than one cell and then breaking down station 1 and station 2.

To organize the work and present the most relevant information regarding the common elements and each station, the following structure was adopted:

4.X – Station Y

4.X.1 – Operation and main considerations

4.X.2 – Specifications

4.X.3 – Brainstorm

4.X.4 – Project

4.X.4.1 – Overview

4.X.4.2 – Focal points

4.X.4.3 – Operation sequence

4.X.4.4 - Command systems

4.X.4.5 – Pneumatic project

4.X.4.6 – Dimensioning

4.X.4.7 – Safety

4.X.4.8 – Budgeting

4.X.4.9 – Bill of materials

It is relevant to state that this structure is not rigid, but acts as a backbone to support the structure of this thesis. In some cases, it was adapted to better fit specific elements of the assembly line, like the ones present in the subchapter 4.2 (Common Elements).

3.6 Dimensioning methodology

Regarding custom-designed equipment, like the one present in this thesis, commonly a lot of dimensioning calculations are overlooked. These types of equipment are commonly produced just one time, and deep analysis, in most cases, is not sustainable from an economic point of view. Often, the components are oversized for the application in question or chosen based on the experience of the designer or similar equipment previously designed. Some of the reasons that lead to overlooking certain analysis are:

- Using similar solutions to what the customer already uses;
- Available space;
- Lack of time for in-depth analysis;
- Aesthetics;
- Supplier recommendations;
- Using stock components;
- Manufacturing processes.

Thus, there are some cases where it is crucial to dimension the components in order to ensure a reliable and safe equipment. For this reason, some of the dimensioning methodologies used during the design process of this equipment will now be briefly explained, being addressed in-depth throughout this thesis.

3.6.1 Finite element method

Some components of the cells have an important structural role, for instance, the structure itself or the press frame. These components need to withstand the load that will be applied as well as being stiff enough to not interfere with the measurements that will be done during the assembly operations.

To analyze these components, the FEM (Finite Element Method) was applied. FEM is commonly used to study applications with a complex distribution of efforts. This method obtains approximate solutions, using the resolution of linear systems.

For this thesis, although the assembly line was designed using the CAD software Creo® Parametric 2.0, the FEM analysis was done in Solidworks® 2017. The reason behind this is that the only CAD license available, at the time, capable of performing the required analysis was from Solidworks®. Moreover, this license only allows to perform static analysis on part files. For this reason, the studies done were adapted and are simplified approximations of the real conditions.

The conditions for carrying out the FEM analysis on Solidworks® are presented in Table 24.

Table 24 - Conditions for carrying out the FEM analysis in Solidworks®

Step	Description
Study type	Solidworks® is capable of performing various studies, such as static, fatigue, linear dynamic, drop test, etc. As stated before, due to limitations on the software license, it is only possible to use the static analysis, which is the appropriate study for the analysis performed for this thesis.
Materials	The material needs to be defined in order to achieve results close to reality. Different materials have different properties and consequently will produce different results.
Connections	The software allows to define different connections between the components being analyzed. Some of these connections are: bonded, with or without penetration, spring, pin, bolts, etc. Regarding this thesis, even though the simulations were performed with part files, is still possible in most cases to define these contacts between the different solid bodies. This being said, during some simulations the software could not define these connections and the solid bodies were combined into a solid body, which eliminates the connections from the simulations. This was the biggest setback and differentiator that did not allow for more accurate results.
Fixtures	The fixing points of the component being analyzed need to be defined as well. Some of the types of fixtures available are, fixed, roller, fixed hinge, etc.
External loads	The definition of the loads to which the component will be exposed is a crucial step to obtain accurate results. In Solidworks®, is possible to define loads such as force, torque, pressure, gravity, etc.
Mesh	<p>This software offers three types of mesh that can be used separately or mixed:</p> <ul style="list-style-type: none"> • Solid mesh: creates a solid mesh with tetrahedral 3D solid elements, which is typically used for bulky components; • Shell mesh: creates a shell mesh at the mid-surface (uniform thickness required) of the component. Commonly used for sheet metals; • Beam mesh: Ideal for using with structural profiles. Creates a line defined by two points and the software automatically defines cross-sectional properties and detects joints. <p>To define the mesh parameters, regardless of the type of mesh, the software has pre-defined configurations:</p> <ul style="list-style-type: none"> • Standard mesh: Creates a uniform mesh, with the same number of nodes and elements across the object; • Curvature-based mesh: Automatically creates more elements on higher-curvature areas.

3.6.2 Actuators

The majority of the movements in this project are performed using pneumatic actuators. To ensure the correct and optimal functioning of the equipment, these components should be dimensioned. Typically, there are two ways to perform this dimensioning, either through the values and formulas supplied by the manufacturer in the datasheets or the actuator (analytical way), or by using specific dimensioning software created by the suppliers, as it is the case of SMC or Festo (electronic selectors). Either way, in some cases the selection of the actuator is not made through these dimensioning options, sometimes, when the application is not critical the actuators are selected by comparing the load they can generate with the mass they will have to move. Obviously, in most cases, it can lead to the selection of oversized actuators but ends up saving valuable time in design tasks.

In this project, not all actuators were dimensioned. During the years of operation, IPTE has created an internal library of actuators for common usage, which are the go-to when starting the design of new equipment. These actuators are already configured to simulate the movements in the CAD software, and choosing to use one of these components will save time to the project, purchase, and logistics departments, since they already exist in the system for all of them.

In some cases, a pneumatic actuator is critical for the correct operation of the system being design, and not dimensioning the actuator could lead to failure or deficient performance. In this case, the actuators must be dimensioned to ensure they are adequate for the job. In this dissertation, these actuators were dimensioned following the values and formulas given by the suppliers on the datasheet, meaning that the usage of software was discarded.

3.6.3 Guiding elements

Throughout the assembly line, linear guides are constantly present. In some cases, it is clear that the linear guides used are oversized, in others it is necessary to perform calculations in order to validate the application. There are also a few cases where, theoretically, the linear guides would be under irrelevant loads, for instance, the presses guiding system, but if for some reason the guide gets blocked or something goes wrong, there is a chance that the guide would be loaded with all the load produced by the press. For these reasons, there are also a few cases where the guides were dimensioned for the worst-case scenario, which in normal operating conditions will never happen.

The dimensioning of the linear guides was performed according to the supplier's catalog since they do not provide any software to simulate the application. The catalog presents several calculations that must be performed to ensure optimal performance of the guiding system, but for this project, some calculations were overlooked, one of them was the service life of the

guides. The customer did not impose any requirement regarding the service life of any component in the assembly line. For this reason, these calculations were ignored. Thus, the dimensioned linear guides were checked on the following values:

- Static load rating (C_0);
- Static permissible moment (M_0 , which is defined in three directions: M_R , M_P , and M_Y);
- Dynamic load rating (C).

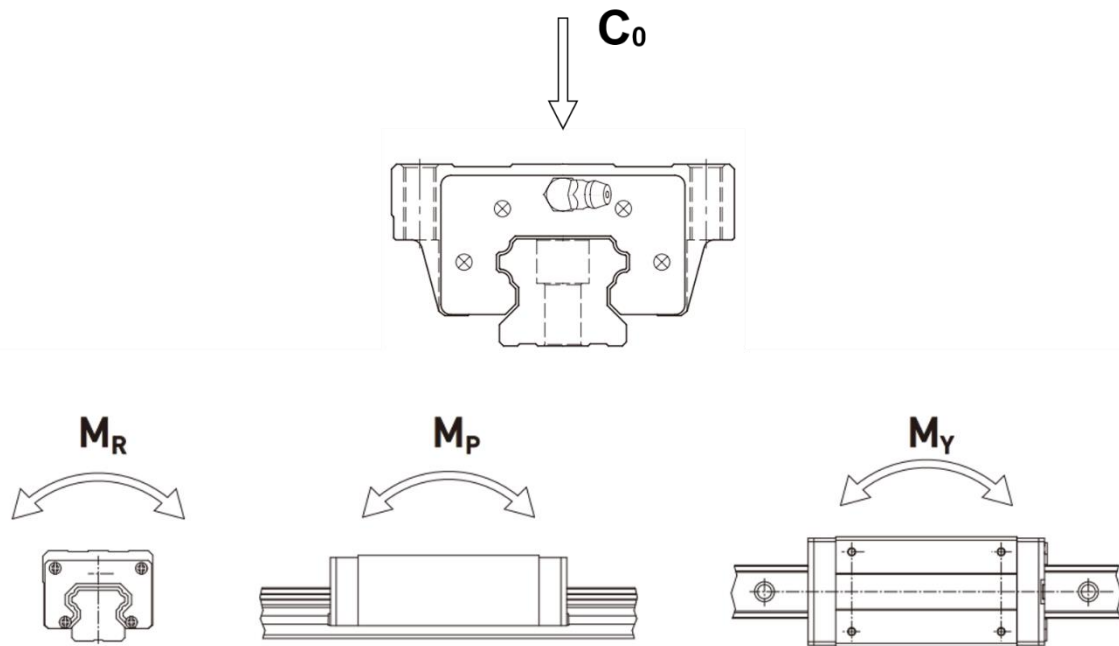


Figure 25 - Linear guides load representation

3.7 Material selection

During the design of this assembly line, the material choices are very important for the correct operation and cost of the final solution. The market offers an endless amount of materials that can be selected for the production of machine parts and, in most cases, more than one material can be considered for a given application, displaying similar performances. To ease the design process and to reduce the materials in stock, IPTE has selected a finite number of materials that can cover almost every application, but still, on rare occasions, materials outside this group are used when needed. In this assembly line, all the materials used belong to this group and were selected according to the demands of their final application. A list of the material used, as well as their main selection criteria to help determine the correct material for each part, is given in Table 25. In Annex I, is possible to consult the datasheets of these materials.

Table 25 - Selection criteria for the materials

	Material	Selection criteria
Metals	115CrV3 (1.2210)	<ul style="list-style-type: none"> • High abrasion resistance; • Simple heat treatment, achieving hardness up to 64 HRC; • Low tendency to crack or deform when being heat treated.
	36CrNiMo6 (1.6582)	<ul style="list-style-type: none"> • Good plasticity; • High yield and tensile strength; • Can achieve a hardness up to 55 HRC after being tempered.
	40CrMnNiMo8-6-4 (1.2738)	<ul style="list-style-type: none"> • Pre-treated material with a hardness of 32 HRC; • Good machinability and excellent polishability; • Can be heat treated, achieving hardness up to 57 HRC; • Reacts very well to nitriding, increasing the abrasion resistance and surface hardness.
	Aluminum	<ul style="list-style-type: none"> • Excellent machinability; • Good dimensional stability; • Lightweight; • Excellent corrosion resistance.
	C45E (1.1191)	<ul style="list-style-type: none"> • Good machinability and excellent dimensional stability; • Moderate tensile strengths and wear resistance; • Can be heat treated, achieving hardness up to 55 HRC.
	S235JR (1.0037)	<ul style="list-style-type: none"> • Good ductility; • Widely available; Excellent weldability.
	X153CrMoV12 (1.2379)	<ul style="list-style-type: none"> • Excellent abrasive wear resistance; • Good through-hardening properties; Can achieve a hardness up to 65 HRC after being tempered.
	X5CrNi18-10 (1.4301)	<ul style="list-style-type: none"> • High resistance to corrosion; • Excellent weldability; Widely available.
Non-metals	Peek 1000	<ul style="list-style-type: none"> • Excellent resistance to wear; • Low friction coefficient; • Very good dimensional stability; • Excellent electric isolation.
	Polycarbonate ESD	<ul style="list-style-type: none"> • Transparent; • Excellent impact resistance; • Prevents charge generations and electrostatic discharges.
	POM Ertacetal C	<ul style="list-style-type: none"> • Good machinability and excellent dimensional stability; • Lightweight; • Good impact resistance.

THESIS DEVELOPMENT

4.1 OVERVIEW

4.2 COMMON ELEMENTS

4.3 STATION 1

4.4 STATION 2

4 THESIS DEVELOPMENT

4.1 Overview

The development of this dissertation will focus on demonstrating the work put into the common elements, station 1, and station 2. Due to the extension of the assembly line, explaining every single component would result in a very extensive work, which after a certain point would become repetitive and would not add any value to the dissertation. For this reason, only a few components were selected to be analyzed in this chapter.

The common elements are divided into two parts, the press, and the cells. This press is present in four of the seven stations and was engineered in such a way that the same system would be adaptable to all of these stations, while the cells are the backbone of every station. These components play a major role on the assembly line and a tremendous effort was put into standardizing them to fulfill the requirements of more than one station, thus, they will be deeply explained in subchapter 4.2.

Both stations 1 and 4 are stations that have two substations. To demonstrate the challenge behind designing a double station and the important considerations regarding safety and control of the whole system, one of these stations needs to be presented in this dissertations. From the whole assembly line, it is in station 1.B that the most complex sequence of assembly operations is given, therefore, station 1 was chosen to demonstrate how a double station is designed and how a complex problem can be solved through innovative solutions.

Station 2, on the contrary, demonstrates the careful planning required to design an efficient, ergonomic, and safe manual station. This is the only manual station of the assembly line, and a lot of small tasks are packed into it. The customer decided to not automate this station, only requesting a station capable of controlling the assembly process and ergonomically present all the tools so that the operator would not be overloaded.

It is important to keep in mind that all of these components mentioned above were designed to be integrated into an assembly line. In Figure 26 an isometric representation of the entire assembly line can be seen. The stations are identified with balloons, and their legend is presented in Table 26. Additionally, other views of the assembly line and the pallet can be found in Annex II.

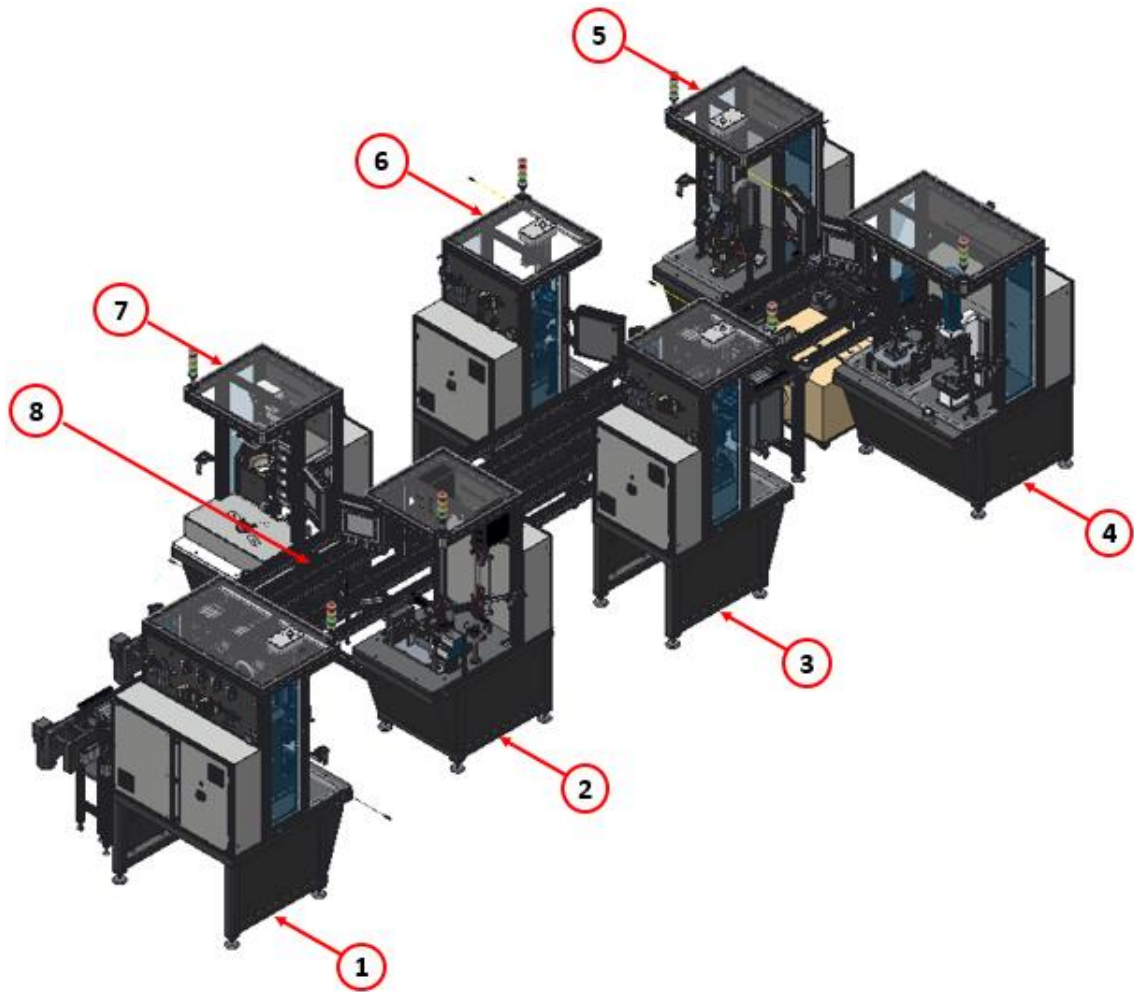


Figure 26 - Isometric view of the assembly line

Table 26 - Identification of the stations

Number	Reference	Description
1	A-A100-99	Station 1 – Bearing press, housing, and retaining ring install
2	A-A200-99	Station 2 – Nut lock and PCB install
3	A-A300-99	Station 3 – Sense magnet press
4	A-A400-99	Station 4 – Magnetizer, rotor, and bearing press
5	A-A500-99	Station 5 – Stator install into the case
6	A-A600-99	Station 6 – Motor closing press
7	A-A700-99	Station 7 – Motor Seal
8	A-A950-99	Conveying system

4.2 Common Elements

4.2.1 Press

4.2.1.1 Operations and main considerations

Across the assembly line, there are six pressing operations. The customer requested multiple servo presses to execute these operations, specifying the actuator and many other components to apply in the final solution. Four operations share very similar specifications for the servo press and for this reason, standardizing the pressing system would allow to save design time and reduce production costs. Thus, a design was studied and developed to achieve this.

The stations previously mentioned (Figure 27), and respective operations, are:

- Station 1.A – Press bearing onto the shaft;
- Station 3 – Press sense magnet onto the shaft;
- Station 5 – Stator press into the case;
- Station 6 – Engine close.

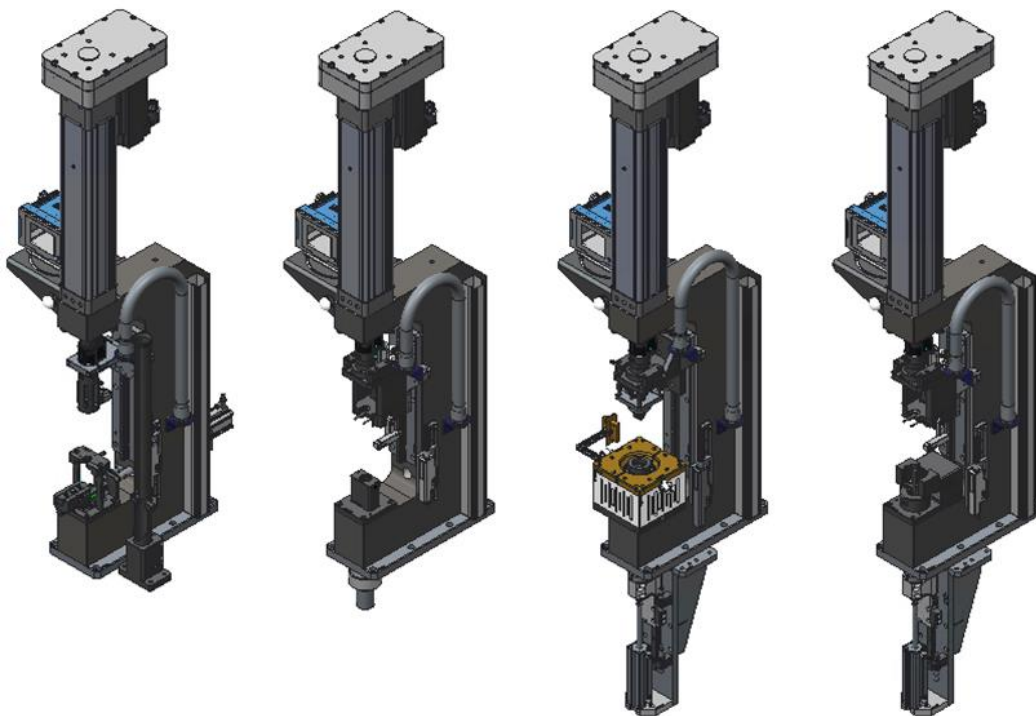


Figure 27 - Presses from station 1.A, 3, 5, and 6 (from left to right)

The operations share the same quality concern. The components of the motor are produced with fine tolerances, and some of them are assembled with tight clearance fits, meaning that the press will only ensure the quality of the parts and supposedly will not apply load until it reaches the final position.

To ensure good results and accurate measurements, the design of the press must guarantee the best alignment possible between the tool and the nest, as well as a sufficiently tough frame to ensure that it will not budge under load and suffer undesirable displacements, which, consequently would affect the precision of the measurements.

4.2.1.2 Press Specifications

In Table 27 it can be found the specifications requested by the customer for each one of the four similar presses.

Table 27 - Press specifications

Specification	Station 1.A	Station 3	Station 5	Station 6
Load	1 kN	3 kN	3 kN	3 kN
Parameter monitoring (load and displacement)	Kistler MaXYmos			
Actuator	Metalwork 371080030048 (size 80; stroke 300 mm)			
Motor	Allen-Bradley MPL-A320P-MJ74AA (1,3 kW)			
Load cell	Kistler 9135B21			
Displacement sensor	Keyence GT2 Series			
Vacuum cleaning	-	Yes	-	-
Tailstock	Yes	-	-	Yes

4.2.1.3 Brainstorm

Since the customer specified most of the components, it is only necessary to design the press body and apply the adjacent equipment (displacement sensor, load cell, nests, etc.).

Concerning manual assembly presses, during the design stage, the main aspects to take into consideration are:

- Load-bearing capacity;
- Alignment between the tool and the nest;
- Workspace.

The load-bearing capacity and the workspace are directly related to the press frame, for which there are basically two options, “C” or “H” frame. A list of pros and cons for these options is presented in Table 28.

The press needs to be capable of withstanding the load without deforming, as well as to have a free workspace with the least amount of restrictions, which allows the operator to handle the product easily and without the need to circumvent obstacles.

Regarding the alignment between the tool and the nest, this must be achieved with external components, such as linear guides or linear bushings, attached with a floating joint to the servo press. The floating joint is needed to eliminate the misalignment that can exist between the actuator and the nest. If this misalignment is not eliminated, stresses can appear in the actuator rod and seriously reduce its service life or, in extreme cases, lead to failure. On the contrary, it can also induce scratches or defects on the product. In Table 29 is possible to see a list of pros and cons regarding the different options for the guiding systems.

Table 28 - Press frame options (images from [102])





	Example	Pros and cons
C Frame		<p>Pros:</p> <ul style="list-style-type: none"> • Very versatile; • More compact; • Large workspace. <p>Cons:</p> <ul style="list-style-type: none"> • Bares smaller loads; • Bigger displacements.
H Frame		<p>Pros:</p> <ul style="list-style-type: none"> • Good stiffness; • Bares greater loads. <p>Cons:</p> <ul style="list-style-type: none"> • Limited workspace; • Bigger footprint.

Table 29 - Guiding system options (images from [103])

	Example	Pros and cons
Linear guide		<p>Pros:</p> <ul style="list-style-type: none"> • High accuracy and repeatability; • Bares high loads; • High stiffness. <p>Cons:</p> <ul style="list-style-type: none"> • Higher maintenance concerns; • Higher cost.
Linear bushing		<p>Pros:</p> <ul style="list-style-type: none"> • Low-cost; • Easier to maintain and service; • Low friction. <p>Cons:</p> <ul style="list-style-type: none"> • Lower accuracy and stiffness; • Cannot stop rotation by itself.

The last points to take into consideration are the vacuum connection and the tailstock. These components of the project will be explained in further detail within the chapter of the respective stations where they are required. In this stage, it is only important to prepare the press body to accommodate these components. Both the tailstock and the vacuum connection will be attached to the bottom of the press and will share the same relief on the press body.

Taking into consideration the peculiarities of the product and the customer’s requirements, a decision was achieved regarding the frame and guiding system. The chosen concepts are presented in Table 30, together with the decisive factors.

Table 30 - Components chosen for the press concept

Component	Decisive factor
“C” Frame	<ul style="list-style-type: none"> • Large workspace; • The loads in question are relatively small, thus, a “C” frame body, with suitable thickness, should be able to withstand the loads easily.
Linear guide	<ul style="list-style-type: none"> • High accuracy and repeatability; • High stiffness.

4.2.1.4 Project

4.2.1.4.1 Overview

In Figure 28 an isometric representation of the press body can be seen. The components are identified with balloons, and their legend is presented in Table 31. Additionally, other views of the press body can be found in Annex II.

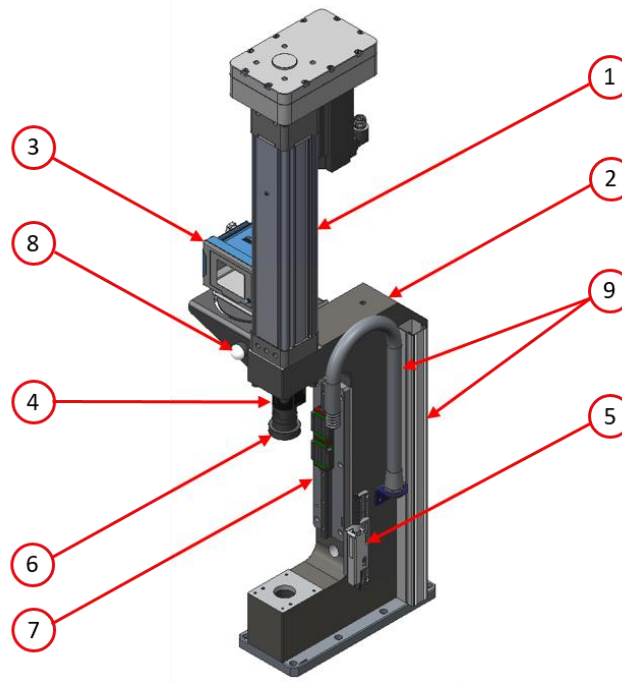


Figure 28 - Isometric view of the press body

Table 31 - Press body components

Number	Material	Description
1	Metalwork and Allen-Bradley	Servo press
2	C45E (1.1191)	Press body
3	Kistler	Process monitoring maXYmos BL
4	Kistler	Piezoelectric load sensor
5	Keyence	Contact displacement sensor
6	36CrNiMo6 (1.6582)	Floating joint
7	Hiwin	Guiding system
8	Banner	Process feedback light
9	Festo and Legrand	Cable management system

4.2.1.4.2 Focal points

The focal points regarding the press are presented and explained in Table 32.

Table 32 - Focal points of the press

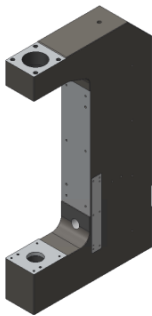
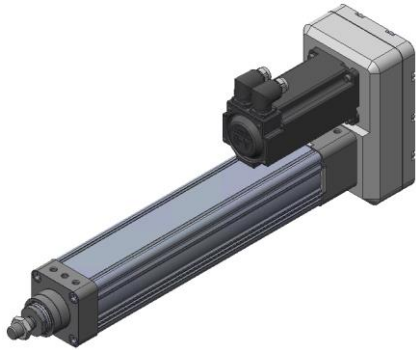

	Illustration	Description
Press body		<p>The body is the most important element of the press. It is mostly in this component that the alignment of the tool and nest is guaranteed and is also the component that needs to withstand the pressing load. Since it is quite a complex part, it will have a dedicated section in this chapter, so that it can be explained in deeper detail.</p>
Servo press		<p>The servo press was defined by the customer, which already uses this configuration in other production lines and has spare parts to fix any problems easily.</p> <p>Main specs:</p> <ul style="list-style-type: none"> • Rated load: 3050 N; • Rated speed: 310 mm/s; • Stroke: 300 mm.
Floating joint		<p>Under the load cell assembly, a detachable joint is added. This joint is the component that will connect to the tool, where two “L” shaped supports will trap the joint in place. When the assembly is completed, the connection is free to move in two axes (X and Z) and it will only be restricted in the Y-axis. This will allow the positioning of the tool to be entirely guaranteed by the guiding system and the press body, yet, keeping the backlash to a minimum in the axis where the movement takes place.</p> <p>The existence of a significant backlash could lead to errors in the load and displacement measurements and, potentially, affect the quality of the final product.</p>

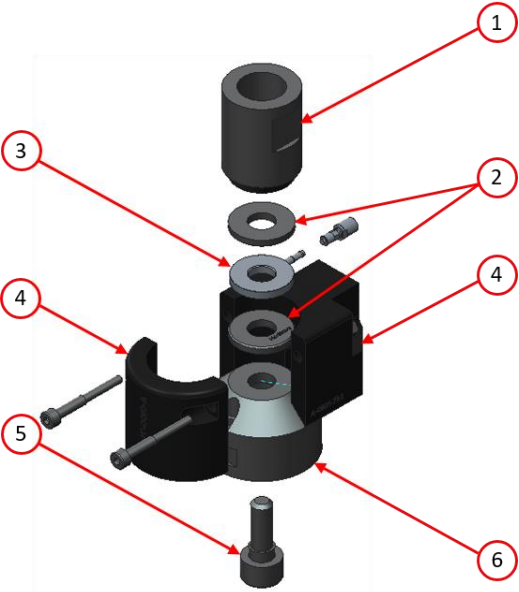
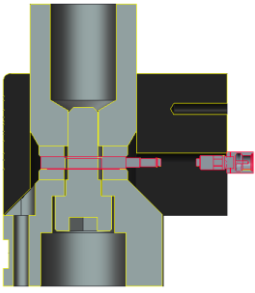
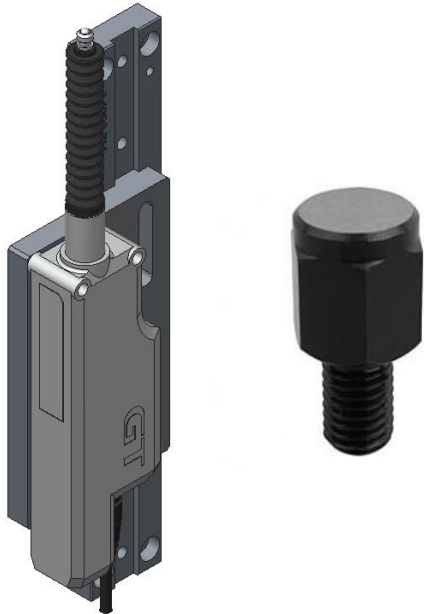
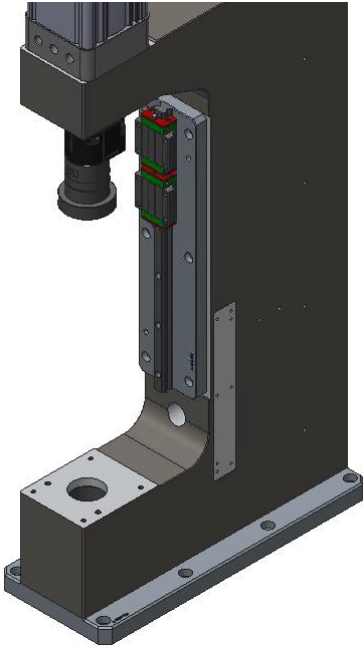

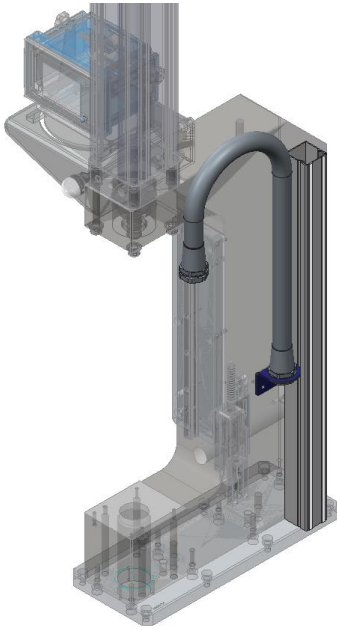
	Illustration	Description														
Load cell	 <table border="1" data-bbox="331 898 815 1211"> <thead> <tr> <th>Number</th> <th>Description</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>Press connection</td> </tr> <tr> <td>2</td> <td>Rectified washer</td> </tr> <tr> <td>3</td> <td>Load cell</td> </tr> <tr> <td>4</td> <td>Load cell protection</td> </tr> <tr> <td>5</td> <td>Preloading screw</td> </tr> <tr> <td>6</td> <td>Floating joint connection</td> </tr> </tbody> </table>	Number	Description	1	Press connection	2	Rectified washer	3	Load cell	4	Load cell protection	5	Preloading screw	6	Floating joint connection	<p>The load cell was also specified by the customer, being the model 9135b21 made by Kistler.</p> <p>Main specs:</p> <ul style="list-style-type: none"> • Measuring range: 0 to 36 kN; • Required preload: $\approx 30\%$ (10,8 kN); • Stiffness: 7,8 kN/μm. <p>For the measurements to be accurate, the load cell needs to be installed on a very flat surface and be preloaded. For this reason, the load cell is installed between two rectified washers and is then secured in place with the preloading screw (the screw is glued to hold the preload).</p> 
Number	Description															
1	Press connection															
2	Rectified washer															
3	Load cell															
4	Load cell protection															
5	Preloading screw															
6	Floating joint connection															
Displacement sensor (image from [104])		<p>Two models of the Keyence GT2 series, the GT2-H32, and GT2-H50. These sensors are basically the same, differing in the measuring range (32 mm and 50 mm).</p> <p>Main specs:</p> <ul style="list-style-type: none"> • Measuring range: 32 mm and 50mm; • Resolution: 0,5 μm; • Indicated accuracy: 3 μm. <p>The sensors were fixed next to the nests, through an interface plate with vertical adjustment so they could be regulated in every press according to the operation. A positioning pin will be installed on the tool so that the sensor can always touch the same reference face.</p>														

	Illustration	Description
Guiding system		<p>By default, at IPTE, for basic linear guiding systems it is used the HG series from Hiwin. For this system, the chosen block was the HGW15CCZ0H. This block is the smallest size of this series and belongs to the high accuracy class. Since there is a floating joint in the assembly, the loads and moments that will reach the guiding system will be, theoretically, null. For this reason, no calculations were made, these blocks are overkill for the loads in action, but are needed because of their accuracy.</p> <p>Main specs:</p> <ul style="list-style-type: none"> • Dimensional tolerance: $\pm 0,03$ mm; • Dynamic load: 14,7 kN.
Feedback light		<p>A feedback light was installed on the press (Banner K30LGRYPQ). The goal is for the operator to easily know when the machine is running and if the operation was successful or not, without consulting the HMI.</p> <ul style="list-style-type: none"> • Green: Operation successful; • Yellow: Start conditions fulfilled; • Blinking yellow: Operating; • Red: Operation failed.
Cable management		<p>To free the workbench from poorly organized cables and pneumatic tubes, which can interfere with automated movements or the operator, it is important to previously plan a cable management system. In this case, there are some stationary cables/tubes and others that will be attached to moving components (tool). For the stationary cables/tubes, a duct (40 mm x 40 mm) is available and for the moving ones, there is a cable conduit (ID $\varnothing 21$ mm). The cables are redirected and secured to the wire mesh that exists on the underside of the workbench, where they will finally enter the electric cabinet through its bottom opening.</p>

Press body

Despite the several concepts that can be used in the design of the press body, the initial goal was to use a standard frame produced by Tox [107]. Unfortunately, there were no models compatible with the dimensions of the solution being designed. Hence, it was clear that a press body needed to be developed specifically for this application.

Thus, it was decided to adopt a design based on the press frames from Tox [107], because they possess a very compact and tough design. The press body will be produced from a single 90 mm thick C45E steel block (approximately the same thickness as the servo press), with the required dimensions and all the holes and reference faces needed to install all the adjacent equipment to the press. Manufacturing the frame on a single part will also help to reduce the accumulation of machining errors and diminish the displacement of the whole mechanism, which will consequently improve the precision of the final solution. The goal was to achieve a design capable of bearing the loads with a displacement lower than 0,05 mm, which will be later confirmed with a FEM analysis in the subchapter 4.2.1.4.4.

In Figure 29, the main tolerances used to fabricate the press frame are shown. The main reference used for the manufacturing of this part was the face A, since it is from this face that all the other geometric tolerances will be referenced.

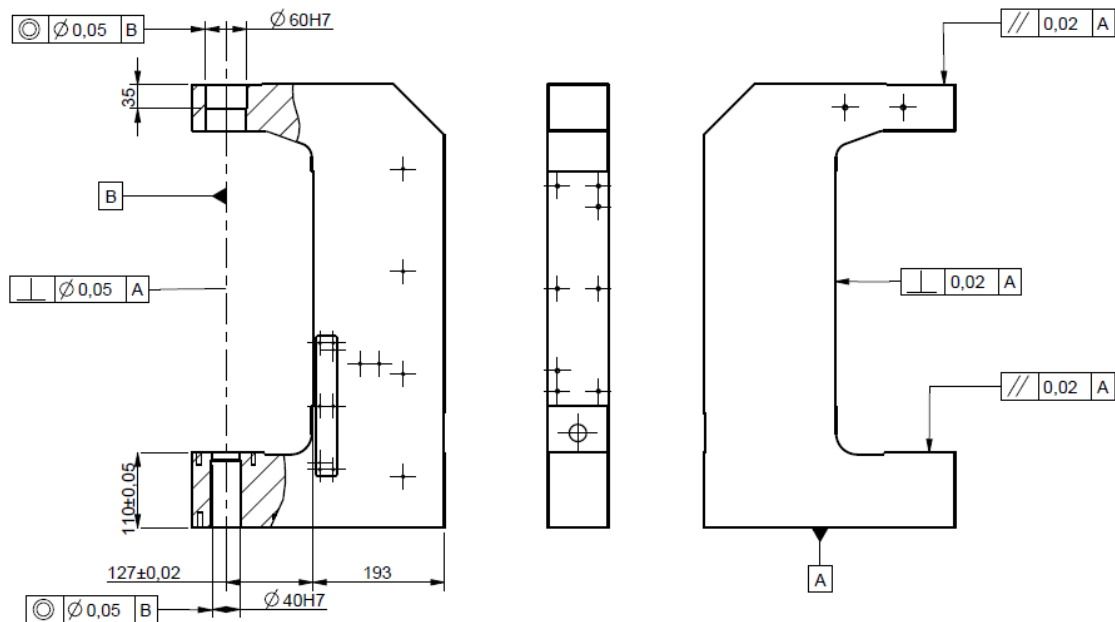


Figure 29 - Main tolerance for the fabrication of the press frame

The face where the linear guide will be installed has a perpendicularity tolerance in relation to the reference face A, while the faces where the servo press and the nest will attach, both have

a parallelism tolerance to the same reference face. These tolerances will ensure the perpendicularity of the linear guides in relation to the nest and press.

The axis B is the reference for the position of the nest and the servo press. This axis has a perpendicularity tolerance related to the reference face A, and the centering holes for the press and nest have positioning tolerances related to this axis. The axis also has a positioning tolerance related to the face where the guiding system will be installed. The combination of these tolerances will ensure the alignment between the press and the nest, but most importantly the alignment between the linear guides and the nest.

All the other holes and machined faces will be referenced after the previously mentioned faces and axis.

After this part has been machined and passes the quality control, it will be painted to protect the steel. It is important to notice that painting the reference faces would compromise the tolerances and consequently the alignment between the adjacent equipment attached to them. For this reason, reference faces are not painted and are finished with an oil coating that should be maintained to avoid corrosion.

4.2.1.4.3 Command system

Apart from the PLC and the HMI, the stations that have this press will also be equipped with a process monitor from Kistler, more specifically the maXYmos BL (5867B1011).

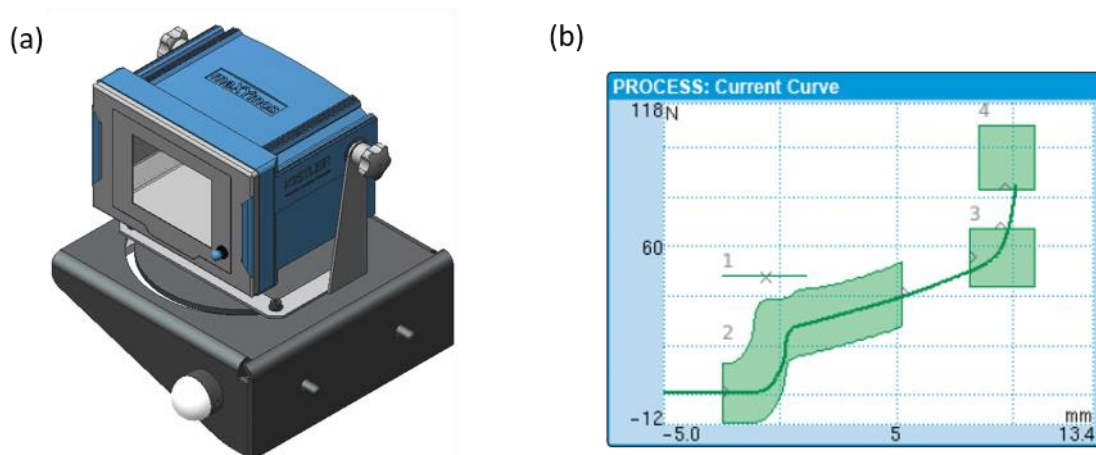


Figure 30 – Process control of the press: a) Isometric view of the maXYmos application; b) Example of a load vs displacement graphic

This device will collect data from the displacement sensor and load cell, process it, and display it as a load vs displacement graphic on its monitor. The maXYmos is responsible for controlling

the quality of the assembly operation, distinguishing the good parts from the ones that do not fulfill the quality standards. This device is also capable of communicating to the PLC a simple OK/NOK message informing if the operation was or not successful. Regarding the load vs displacement graphic, the device will send the resultant graphic to the server, where it will be stored and related to the production history of the respective product.

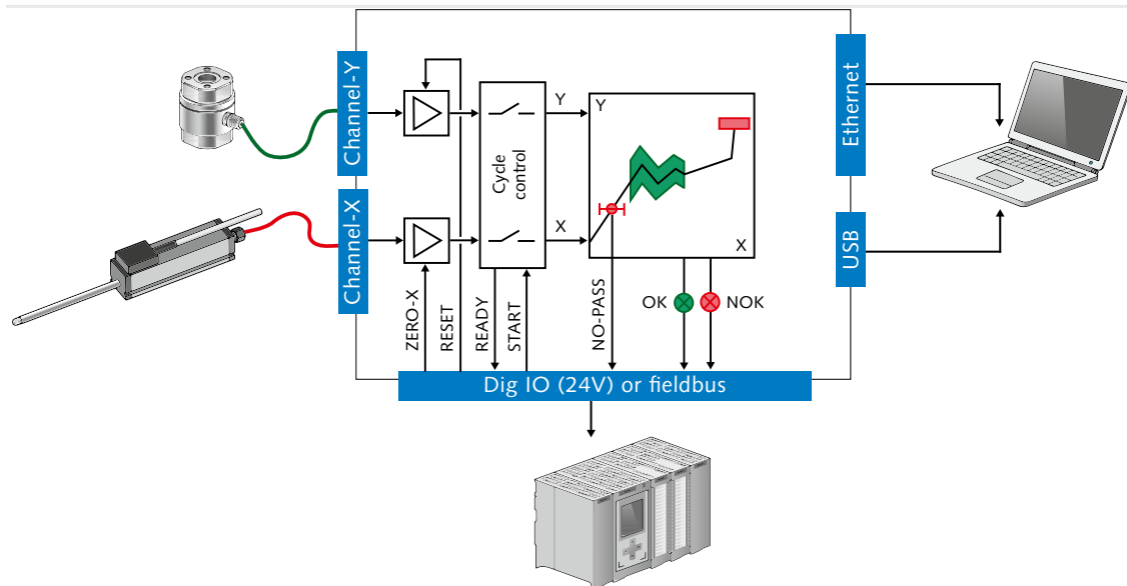


Figure 31 - Schematic representation of the maXYmos BL and its connections [105]

4.2.1.4.4 Dimensioning

Press frame FEM analysis

To validate the design achieved, a FEM analysis was performed to the press frame. It is foreseeable that the press body is capable of bearing the loads without even reaching close to the yield strength of the material used, thus, this analysis will have a main focus on confirming that the press frame can withstand the load while maintaining the displacement under 0,05 mm.

To perform the FEM with the Solidworks® software all the parameters that influence the results must be inserted. This includes the definition of the material, connections, fixtures, and external loads, which are presented from Table 33 to Table 35. In this analysis, the connections are not applicable since the FEM was done to a single part instead of an assembly.

Table 33 – Press frame material properties


Press frame	Illustration	Properties		
		Material	C45E (1.1191)	
		Yield strength	565 MPa	
		Tensile strength	750 MPa	
		Elastic modulus	210 GPa	
		Poisson's ratio	0,28	
		Mass density	7800 kg/m ³	
		Shear modulus	79 GPa	

Table 34 – Fixtures applied for the press frame analysis

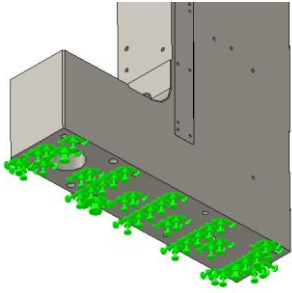
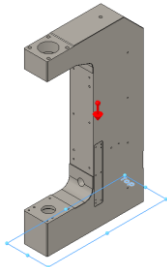
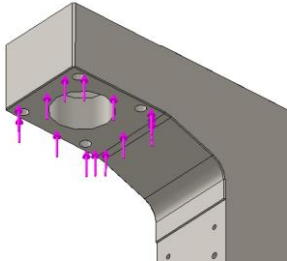
Illustration	Fixture details
	<ul style="list-style-type: none"> • Entities: 1 face; • Type: Fixed geometry.

Table 35 – External loads applied regarding the press frame analysis

External loads	Illustration	Properties
Gravity		<ul style="list-style-type: none"> • Reference: Top plane; • Value: 9,81 m/s².
Load		<ul style="list-style-type: none"> • Entities: 1 face; • Type: Normal load; • Value: 3000 N.

With all the conditions for the study defined, it is still necessary to define the mesh type and its parameters. The most important information regarding the mesh used can be seen in Table 36 and a representation of the mesh generated can be seen in Figure 32.

Table 36 - Information regarding the mesh used for the press frame analysis

Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Maximum element size	23,78 mm
Minimum element size	4,76 mm
Total Nodes	108 517
Total elements	71 907

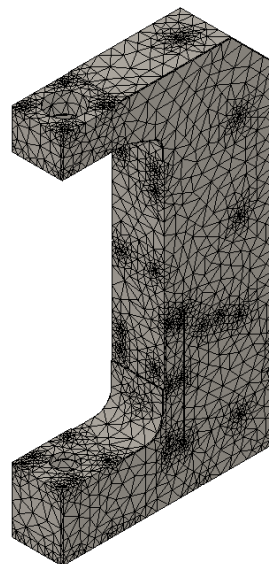


Figure 32 - Mesh generated for the press frame analysis

With all the conditions and mesh defined, the FEM analysis was performed. The results achieved for the von Mises equivalent stress and displacement can be seen, respectively, in Figure 33 and Figure 34.

Analyzing the values obtained, it is possible to confirm that, as predicted, the von Mises equivalent stress is far from the yield strength of the material. Regarding the displacement, the maximum value registered is approximately 0,022 mm, meaning that the press frame displacement is less than half of the maximum allowable displacement. These values validate the press frame design and allow to conclude that the design is over-dimensioned and it would be possible to slightly adjust it in order to optimize it.

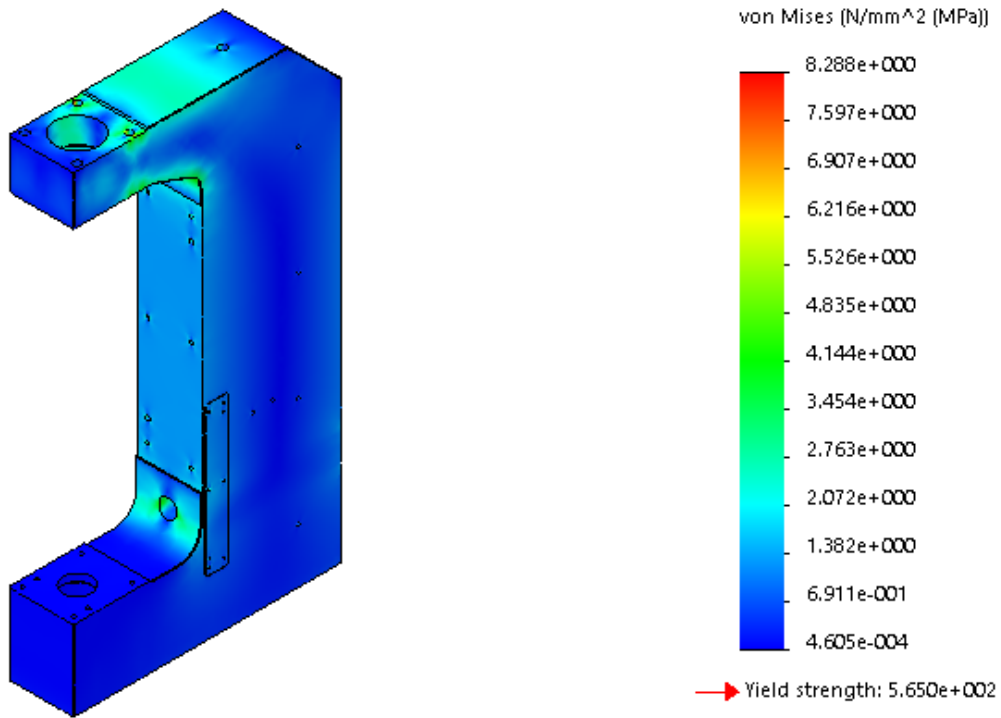


Figure 33 - Von Mises equivalent stress from the press frame analysis

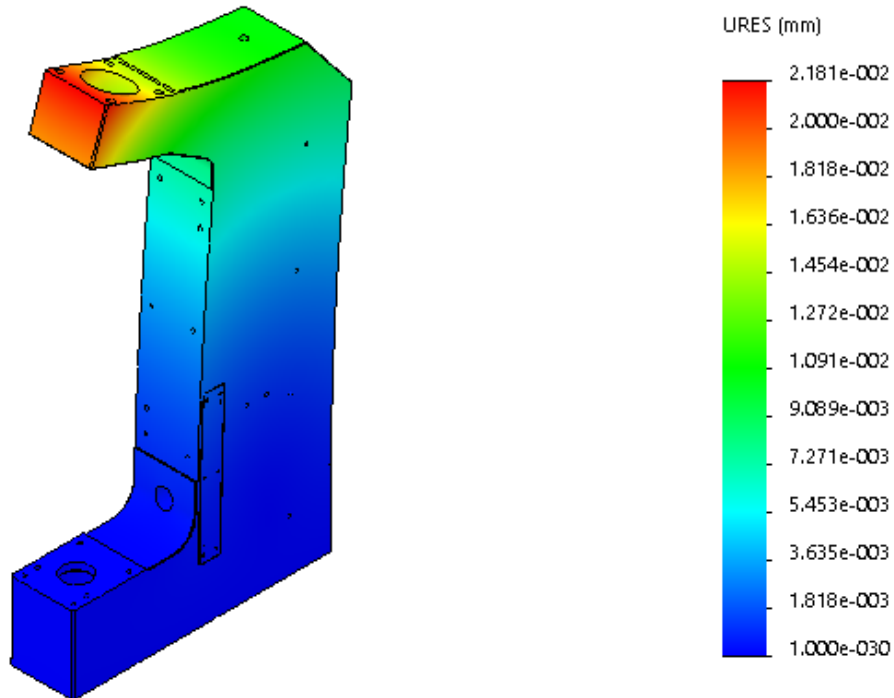


Figure 34 - Displacement from the press frame analysis

4.2.2 Cells

4.2.2.1 Overview

In Figure 28 is possible to see the isometric representations of the multiple operation cell, single operation cell, and manual operation cell. In Annex II, other representations of these three types of cells can be found.

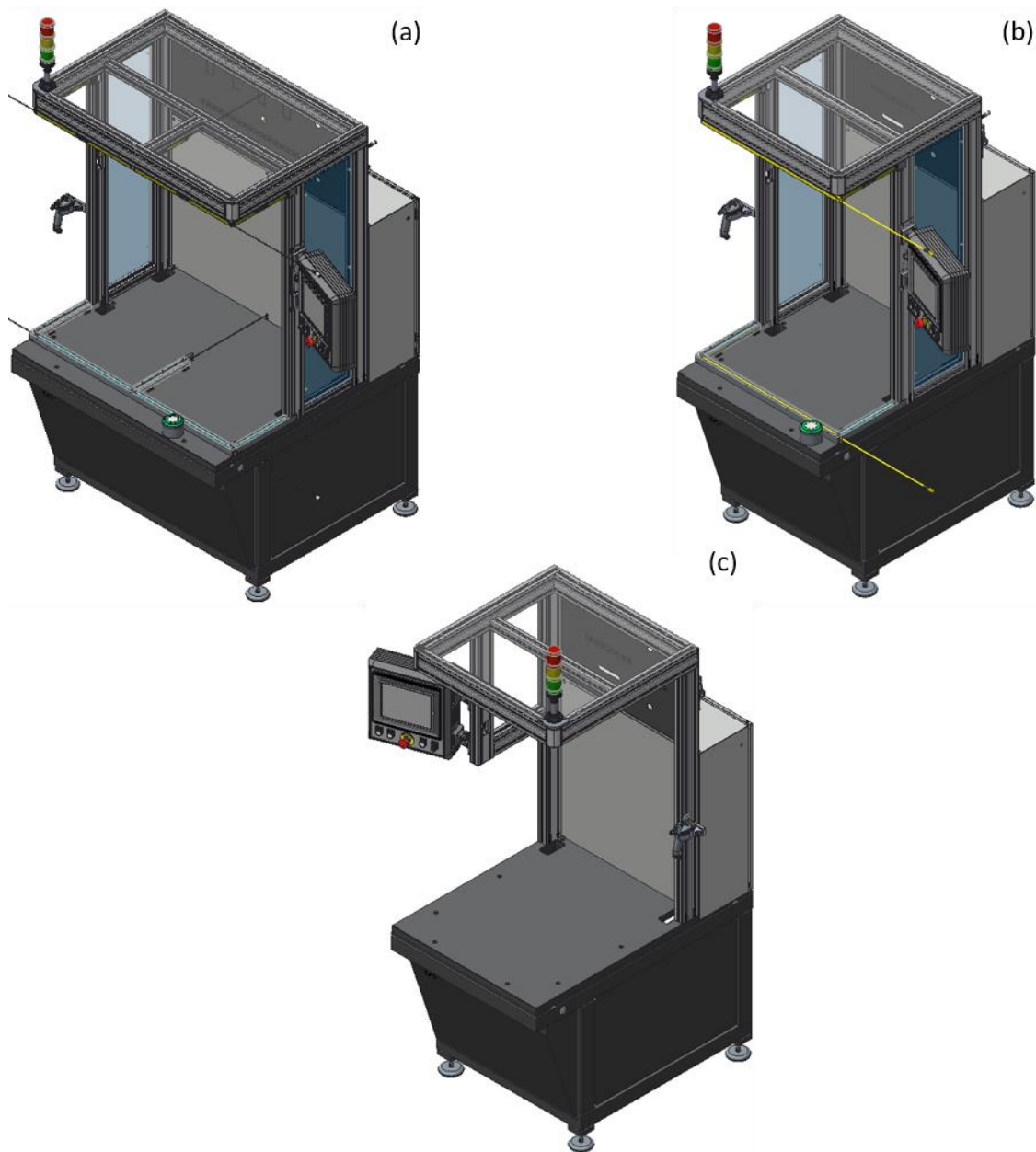


Figure 35 - Isometric view of: a) Multiple operation cell; b) Single operation cell; c) Manual assembly cell;

4.2.2.2 Design separation

The cells are the base and a common link between all stations, all the other components will be designed around their dimensions and will be ready to incorporate and operate with the existent elements.

The cells incorporate and fulfill a lot of the requirements present in the equipment's specification. Some of the specifications fulfilled and integrated into the cells are:

- Command system;
- 2D scanners;
- Safety system;
- Air treatment unit;
- Antistatic wristband;
- Lighting.

Other general specifications are also fulfilled, such as the paint color, antistatic materials, the workbench, specified brands, among others.

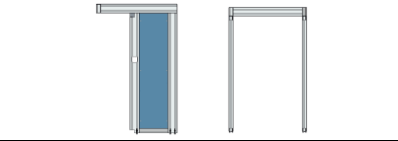
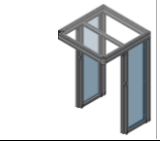
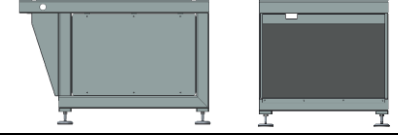

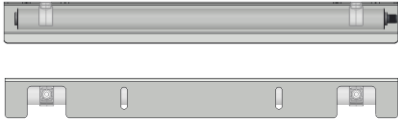




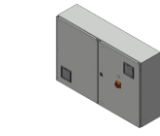
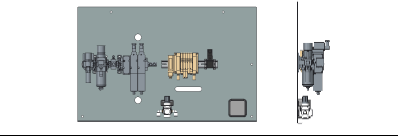
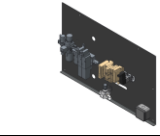
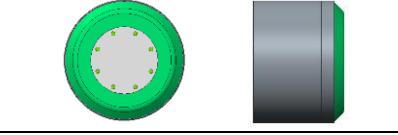
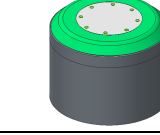
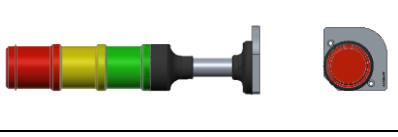

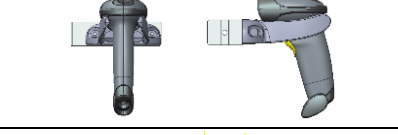

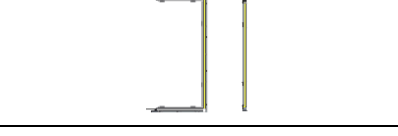
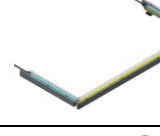

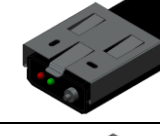

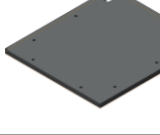
The cells will be explained in this chapter to avoid repetition throughout this thesis, but is important to state that in every station minor changes were made to the cell. For this reason, a parts list will not be made, neither a budget, this will be included in each respective station.

In this assembly line, to simplify the design explanation, the cells will be divided into three groups:

- Structure;
- Command system;
- Safety system.

The different components that constitute the three different types of cells are identified in Table 37 as well as the corresponding group to which they belong. The identification is made with an "X" in the columns A, B, and C, which respectively represents the structure, command system, and safety system. Some components take a part in more than one group, such as the light tower which possesses command and safety properties. For this reason, some components are marked more than once.

Table 37 – Cells components

Component	Illustration	A	B	C	
Top Frame			X		X
Bottom structure			X		
Lighting			X		
Human-machine interface				X	X
Electric Cabinet				X	
Pneumatic controls				X	X
Start Button				X	
Light Tower				X	X
2D scanner				X	
Light curtains					X
Anti-Static Wrist Strap Connection			X		
Workbench			X		

4.2.2.3 Structure

4.2.2.3.1 Overview

Regarding the structure of the cells, the design is common between the three types of cells. In Figure 36 an isometric representation of the cell's structure can be seen. The components are identified with balloons, and their legend is presented in Table 38.

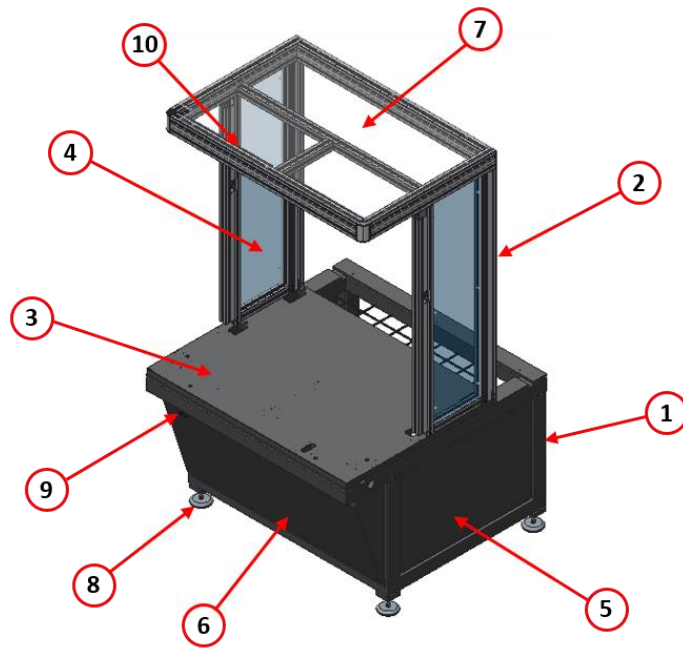


Figure 36 - Isometric view of the structure

Table 38 - Structure components

Number	Material	Description
1	S235JR (1.0037)	Welded structure
2	Bosch	Aluminum profile frame
3	S235JR (1.0037)	Workbench
4	Polycarbonate ESD	Side protections
5	S235JR (1.0037)	Side covers
6	S235JR (1.0037)	Front cover
7	Polycarbonate ESD	Roof
8	Elesa+Ganter	Leveling feet
9	Wolfgang Warmbier	Anti-Static Wrist Strap Connection
10	Banner	Lighting

Apart from the dimensions, the only other difference is that the manual assembly cell will not have any polycarbonate covers on the sides. In this cell the operation is manual and there is no need for light curtains, which means that the side protections can be removed. This also allows for a greater range of movements to the operator.

4.2.2.3.2 Focal points

The focal points of the cell’s structure are presented and explained in Table 39.

Table 39 - Focal points of the cell's structure

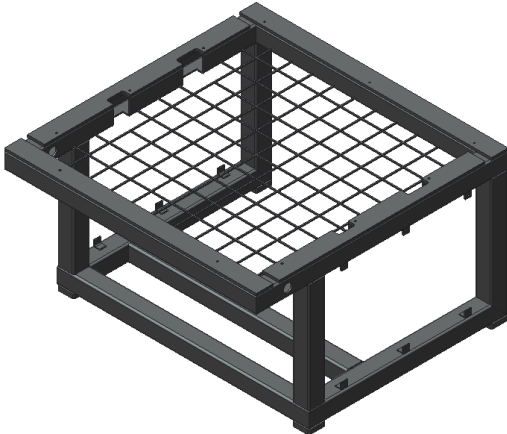
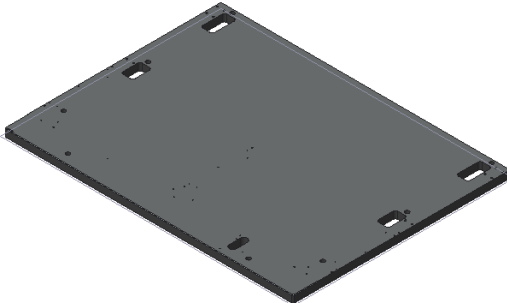
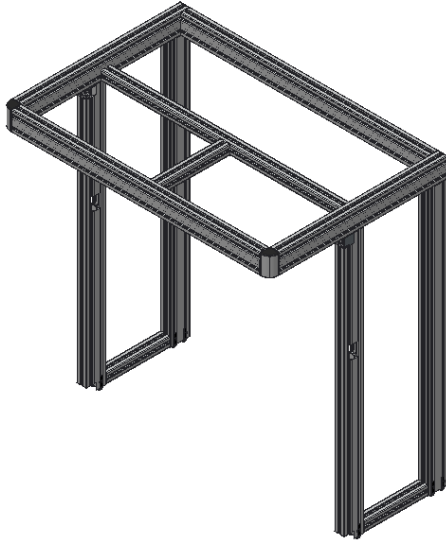
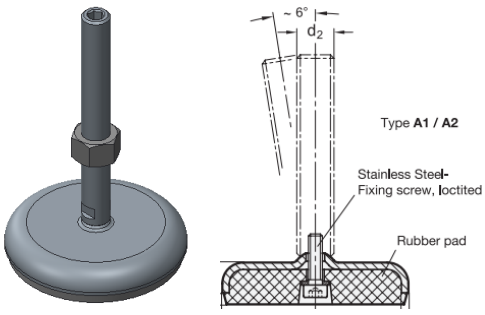

	Illustration	Description
Welded Structure		<p>The main component of the structure, and the most complex, is the welded structure. This component was produced using S235JR steel, mainly with 80 mm square profiles, with a thickness of 6 mm. The structure was provided with cuts on the profiles and a metal grid to assist cable management. Small-angle plates were also welded on the sides to fix the side covers, allowing them to be embedded on the inner side of the profiles. On the top, four plates were welded across the profiles which, after the welding process is finished, will serve as extra material to be rectified and create a flat plane for the workbench to rest. After the structure has been rectified, it will be finished with a coat of ESD RAL7032 paint. Just like the press body, the faces that were rectified, to receive the workbench, will be finished with an oil coating instead of paint.</p>
Workbench		<p>The workbench was produced respecting the customer’s requirements. The workbench is fully customized to each station, but, all of them were designed with a thickness of 30 mm and a parallelism of $\pm 0,02$ mm between the top and bottom faces. The material used was S235JR and the workbenches were finished with a hard chrome plating treatment.</p>

	Illustration	Description
Aluminum profile frame		<p>The upper structure needs to support the covers, HMI, lighting, manual 2D reader, and the pneumatic plate. Since the requirements and the load are not as demanding as the ones for the bottom structure, this frame was produced with aluminum structural profiles, from Bosch. This material is lighter, easier to use, install, and also provides great flexibility for future alterations. Like the welded structure, some profiles were machined to create access to the hollow interior of the profiles, which will allow the usage of these channels to conduct and protect tubes and cables. This structure will be directly attached to the workbench.</p>
Leveling feet		<p>The feet chosen for this project were the reference GN 30-100-M16-125-A2-UK from Elessa+Ganter. According to the datasheet present in Annex VI, one foot can withstand a static load of 10kN, which, when combined with the other three is more than needed. These feet possess a rubber pad that helps to dampen the vibrations created by the equipment, as well as to isolate it from external vibration. These feet can also absorb an angular deviation of up to 6 degrees.</p>
Covers		<p>Regarding the covers, there are only two types in these cells, steel sheet, and ESD polycarbonate covers. Steel sheet is cheaper and preferable when possible, but on the sides and the roof, polycarbonate was preferred. On the sides, it is important to keep visual access to the machinery, while on the roof, the polycarbonate allows the light from the factory to pass and help illuminate the equipment. The steel sheet covers were finished with a RAL7032 ESD paint, the same finish as the structure.</p>

4.2.2.3.3 Dimensioning

Multiple operation cell – Bottom structure FEM analysis

It was required by the customer that the bottom structure of the multiple operation cells was able to withstand on top of the workbench a mass of 1000 kg. Additionally, during the design, it was established that the structure should not deform more than 1 mm. To validate the structure designed a FEM analysis was performed.

As already mentioned in the subchapter 3.6.1, the license available only allows to perform this analysis on part files, thus, the assembly of the structure with the workbench was converted into a Solidworks® part file. Later, various attempts were made to perform the analysis with a global bonded connection condition between the different bodies existing within the part file, but all of them failed to deliver results. The only solution found was to combine the bodies present in the part and analyze the structure as a whole solid body. For these reasons, the conditions of the connections are not included in this analysis.

The definition of the material, fixtures, and external loads used for this study are presented from Table 40 to Table 42, respectively.

Table 40 - Multiple operation cell: Bottom structure material properties

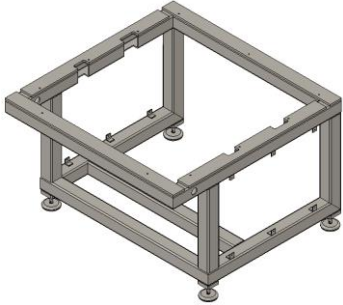
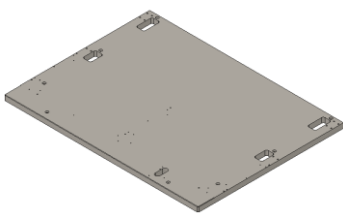
	Illustration	Properties														
Welded structure		<table border="1"> <tr> <td>Material</td> <td>S235JR (1.0037)</td> </tr> <tr> <td>Yield strength</td> <td>235 MPa</td> </tr> <tr> <td>Tensile strength</td> <td>360 MPa</td> </tr> <tr> <td>Elastic modulus</td> <td>210 GPa</td> </tr> <tr> <td>Poisson's ratio</td> <td>0,28</td> </tr> <tr> <td>Mass density</td> <td>7800 kg/m³</td> </tr> <tr> <td>Shear modulus</td> <td>79 GPa</td> </tr> </table>	Material	S235JR (1.0037)	Yield strength	235 MPa	Tensile strength	360 MPa	Elastic modulus	210 GPa	Poisson's ratio	0,28	Mass density	7800 kg/m ³	Shear modulus	79 GPa
Material	S235JR (1.0037)															
Yield strength	235 MPa															
Tensile strength	360 MPa															
Elastic modulus	210 GPa															
Poisson's ratio	0,28															
Mass density	7800 kg/m ³															
Shear modulus	79 GPa															
Workbench																

Table 41 - Multiple operation cell: Fixtures applied for the bottom structure analysis

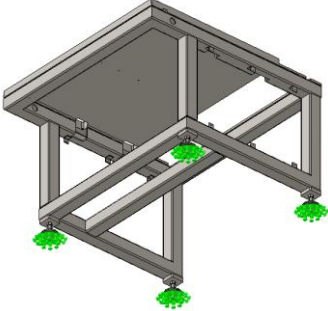
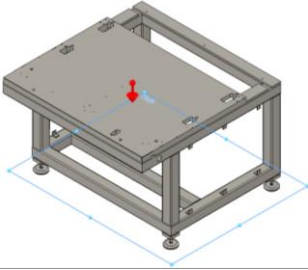
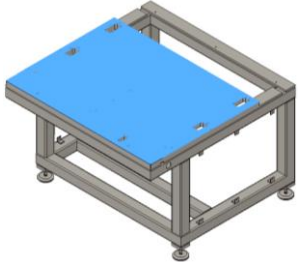
Illustration	Fixture details
	<ul style="list-style-type: none"> • Entities: 4 faces; • Type: Fixed geometry.

Table 42 - Multiple operation cell: External loads applied regarding the bottom structure analysis

External loads	Illustration	Properties
<p>Gravity</p>		<ul style="list-style-type: none"> • Reference: Top plane; • Value: 9,81 m/s².
<p>Distributed mass</p>		<ul style="list-style-type: none"> • Entities: 1 face; • Type: Displacement (direct transfer); • Value: 1000 kg.

With all the conditions for the study defined, the mesh type and parameters were defined. The most important information regarding the mesh used can be seen in Table 36 and a representation of the mesh generated can be seen in Figure 32.

Table 43 - Multiple operation cell: Information regarding the mesh used for the bottom structure analysis

Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Maximum element size	57,54 mm
Minimum element size	11,51 mm
Total Nodes	327 511
Total elements	173 511



Figure 37 - Multiple operation cell: Mesh generated for the bottom structure analysis

With all the conditions and mesh defined, the FEM analysis was performed. The results achieved for the von Mises equivalent stress and displacement can be seen, respectively in Figure 38 and Figure 39.

Analyzing the values obtained, it is possible to confirm that the maximum von Mises equivalent stress registered, 117,8 MPa, is far from the yield strength of the material and the displacement achieved a maximum value of approximately 0,264 mm, which is under the 1 mm limit pre-established. These values do not show any problem with the bottom structure design for the multiple operation cells, validating this option.

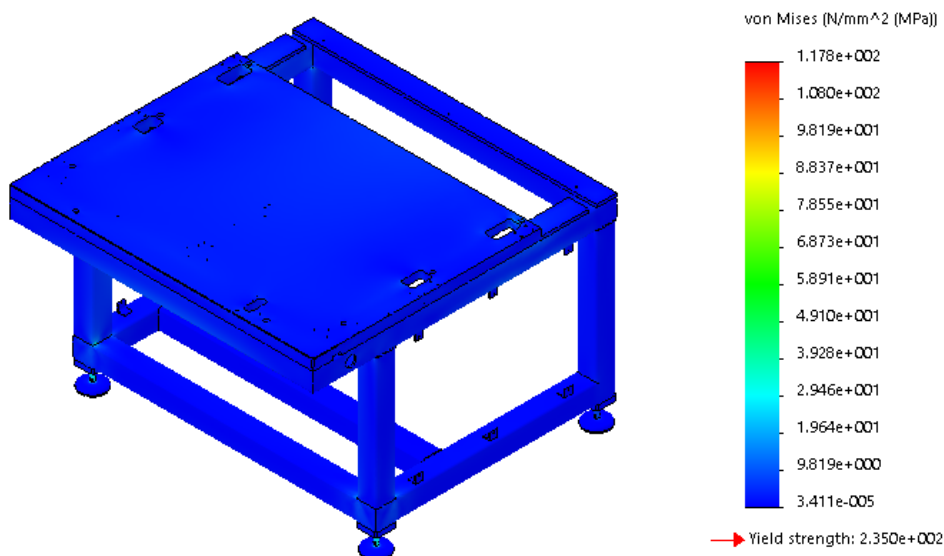


Figure 38- Multiple operation cell - Von Mises equivalent stress from the bottom structure analysis

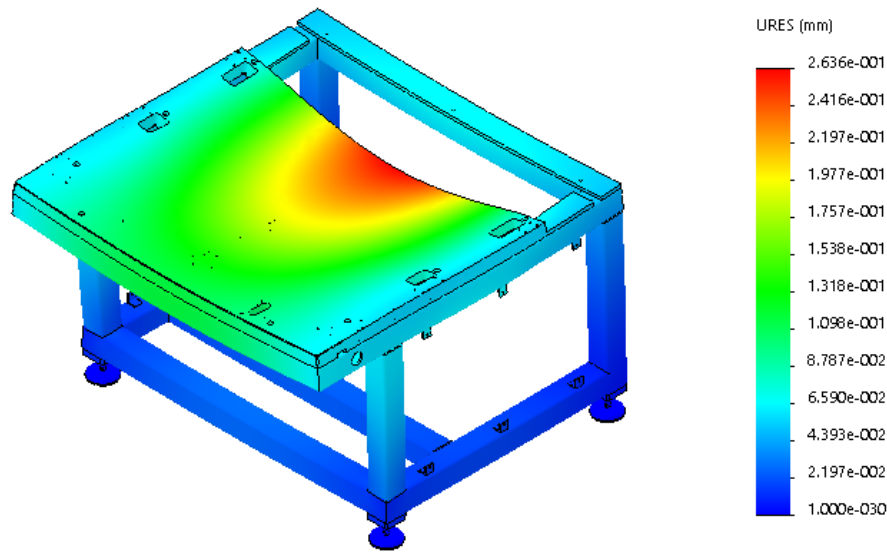


Figure 39 - Multiple operation cell - Displacement from the bottom structure analysis

Single operation cell – Bottom structure FEM analysis

The bottom structure of the single operation cells (same as the manual assembly cell) needs to withstand on top of the workbench a mass of 750 kg. Just like the multiple operation cells, during the design, it was established that the structure should not deform more than 1 mm. To validate the structure designed a FEM analysis was performed, but, just like the multiple operation cell, to obtain results from the Solidworks® study, the bottom structure was studied as a solid body and for these reasons, the conditions of the connections are also not included in this analysis.

The definition of the fixtures, material, and external loads used for this study are presented from Table 44 to Table 46, respectively.

Table 44 - Single operation cell: Fixtures applied for the bottom structure analysis

Illustration	Fixture details
	<ul style="list-style-type: none"> • Entities: 4 faces; • Type: Fixed geometry.

Table 45 - Single operation cell: Bottom structure material properties

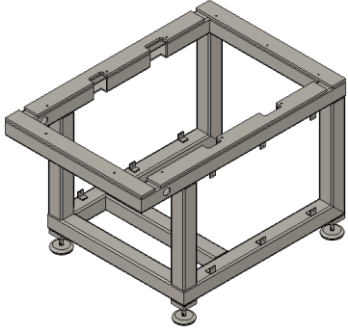
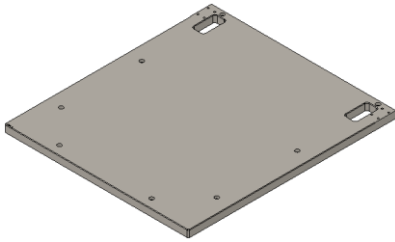
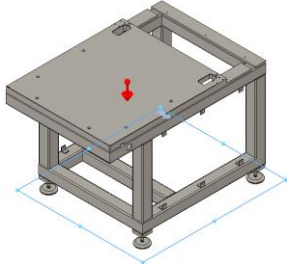
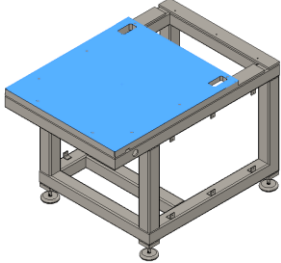
	Illustration	Properties														
Welded structure		<table border="1"> <tr> <td>Material</td> <td>S235JR (1.0037)</td> </tr> <tr> <td>Yield strength</td> <td>235 MPa</td> </tr> <tr> <td>Tensile strength</td> <td>360 MPa</td> </tr> <tr> <td>Elastic modulus</td> <td>210 GPa</td> </tr> <tr> <td>Poisson's ratio</td> <td>0,28</td> </tr> <tr> <td>Mass density</td> <td>7800 kg/m³</td> </tr> <tr> <td>Shear modulus</td> <td>79 GPa</td> </tr> </table>	Material	S235JR (1.0037)	Yield strength	235 MPa	Tensile strength	360 MPa	Elastic modulus	210 GPa	Poisson's ratio	0,28	Mass density	7800 kg/m ³	Shear modulus	79 GPa
		Material	S235JR (1.0037)													
Yield strength	235 MPa															
Tensile strength	360 MPa															
Elastic modulus	210 GPa															
Poisson's ratio	0,28															
Mass density	7800 kg/m ³															
Shear modulus	79 GPa															
Workbench																

Table 46 - Single operation cell: External loads applied regarding the bottom structure analysis

External loads	Illustration	Properties
Gravity		<ul style="list-style-type: none"> • Reference: Top plane; • Value: 9,81 m/s².
Distributed mass		<ul style="list-style-type: none"> • Entities: 1 face; • Type: Displacement (direct transfer); • Value: 750 kg.

With all the conditions for the study defined, the mesh type and parameters were defined. The most important information regarding the mesh used can be seen in Table 47 and a representation of the mesh generated can be seen in Figure 40.

Table 47 - Single operation cell: Information regarding the mesh used for the bottom structure analysis

Mesh type	Solid mesh
Mesher used	Curvature-based mesh
Maximum element size	51,42 mm
Minimum element size	10,28 mm
Total Nodes	326 951
Total elements	172 776

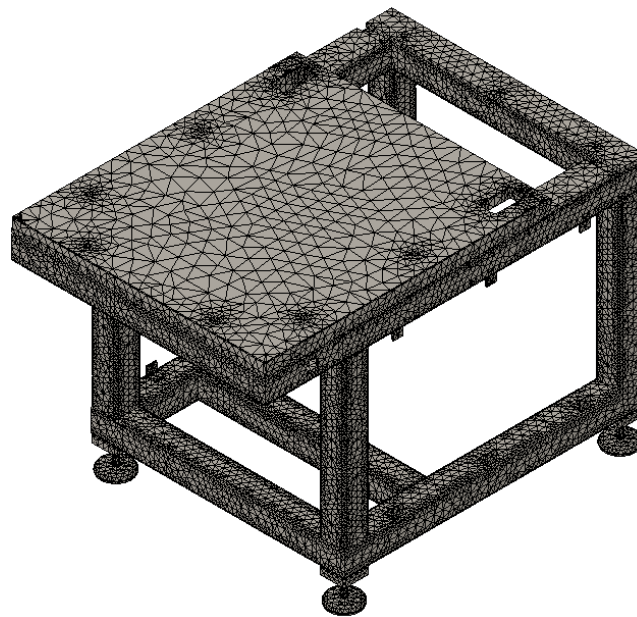


Figure 40 - Single operation cell: Mesh generated for the bottom structure analysis

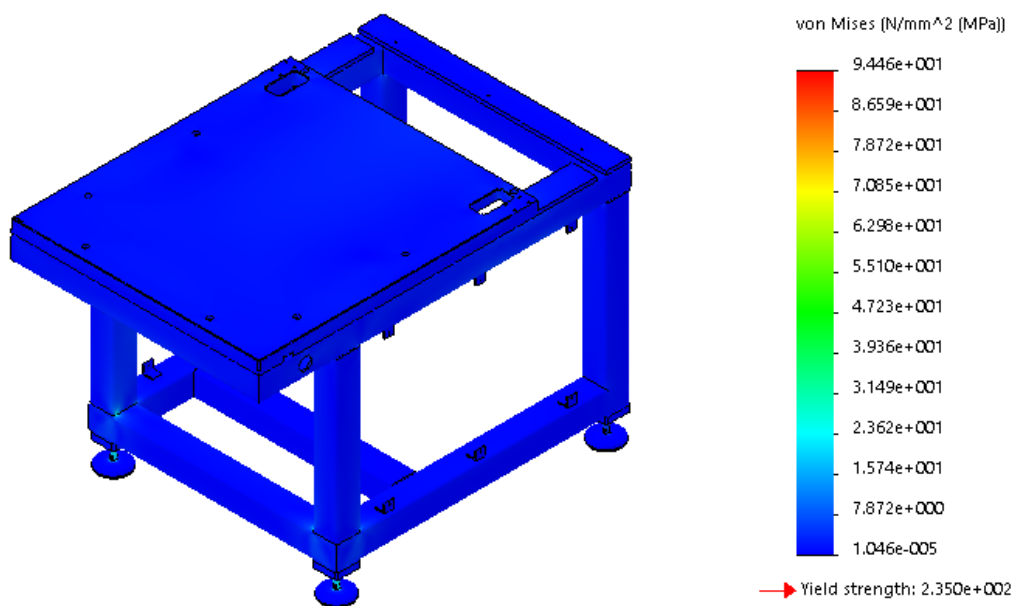


Figure 41 - Single operation cell - Von Mises equivalent stress from the bottom structure analysis

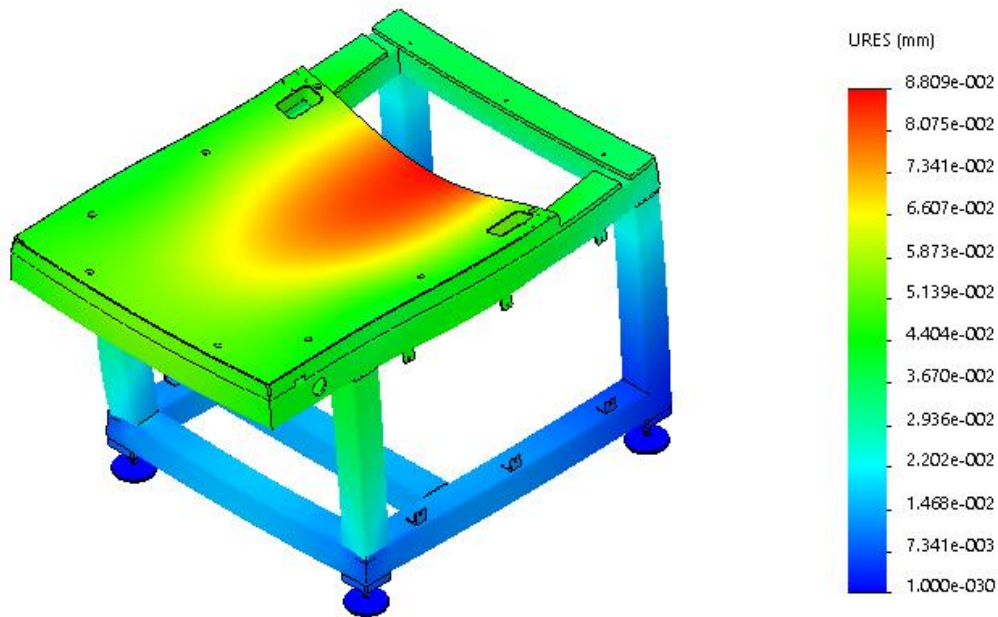


Figure 42 - Single operation cell - Displacement from the bottom structure analysis

With all the conditions and mesh defined, the FEM analysis was performed. The results achieved for the von Mises equivalent stress and displacement can be seen, respectively in Figure 41 and Figure 42.

Analyzing the values obtained, it is possible to confirm that the maximum von Mises equivalent stress achieved, 94,46 MPa, is far from the yield strength of the material and the displacement registered a maximum value of approximately 0,185 mm, which is under the 1 mm limit pre-established. These values do not show any problem with the bottom structure design for the single operation cells, validating this option.

With both bottom structures analyzed, is possible to consider that they are over-dimensioned for the application and it would be possible to optimize the design. This being said, there are reasons that led to this design.

The customer specified the workbench material, thickness, and treatment in order to maintain the workstations of their factory uniform. Even though it was used the minimum thickness allowed, the workbench created is very stiff and capable of bearing a much higher load than the minimum required. On the other hand, the welded structures were made from 80mm square profiles with a 6mm wall thickness. These profiles could have been smaller and still comply with the bottom structure stiffness and load-bearing capacity required. But, since they are also utilized for cable management and to fasten components, the profiles needed to have a large internal section to pass cables and enough thickness to tap holes. For this reason, the bottom structure design was not adjusted after the results of these analyses.

4.2.2.4 Command System

4.2.2.4.1 Overview

The command system is composed of multiple elements. These elements are spread across the cell in locations suitable for their purpose. In Figure 43 these elements are highlighted and identified and it is possible to see where they are located within the cell. In Table 48 further information is given about the components of the command system.

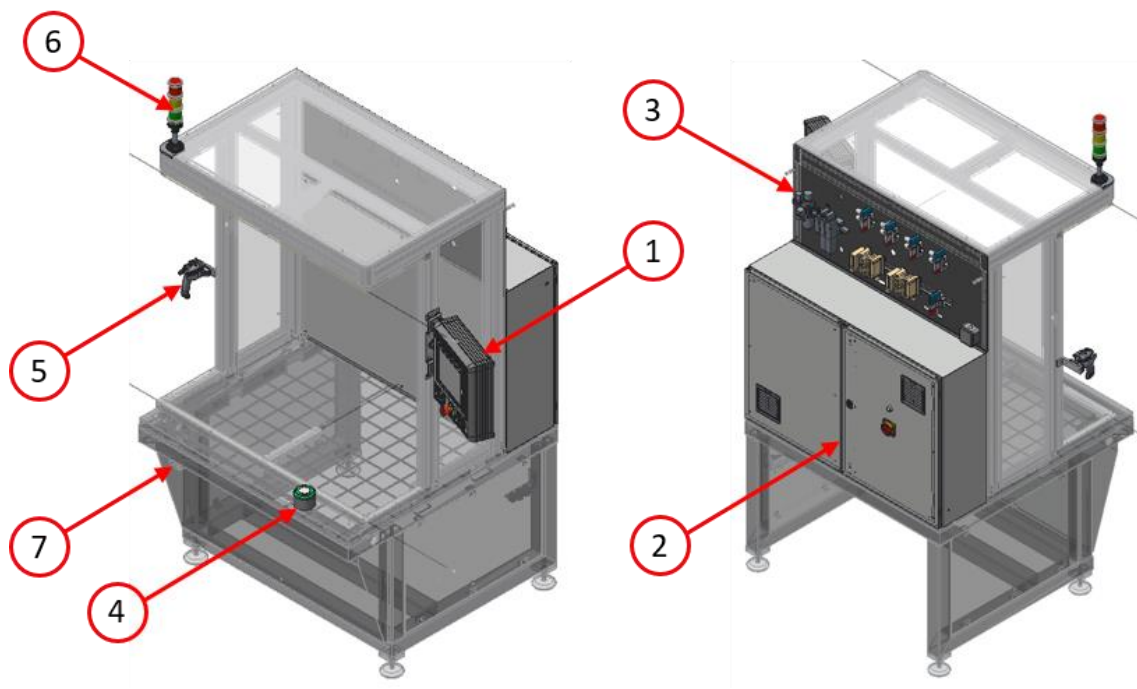


Figure 43 - Identification of the command system components

Table 48 - Command system components

Number	Material	Description
1	Rittal and Allen-Bradley	Human-machine interface
2	Rittal and Allen-Bradley	Electric cabinet
3	SMC	Pneumatic controls
4	Captron	Start button (capacitive sensor switch)
5	Motorola	2D scanner
6	Allen-Bradley	Signal light tower
7	Wolfgang Warmbier	Antistatic wristband connection

4.2.2.4.2 Focal points

The focal points of the cell’s command system are presented and explained in Table 49.

Table 49 - Focal points of the cell's command system

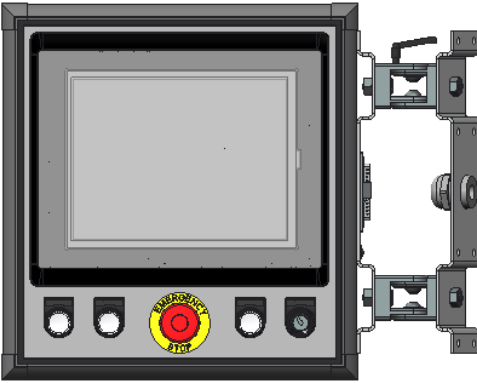
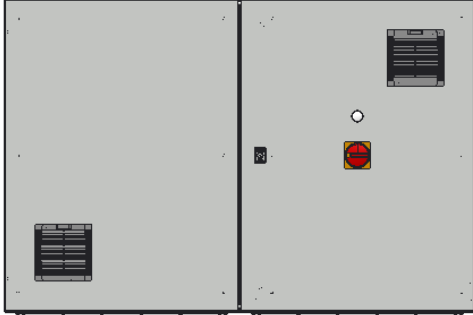


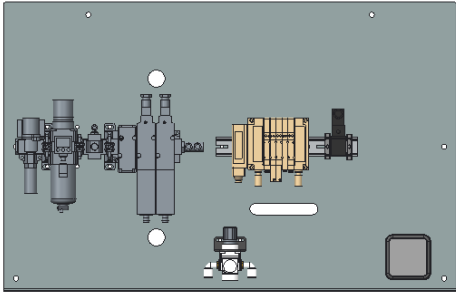
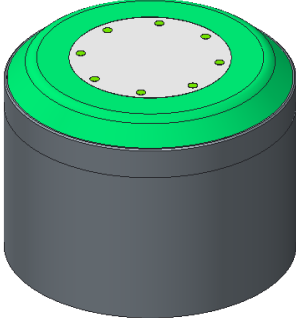
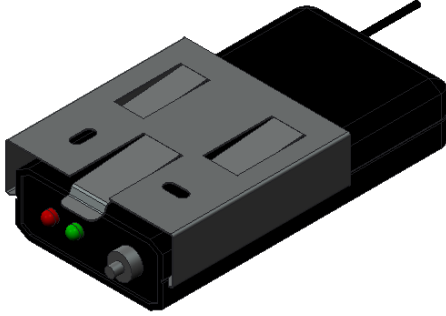
	Illustration	Description																												
Human-machine interface		<p>The HMI is the main component of the command system. The touchscreen allows to navigate different menus which display all the info needed to the operator. The HMI also enables a supervisor to manually control and change all the parameters of the operation in question. From left to right, the buttons represent respectively action “A”, action “B”, emergency stop, power ON, and supervisor key switch. Due to the complexity of the Human-machine interface, a more detailed explanation is given in subchapter 4.2.2.4.3.</p>																												
Electric Cabinet		<p>The electric cabinet houses the majority of the electric components and software-hardware (power source, PLC, safety relay, etc.). On the door of the cabinet, a main ON/OFF switch is installed and above it, there is an LED light that indicates if the equipment is receiving electricity. For equipment that has three-phase power supplies, a light for each phase is available.</p>																												
Signal light tower		<p>The signal light tower is situated on top of the structure. It is composed of a green (G), yellow (Y) and red (R) light. In the following table the signals are explained (“F” stands for flashing and “X” for continuously activated).</p> <table border="1" data-bbox="842 1704 1358 2018"> <thead> <tr> <th>G</th> <th>Y</th> <th>R</th> <th>Condition</th> </tr> </thead> <tbody> <tr> <td>-</td> <td>-</td> <td>-</td> <td>The machine is turned off</td> </tr> <tr> <td>X</td> <td>-</td> <td>-</td> <td>Operating in automatic</td> </tr> <tr> <td>-</td> <td>X</td> <td>-</td> <td>Operating in manual</td> </tr> <tr> <td>-</td> <td>-</td> <td>X</td> <td>Error occurred</td> </tr> <tr> <td>-</td> <td>F</td> <td>-</td> <td>Machine in stand-by</td> </tr> <tr> <td>-</td> <td>-</td> <td>F</td> <td>Emergency activated</td> </tr> </tbody> </table>	G	Y	R	Condition	-	-	-	The machine is turned off	X	-	-	Operating in automatic	-	X	-	Operating in manual	-	-	X	Error occurred	-	F	-	Machine in stand-by	-	-	F	Emergency activated
G	Y	R	Condition																											
-	-	-	The machine is turned off																											
X	-	-	Operating in automatic																											
-	X	-	Operating in manual																											
-	-	X	Error occurred																											
-	F	-	Machine in stand-by																											
-	-	F	Emergency activated																											

	Illustration	Description
2D Scanner		<p>The 2D scanner will be used to control the batches being used. The operator will have to scan the boxes/crates where the raw parts arrive and the PLC will then count the number of parts used until the box is presumably empty. Subsequently, it will request a new reading. The operation will not proceed without a valid batch number.</p>
Pneumatic controls		<p>The pneumatic controls are situated above the electric cabinet. They vary in every station, but these controls always have an air treatment unit and at least one valve block. The air treatment unit is composed of a shut-off valve, air filter, pressure regulator with a digital display, a soft-start valve, and two redundant emergency valves. The emergency valves are controlled by the safety relays and the valve block is controlled by the PLC.</p>
Start button		<p>The start button is present in all cells, except for the manual assembly cell. The button is located in the workbench, outside the safety light curtains, for easy access. A capacitive sensor switch was chosen because they do not require pressure to recognize the touch, and the specific type chosen is extremely durable and reliable.</p>
Antistatic Wristband		<p>The operator will be handling a PCB and components that will be installed around it. A static electricity discharge can induce permanent damages to the PCB, thus, to prevent this, the operator is grounded by using an antistatic wristband. The product chosen was the WL20878 produced by Wolfgang Warmbier. This device can detect and inform the PLC if the operator is wearing the wristband. The machine will not operate unless the operator is grounded.</p>

4.2.2.4.3 Human/machine interface

The HMI allows the operator to control the equipment and receive feedback on the operations being executed. It also allows a supervisor to reconfigure the production process and control de equipment manually. The layout and operation of the HMI menus will be shown and explained in the following sequence of images and tables. In Figure 44 the main screens are identified and in Table 50 a short description is given.



Figure 44 - HMI menus

Table 50 - Figure 44 legend

Number	Description
1	Main screen
2	Manual control screen
3	Information and process control screen
4	Configuration screen

The HMI is divided into four categories, main screen, manual control screen, information and process control screen, and configuration screen. These categories can be accessed by clicking the menu button. The manual control screen and the configuration screen are locked through the supervisor key and without it they cannot be accessed. During the normal operation of the equipment, the main screen will be active most of the time.

Main screen

The main screen can be divided into four sections which are identified in Figure 45 with color-coded rectangles. The red represents the information about the operation being executed. The yellow area shows information regarding the materials being used (batch code and when it is needed to scan a new batch). The green area can be used in the multiple operation cells to show the information regarding the second operation being executed, or, in case only one operation is done, can show extra information regarding that operation. Finally, the blue area is where the main controls are located, which are, from left to right, reset, step by step, start cycle, stop cycle, alarms, and the menu button. In Figure 46 the components of the areas previously explained are identified and in Table 51 a short description is given.

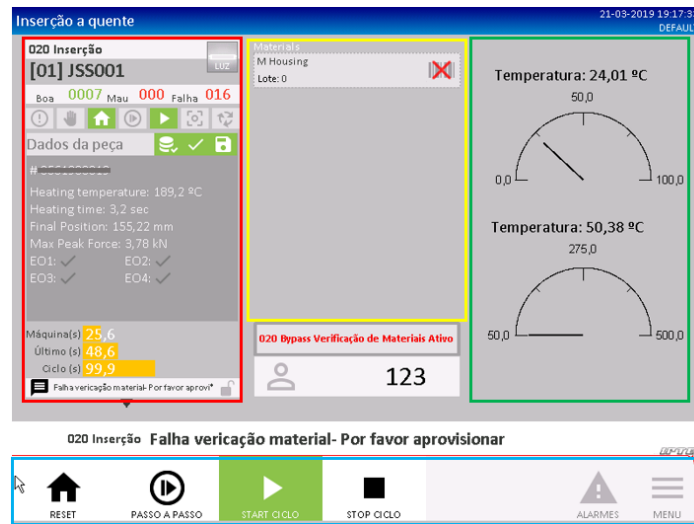


Figure 45 – Main screen sections

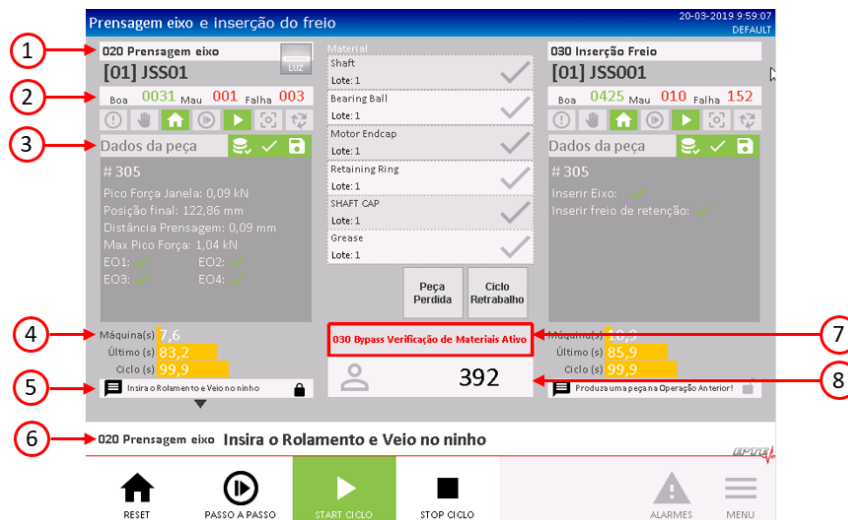


Figure 46 – Main screen focal points

Table 51 - Figure 46 legend

Number	Description
1	Operation description
2	Good, bad, and failed parts counters
3	Information and results from the previously produced part
4	Timers regarding the operation and cycle time
5	Shows the action waiting to be executed
6	Shows the action that the operator must perform and error messages
7	In any, shows steps being bypassed
8	Displays the operator code

Manual control screen

In the manual control screen is possible to control all the movements that the equipment is capable of performing, as well as triggering scanners and other equipment that interact with the operations, for instance, the magnetizer or the induction heater. It is also on this screen that the supervisor can calibrate the machine using the respective masters supplied with the equipment.

In Figure 47 the controls of the manual screen are identified and a short description is given in Table 52.

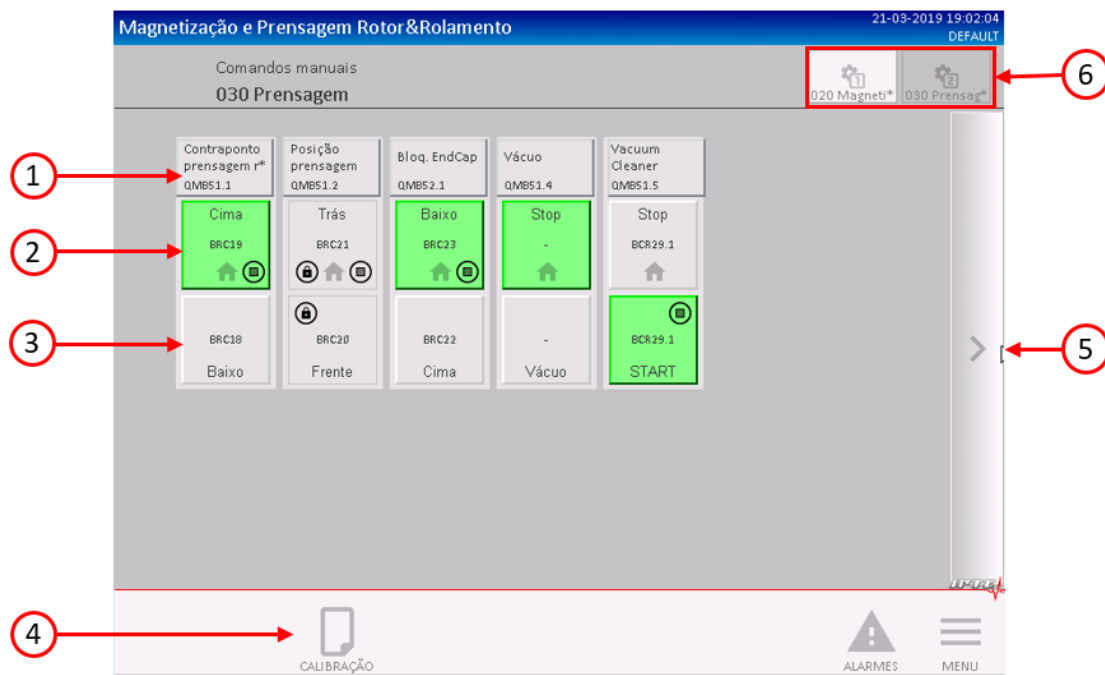


Figure 47 - Manual control screen 1

Table 52 - Figure 47 legend

Number	Description
1	Description of the actuator
2	Action "A" (can be controlled with the external button)
3	Action "B" (can be controlled with the external button)
4	Calibration screen button
5	Navigation button
6	Operation selector

When the actuators and equipment that can be controlled manually cannot fit in one screen, it is possible to create multiple screens. For these cases, navigation keys appear on the sides of the screen, which are highlighted with the balloon 5 in Figure 47 and balloon 1 in Figure 48. Also, when the cell has multiple operations, in the upper right corner of the screen two buttons appear to select the desired operation. This can be seen in Figure 47 highlighted with balloon 6.

In Figure 49 the calibration screen is shown and in Table 53 its legend is presented.

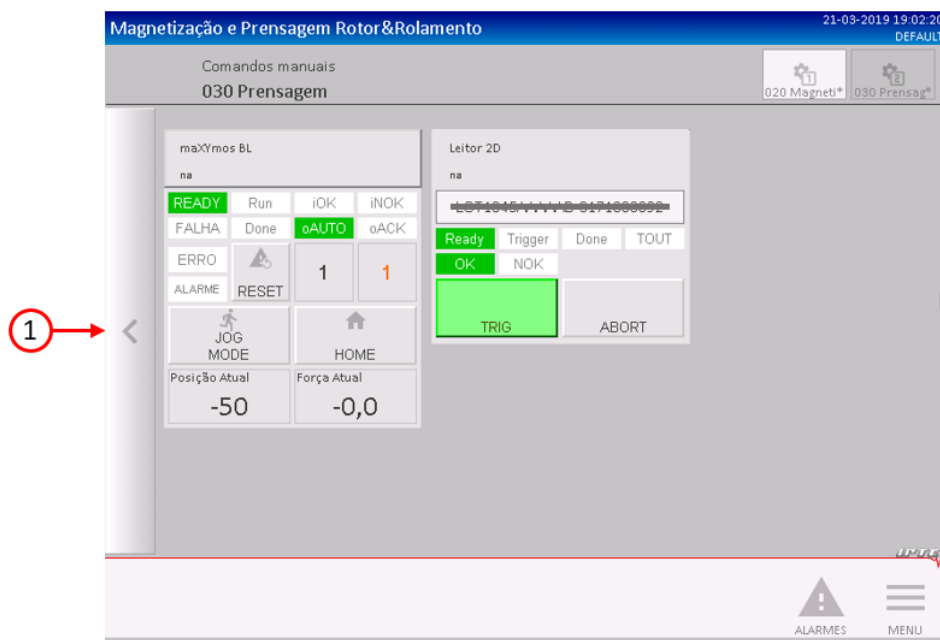


Figure 48 - Manual control screen 2

Table 53 - Figure 49 legend

Number	Description
1	Jog mode activation
2	Action "A" and "B" control buttons
3	Teach the machine the calibrated position

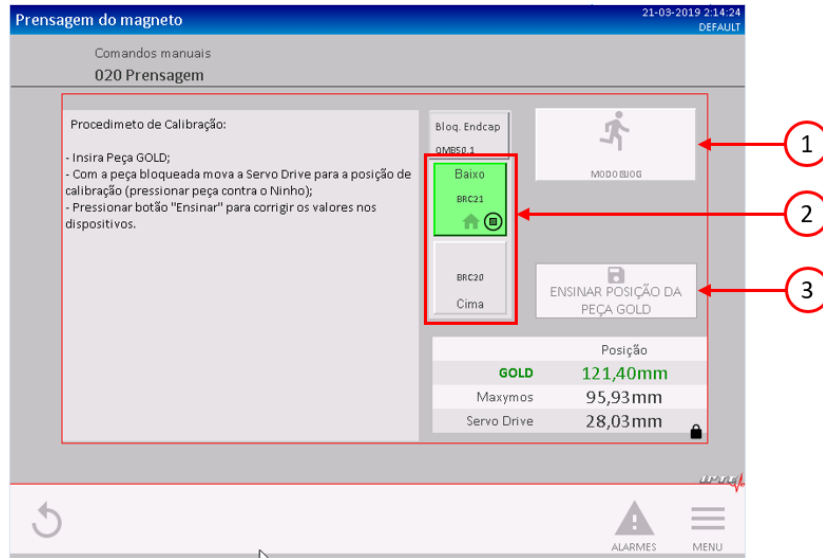


Figure 49 - Calibration screen

Information and process control screen

This section of the menu is divided into two sections, the counters (Figure 50 to Figure 52) and the historic (Figure 53). The operator, or a supervisor, can access all the information regarding the shifts and the production. In the first section, information such as the different counters and error codes can be accessed, while in the second section, the complete history of a given part can be searched and shown in deep detail. The different areas and controls present in these screens are identified in Figure 50 and Figure 53 and are respectively described in Table 54 and Table 55.

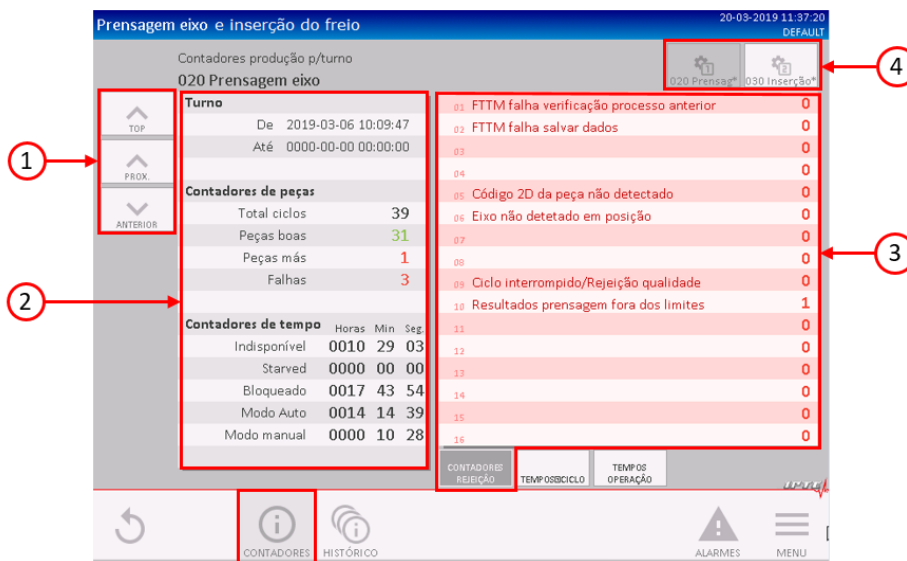


Figure 50 - Rejection counter screen

Table 54 - Figure 50 legend

Number	Description
1	Shift navigation keys
2	Shift information; Part counter; Machine states timer.
3	Can show 3 sub-menus: Rejection counter and respective error codes (Figure 50); Cycle time of the last 16 parts (Figure 51); Machine operation time of the last 16 parts (Figure 52).
4	Operation selector

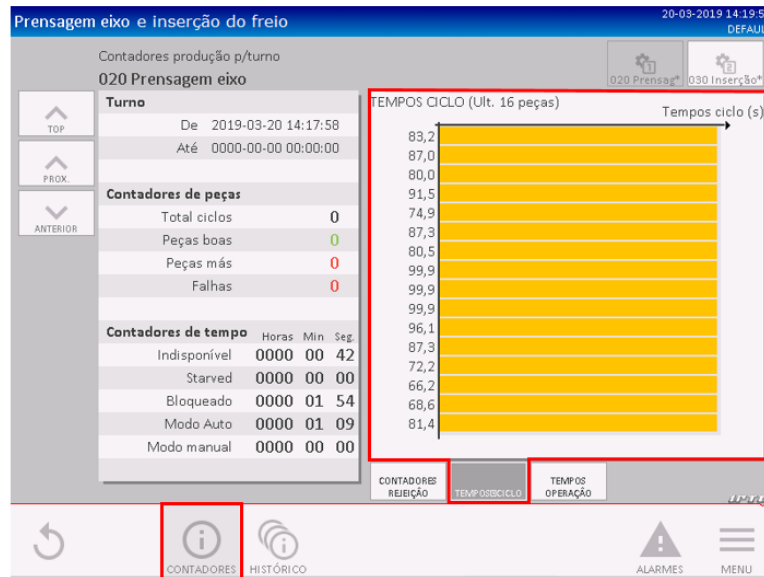


Figure 51 - Cycle time screen

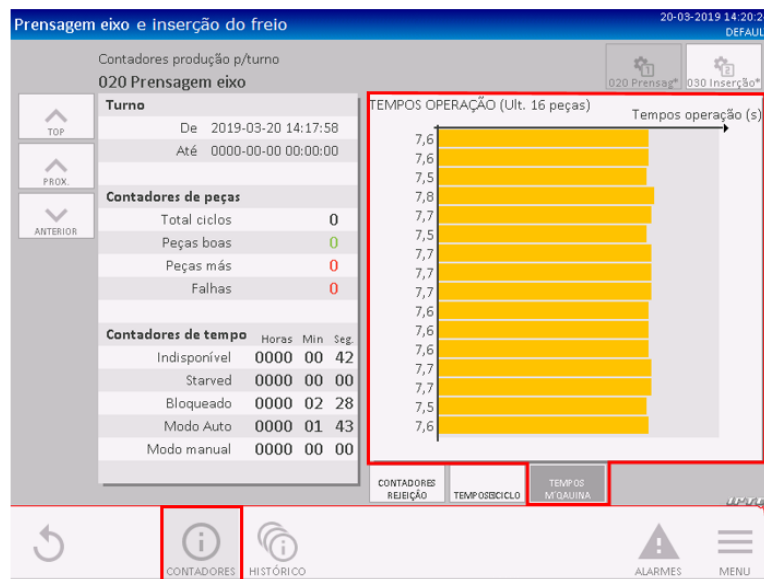


Figure 52 - Machine operation time screen

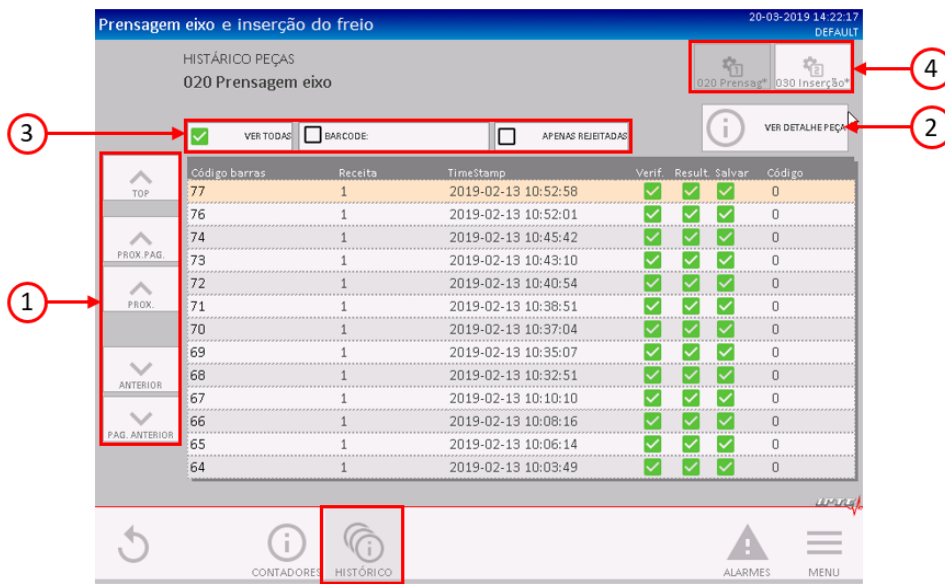


Figure 53 - Production historic screen

Table 55 - Figure 53 legend

Number	Description
1	Navigation keys
2	Show production details of the selected part
3	Search filters
4	Operation selector

Configuration screen

The configuration screen is divided into four sections, the station parameters, recipes, bypass, and materials. These sections are explained in Table 56 and shown in Figure 54.

Table 56 - Configuration screen sections

Section	Description
Station parameters	The section shows the parameters on which the equipment is operating (Figure 54.A)
Recipes	This is where the supervisor can tune the parameters of some components of the equipment, such as the electric actuators (Figure 54.B)
Bypass	A list of steps that can be temporarily bypassed is shown (Figure 54.C)
Materials	A list of the materials used is shown and can be edited (add materials, change material reference, etc.) (Figure 54.D)



Figure 54 - Configuration screens: a) Parameters screen; b) Recipes screen; c) Bypass screen; d) Materials screen;

4.2.2.5 Pneumatic project

The cells are equipped with the same basic air treatment unit, which controls and regulates the air intake. All the stations have a customized pneumatic project, but this common unit allows to manually shut-off the air, filter, regulate the pressure, softly fill the system (tubes and actuators), and exhaust the air when the emergency button is activated. In Figure 55 and exploded view of the air treatment unit is presented and the components are identified with balloons. The legend of these balloons is presented in Table 57.

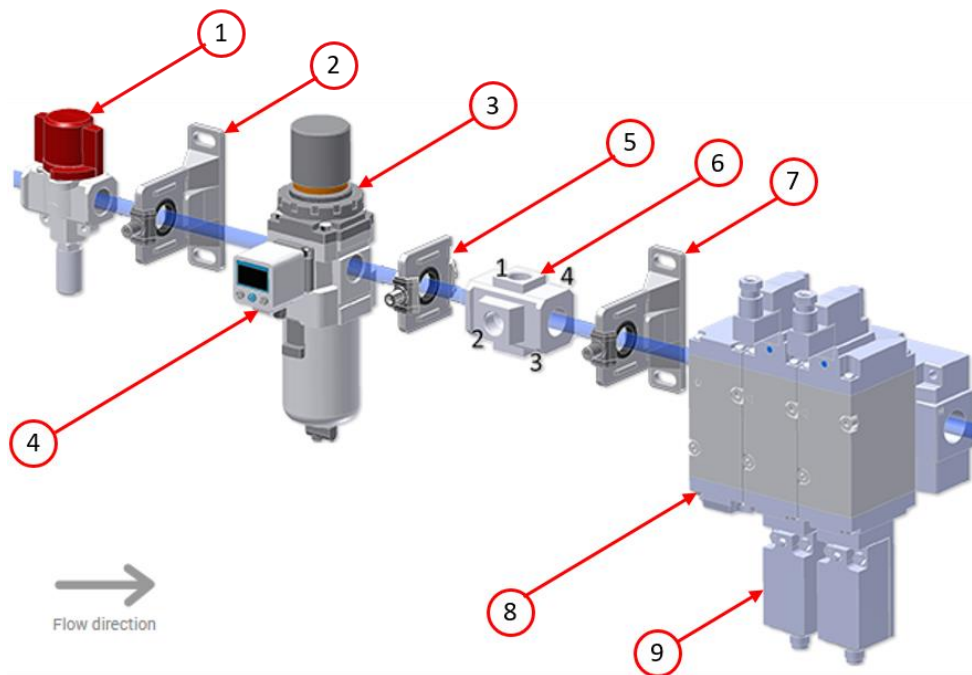


Figure 55 - Air treatment unit

Table 57 - Figure 55 legend

Number	Brand	Reference	Description
1	SMC	VHS30-F03A	3 port pressure relief manual valve
2	SMC	Y300T-A	Spacer with bracket
3	SMC	AW30-F03-B	Filter with a digital pressure regulator
4	SMC	ISE40A-01-P-L	High precision digital pressure switch
5	SMC	Y300-A	Spacer
6	SMC	Y34-F02-A	Cross spacer
7	SMC	Y300T-A	Spacer with bracket
8	SMC	VP544-5DZ1-03F-M-X585	Soft start-up valve
9	SMC		Dual residual pressure release valve

4.2.2.6 Safety System

All the machinery designed at IPTE Ovar goes through a careful and methodical analysis regarding their safety. Producing a reliable, easy to operate, and safe equipment is of extreme importance. To back up this commitment, all the machines produced by IPTE Ovar are delivered with the following certifications:

- Machine Directive 2006/42/EC;
- (EMC) Directive 2014/30/EU.

4.2.2.6.1 General safety instructions



For safely operating the equipment some safety instructions are hereby mentioned:

- Only trained personal can install, operate and perform maintenance to the equipment;
- Do not run the machine in automatic mode with safety bypasses or removed protections;
- Ensure the machine has its movements restricted before accessing potentially dangerous zones;
- Tie hair and tighten clothing before operating or performing maintenance to the equipment;
- Do not try to approach any moving part during operation;
- Before removing protections or safety guards, deactivate the machine to ensure that it cannot be rearmed;
- Before maintenance or cleaning procedures ensure that the actuators are stationary in their home position and the machine is disabled;
- After maintenance or cleaning, no tool or other object can be forgotten inside the working area as it can damage the machine or affect its performance;
- Do not operate the machine with the electric cabinet open;
- Any unauthorized alteration to the equipment, maintenance/operating done by untrained personal, or using the equipment for other use than the one it was designed to execute, can lead to safety issues and will lead to warranty void.

4.2.2.6.2 Safety warnings

Safety warnings are used in specific spots of the equipment where attention to a residual hazard is required, or to inform the personnel of mandatory/forbidden behaviors they must adopt. On the customer’s factory floor it is already mandatory for the workers to wear individual protective gear, namely, glasses, boots, gloves, and earplugs. The safety warnings present in the assembly line are indicated in Table 58.

Table 58 - Safety warnings present in the assembly line

Symbol	Description
	This signal represents electric risks and can be found in the doors of the electric cabinets.
	This sign warns a hot surface hazard and can be found in station 5 where an induction heating operation is performed.

4.2.2.6.3 Main power switches

The cells need two power sources to operate, compressed air and electricity. For each power source, there is a main on/off switch. These are provided to cut-off the power when the machine is not operating, or undergoing maintenance, and must not be used as emergency stops. The location of the two main switches can be seen in Figure 56.

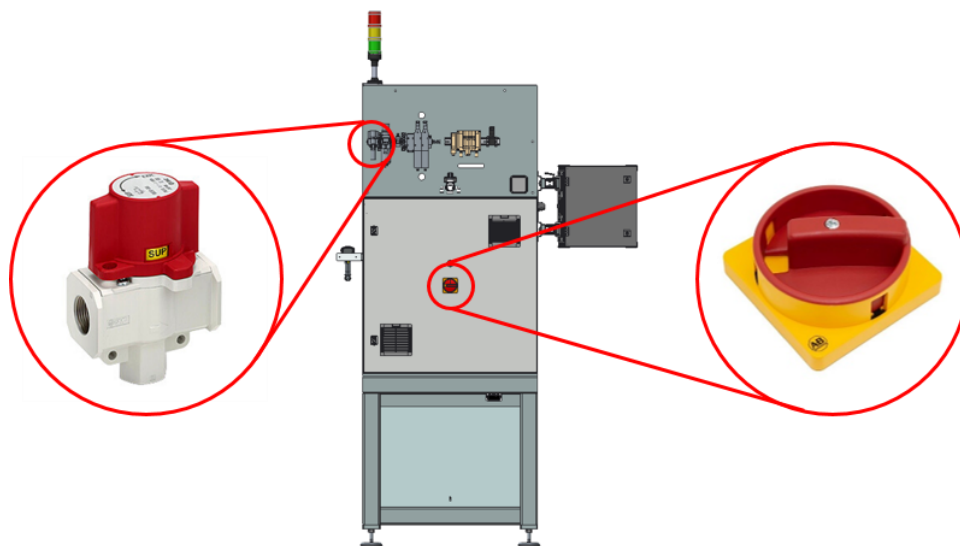


Figure 56 - Main power switches locations

4.2.2.6.4 Emergency stop

The emergency stop button is located beneath the HMI screen (Figure 57). This button should be activated by the operator when the machine presents a hazard to the personnel or risk of damaging the equipment. This button is hardwired to the safety relays and to the PLC, which ensures that the safety response is immediate and is not depending on the response time of the PLC. The emergency stop will ensure a fast and safe stop of all the moving parts and will cut all the power supplies to the actuators.

After the hazard has been eliminated, the emergency stop button must be unlocked and the machine will need to go through a reset cycle before it is ready to start operating again.



Figure 57 - Emergency stop location

4.2.2.6.5 Safety light curtains

As already established, the cells are meant to operate in a semi-automatic configuration, meaning, in this case, that the operator will consistently need to access the machine, but it must still be protected when the equipment enters the automatic cycle. To achieve this, safety light curtains will be used.

In subchapter 3.4.1, it was already defined that two types of configuration for the light curtains are going to be applied, an “E” type configuration and a “C” type (Figure 58 and Figure 59, respectively). These configurations will now be further explained.

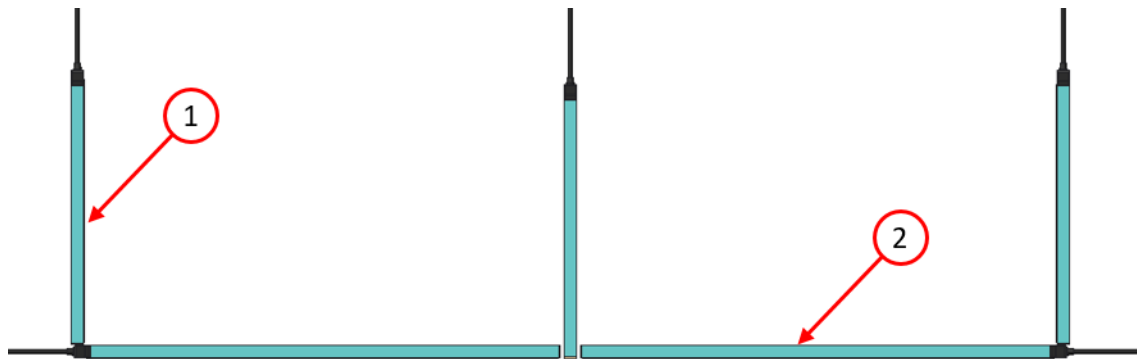


Figure 58 - Safety light curtains in the "E" configuration

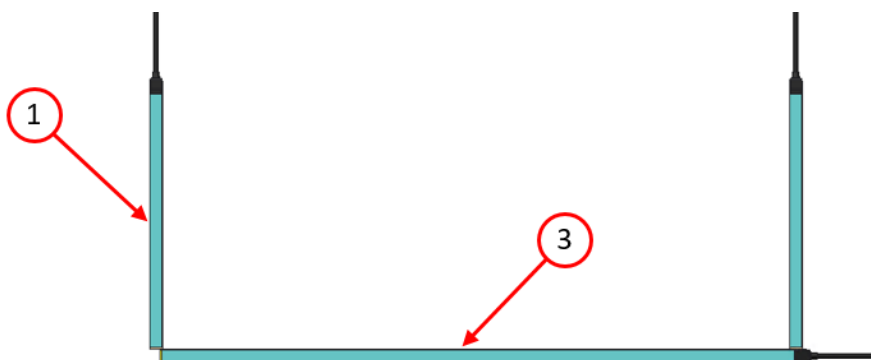


Figure 59 - Safety light curtains in the "C" configuration

Table 59 - Details about the safety light curtains

Number	Brand	Reference	Length	Resolution	Response time
1	Allen-Bradley	445L-P4C0300FP	300 mm	14 mm	< 18,5 ms
2	Allen-Bradley	445L-P4C0550FP	550 mm	14 mm	< 25,0 ms
3	Allen-Bradley	445L-P4C0750FP	750 mm	14 mm	< 30,2 ms

In Table 59 the main features of the light curtains are. These light curtains were selected taking into care what the customer already uses in his factory and possesses as a spare part.

The “C” configuration is pretty straight forward regarding its work. The operation is isolated from the operator on 3 sides. When in automatic mode, if someone, or something, crosses the light curtains, the safety system is triggered and the machine comes to a stop.

The working principle of the light curtains in the “E” configuration is basically the same, but the curtains work alternately. In Figure 60 the combinations that this configuration can assume are displayed.

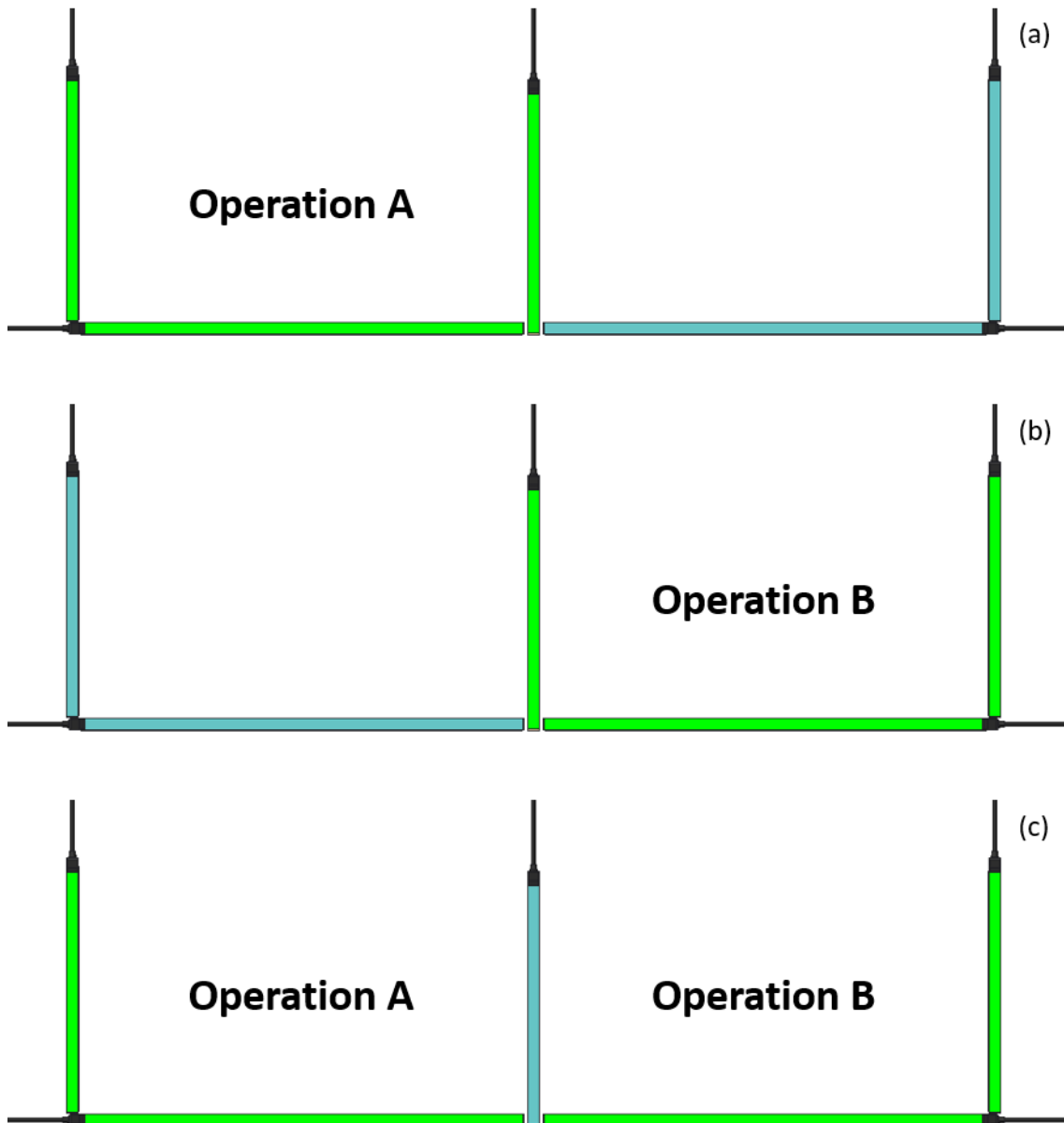


Figure 60 - "E" safety light curtains operating groups: a) Operation "A"; b) Operation "B"; c) Both operations.

In the multiple operation cells, there are only three possibilities when the equipment is working the automatic part of the cycle, it is possible to have: only the operation "A" executing; only operation "B" executing; both operations executing simultaneously. The barriers highlighted in green are the ones that will be activated according to the operations being executed. This alternative work of the barriers, unlike the "C" configuration, allows to perform two operations independently, as well as both in simultaneously.

Safety distance calculation

According to EN ISO 13855 [110], the way to calculate the safety distance between the light curtains and the point of danger is as follows:

- First, calculate the distance using the formula:

$$S = 2000 \times T + 8 \times (d - 14) \tag{1}$$

Where,

T – Stop time + response time [s]

d – Resolution of the light curtain [mm]

S – Safety distance [mm]

- If the result *S* is ≤ 500 mm, then use the determined value;
- If the result *S* is > 500 mm, then recalculate *S* using the formula:

$$S = 1600 \times T + 8 \times (d - 14) \tag{2}$$

At this point, the only unknown variable is *T*, the resolution is already given in Table 59. To calculate *T* is necessary to define which components are going to be used. To calculate the safety distance, the electric actuators from the presses will be studied, as this is the component that presents the biggest hazard to the operator. The components that will affect the response and stopping times are the light curtains, safety relay, actuator, and the servo motor that drives the actuator. The datasheets of these components can be found in Annex VI.

The stopping time also depends on and load applied. The actuator and motor were specified by the customer since they already use the given configuration in other applications and have them as spare parts. The actuator components are specified in Figure 61. Table 60 and Table 61 shows the information from the motor and actuator, given by the datasheets, which will be needed to calculate the stopping time.

Table 60 – Information concerning the servo motor

Brand	Reference	Brake torque	Rotor inertia	Brake response time
Allen-Bradley	MPL-A320P-MJ74AA	4,18 N·m	92×10 ⁻⁶ kg·m ²	< 20,0 ms

Table 61 – Information concerning the actuator

Brand	Reference	J0	J1	J2	J3	Mx
Metalwork	371080030048	$420,3 \times 10^{-6}$ kg·m ²	608×10^{-6} kg·m ² /m	$2,54 \times 10^{-6}$ kg·m ² /kg	$281,2 \times 10^{-6}$ kg·m ²	3,73 kg

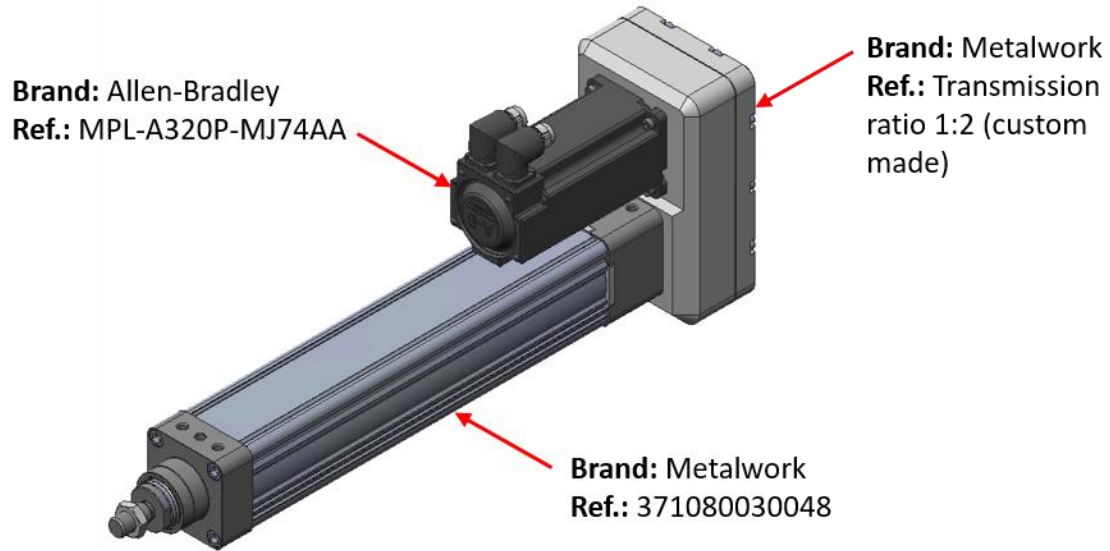


Figure 61 - Actuator components

To discover the stopping time, the formula used to calculate the acceleration/deceleration torque can be used:

$$T_A = \frac{2 \times \pi \times N}{60 \times t_A} + J_m \tag{3}$$

Where,

T_A – Acceleration/deceleration torque [N·m]

N – Rotation speed [rpm]

t_A – Acceleration/deceleration time [s]

J_m – Motor shaft and load inertia [kg·m²]

The variable J_m is the combination of the motor’s rotor inertia (J_{rotor}) and the inertia from the actuator and its load (J_{tot}), passed through the transmission. The rotor inertia is given in Table 60, and in the datasheet of the actuator it can be found the formula to calculate the inertia passed to the motor’s shaft, which is:

$$J_{tot} = (J_1 \times stroke[m] + J_2 \times (load[kg] + M_x) + J_0) \times \tau^2 + J_3 \tag{4}$$

Where,

J_{tot} – Total mass moment of inertia reduced for the motor [$\text{kg}\cdot\text{m}^2$]

J_0 – Mass moment of inertia at stroke 0 [$\text{kg}\cdot\text{m}^2$]

J_1 – Mass moment of inertia for each meter of stroke [$\text{kg}\cdot\text{m}^2/\text{m}$]

J_2 – Mass moment of inertia for each kilogram of load [$\text{kg}\cdot\text{m}^2/\text{kg}$]

J_3 – Mass moment of inertia of the transmission [$\text{kg}\cdot\text{m}^2$]

τ – Transmission ratio

M_x – Moving mass at stroke 0 [kg]

As previously mentioned the stroke of the actuator is 300 mm and through the CAD software is possible to estimate that the heaviest tool attached to the actuator is approximately 7 kg. Thus, using the values from Table 61 on equation (4), is possible to calculate the J_{tot} :

$$J_{tot} = ((608 \times 0,3 + 2,54 \times (7 + 3,73) + 420,3) \times 10^{-6}) \times 0,5^2 + 281,2 \times 10^{-6} \quad (5)$$

$$\Leftrightarrow J_{tot} \approx 438,7 \times 10^{-6} \text{ kg} \cdot \text{m}^2$$

Adding the two values together is possible to find the J_m :

$$J_m = J_{rotor} + J_{tot} \quad (6)$$

$$\Leftrightarrow J_m = 92 \times 10^{-6} + 438,7 \times 10^{-6} = 530,7 \times 10^{-6} \text{ kg} \cdot \text{m}^2$$

Another variable that needs to be defined is the rotation speed (N). The maximum linear speed specified for the presses is 100 mm/s. In the datasheet of the actuator is possible to find information regarding the pitch, which in this case is 10 mm. With these values, the rotation speed of the servo motor can be calculated using the following equation:

$$V_l = \frac{N \times \tau}{60} \times P \quad (7)$$

Where,

V_l – Linear velocity [mm/s]

N – Rotation speed [revolutions per minute]

P – Pitch [mm per revolution]

τ – Transmission ratio

Replacing the values in equation (7), the following result is obtained:

$$100 = \frac{N \times 0,5}{60} \times 10 \quad (8)$$

$$\Leftrightarrow N = 1200 \text{ rpm}$$

The final variable is T_A , and it can be found in Table 60. Now that all variables are known, except t_A , is possible to solve the equation (3):

$$T_A = \frac{2 \times \pi \times N}{60 \times t_A} \times J_m \quad (9)$$

$$\Leftrightarrow t_A = \frac{2 \times \pi \times N \times J_m}{60 \times T_A}$$

$$\Leftrightarrow t_A = \frac{2 \times \pi \times 1200 \times 530,7 \times 10^{-6}}{60 \times 4,18} \approx 0,016 \text{ s}$$

The response time depends on the safety light curtains, safety relays used, and the brake response time. The response time of the light curtains is shown in Table 59, and the values used in the calculations are from the light curtain number 3 because it is the worst-case scenario. The safety relay is chosen by the electric department and in this case, the one to use is the reference 440R-P221AGS from Allen-Bradley. According to the datasheet, this relay has a response time of 9,10 ms. The response time of the brakes is shown in Table 60. To obtain the total response time of the system all that is needed to do is add these three values:

$$T_{response} = T_{relay} + T_{curtain} + T_{brake} \quad (10)$$

$$\Leftrightarrow T_{response} = 9,1 + 30,2 + 20 = 59,3 \text{ ms}$$

Finally, is possible to calculate the safety distance:

$$S = 2000 \times T + 8 \times (d - 14) \quad (11)$$

$$\Leftrightarrow S = 2000 \times (0,0593 + 0,016) + 8 \times (14 - 14) = 150,6 \text{ mm}$$

Thus, all the moving parts that present and hazard for the operator will need to be installed at a distance of at least 150,6 mm from the safety light curtains.

4.3 Station 1

4.3.1 Operation and main considerations

The first four components (shaft, bearing 1, housing, and retaining ring) will be assembled in three different operations in station 1, producing the subassembly 3. As established in subchapter 3.4.2, station 1 will be divided into two sub-stations, A and B, which will be explained separately upfront. In the end, the pneumatic diagram, budgeting, and parts list will be presented for the station as a whole.

4.3.2 Overview

In Figure 62 an isometric view of station 1 is presented and the location of station 1.A and station 1.B is highlighted.

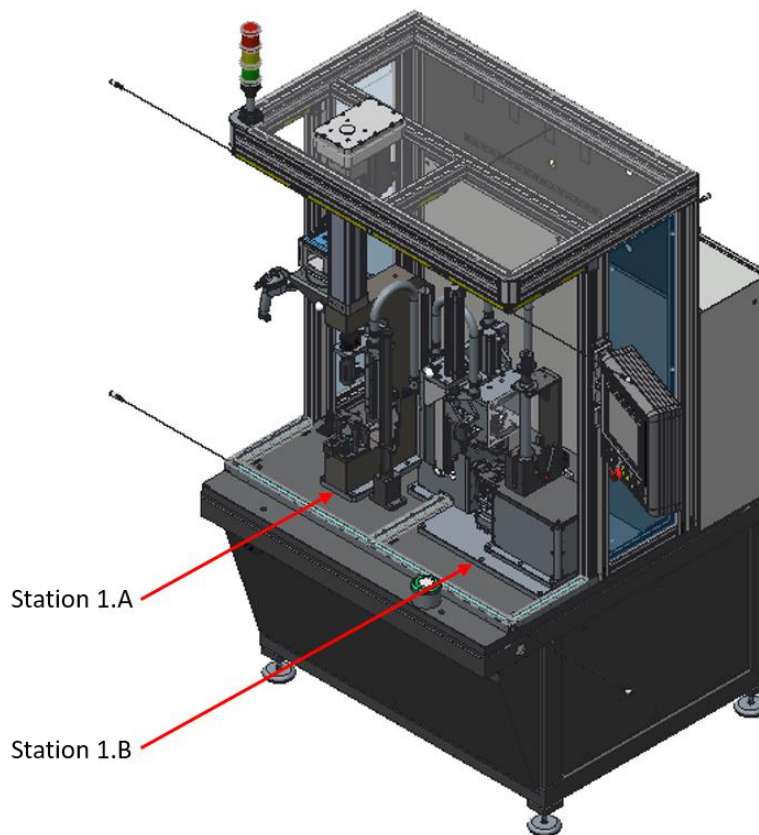


Figure 62 - Isometric view of Station 1

4.3.3 Station 1.A

4.3.3.1 Operation and main considerations

The first operation to be executed in the assembly line is done in station 1.A and consists of pressing bearing 1 onto the shaft. This operation has two important points to take into consideration, first is the fitting between the bearing and the shaft and second is the zone in the shaft that cannot be touched (highlighted in green in Figure 63).

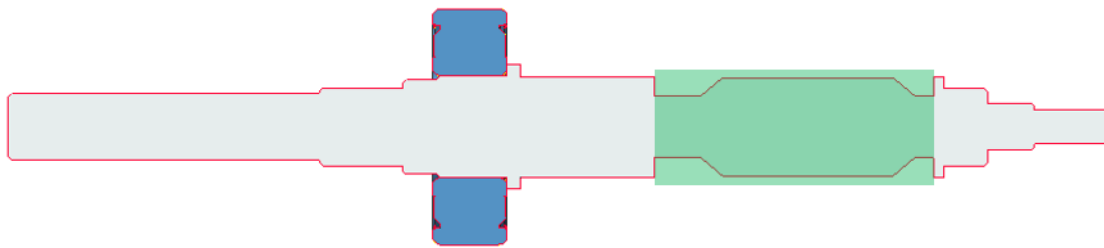


Figure 63 - Cross-section of subassembly 1

The bearing will assemble to the shaft with a tight clearance fit. This means that the insertion will be done without applying load and only when the bearing hits the stop face the load cell should register a significant load. If for some reason the press is applying a load to insert the bearing, the subassembly should be rejected since either the bearing or the shaft is defective.

The area highlighted in green in Figure 63 cannot be touched, neither by the operator or the machine's components. This is a sensible area of the product since it is where the motor will connect to the components of the application where it will be installed.

Regarding the orientation of the parts to install, the bearing can only be oriented by the external diameter, since the internal diameter must be free to receive the shaft. The shaft has two orientations points available, the $\varnothing A$ and $\varnothing B$, which are represented in Figure 64.

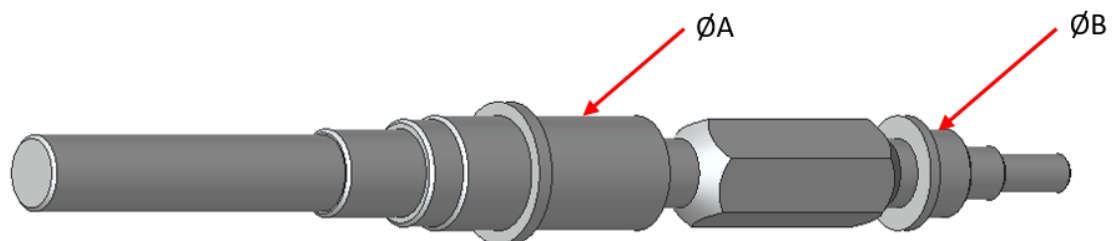


Figure 64- Orientation points of the shaft

4.3.3.2 Specifications

Most of the requirements for station 1.A are related to the press and were already mentioned in Table 27. In Table 62 is shown the remaining requirements for this station.

Table 62 - Station 1.A specifications

Specification	Description
Parts loading	<ul style="list-style-type: none"> • Manual load of bearing 1 on the tool; • Manual load of the shaft on the nest; • A bearing feeder must be provided (manual load/unload).
Part detection	<ul style="list-style-type: none"> • Detection of the parts in the nests and throughout the whole assembly operation.
Process	<ul style="list-style-type: none"> • The shaft must be guided by a tailstock during the insertion; • In case of emergency activation, the parts should stay stationary.

4.3.3.3 Brainstorm

In this station, there are three components left to design, the bearing feeder, the tool, and the nest, which will be explored in this order.

The customer wants a feeder for the bearings to help the operator picking them up. This component arrives at the factory floor in lots of forty, packaged inside long plastic tubes. A smaller representation of the packing style can be seen in Figure 65. Instead of constantly reaching for the package to grab a bearing or unload them randomly on the workbench, the operator will only interact with the package once and the bearings will be easily accessible and oriented inside the feeder.



Figure 65 - Bearing package example

Since the customer does not require an automatic feeder, this system will be manually loaded and unloaded by the operator. The simplest concept to apply in this scenario is a gravity feeder. This consists of a vertical guiding system with side openings for the operator to see the number of bearings remaining and to help load the feeder gently. At the bottom, a stopper provides a face to stack the bearings while still allowing the operator to unload them individually. In Figure 66 is shown an example of a gravity feeder concept already used by IPTE in other projects.

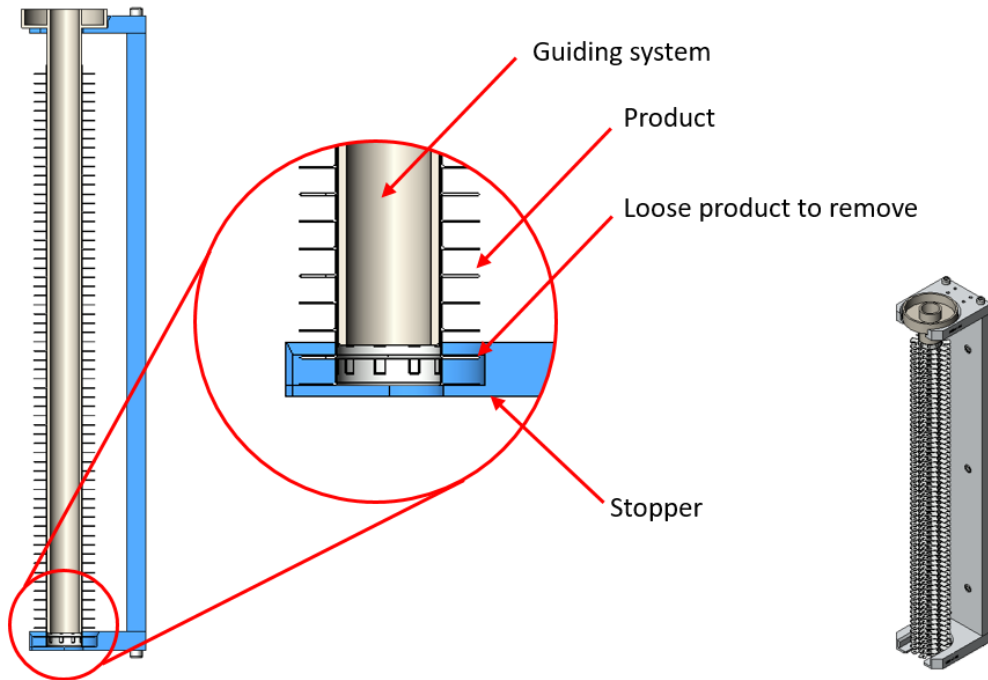


Figure 66 - Gravity feeder concept

Regarding the bearing, which will be loaded into the tool, it is necessary to design a system capable of locking it in place and orient it. The different options taken into consideration for the solution are presented in Table 63, along with their pros and cons. It is also necessary to take into consideration that the tool should be designed in such a way that the pressing load is only applied to the inner ring since it is where the junction to the shaft makes contact (Figure 67). Applying loads to the outer ring may damage the bearing and lead to future product failures.

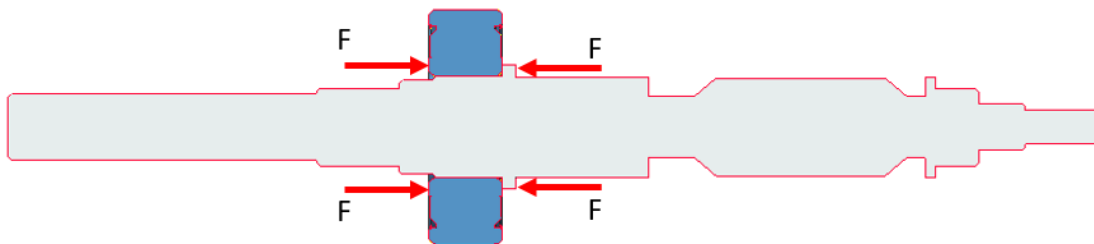

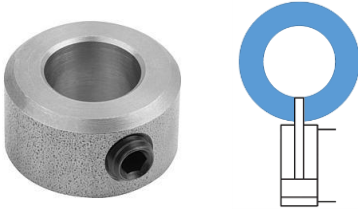



Figure 67 - Bearing press load locations

Table 63 – Station 1.A tool options

	Example	Pros and cons
3-finger gripper [106]		<p>Pros:</p> <ul style="list-style-type: none"> • Self-centered; • Good process control. <p>Cons:</p> <ul style="list-style-type: none"> • Higher cost; • Requires external support for pressing; • Presents a risk for the operator.
Side lock [108]	 <p>(Similar to a shaft collar, but with a linear cylinder in place of the set screw.)</p>	<p>Pros:</p> <ul style="list-style-type: none"> • Good process control; • The same component can center and press; • Safe for the operator. <p>Cons:</p> <ul style="list-style-type: none"> • May cause the bearing to stay off-center; • May leave a contact mark on the bearing.
Magnetic holder [108]		<p>Pros:</p> <ul style="list-style-type: none"> • Low cost; • Simple solution. <p>Cons:</p> <ul style="list-style-type: none"> • Reduced process control; • Accumulates dirt (magnetic particles) over time.

Taking into consideration Table 63, the chosen concept was the side lock. From all the three options presented, it is the one that cons are most easily fixed. The risk of the bearing staying off-center can be avoided by using tight tolerances on the face of the tool that will orient it. The risk that the 3-finger gripper presents for the operator (the gripper would have to close when the operator is loading the bearing) and the accumulation of dirt on the magnet, make this two options unsuitable for the final solution.

Regarding the nest where the shaft will be placed, apart from the considerations already mentioned in subchapter 4.3.3.1, and much like the bearing, the shaft must withstand the pressing load in a specific location, which is indicated in Figure 67. So the challenge is to design a nest that will protect the zone of the shaft that cannot be manipulated, as well as supporting the shaft in the brim previously mentioned. Upon discussion with the customer, it was agreed that the best solution to achieve this, was to create a sliding nest to separate the loading operation from the pressing operation since any direct loading by the operator would facilitate the possibility of touching or hitting the forbidden zone into the nest.

4.3.3.4 Project

In this subchapter, the solution designed to meet the customer’s requirements for station 1.A will be explained in detail. Since the main component is the press and it has already been covered in detail in the subchapter 4.2.1, only the components specifically design for this pressing operation will be addressed.

4.3.3.4.1 Overview

In Figure 68 an isometric representation of the station 1.A can be seen. The components are identified with balloons, and their legend is presented in Table 64. Additionally, other views of this station can be found in Annex II.

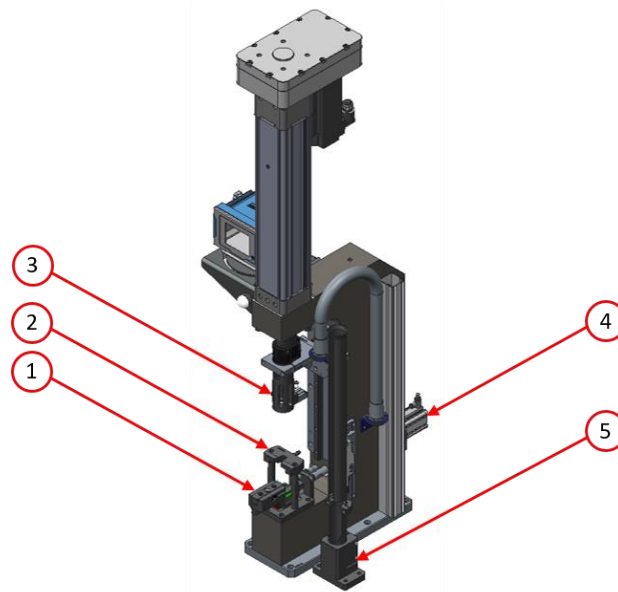


Figure 68 - Isometric view of station 1.A

Table 64 - Station 1.A components

Number	Reference	Description
1	A-A105-99	Nest
2	A-A105-99	Pressing Support
3	A-A108-99	Tool
4	A-A105-99	Nest Carrier
5	A-A110-99	Bearing feeder

4.3.3.4.2 Focal points

The focal points regarding station 1.A are presented and explained in Table 65.

Table 65 - Focal points of station 1.A

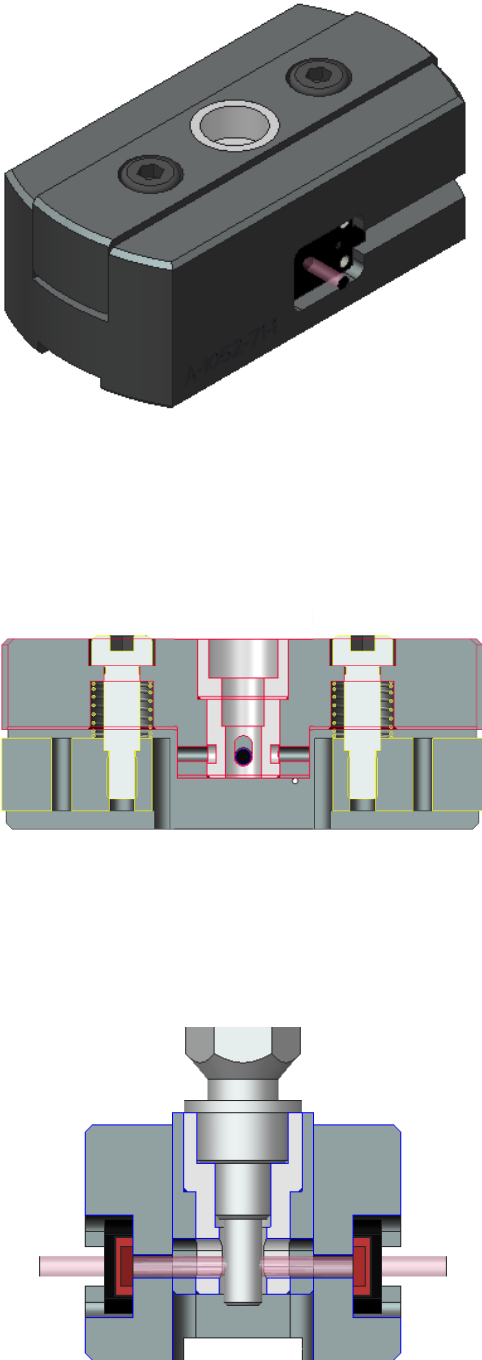
	Illustration	Description
Nest		<p>The nest is mounted onto a carrier and will hold the shaft during the whole press operation. This nest has three main features:</p> <ul style="list-style-type: none"> <p>Spring load: The nest is spring-loaded to transport the shaft until the pressing support without the risk of the shaft's brim hitting the pressing support. This way, the brim enters the support on a higher plane and, when the pressing operation takes place, the press will compress the springs and the brim will rest on the pressing support.</p> <p>PEEK (Polyether Ether Ketone) bushing: To prevent damage to the part of the shaft that will enter the nest (contains a thread and a reference diameter), a PEEK bushing was used. This material is quite resistant to wear, but at the same time is softer than the shaft's material, making it much less likely to damage it. The bushing is held in place by two set screws, making it easy to replace when needed.</p> <p>Photoelectric sensor: Although an inductive sensor could be used to detect the product, due to the small available space to install it, a small photoelectric sensor was preferred. The sensor chosen was the ET3-FT14 from Omron, which has an emitter that sends a 2,5 mm beam to a receiver, which consequently sends a signal to the PLC when the beam is interrupted by the shaft.</p>

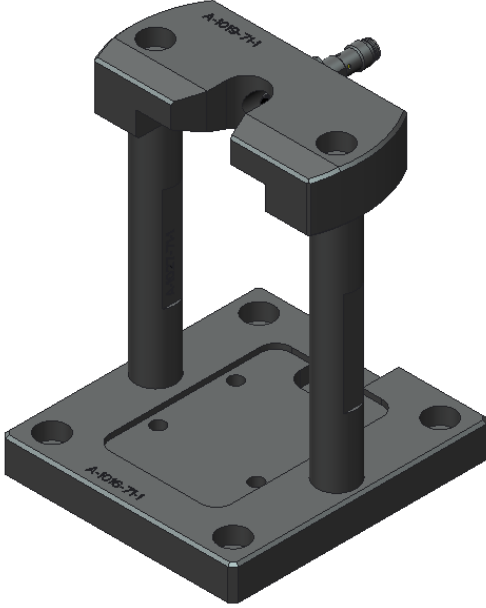
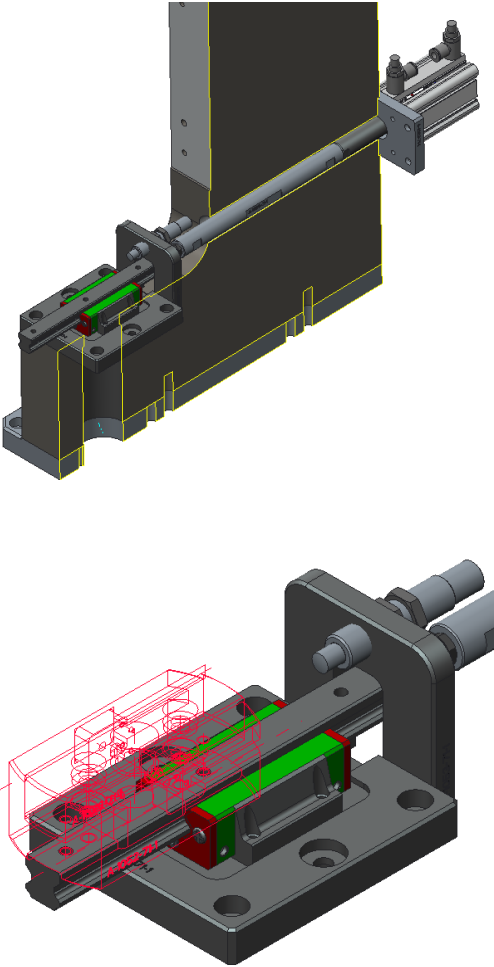
	Illustration	Description
Pressing support		<p>The pressing support is the component that will withstand all the load applied by the press to the subassembly. Since the load applied is relatively small when talking about pressing operations, this support can be designed with a simple construction, meaning that in this case it is made with two $\varnothing 15\text{mm}$ steel columns and the support plate where the shaft's brim will rest. This plate was produced in X153CrMoV12 and quenched, so it could withstand the press load without suffering indentations. It also has several entry chamfers for the eventuality of a direct manual loading needs to be performed. To detect the presence of the shaft and its correct alignment, an inductive sensor was installed at the back of the support.</p>
Nest carrier		<p>The nest carrier does not need to bear any loads or move big masses, for this reason, a simple system with a linear guide and a pneumatic cylinder can be applied. The guiding system chosen is the same that is used for the guiding system of the press. The biggest peculiarity of this system is that instead of a fixed guide and a moving block (common configuration of linear guides), the block is fixed and the nest is attached to the guide that in turn is attached to the cylinder. This allows to free space on the side where the operator will be working. For the same reason, the cylinder was installed on the backside of the press and reaches the front via an extension rod that passes through a hole made in the press body. The hole and the face where this cylinder attaches were specially machined for these components, but in other stations, the hole was used for cable management. Finally, a shock absorber was installed to ensure a smooth entry of the shaft onto the pressing support and to adjust the stopping position of the nest, ensuring a good alignment.</p>

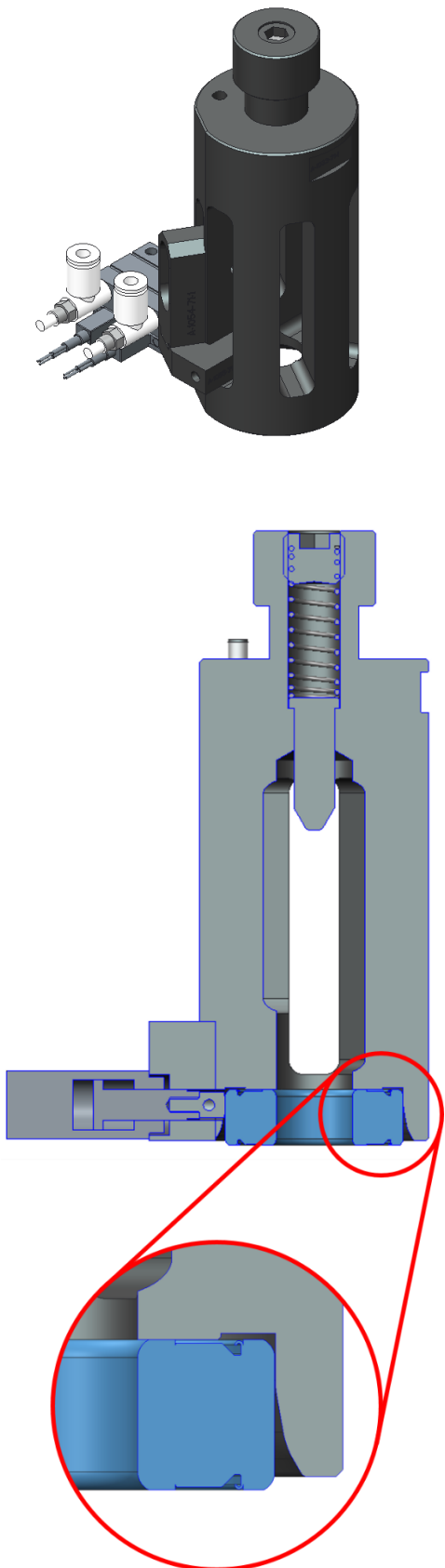
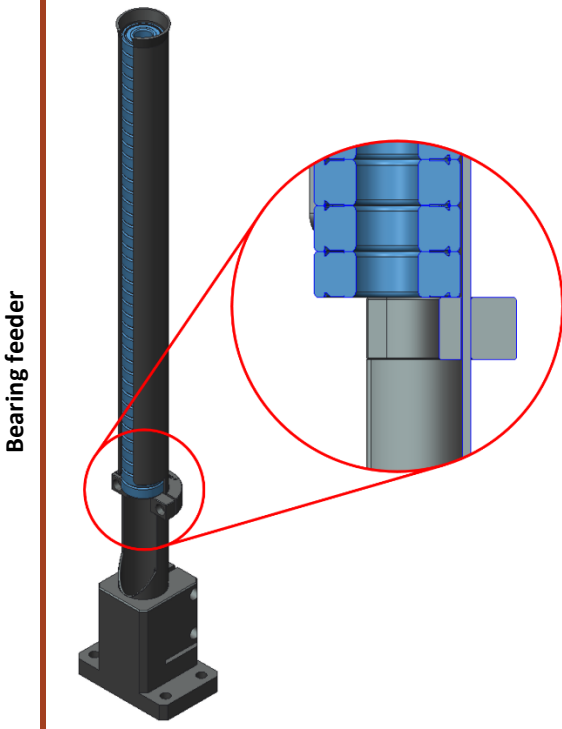
	Illustration	Description
<p>Tool</p>		<p>The tool is responsible for holding the bearing, aligning the bearing, and aligning the shaft (tailstock).</p> <ul style="list-style-type: none"> Bearing lock and orientation: The main component of the tool (A-1033-71) is mainly responsible to orient and support the bearing. In the figure beside it is possible to see the profile of the cavity where the bearing is placed. The entry chamfer allows easy insertion of the bearing and, only in the last few millimeters of the cavity, the bearing is oriented to the pressing position. The detection of the bearing is made through an inductive sensor, which can be adjusted to only signal de PLC when the bearing rests flat on the cavity. A miniature cylinder from SMC (CDUJB10-10D) is used to apply a small side load on the bearing, locking it in place. This cylinder moves forward as soon as the bearing sensor detects its presence. This cylinder is commanded by a 5/3 closed center valve, meaning that when the air is cut, the cylinder does not move, and consequently, the bearing does not fall. Tailstock: The other main feature of the tool is the tailstock. The shaft is oriented and passively supported on a spring-loaded nest (not stiff), thus, a slight misalignment with the tool can exist. The tailstock is responsible to ensure that the shaft axis is aligned with the bearing axis, guaranteeing a smooth insertion of the bearing. This tailstock was achieved with a small spring-loaded shaft. This shaft is installed and guided in the same part that orients the bearing, which reduces possible misalignments between the tailstock and the bearing axis.

Illustration	Description
	<p>The bearing feeder is a very simple vertical gravity feeding system, without detections or automated movements. It is made of only 3 parts, the base, tube, and stopper. The tube has an inner diameter slightly larger than the bearing and is used to guide and store the bearings. This tube has slots and cuts that allow the operator to gently load the feeder, visually know how many bearings are left, and easily remove one bearing at a time. As already mentioned in subchapter 4.3.3.4.2, the bearings come in packs of 40 units, which is exactly the capacity of the feeder. The 40 bearings package is loaded into the tube and are held in place by a stopper. The feeder base holds the tube and is directly attached to the workbench.</p>

4.3.3.4.3 Operation sequence

In this subchapter, and the equivalent subchapter from the upcoming stations, the operation sequence will be explained. A list of all the sensors that detect the parts to assemble and the actuator’s positions will also be made available, including their brands and references (Table 67). All the pneumatic actuators will also be identified as well (Table 66).

This will help to better understand how the operation sequence functions, as well as connect this sequence with the information present in the pneumatic diagram.

Table 66 - Station 1.A actuators

Actuator ID	Brand	Reference	Description
MMA01	Allen-Bradley	MPL-A320P-MJ74AA	Servo press motor
MMB501	SMC	CDUJB10-10D	Bearing lock
MMB511	SMC	CDQ2B32-50DZ	Shaft carrier
TAC01	Allen-Bradley	MPL-A320P-MJ74AA	Servo press motor brake

Table 67 - Station 1.A sensors

Sensor ID	Brand	Reference	Description
BRA07	Omron	E3T-FT14	Shaft presence on the nest
BRC09	Omron	E2A3-S08KS03-M5-B1	Shaft in pressing position
BRC10	Omron	E2E-C04S12-WC-B1	Bearing presence
BRC20	SMC	D-F8PSAPC	Bearing lock (front)
BRC21	SMC	D-F8PSAPC	Bearing lock (back)
BRC22	SMC	D-M9PSAPC	Shaft carrier (back)
BRC23	SMC	D-M9PSAPC	Shaft carrier (front)

The operation sequence of station 1.A will now be explained in Table 68, and the actuators and sensors will be mentioned according to the identifications present in Table 66 and Table 67.

Table 68 - Station 1.A operation sequence

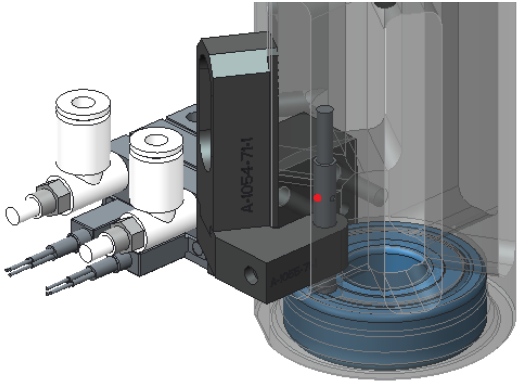
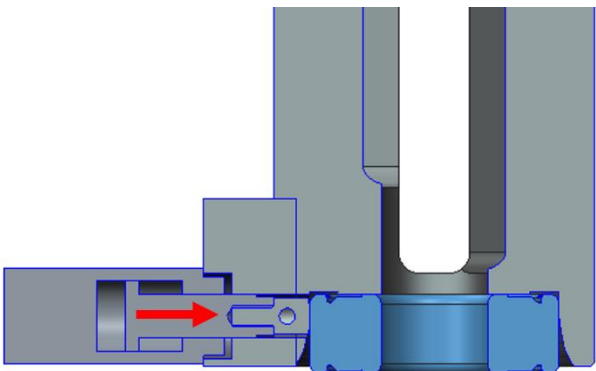
	Illustration	Description
Step 1		<p>The operator loads the bearing into the tool. Once the bearing is located in the desired position, the sensor BRC10 activates and sends a signal to the PLC.</p>
Step 2		<p>As soon as the PLC receives an input from the sensor BRC10 it sends a signal for the actuator MMB501 to move forward. At the end of this step, the PLC now has a signal from BRC10 and BRC20.</p>

	Illustration	Description
Step 3		<p>The operator loads the shaft onto the nest. Once the shaft is inserted, the sensor BRA07 is activated, sending a signal to the PLC.</p>
Step 4		<p>The operator presses start, and if the sensors BRC10, BRC20, and BRA07 are triggered, the safety light curtains are activated. Afterward, the actuator MMB511 moves the nest to the pressing position, which consequently activates the sensors BRC09 and BRC22.</p>
Step 5		<p>At this point, if all the sensors previously mentioned are activated, the PLC commands the servo press to initiate the approach movement at a speed of 80mm/s (the press moves forward at different speeds during the whole operation).</p>
Step 6		<p>When the press is close to initiate contact with the shaft, the velocity drops to 15mm/s. Eventually, the tailstock enters the shaft's center hole, guaranteeing the alignment between the shaft and the bearing.</p>

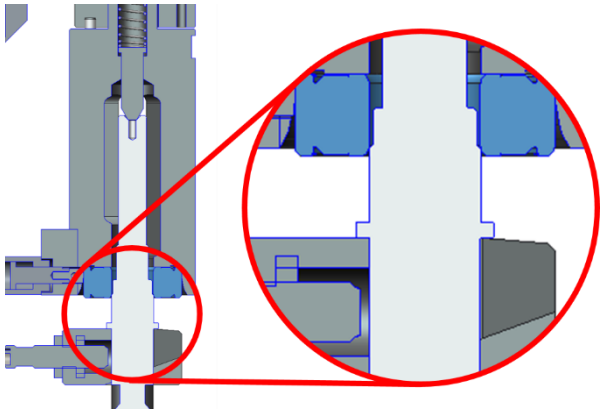
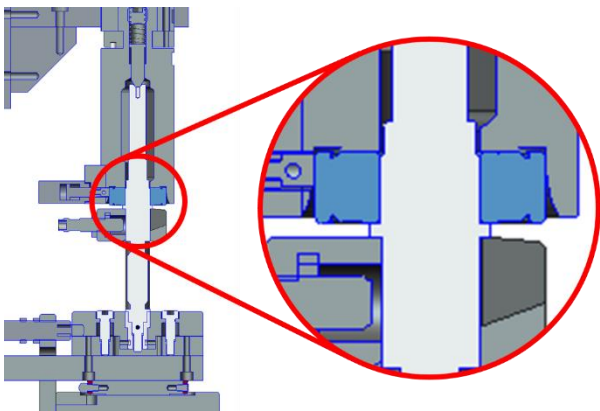
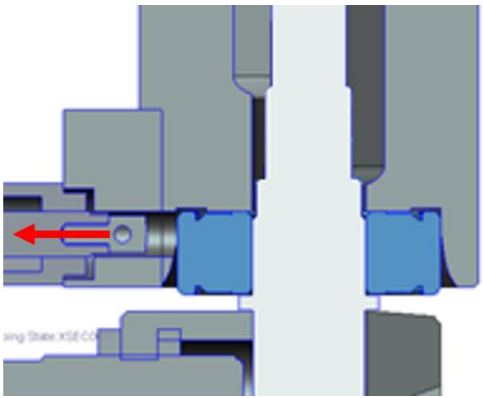
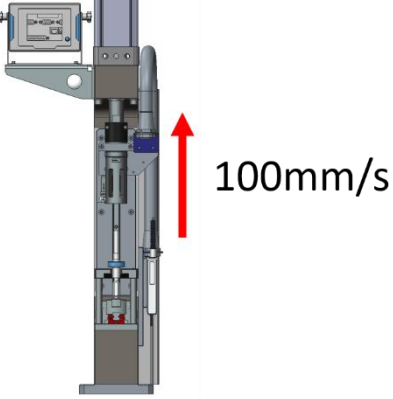
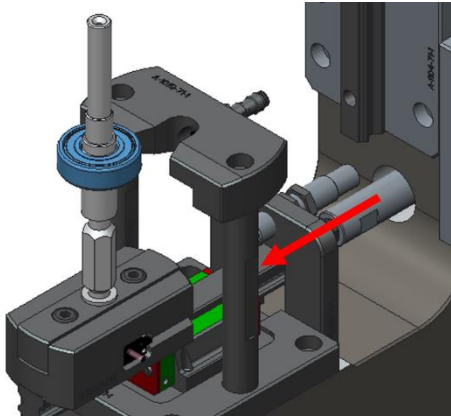
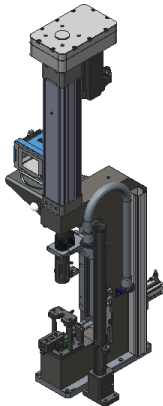
	Illustration	Description
Step 7		<p>Right after the tailstocks aligns the shaft, the bearing initiates contact with the shaft's zone where it will be installed. At this point, depending on the clearance between the shaft and the inner diameter of the bearing, the springs in the nest may or not be compressed.</p>
Step 8		<p>The press slows down once more, and finishes the pressing operation at a speed of 1mm/s, stopping once the peak load of 1kN is achieved. During steps 5-8 the Kistler maXYmos is monitoring the load cell and displacement sensor, and in the end, signals the PLC if the operation was or not successful.</p>
Step 9		<p>The cylinder MMB501 retracts and releases the bearing, activating the sensor BRC21</p>
Step 10		<p>With the signal from BRC21, the PLC commands the servo press to return to the home position at maximum speed (100mm/s).</p>

	Illustration	Description
Step 11		<p>After the servo press is completely retracted, the cylinder MMB551 moves forward. When the sensor BRC23 is activated, the light curtains are deactivated and the process feedback light signals the operator if the subassembly produced is OK or NOK.</p>
Step 12		<p>The operator removes the subassembly, deactivating the sensor BRA07. This resets the station 1.A, making it ready to execute another assembly cycle.</p>

During the design stage of new equipment, the person responsible to execute the mechanical project is usually the person that plans the working sequence, defining all the movements and conditions necessary for the equipment to operate correctly. In order to transfer this information (present in Table 68) to the team responsible for the programming of the PLC, a GRAFCET can be created. These charts are commonly used to establish the link between these two engineering departments and, for this assembly line, GRAFCETS were used for this exact purpose.

The GRAFCET of station 1.A can be found in Annex III, which is divided into three separate charts. The first chart (X100) describes, simultaneously, the normal operating cycle of the machine and the step-by-step mode. The other two charts (X400 and X300) describe the safety circuits of the machine.

The chart X400 describes the safety cycle for when the safety light curtains are interrupted, while the chart X300 describes the safety cycle of the emergency button. This last chart interlinks both substations of station 1, since this station only has one emergency button. When this button is activated the whole machine must come to a stop and all the power supplies must be shut-off, but when the safety light curtains are interrupted only the substation affected must come to a stop, while the other can continue to operate normally.

4.3.3.4.4 Dimensioning and selection criteria

Pressing support FEM analysis

The pressing support needs to withstand the 1 kN load used to press the bearing onto the shaft and, much like the press frame, the displacement values should not surpass 0,05 mm. In order to validate the design achieved, a FEM analysis was performed in Solidworks®.

Just like the studies performed to the bottom structures, the pressing support assembly was converted into a Solidworks® part file, but in this case, it was still possible to define the global contact and connections between the components without errors during the study.

The definition of the materials, fixtures, and external loads used for this study are presented from Table 69 to Table 71, respectively. Regarding the material, since the material used for the column and base, 40CrMnMo7 (1.2738), was not available in Solidworks®, a material with similar properties was selected to use in this analysis.

Table 69 - Pressing support material properties

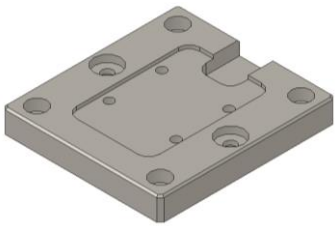

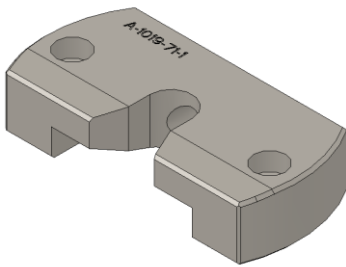
	Illustration	Properties														
Base		<table border="1"> <tr> <td>Material</td> <td>40CrMnMo7 (1.2311)</td> </tr> <tr> <td>Yield strength</td> <td>821MPa</td> </tr> <tr> <td>Tensile strength</td> <td>992 MPa</td> </tr> <tr> <td>Elastic modulus</td> <td>205 GPa</td> </tr> <tr> <td>Poisson's ratio</td> <td>0,28</td> </tr> <tr> <td>Mass density</td> <td>7800 kg/m³</td> </tr> <tr> <td>Shear modulus</td> <td>79 GPa</td> </tr> </table>	Material	40CrMnMo7 (1.2311)	Yield strength	821MPa	Tensile strength	992 MPa	Elastic modulus	205 GPa	Poisson's ratio	0,28	Mass density	7800 kg/m ³	Shear modulus	79 GPa
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Mass density	7800 kg/m ³															
Shear modulus	79 GPa															
Support plate		<table border="1"> <tr> <td>Material</td> <td>X153CrMoV12 (1.2379)</td> </tr> <tr> <td>Yield strength</td> <td>1034 MPa</td> </tr> <tr> <td>Tensile strength</td> <td>1158 MPa</td> </tr> <tr> <td>Elastic modulus</td> <td>200 GPa</td> </tr> <tr> <td>Poisson's ratio</td> <td>0,27</td> </tr> <tr> <td>Mass density</td> <td>8000 kg/m³</td> </tr> <tr> <td>Shear modulus</td> <td>80 GPa</td> </tr> </table>	Material	X153CrMoV12 (1.2379)	Yield strength	1034 MPa	Tensile strength	1158 MPa	Elastic modulus	200 GPa	Poisson's ratio	0,27	Mass density	8000 kg/m ³	Shear modulus	80 GPa
Material	X153CrMoV12 (1.2379)															
Yield strength	1034 MPa															
Tensile strength	1158 MPa															
Elastic modulus	200 GPa															
Poisson's ratio	0,27															
Mass density	8000 kg/m ³															
Shear modulus	80 GPa															

Table 70 - Fixtures used for the bottom structure analysis

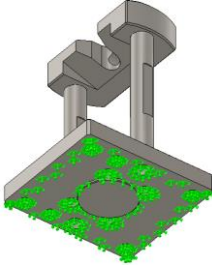
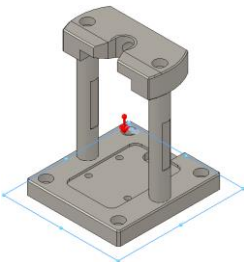
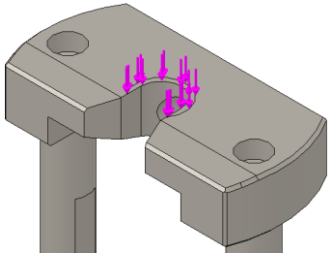
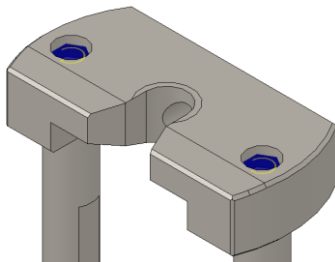
Illustration	Fixture details
	<ul style="list-style-type: none"> • Entities: 1 face; • Type: Fixed geometry.

Table 71 - External loads used regarding the pressing support analysis

External loads	Illustration	Properties
<p>Gravity</p>		<ul style="list-style-type: none"> • Reference: Top plane; • Value: 9,81 m/s².
<p>Load</p>		<ul style="list-style-type: none"> • Entities: 1 face; • Type: Normal load; • Value: 1000 N.

In this assemble the parts are held together by fours M6 screws, thus, this connection was defined in the software. This information can be seen in Table 72. The global contact between the components was defined as “no penetration”.

Table 72 - Connection defined for the pressing support analysis

Connection	Illustration	Properties
<p>Counterbore screw</p>		<ul style="list-style-type: none"> • Number of connections: 4; • Head diameter: 10 mm; • Nominal shank diameter: 6 mm; • Preload (torque): 10 N·m; • Young's modulus: 210 GPa.

With all the conditions to perform the study defined, the mesh type and parameters were then defined. The most important information regarding the mesh used can be seen in Table 73 and a representation of the mesh generated can be seen in Figure 69.

Table 73 - Information regarding the mesh used for the pressing support analysis

Mesh type	Solid mesh
Mesher used	Standard mesh
Element size	2,86 mm
Tolerance	0,14 mm
Total Nodes	99 190
Total elements	63 522

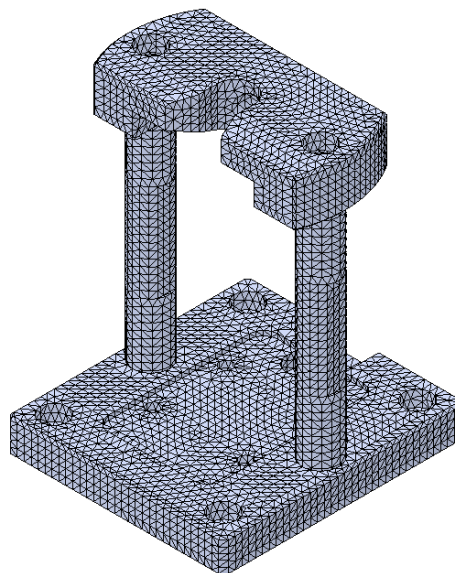


Figure 69 - Mesh generated for the pressing support analysis

With all the conditions and mesh defined, the FEM analysis was performed. The results achieved for the von Mises equivalent stress and displacement can be seen, respectively in Figure 70 and Figure 71.

Analyzing the values obtained, the maximum value registered for von Mises equivalent stress was 130,6 MPa and the maximum displacement achieved was approximately 0,036 mm. Regarding the von Mises equivalent stress, it is possible to state that a weaker material could have been used, the stress registered is very far from the yield strength of both material, but when taken into consideration the acceptable displacement limit for this assembly (0,05 mm), it is shown that the materials selected are suitable for this application.

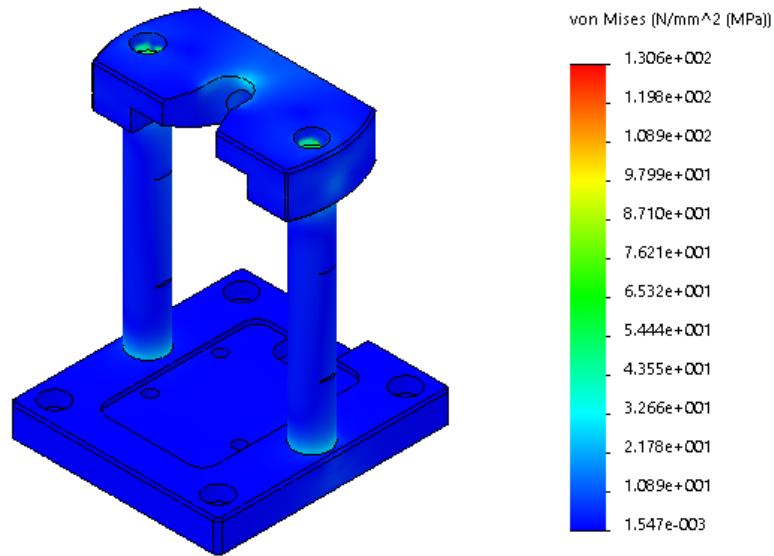


Figure 70 - Von Mises equivalent stress from the pressing support analysis

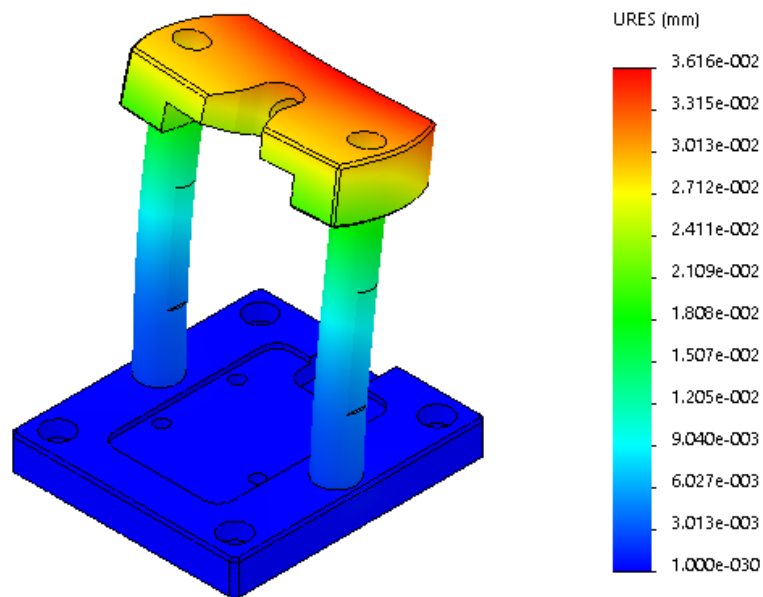


Figure 71 - Displacement from the pressing support analysis

Linear actuator from the bearing side lock

This actuator must apply enough load to hold the bearing 1 inside the tool. To validate this actuator is necessary to calculate how much load the actuator must apply on the bearing so that the resulting friction force is greater than the weight of the bearing, which is approximately 0,062 kg. The frictional coefficient used was 0,8 which is the worst-case scenario between two steel parts.

The friction force (F_f) is given by the following equation:

$$F_f = \mu \times N \quad (12)$$

Where,

F_f – Friction force [N]

μ – Coefficient of friction

N – Normal load [N]

In this case, the normal friction force will be replaced by the weight of the bearing times the gravity acceleration (approximately $9,81 \text{ m/s}^2$), which will consequently allow knowing the normal load that the actuator needs to apply:

$$\begin{aligned} W \times g &= 0,8 \times N & (13) \\ \Leftrightarrow N &= \frac{0,062 \times 9,81}{0,8} \approx 0,76 \text{ N} \end{aligned}$$

The actuator selected for this job was the CDUJB10-10D from SMC, and in the catalog is stated that at 6 bar this actuator is capable of outputting a force of approximately 47,1 N, which is more than enough and validates this actuator for this application.

Linear actuator from the nest carrier

This actuator was selected from the CAD library already existing at IPTE. It was selected due to its dimensions, being that no calculations were made to implement it. The actuator selected was the CDQ2B32-50DZ from SMC and according to its catalog it has a theoretical force of approximately 482,5 N in the forward motion and 362,5 N in the return motion, which is more than enough for the application in question.

The linear guide from the nest carrier

The linear guide used to hold the nest was not dimensioned either. This guide will not suffer any loads apart from the weight of the nest and the subassembly 1, since the pressing load is bared by the pressing support. Thus, the guide used was the standard type commonly used at IPTE, the HGW15CCZ0H from HIWIN, which is capable of bearing a dynamic load of 14,7 kN, meaning that the guide should fit the job without any issues. If by any chance the pressing load reaches the linear guide it should not be a problem as well since this load is around 1 kN.

The linear guide from the press tool

The linear guide used to align the tool with the nest was not dimensioned either. This guide will, theoretically, not suffer any loads since the press is attached to the tool through a floating joint. Thus, the guide used was the standard type commonly used at IPTE, the HGW15CCZ0H from HIWIN. Additionally, in the first two stations presented in this dissertation, no linear guides were dimensioned, only in station four exists a case that requires study since the guides will be under direct load. Still, in order to demonstrate the procedure needed to validate and dimension a linear guide, the theoretical hypothesis of the tool's block getting jammed and prevented from sliding on the rail will be analyzed and studied. In this case, the block would receive a load of 1kN from the servo press.

To analyze a linear guide system is necessary to identify all the loads and moments that will be applied to the linear guiding system. The supplier defines in the catalog the maximum allowable values for such loads and moments, which must be respected to ensure that the system is not compromised or likely to fail. In Figure 72 is possible to see the maximum allowable loads and moments for the linear guide selected for this application.

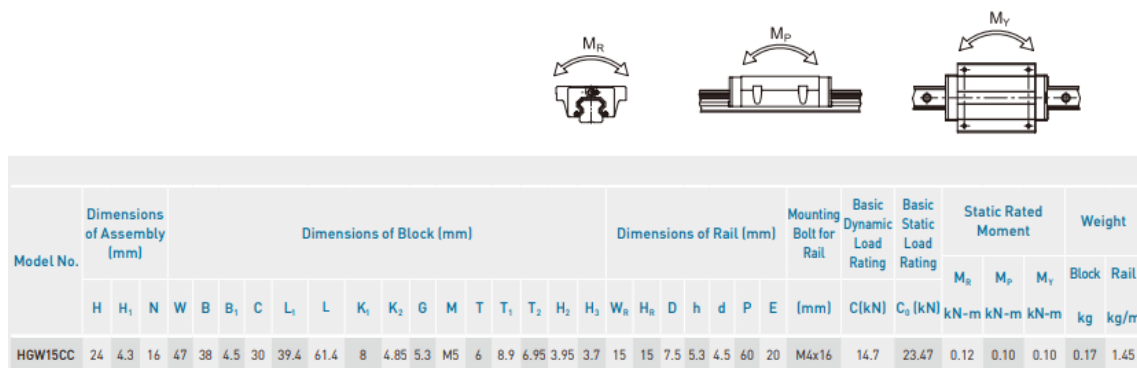


Figure 72 - Maximum loads and moments allowed according to the linear guide supplier

For the linear guide of the press tool, the main load applied is the 1 kN load, but the tool weight is also a factor to take into consideration. In Figure 73 the location of the press load and tool's center of gravity is given, as well as their values. Analyzing the location of these loads is possible to identify which moments the linear guide will be subjected to. In Figure 73.a is possible to observe that the press load will not apply any moment in relation to the Y or X-axis, but the weight generated a moment around the Z-axis, which is identified in the catalog as M_Y and must be lower than 0,10 kN·m. In Figure 73.b is shown that both loads will generate a moment around the X-axis, which is identified in the catalog as M_P , having a maximum allowable value of 0,10 kN·m as well. These are the two moments that need to be calculated in order to validate the linear guides selected.

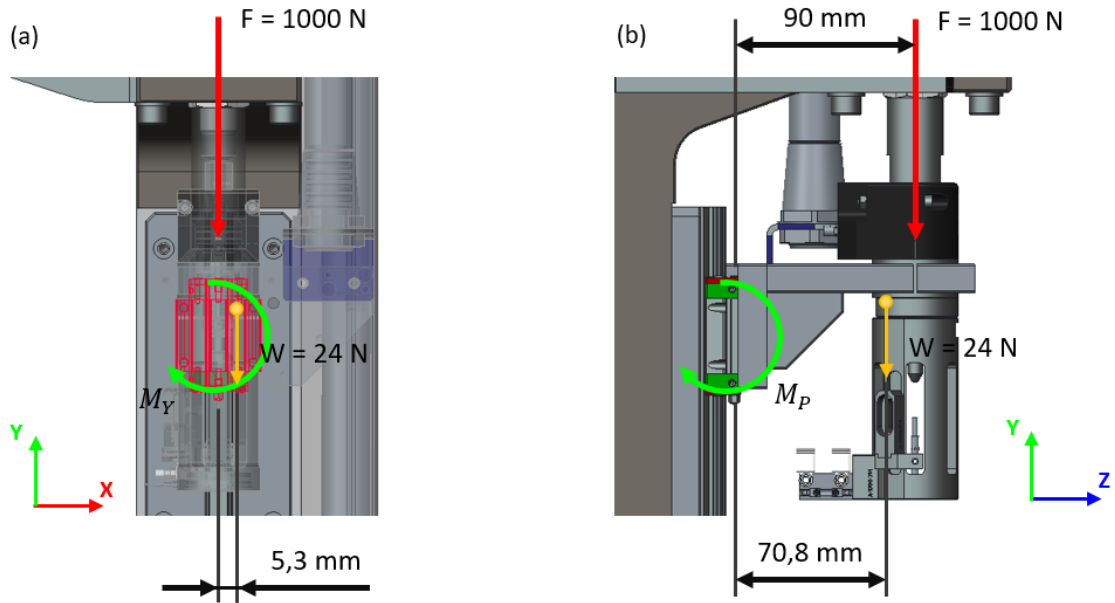


Figure 73 - Free body diagram of the press tool linear guide: a) Front view; b) Left view;

With the load values and locations known, it is now possible to calculate M_P and M_Y , which are respectively shown in equation (14) and (15).

$$M_P = (1 \times 0,09) + (0,024 \times 0,0708) \tag{14}$$

$$\Leftrightarrow M_P = 0,09 + 0,0017 \approx 0,092 \text{ kN} \cdot \text{m}$$

$$M_Y = (0,024 \times 0,0053) \tag{15}$$

$$\Leftrightarrow M_Y \approx 0,0001 \text{ kN} \cdot \text{m}$$

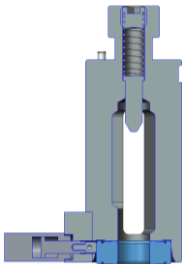
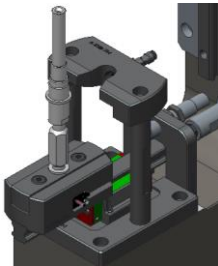
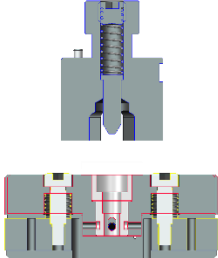
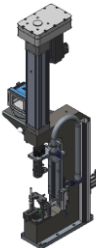
Comparing the values achieved through the calculations to the values given by the catalog is possible to see that M_P (0,092 kN·m) comes quite close to the maximum value specified by the supplier (0,1 kN·m). In normal scenarios, this could lead to a replacement of the linear guide by another capable of bearing higher moments and loads, but since this study is hypothetical and this should never happen under normal conditions, the linear guide initially selected will be kept. The M_Y calculated was 0,0001 kN·m, which is very far from the maximum 0,1 kN·m specified by the supplier.

The results achieved in this study validate the linear guide selected, even though these calculations were only made for demonstration purposes.

4.3.3.5 Final remarks

This station allowed to develop and implement various simple and innovative solutions that, through careful planning and meticulous design choices, were capable of complying with all the customer’s requirements. Some of the main challenges and innovative solutions achieved are presented in Table 74.

Table 74 - Main challenges and solutions from Station 1.A

Problem	Illustration	Solution
<p>How to secure the bearing onto the tool and locking it in such a way that it will not fall when the safety light curtains are interrupted?</p>		<p>A side pneumatic lock was used. This solution allows locking the bearing as soon as the operator inserts it onto the tool since the valve group that controls the actuator is isolated from the security system of the safety light curtains. The 5/3 closed center valve used, ensures that the bearing will never fall, even if the air supply is shut-off.</p>
<p>How to isolate and protect the zone of the shaft that cannot be touched during the insertion of the shaft onto the nest?</p>		<p>One of the main requirements is to never touch and prevent contact with a specific zone of the shaft. To allow this, in this station, a carrier was added to separate the loading zone from the pressing zone, giving to the operator a free zone to load the shaft.</p>
<p>How to guarantee the alignment between the shaft and the bearing to not influence the results of the values measured?</p>		<p>The shaft’s nest is spring-loaded, which allows it to float. This mechanism has two purposes, first is to allow the shaft to rest on the pressing support, and secondly, it gives to the shaft the flexibility required so that the counterpoint can align it perfectly with the bearing, ensuring a smooth assembly of the components.</p>
<p>How to design a press capable of being adapted to various operations with the least amount of changes possible?</p>		<p>The press was designed through a persistent effort to use the same components and concept in all the pressing operations, which was accomplished. This component is explained in deep detail in the subchapter 4.2.1. The solution achieved was a compact and flexible servo press system.</p>

When the station 1.A finishes its operating cycle, the operator collects the subassembly 1 from the nest and moves to the station 1.B, where the next components will be assembled.

4.3.4 Station 1.B

4.3.4.1 Operation and main considerations

The station 1.B will execute the operation 2 and 3 (see Table 20). First, the subassembly 1 will be inserted in the housing and after it will be locked in place by a retaining ring. This will be done in two separate steps. The resulting product from this station will be the subassembly 3 (an exploded view can be seen in Figure 74).

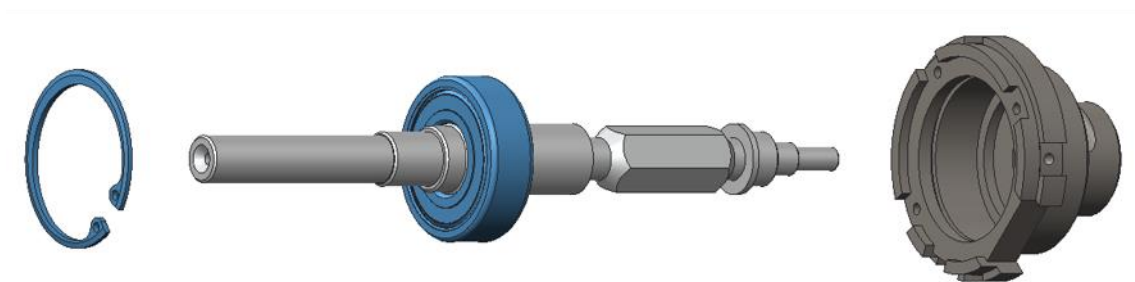


Figure 74 – Exploded view of subassembly 3

The retaining ring must be inserted in a specific orientation. Once the sense magnet it pressed, which is after the installation of the PCB, the motor can only be disassembled if the retaining ring is removed. The sense magnet does not allow the removal of the PCB, and the retaining is hidden under it. This being said, the PCB has an opening where the holes of the retaining ring should be exposed to allow the removal with a pair of pliers. Besides this, the retaining ring also possesses a small chamfer that must be placed upwards. This chamfer is responsible to apply a downwards load on the bearing and in this way guarantees that the outside ring of the bearing has a null axial play. A representation of this orientation is presented in Figure 75.

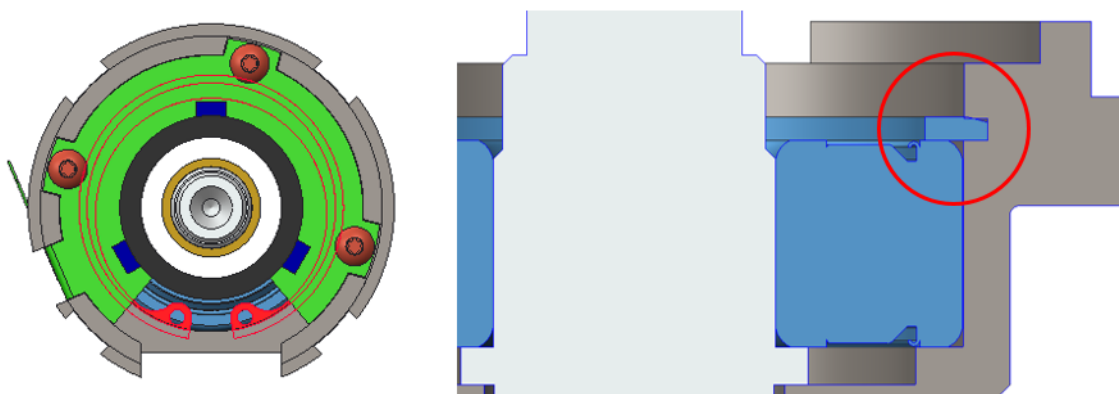


Figure 75 - Retaining ring orientation

Regarding the subassembly 1, the restrictions concerning the zone of the shaft that cannot be touched are still present in this operation. In fact, it will persist throughout the entire assembly line. For this reason, from the point when the shaft is installed on the housing and until the end, the customer wants to avoid a manual vertical load or unload of the product (along the axis of the shaft). Whenever possible, the product should be loaded and unloaded using the half-holes of the housing (Figure 77), in a direction perpendicular to the shaft axis.

Regarding the insertion of subassembly 1, is important to mention that the shaft's orientation points used in the previous operation, cannot be used in this station. Instead, the subassembly 1 must be oriented by the section of the shaft that stays above the bearing, which presents yet another challenge. This section of the shaft has four grooves that were pressed onto it, in order to create a protruding edge for a tighter installation of the sense magnet and rotor. These protruding edges are similar to the example presented in Figure 76. These edges cannot be damaged until the assembly of the components just mentioned.



Figure 76 - Protruding edges for a press-fit assembly

The bearing is the component that guarantees the alignment between subassembly 1 and the housing and they assemble with a clearance fit. The housing also possesses a pre-alignment diameter (slightly larger than the diameter where the bearing will be installed) above the slot where the retaining ring will expand. This diameter facilitates the entry of the bearing, reducing the likelihood of it getting wedged.

Regarding the housing, this is the component that will be used to fix the motor on its application. Thus, for this reason, the housing has three reference points specifically designed to align it, a reference face (A), a diameter (B), and two half holes (C). These three main orientation points are highlighted in Figure 77.

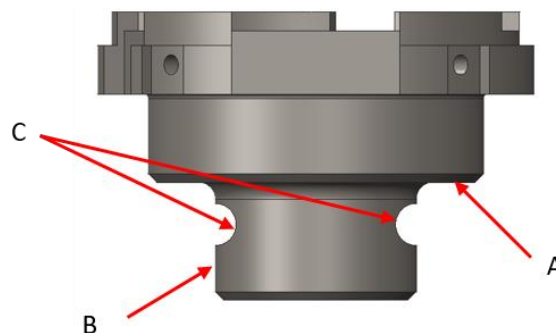


Figure 77 - Housing orientation points

Besides these orientation points already mentioned, the housing has more than one cylindrical face which can be used to center it, however, to stop it from twisting, only the two half holes are available. During the design of this station, the necessity to find a different anti-rotation point emerged. The reason why will be explained upfront, but a representation of the new orientation point can be seen in Figure 78. It consists of taking advantage of two points created (on the largest diameter) by a relief cut, to create a plan that is parallel in relation to the housing axis and perpendicular to the half holes axis.

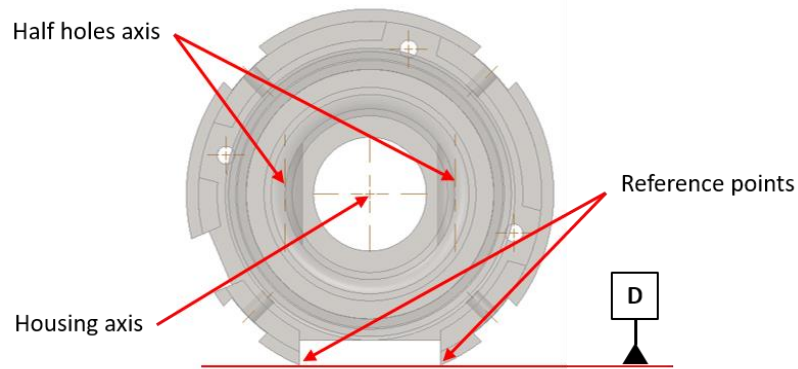


Figure 78 - Alternative anti-rotation reference for the housing

The only component left to evaluate is the retaining ring. From the manufacturer catalog, it is possible to obtain most of the dimensions and tolerances. The representation of the dimensions can be seen in Figure 79.

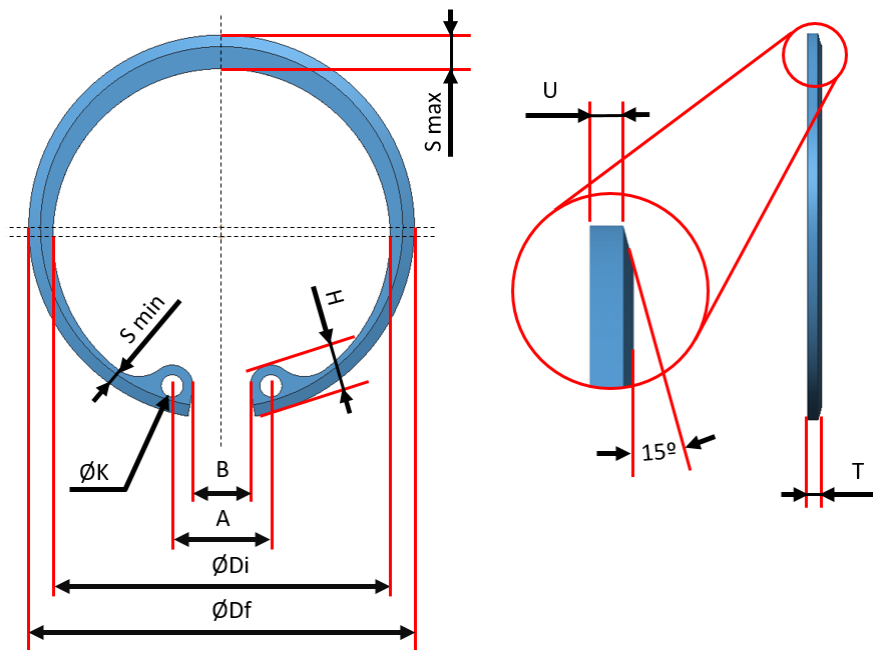


Figure 79 - Retaining ring dimensions

Besides the information given by the catalog, during the design stage, it was necessary to deduce certain pieces of information that are not present in the catalog, which are the dimensions D_i , A , and B , as well as the load necessary to close the retaining ring. To achieve this, a sample of 50 retaining rings, from different batches, was collected and analyzed. These three dimensions were measured and related to the external diameter of the retaining ring, in order to create a trendline. The resulting graphics are presented in Figure 80, Figure 81, and Figure 82, but with the dimensions occulted since this cannot be shared. Once the trendlines were established, it was possible to consult the catalog and obtain the maximum and minimum dimensions for the D_f . Using these values and the linear equations present in the graphics, it is possible to estimate the maximum and minimum values for D_i , A , and B . It is important to mention that the values calculated are only approximate and were used carefully, with the largest clearance possible.

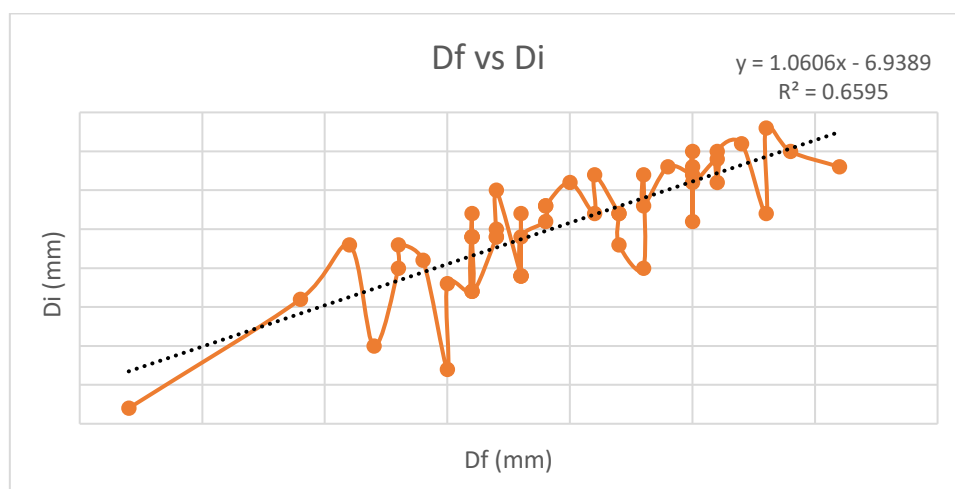


Figure 80 - Df vs Di relation

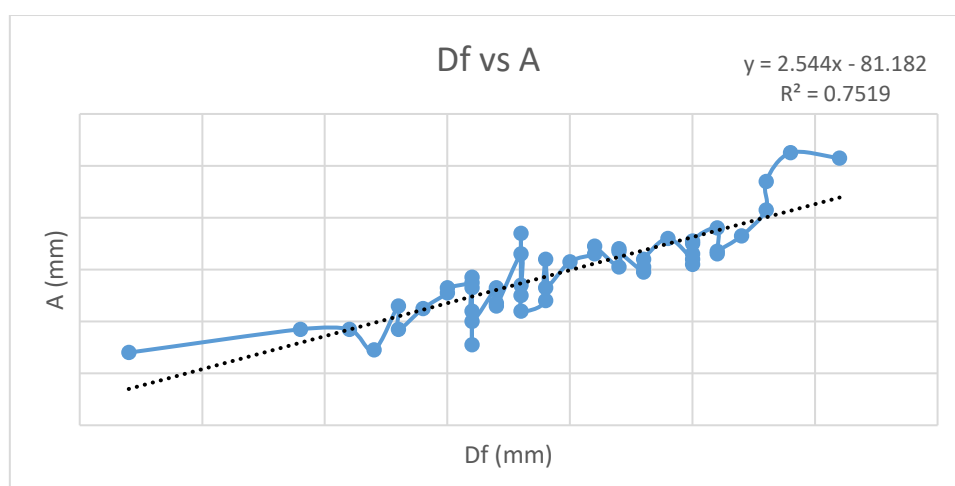


Figure 81 - Df vs A relation

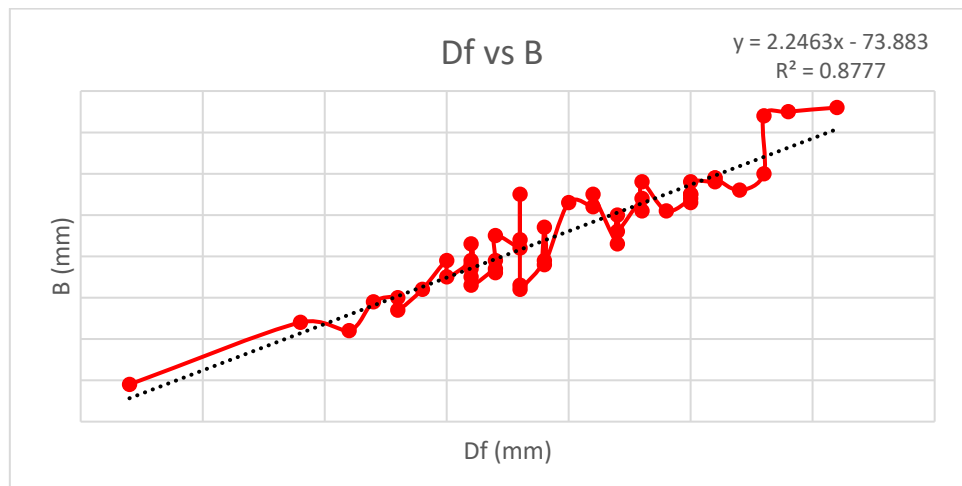


Figure 82 - Df vs B relation

Regarding the load needed to close the retaining ring, the same sample of 50 parts was tested using a digital load gauge. The test consisted of holding the retaining ring in suitable 90° pliers and then applying a load to the fingers of the pliers with the digital load gauge press. No load was applied on the pliers handle during the tests, meaning the pliers were solely used to hold the retaining ring and transmit the force. A representation of the test conditions can be seen in Figure 83.

Is important to state that the results from these measurements are an approximation of reality and the influence of the pliers on the measurements is unknown. Still, with the results provided by the test, and using a safety factor, it was possible to calculate an actuator to close the retaining rings. The result from the 50 measurements can be seen in the graphic of Figure 84.

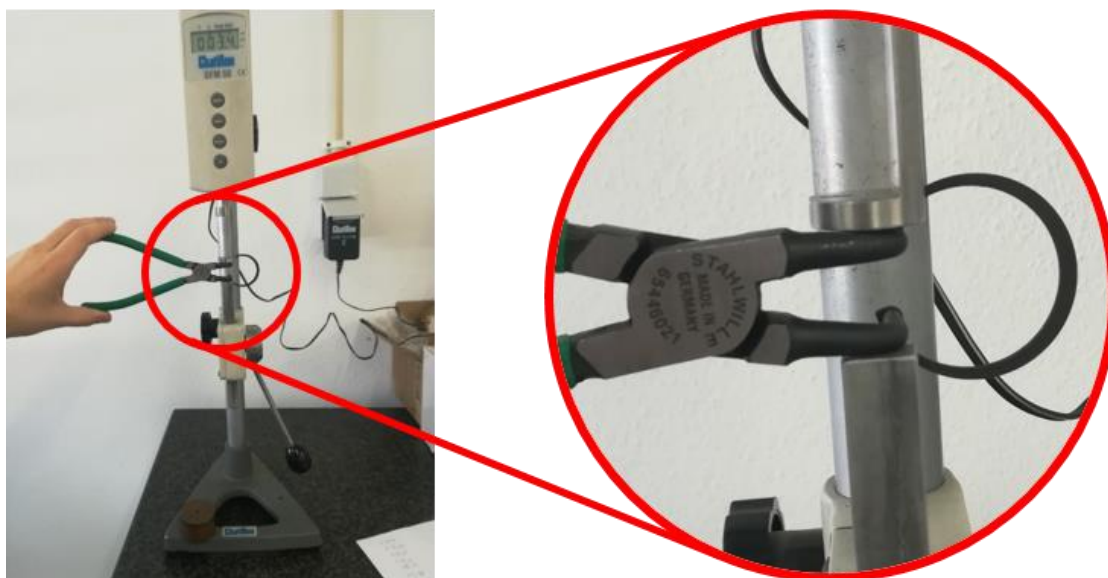


Figure 83 - Retaining ring closing load test

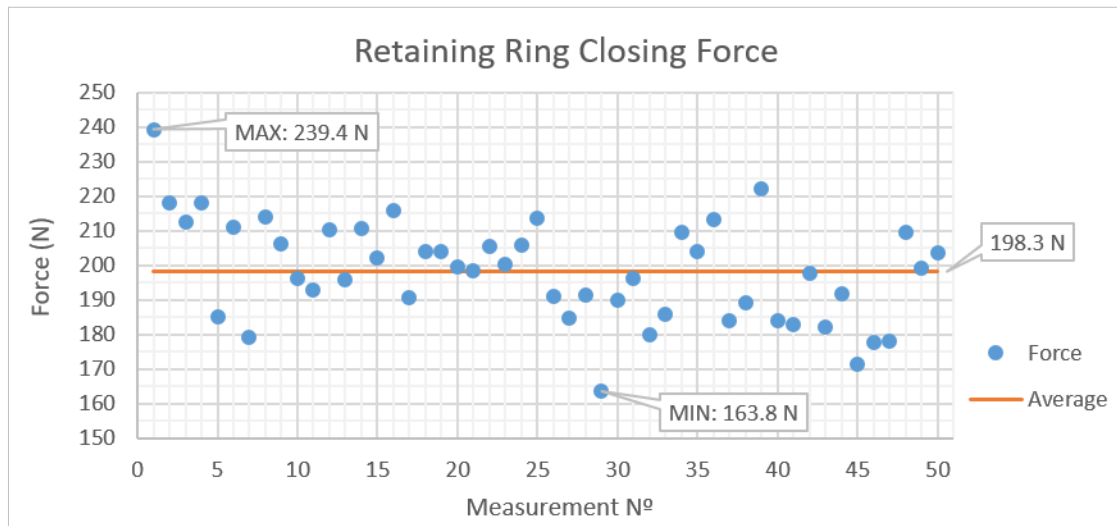


Figure 84 - Retaining ring closing load measurements

4.3.4.2 Specifications

The requirements imposed by the customer for the station 1.B are listed in Table 75.

Table 75 - Station 1.B specifications

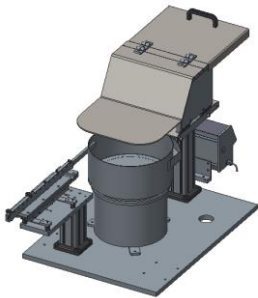
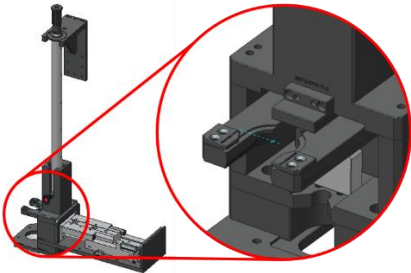
Specification	Description
Parts loading	<ul style="list-style-type: none"> Manual loading of subassembly 1 on the tool; Manual loading of the housing on the nest; A retaining ring feeder must be provided (manual loading/automatic feed) with autonomy for at least 100 units.
Part detection	<ul style="list-style-type: none"> Detection of the parts in the nests and throughout the whole assembly operation; The retaining ring buffer level must be supervised.
Process	<ul style="list-style-type: none"> Is necessary to check if the retaining ring is correctly installed; The retaining ring must be oriented in such a way that aligns with the relief present in the housing and the chamfer is placed upwards; The insertion of subassembly 1 into the housing can be done pneumatically but must be prepared to exchange the pneumatic actuator for an electric one; In case of emergency activation, the parts should stay stationary.

4.3.4.3 Brainstorm

For station 1.B there are four main components to design, the retaining ring feeder, retaining ring insertion tool, the subassembly 1 insertion tool, and the housing nest.

Starting with the retaining ring feeder, for this mechanism, two systems were considered, a vibratory feeder and a gravity feeder with a pusher. The first system is vastly used in automation, for the most various application, and there are a lot of companies dedicated to the development of these systems, therefore its design would be outsourced. The second option would be developed in house and would consist of a system similar to the bearing feeding already used in station 1.A, although, instead of manual picking, an actuator would push the retaining rings individually out of the vertical feeder. In Table 76, the two systems are analyzed and a list of pros and cons is presented. It is also important to remind that the mechanism developed needs to orient the retaining ring, as explained in the subchapter 4.3.4.1.

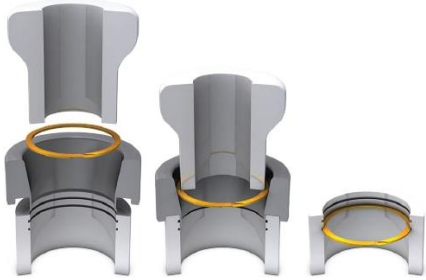

Table 76 - Retaining ring feeder options

	Example	Pros and cons
Vibratory feeder		<p>Pros:</p> <ul style="list-style-type: none"> • Outsourced; • Large capacity. <p>Cons:</p> <ul style="list-style-type: none"> • Higher cost; • Very hard, or even impossible, to orient the retaining ring.
Vertical gravity feeder		<p>Pros:</p> <ul style="list-style-type: none"> • Lower cost; • Easier to orient the retaining ring. <p>Cons:</p> <ul style="list-style-type: none"> • Possible design complications due to the retaining ring geometry; • The operator will be responsible to place the chamfer on the right orientation.

Looking at the pros and cons, the major deciding factor was the orientation of the retaining ring. Due to the complexity of designing a vibratory system capable of orienting the ring, especially its chamfer, this option was abandoned and the vertical gravity feeder was adopted. IPTE Ovar has experience developing this type of equipment, which means that previous designs can be adapted.

For the retaining ring insertion, two options are presented in Table 77. The most common solution found in automated assemblies consists of using an insertion tool with a tapered hole. Regarding internal retaining rings, when being pushed through the tapered hole, the retaining ring contracts until the size of the bore where it will be installed, expanding when it reaches the respective groove and locking in place. The second option consists of designing an automated system that emulates the movement of common retaining ring pliers. This system is more complex since a geared system must be implemented to synchronize the fingers' movement. Taking into consideration the pros and cons, although it is more complex and time-consuming, the option chosen was to design the automated mechanical pliers. It is required by the customer that the retaining ring must be installed in a specific orientation, therefore the tapered inserter mechanism cannot be used.

Table 77 - Retaining ring insertion options

	Example	Pros and cons
Tapered inserter [109]		<p>Pros:</p> <ul style="list-style-type: none"> • Simple solution; • Lower cost. • Standard solutions available; <p>Cons:</p> <ul style="list-style-type: none"> • Not possible to control the retaining ring orientation during insertion.
Automated pliers [111]		<p>Pros:</p> <ul style="list-style-type: none"> • The orientation of the retaining ring is guaranteed. <p>Cons:</p> <ul style="list-style-type: none"> • Higher cost; • Most complex solution.

Concerning the nest, which will receive the housing, it will have to be designed in such a way that only allows the subassembly 3 to be unloaded in a direction perpendicular to its axis, meaning that the housing will need to be loaded in this direction as well. Originally the idea was to orient the housing through its half holes, but due to space restriction and the way that station 1.B was laid out, the housing ended up being oriented through the plan mentioned in Figure 78. A representation of the housing loading is shown in Figure 85. The idea is to center the housing using one of its external round faces and the plane created by the two points in the relief, to prevent rotation. Once the housing is inserted onto the nest, is necessary to secure it in place. To achieve this, two options were considered and are presented in Table 78.

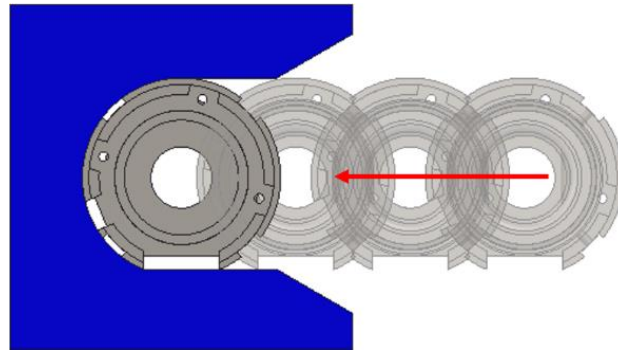


Figure 85 - Nest loading representation

Table 78 - Housing lock options

	Example	Pros and cons
Gripper		<p>Pros:</p> <ul style="list-style-type: none"> • Self-centered; • Supplier ready product. <p>Cons:</p> <ul style="list-style-type: none"> • Higher cost; • Harder to implement.
Side wedge		<p>Pros:</p> <ul style="list-style-type: none"> • A simple and cheaper solution; • Easier to implement. <p>Cons:</p> <ul style="list-style-type: none"> • May leave a mark on the housing.

These two solutions are both viable, although the side wedge seems more attractive from a design and financial point of view. Thus, a test was made to simulate the wedge and see if it would leave a mark on the housing. It was found that a small cylinder with an $\varnothing 10\text{mm}$ bore was strong enough to guarantee that the housing was centered, while not having enough strength to leave a mark. For this reason, the side wedge option was applied.

Regarding the tool that will install the subassembly 1 on the housing, the options considered were basically the same as the ones for the tool of station 1.A, and a listing of the pros and cons are taken into consideration was already shown in Table 63. For the same reasons, the side lock was also chosen for this application. During the tool design stage, special attention will be given to the protruding edges of the shaft.

4.3.4.4 Project

4.3.4.4.1 Overview

In Figure 86 an isometric representation of the station 1.B can be seen. The components are identified with balloons, and their legend is presented in Table 79. Additionally, other views of this station can be found in Annex II.

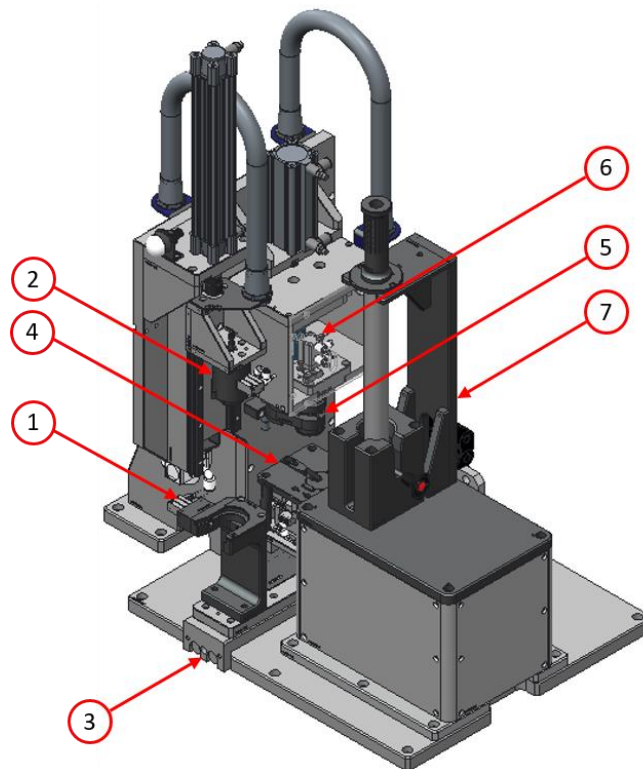


Figure 86 - Isometric view of station 1.B

Table 79 - Station 1.B components

Number	Reference	Description
1	A-A153-99	Nest
2	A-A158-99	Tool
3	A-A151-99	Nest carrier
4	A-A164-99	Retaining ring unitary feeder
5	A-A155-99	Retaining ring inserter
6	A-A149-99	Retaining ring placement checker
7	A-A160-99	Retaining ring vertical feeder

4.3.4.4.2 Focal points

In this station, there were a lot of components to be installed into a small space. The operator will need to have access to load the nest, tool, and the retaining ring feeder. In the space available (taking into consideration the safety distance required from the safety light curtains) it was impossible to have these three points equally accessible for the operator, thus, since the retaining ring feeder will only be accessed sporadically, a compromise was made and the support for the retaining ring cartridge was placed further back in relation to the front of the station.

A 3D dummy that represents the dimensions defined by the ISO 14738 was used to validate these positions. It was possible to observe that the nest and tool are placed ergonomically and the retaining ring feeder is outside the desirable distances (Figure 87.B). In Figure 87.A is possible to see the layout that was achieved during the design stage. The operator loads the housing and subassembly 1 at the position “A”, which is also where the subassembly 1 will be inserted into the housing. The nest then moves to position “B”, where the retaining ring is installed, locking the subassembly 1 in place. In position “C” the operator loads the retaining ring feeder, which in turn delivers the parts individually to position B.

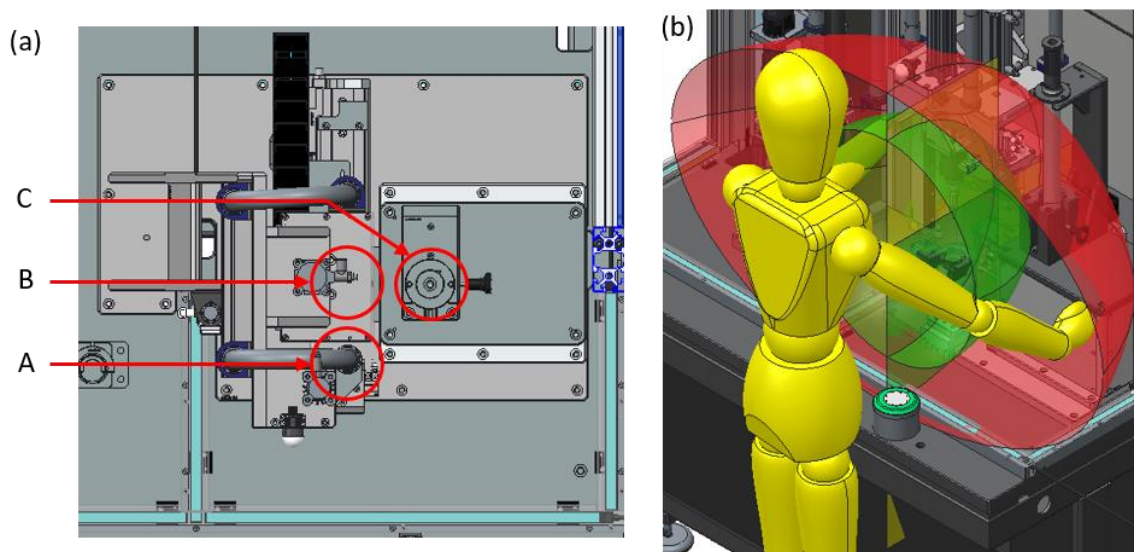


Figure 87 – Station 1.B details: a) Station 1.B layout; b) Station 1.B ergonomic study

A detailed explanation of the focal points of station 1.B is presented in Table 80. Apart from the components mentioned in this table, a support for the secondary cartridge was also supplied with this station. This support will secure the cartridge upside down so that a worker can manually load the retaining rings in the correct orientation. Once the cartridge that is inserted on the retaining ring feeder is empty, the operator allocated to station 1 will have a full cartridge ready to quickly exchange it.

Table 80 - Focal points of station 1.B

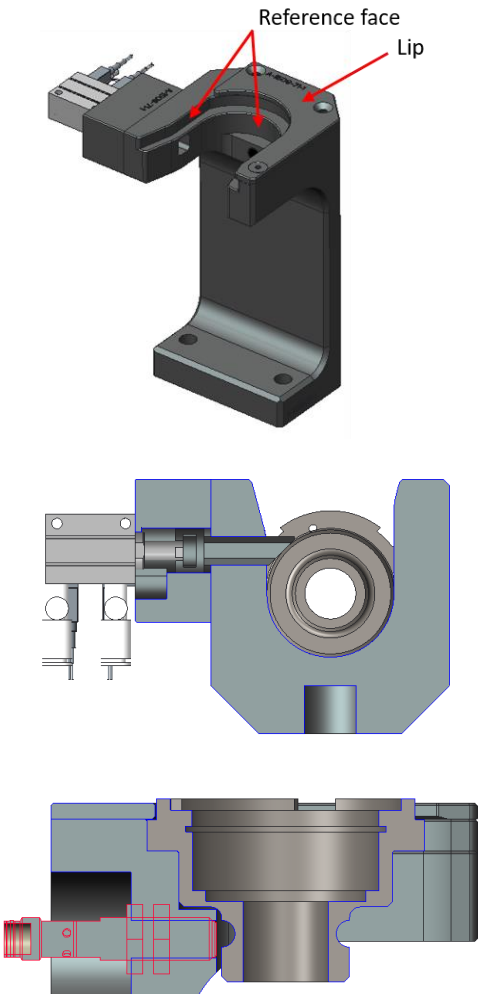
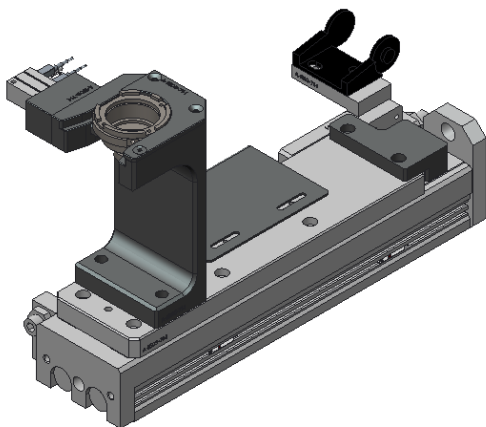
	Illustration	Description
<p>Nest</p>		<p>The nest is where the housing will be loaded and held in place during the insertion of subassembly 1 and the retaining ring. The nest has three main features:</p> <ul style="list-style-type: none"> • Orientation: The nest can guarantee the correct orientation of the housing by using two reference faces (one for one of the outside diameters of the housing and other to orient it through the plane created by the relief). It also has a lip to prevent a vertical load of the housing and vertical unload of subassembly 1. • Wedge: The wedge is responsible to lock the housing and make sure the reference diameters of the nest and the housing are in full contact, making sure the part is in the desired position. • Inductive sensor: An inductive sensor is used to sense the presence of the housing in the nest. The sensor is adjusted in such a way that the housing is only detected if it is fully inserted onto the nest.
<p>Nest Carrier</p>		<p>As established at the beginning of this subchapter, the nest needs to move between two positions. To achieve this movement is necessary a guiding system and an actuator. Due to the lack of space, the preferable option is guided actuators. These components are shelf-ready and save a substantial amount of design time. In this application, a slide table from the series MXS, produced by SMC, was applied. The nest is mounted directly onto the top of the actuator via an interface plate. To ensure the longest life possible of this actuator, all the vertical insertion movements are pressure regulated, and the movement of the nest is slowed down using flow regulators.</p>

	Illustration	Description
<p>Tool</p>		<ul style="list-style-type: none"> Actuator: The customer stated that the insertion of the subassembly 1 could be done pneumatically, but the pneumatic actuator should be easily exchanged by an electric one. To achieve this, a cylinder with a standardized body according to the ISO 15552 was used. Unfortunately, the smallest size is $\varnothing 32$ mm bore, which is more than required for this application. Guiding system: To guide the tool during the insertion and guarantee the alignment with the nest, a guiding system from Hiwin was applied (the same size and reference used in the press guiding system). Side lock: To lock the subassembly 1, a small cylinder is used to apply a lateral load. The cylinder used is the same one that was applied on the nest and tool of station 1.A. Since the shaft is not as hard as the bearing, a rubber point was used to not damage this component. Sensing: Since the bearing is sitting freely on the shaft, is important to verify that the shaft is being loaded together with the bearing. To verify this, two inductive sensors are used and only detect both components in their final positions. Tool head: The tool head is responsible for orienting the shaft, using its upper portion to locate it during the whole insertion process. To avoid the protruding edges of the shaft, four reliefs were made on the inner channel of the head. This tool was designed and dimensioned to only allow the shaft to enter without resistance if the protruding edges are aligned with the relief. The operators will also be trained to previously orient the shaft before inserting the subassembly 1 into the tool head.

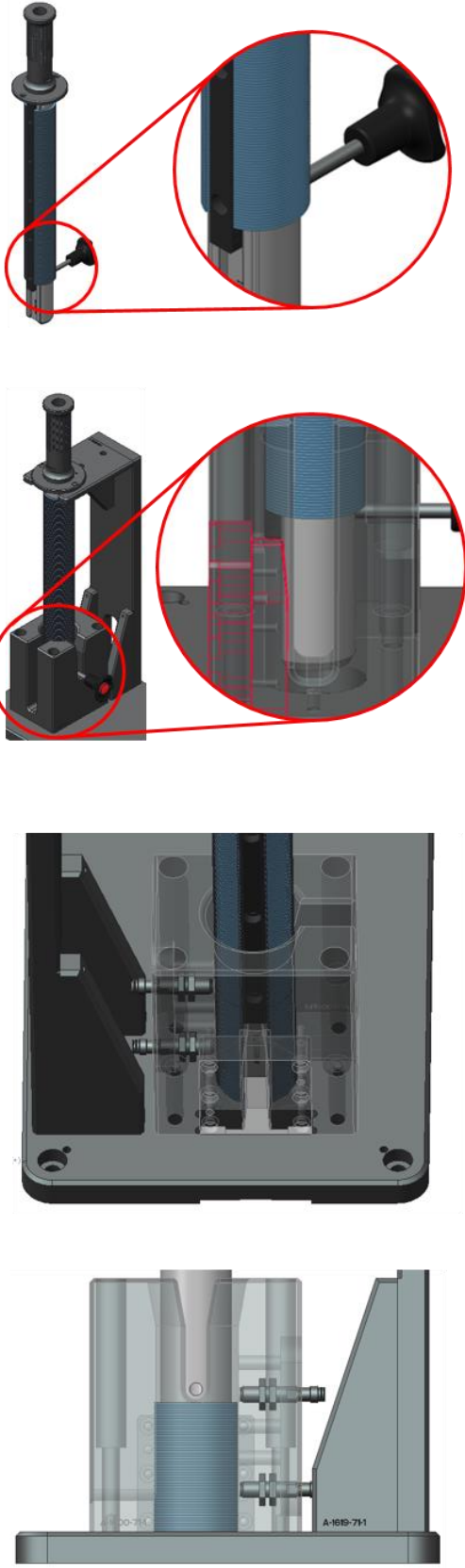
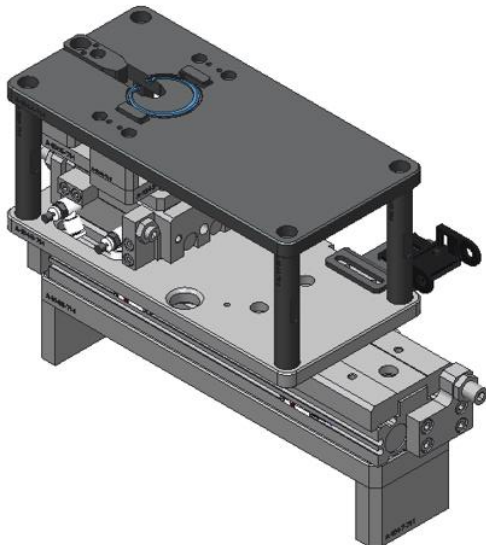
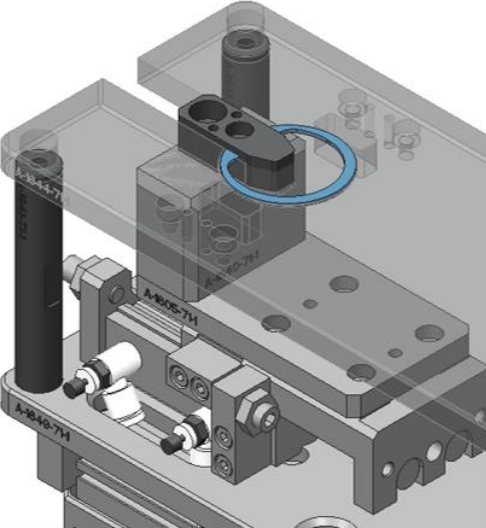
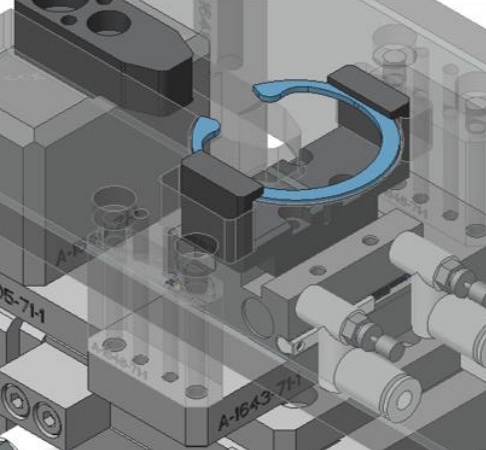
	Description
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Retaining ring vertical feeder</p> <div style="display: flex; flex-direction: column; align-items: center;">  </div>	<ul style="list-style-type: none"> <p>Magazine: The magazine is the way the operator will load the feeder. It consists of a rod and guide to orient the retaining rings, a removable spring plunger to hold the parts during the loading operation, and a handle. This magazine is manually loaded by an operator outside the machine with approximately 210 retaining rings, which with a cycle time of 40 seconds, should last at least two hours. During this external loading operation, the worker must make sure the chamfer of the retaining ring is in the correct orientation. This will later be verified after the insertion of the retaining ring into the housing is performed.</p> <p>Buffer and magazine support: The magazine is placed in the support by the operator. When doing so, the operator inserts the tip of the magazine into the buffer and the insertion is only possible to make if the magazine is in the right orientation. Once the magazine is inserted, the operator can remove the spring plunger that was holding the retaining rings on the magazine. Inside the buffer, there is a continuation of the guide present in the magazine. This ensures that the retaining rings are correctly oriented until they reach the individual feeder.</p> <p>Sensing: On the buffer, two inductive sensors are installed, one sensor signals the operator that the sword can be removed (meaning all the parts on the buffer are oriented by the stationary guide), while the other sensor signals the operator that the buffer is almost empty and another magazine must be loaded. If a magazine is not loaded within 20 cycles after the warning, the machine will cease operating.</p>

	Illustration	Description
<p>Retaining ring unitary feeder</p>		<p>The retaining ring unitary feeder is capable of separating and feeding these parts individually. This component will also guarantee that the retaining rings are correctly oriented when the insertion tool picks them up. This system is composed of the carrier, wedge, and holder.</p>
		<ul style="list-style-type: none"> • Carrier: The retaining ring needs to be transferred from the vertical feeder and delivered to the insertion tool. To perform this movement a slide table from the series MXS, produced by SMC, was used. • Wedge: During the study made to the sample of 50 retaining rings, it was possible to observe that the variations of dimension A, in comparison to the size of the holes $\varnothing K$, would in some cases cause a collision problem with the tip of the fingers, meaning that when misaligned the finger would collide with the top surface of the retaining ring. The variations between the dimension A and B are very small and vary in a constant way with each other. Thus, to always have the holes $\varnothing K$ in the same position a wedge can be inserted to force dimension B, and consequently, dimension A, to a constant value, allowing the fingers to always enter the holes in the same position.
		<ul style="list-style-type: none"> • Holder: When inserting the wedge on the retaining ring, this part acts like a spring and a tension is created. To prevent the retaining ring from projecting itself in order to release such tension, a holder was added to this feeding system. This Holder consists of two fingers attached to a gripper, which upon closing creates a barrier that prevents the retaining ring from being projected out of the carrier.

Retaining ring inserter

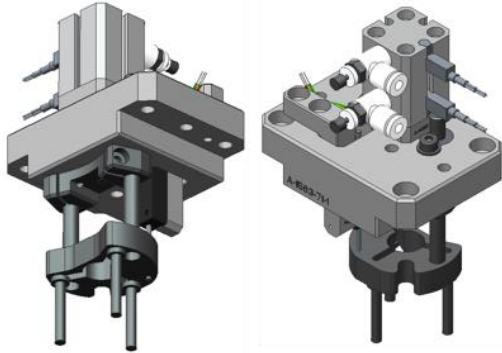



Illustration



Description

The retaining ring inserter system consists of a rotary pneumatic actuator and a gear system to move the fingers simultaneously. This system also uses a pneumatic actuator to move vertically, in order to approach the housing and the carrier. This movement is guided using the same linear guides from Hiwin used so far.

- **Rotary actuator:** The rotary actuator was dimensioned using the closing load measurements from the 50 unit sample and a safety factor, which will be better explained in subchapter 4.3.4.4.4. The actuator is connected to the driving shaft through a floating joint.
- **Gear system:** The gear system consists of a driving shaft, driven shaft, gears, and bearings. Each shaft is supported by two bearings. The driving shaft is connected to the floating joint, receiving the rotary motion of the actuator and transmitting it to the driven shaft through a gear system that has a ratio of 1:1. At the end of each shaft, there is a cavity to house the fingers, which references this component in all directions, ensuring a constant position of the fingers when they are replaced.
- **Fingers:** The fingers are parts with a very specific and complex geometry to fit the available space and geometry of the housing, as well as having enough stiffness on the tips so they do not break or bend during the insertion of the retaining ring. The fingers are produced with tool steel X153CrMoV12 (1.2379) and are quenched and tempered to achieve a hardness of 54-56 HRC. Besides this, the movement of the fingers is adjustable on the opening motion, while on the closing motion they go as far as the retaining ring allows.

	Illustration	Description
Retaining ring placement checker		<p>The retaining ring placement checking is done using probes to feel if the retaining ring has fully expanded inside its cavity. This system contains three main components, a pneumatic actuator, a displacement sensor, and three adjustable probes.</p>
	<p style="text-align: center;">Corret and full insertion</p> 	<ul style="list-style-type: none"> Actuator: The actuator is responsible for moving the probes up and down inside the housing. This actuator, from the series CDQ by SMC, has a bore of $\varnothing 12$ mm. This cylinder produces a load (at 6bar) of approximately 68 N. This load is not enough to damage the bearing or the retaining ring, has pretended.
	<p style="text-align: center;">Incomplete insertion</p> 	<ul style="list-style-type: none"> Displacement sensor: The sensor used in this device, unlike specified by the customer, is from Megatron instead of Keyence. The reason is that the space available is very small and Keyence does not produce transducers so small. This being said, this sensor will read how far the probes have traveled. The difference in the readings between a good placement and a bad placement is around 1,5 mm and the sensor has a resolution of $\pm 0,5$ mm.
	<p style="text-align: center;">Insertion with the chamfer down</p> 	<ul style="list-style-type: none"> Probes: The probes consist of three small rods. These probes are adjusted to pass closely to the inner face of the retaining ring when this is correctly placed. When the retaining ring insertion is incomplete or the retaining ring was inserted with the chamfer on the wrong orientation, it will not expand completely and will be protruding more than the correctly inserted one. In this case, when the probes are moved down to check the position, they will collide with the retaining ring and not travel as far as when the insertion is correct. This is the difference that the displacement sensor will detect.

4.3.4.4.3 Operation sequence

In this subchapter, a list of all the sensors that detect the parts to assemble and the actuator’s positions will be provided (Table 81), including their brand and reference. All the pneumatic actuators will also be identified (Table 82). This will help to better understand how the operation sequence functions, as well as connect this sequence with the information present in the pneumatic diagram.

Table 81 - Station 1.B sensors

Sensor ID	Brand	Reference	Description
BRC12	Omron	E2E-C04S12-WC-B1	Bearing Presence
BRC15	Omron	E2A-S08KS02-M5-B1	Shaft Presence
BRC16	Omron	E2A-S08KS02-M5-B1	Housing Presence
BRC17	Omron	E2E-C04S12-WC-B1	Retaining Ring Presence
BRC18	Omron	E2A-S08KS02-M5-B1	Retaining Ring cartridge without rings
BRC19	Omron	E2A-S08KS02-M5-B1	Retaining Ring Buffer empty
BRC28	SMC	D-M9PSAPC	Subassembly 1 insertion (down)
BRC29	SMC	D-M9PSAPC	Subassembly 1 insertion (up)
BRC30	SMC	D-M9PSAPC	Retaining ring insertion (down)
BRC31	SMC	D-M9PSAPC	Retaining ring insertion (up)
BRC32	SMC	D-M9PSAPC	Nest carrier (back)
BRC33	SMC	D-M9PSAPC	Nest carrier (front)
BRC34	SMC	D-F8PSAPC	Housing lock (front)
BRC35	SMC	D-F8PSAPC	Housing lock (back)
BRC36	SMC	D-M9PSAPC	Retaining ring carrier (front)
BRC37	SMC	D-M9PSAPC	Retaining ring carrier (back)
BRC38	SMC	D-M9PSAPC	Retaining ring wedge (front)
BRC39	SMC	D-M9PSAPC	Retaining ring wedge (back)
BRC40	SMC	D-M9PSAPC	Retaining ring holder (close)
BRC41	SMC	D-M9PSAPC	Retaining ring holder (open)
BRC42	SMC	D-M9PL	Retaining ring gripper (close)
BRC43	SMC	D-M9PL	Retaining ring gripper (open)
BRC44	SMC	D-F8PSAPC	Retaining ring position check (down)
BRC45	SMC	D-F8PSAPC	Retaining ring position check (up)
BRC46	SMC	D-F8PSAPC	Subassembly 1 lock(front)
BRC47	SMC	D-F8PSAPC	Subassembly 1 lock(back)
BRC52	SMC	D-M9PSAPC	Activate retaining ring holder

Table 82 - Station 1.B actuators

Actuator ID	Brand	Reference	Description
MMB502	SMC	CDUJB10-10D	Subassembly 1 lock
MMB503	SMC	CDRA1BSU50TF-90Z	Retaining ring gripper (fingers)
MMB521	SMC	CP96SDB32-220C	Subassembly 1 insertion
MMB522	SMC	CDQ2A40TF	Retaining ring insertion
MMB523	SMC	MXS20-150A	Nest carrier
MMB524	SMC	CDUJB10-10D	Housing lock
MMB525	SMC	MXS16-125A	Retaining ring carrier
MMB526	SMC	MXS12-30A	Retaining ring wedge
MMB527	SMC	MHF2-8DR	Retaining ring holder
MMB528	SMC	CDQSB12-10D	Retaining ring position check

The operation sequence of station 1.B will now be explained in Table 83, and actuators and sensors will be mentioned according to the identifications present in Table 81 and Table 82.

Table 83 - Station 1.B operation sequence

	Illustration	Description
Step 1		<p>The operator loads the subassembly 1 into the insertion tool. The operator needs to be careful when manipulating this assembly since they cannot touch a certain part of the shaft and the bearing is loose.</p>
Step 2		<p>The sensors BRC12 and BRC15 will respectively detect the bearing and the shaft. Once these components are on the required position, the sensors send a signal to the PLC, which in turn commands the actuator MMB502 to move forward, locking the subassembly and activating BRC46.</p>

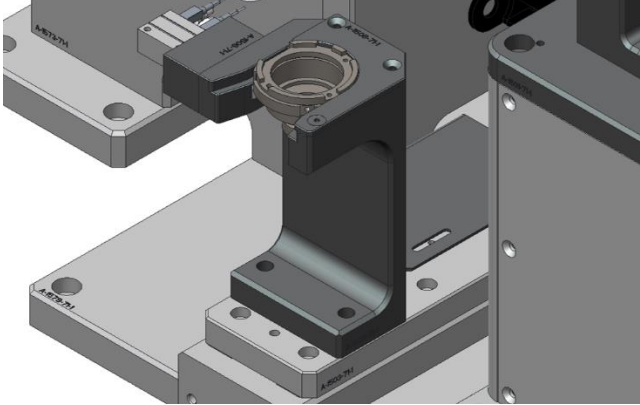
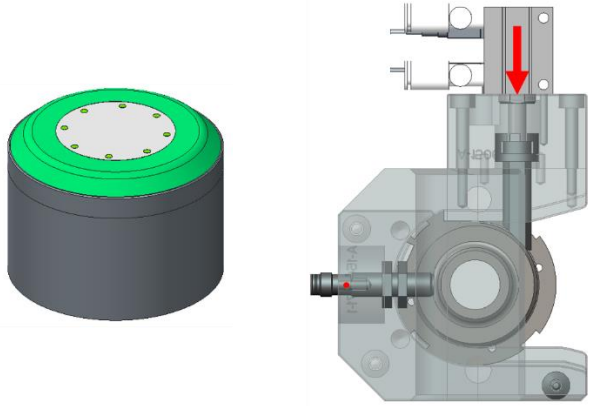
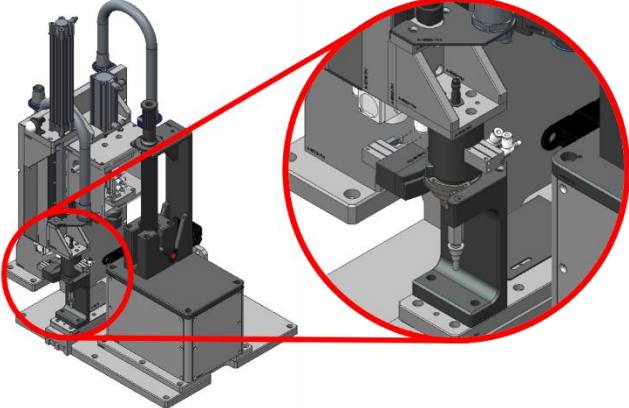
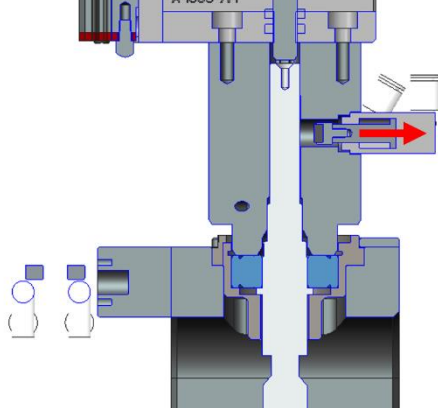
	Illustration	Description
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Step 3</p>		<p>The operator loads the housing into the nest. The subassembly 1 must be inserted before since the housing takes up space that can be helpful to manipulate the subassembly 1.</p>
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Step 4</p>		<p>The operator presses start, and if the sensors BRC12, BRC15, BRC16, and BRC46 are triggered, the safety light curtains are activated. Afterward, the actuator MMB524 moves forwards, locking the housing in place and activating the sensor BRC34.</p>
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Step 5</p>		<p>Upon receiving the signal from the sensor BRC34, the PLC commands the actuator MMB521 to move forward. When the subassembly 1 is fully inserted in the housing the sensor BRC28 is activated.</p>
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Step 6</p>		<p>Once the sensor BRC28 signals the PLC that the insertion is completed, the actuator MMB502 is ordered to move back and release the shaft. This action activates the sensor BRC47.</p>

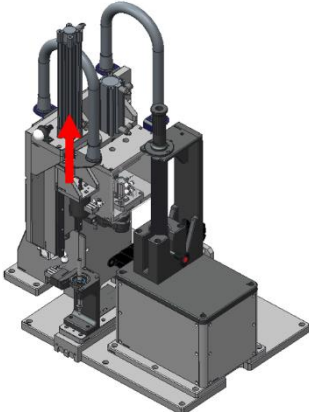
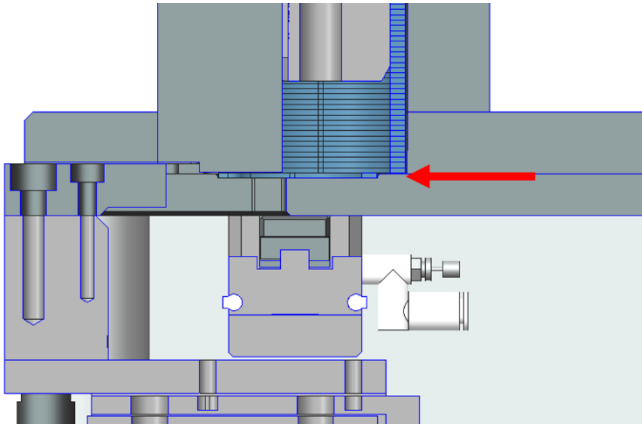
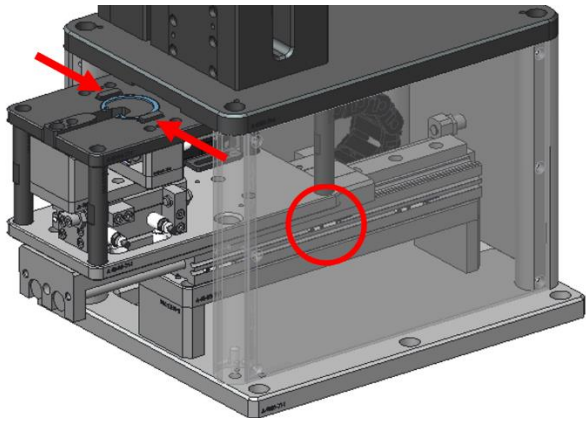
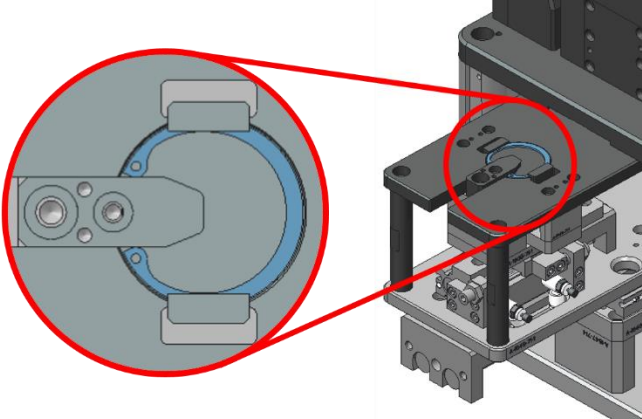
	Illustration	Description
Step 7		<p>When the sensor BRC47 is activated the PLC knows that the shaft is now free and orders the MMB521 to retract, which in turn activates the sensor BRC29.</p>
Step 8		<p>At the push of the start button, the cylinder MMB525 is also commanded to move forward. This movement separates a single retaining ring from the buffer since it is inside a cavity on the carrier plate.</p>
Step 9		<p>In the middle of the forward movement of the actuator MMB525, when the retaining ring is no longer under the buffer, the sensor BRC52 is activated and at this instant, the PLC commands the holder to close (MMB527). Upon closing it activates the sensor BRC40.</p>
Step 10		<p>Once the carrier finishes its course, the sensor BRC36 is activated. The combination of BRC40 and BRC36 allows the PLC to command the actuator MMB526 to move forward, inserting the wedge on the retaining ring and activating the sensor BRC38.</p>

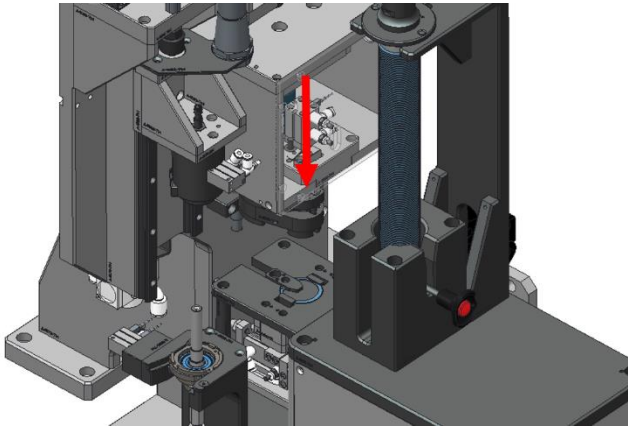
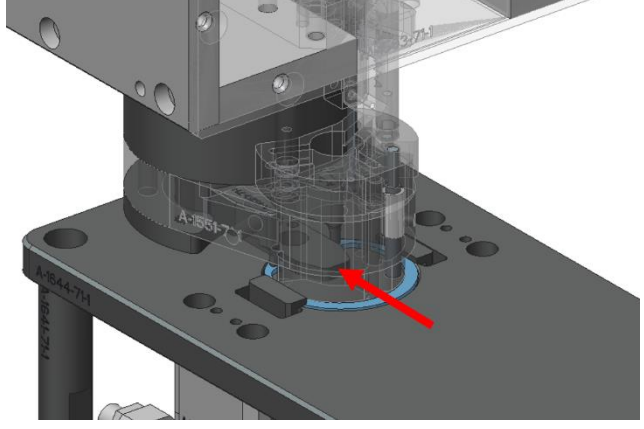
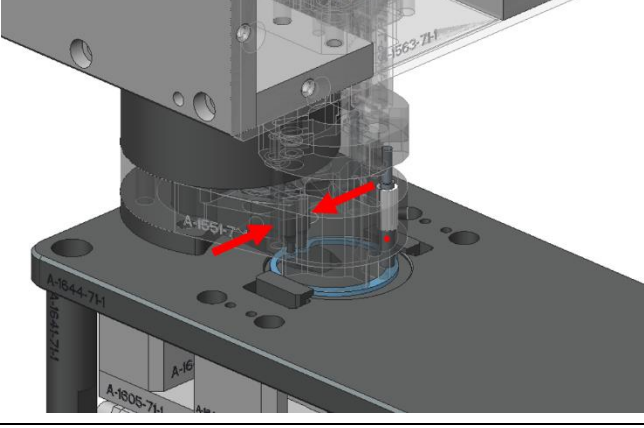
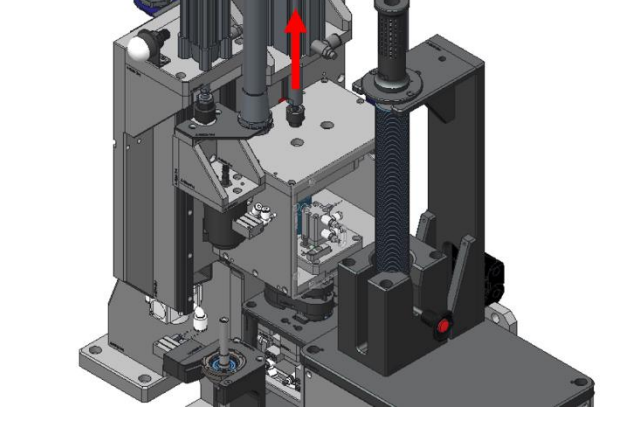
	Illustration	Description
Step 11		<p>With the signals from BRC36, BRC38, and BRC40, the PLC knows a retaining ring is ready to be picked up. The actuator MMB522 is commanded to move forward, lowering the retaining ring insertion mechanism and activating the sensor BRC30 when it reaches the picking position.</p>
Step 12		<p>At this stage the fingers are already inserted on the retaining ring holes, meaning that the wedge can be removed. The actuator MMB26 is commanded to retreat, which activates the sensor BRC39.</p>
Step 13		<p>With the activation of the sensor BRC39, it is now possible to close the retaining ring gripper. The actuator MMB503 closes, activating the sensor BRC42. When the retaining ring is contracted it also activates the sensor BRC17. This last sensor is monitored until the retaining ring is inserted.</p>
Step 14		<p>Once the sensors BRC17 and BRC42 are activated, the retaining ring insertion toll can move back up again. The actuator MMB522 retracts and the sensor BRC31 is activated.</p>

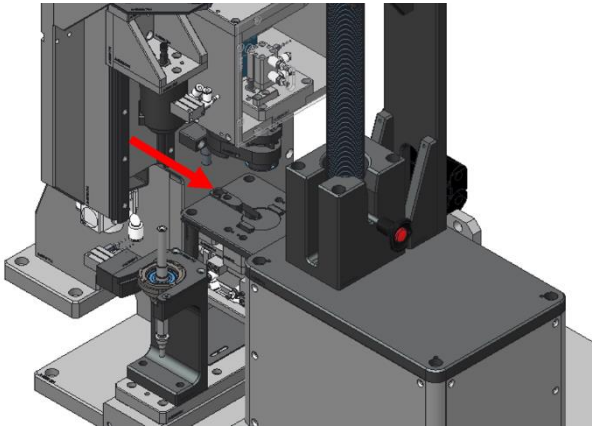
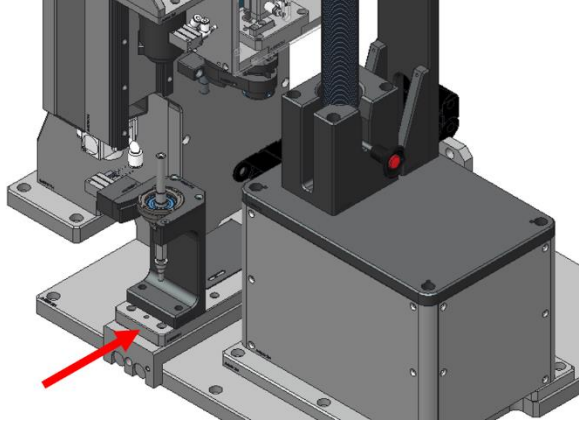
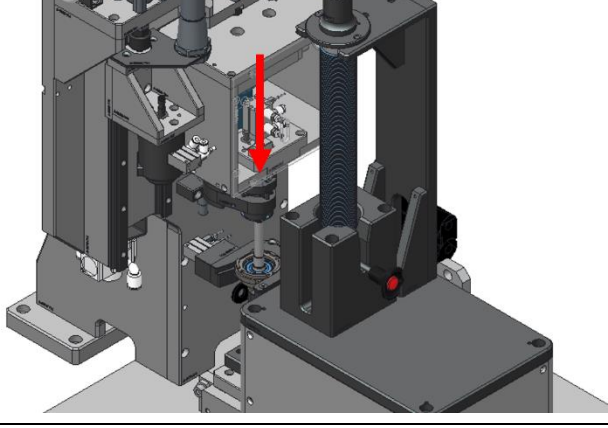
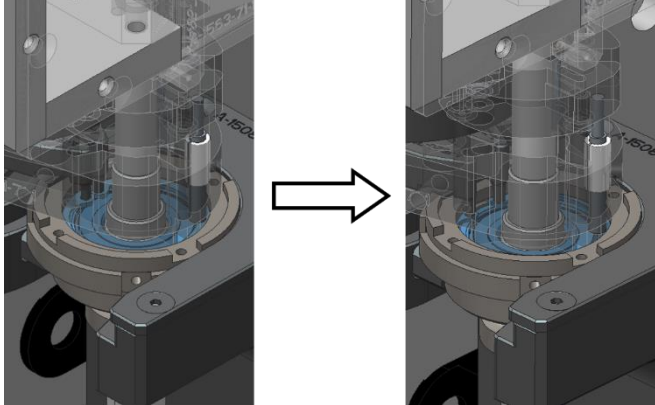
	Illustration	Description
Step 15		<p>The activation of the sensor BRC31 triggers the PLC to command the actuator MMB525 to retract, which frees the space for the nest to move to the retaining ring insertion position. When the carrier is fully retracted, the sensor BRC37 is activated.</p>
Step 16		<p>The steps 4 and 8 starts at the same time, and the conclusion of step 7 (BRC29) and 15 (BRC37) allows the PLC to know that the path is free for the nest carrier and commands the actuator MMB523 to retract. When the nest reaches the insertion position, the sensor BRC33 is activated.</p>
Step 17		<p>With the nest on the insertion position and the insertion tool loaded with a retaining ring, the conditions are gathered for the execution of this task. The PLC orders the actuator MMB522 to move forward, which lowers the retaining ring insertion tool and activates the sensor BRC30.</p>
Step 18		<p>As soon as the tool reaches the retaining ring insertion position, the PLC cuts the signal of the valve that controls the retaining ring gripper. Since the valve is a 5/3 open center, the chambers of the actuator empty, and the retaining ring forces the fingers to open, allowing the ring to enter its groove in the housing.</p>

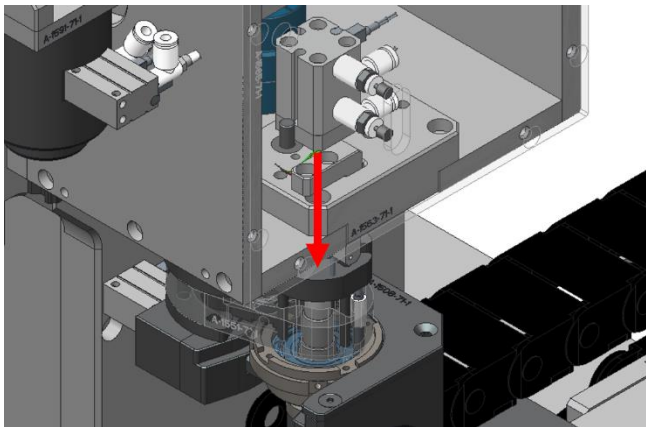
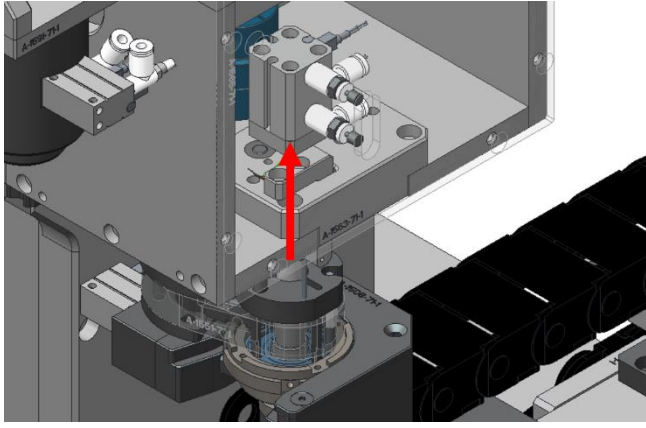
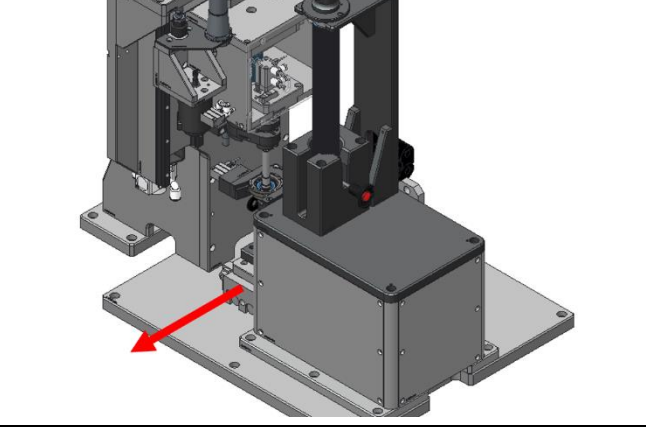
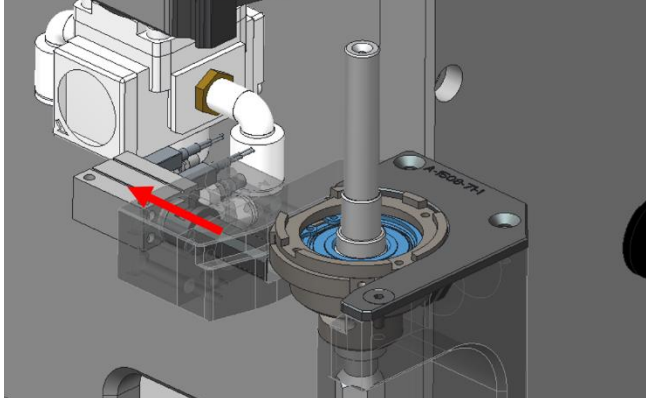
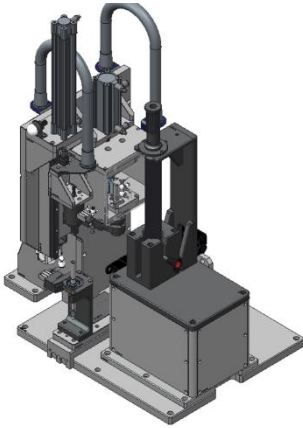
	Illustration	Description
Step 19		<p>Once the fingers are forced open, the sensor BRC42 is deactivated and the PLC now commands the actuator MMB528 to move forward and check the retaining ring position. The PLC will analyze the analogic signal sent by the displacement sensor.</p>
Step 20		<p>After processing the analogic signal, the PLC commands the actuator MMB528 to retract, moving the probe system up and activating the sensor BRC45.</p>
Step 21		<p>When the sensor BRC45 is activated, the PLC knows that it can send the nest to the start position. The actuator MB523 moves forward, activating the sensor BRC33 when it reaches its final position. This triggers the PLC to command the actuator MMB503 to open the retaining ring gripper.</p>
Step 22		<p>The activation of sensor BRC33 is the condition required to unlock the subassembly 3. The PLC commands the actuator MMB524 to retract, which in turn activates the sensor BRC35.</p>

	Illustration	Description
Step 23		<p>With the activation of the sensor BRC35, the safety light curtains are deactivated and the feedback light changes color according to the results of the operation. The operator can now unload the subassembly 3, which deactivates the sensor BRC16 and resets the machine.</p>

Apart from the operation sequence described in Table 83, one external operation needs to be performed, which is the loading of the cartridge of the retaining rings (Figure 88.A). This operation, if done continuously, should not take more than 10 minutes, but since the cartridge lasts for at least 2 hours, this is the time available to load it. The support supplied to hold the cartridge during this operation (Figure 88.B) is designed to be attached to the conveyor's profiles and its final location was still to be defined by the customer. Most likely this operation was allocated to the operator of station seven since it is the person with fewer tasks to perform.

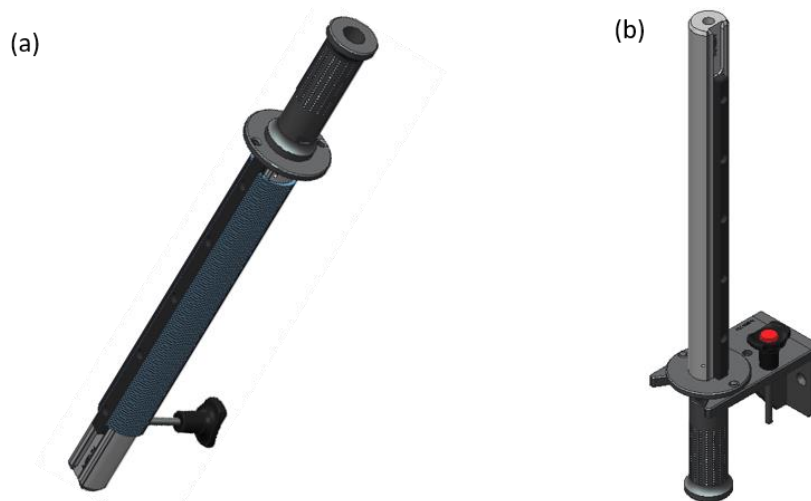


Figure 88 - Retaining rings' cartridge: a) Cartridge; b) Cartridge support;

The GRAFCET of station 1.B can be found in Annex III and is divided into three separate charts. The first chart (X200) describes, simultaneously, the normal operating cycle of the machine and the step-by-step mode. The other two charts are the X300 and X500, which describe respectively the safety cycle of the emergency button and the safety cycle for when the safety light curtains are interrupted.

4.3.4.4.4 Dimensioning and selection criteria

Rotary actuator from the Retaining ring inserter

To select the rotary actuator is necessary to calculate the torque needed to close the retaining ring with the designed system. To discover this value, the loads measured during the retaining ring tests will be the starting point.

The maximum load value registered during the analysis of the 50 retaining rings sample was approximately 240 N, while the average was approximately 198 N. To compensate for the fact that this 50 retaining rings group is a small sample, eventual measuring errors due to the conditions which the measurements were made and eventual torque losses in the system, the highest value measured will be the value used for the calculations, being added a safety factor of 1,5. This means that the system will be dimensioned to produce a load of at least 360 N, thus, each finger will need to apply 180 N to the system, as represented in Figure 89.

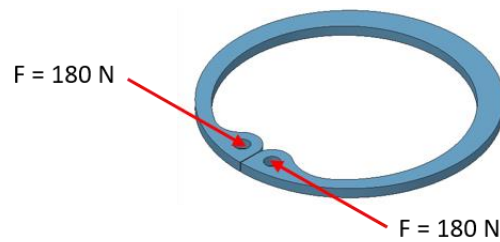


Figure 89 - Representation of the load each finger must apply to the retaining ring

Now that the closing load required from the system is defined, is time to evaluate the closing mechanism designed. In Figure 90 a schematic representation of this mechanism is provided.

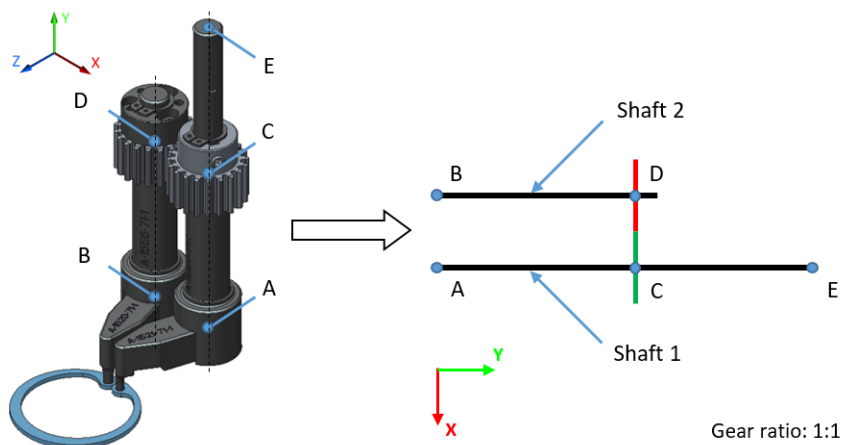


Figure 90 - Schematic representation of the retaining ring closing mechanism

Looking at Figure 90, the value needed to select the rotary actuator is the resultant moment in point "E". To start solving the system, it is necessary to calculate the moment in both points, "A" and "B", through the closing load of the retaining ring.

In Figure 91 all the data needed to calculate the moment reactions, in point "A" and "B", is available. The force "F" presented in the picture is the load that each finger must apply to the retaining ring in order to close it. Taking into consideration the dimensions presented, is also shown that the resultant moments will be equal in both points but with different directions, thus, the calculations will only be for the point "A". A detailed view of the finger attached to point "A" is shown in Figure 92.

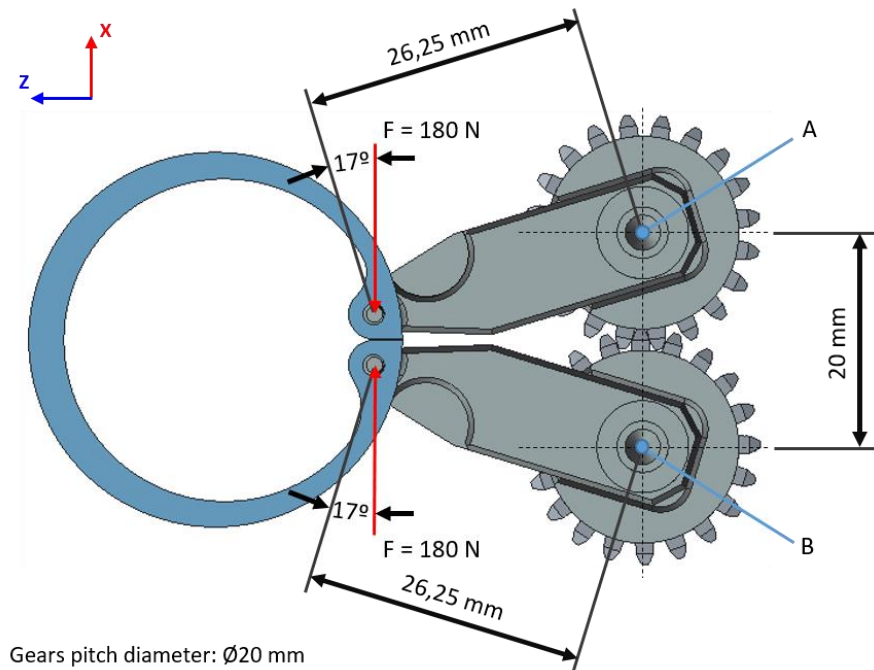


Figure 91 - Dimensions required to calculate the moment in points "A" and "B"

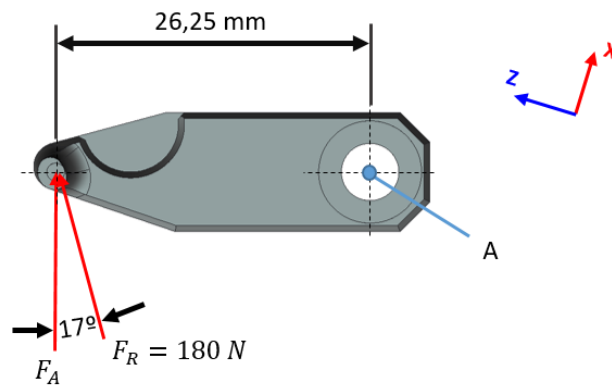


Figure 92 - Detail view of the finger attached to point "A"

This time the force presented is F_R , the reaction of the retaining ring on the finger. This was done to obtain the moment in the correct direction. Anyhow, the force is applied at an angle in relation to the lever arm and it must be converted to the normal force F_A . Since the angle is known, this calculation can be performed (equation (16)), so that after the sum of moments in point "A" can be calculated to discover the resultant moment M_A (equation (17)):

$$\cos(17) = \frac{F_R}{F_A} \tag{16}$$

$$\Leftrightarrow F_A = \frac{180}{\cos 17}$$

$$\Leftrightarrow F_A \approx 188,23 \text{ N}$$

$$\sum M_A = 0 \tag{17}$$

$$\Leftrightarrow M_A + F_A \times d = 0$$

$$\Leftrightarrow M_A = -(188,23 \times 26,25 \times 10^{-3}) \approx -4,94 \text{ N} \cdot \text{m}$$

Since the resultant moment in "A" is $-4,94 \text{ N} \cdot \text{m}$, it can be deduced that the resultant moment in "B" is $4,94 \text{ N} \cdot \text{m}$. With the value of M_B is possible to discover the resultant moment in point "D" by calculating the sum of the torsion moments (M_T) of shaft 2.

$$\sum M_t = 0 \tag{18}$$

$$\Leftrightarrow M_B + M_D = 0$$

$$\Leftrightarrow M_D = -M_B = -4,94 \text{ N} \cdot \text{m}$$

With these values the free body diagram and the torsion moment diagram of shaft 2 can be made, which are shown in Figure 93, as well as the sign convention used to create them.

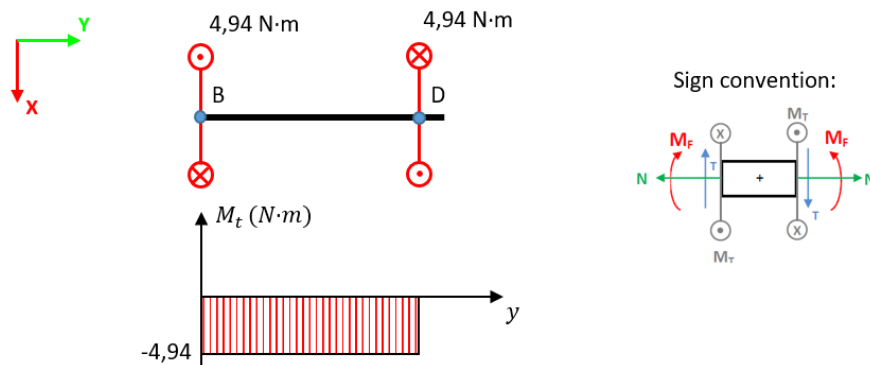


Figure 93 - Free body diagram and torsion moments diagram of shaft 2

As already mentioned in Figure 90, the gear ratio of this system is 1:1. This permits to deduce that M_D is the same as M_C , meaning:

$$M_D = M_C = 4,94 \text{ N} \cdot \text{m} \tag{19}$$

Knowing the value of M_C is now possible to calculate the sum of the torsion moments of shaft 1 in order to discover M_E (equation (20)). The torsion moments diagram and the free body diagram are shown in Figure 94.

$$\begin{aligned} \sum M_t &= 0 & (20) \\ \Leftrightarrow M_A + M_C + M_E &= 0 \\ \Leftrightarrow M_E &= -(-4,94) - (-4,94) = 9,88 \text{ N} \cdot \text{m} \end{aligned}$$

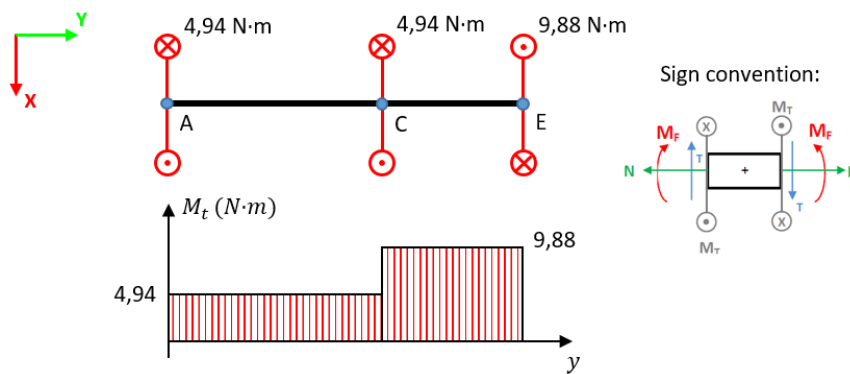


Figure 94 - Free body diagram and torsion moments diagram of shaft 1

With the moment M_E is now possible to select an actuator, which needs to be capable of outputting a torque superior to 9,88 N·m. For this application, the actuator selected was the CDRA1BSU50TF-90Z from SMC (Figure 95). This actuator is capable of outputting a torque of 11,2 N·m at 6 bar and can be directly attached to the floating joint. SMC has many other rotary actuators, but this one was selected because it had the best size/torque relation.

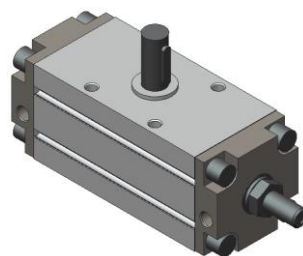


Figure 95 - SMC CDRA1BSU50TF-90Z rotary actuator

Guided actuator from the nest carrier

The actuator selected for the nest carrier was the MXS20-150A. This actuator was mainly selected due to its dimensions and load capacity. The components that will be attached on top of this actuator have a mass of about 4 kg. Consulting the catalog is possible to verify that the maximum load weight the actuator can bare is 6 kg, meaning that in this aspect the actuator is suitable for the application.

Apart from this, it was needed to verify how this actuator would react to the loads applied during the subassembly 1 insertion. As already explained, the actuator selected needed to be with a standard body according to the ISO 15552 so it would be possible to replace it with an electric actuator in the future. This means that the actuator needs to have a minimum size bore of Ø32 mm, which at 6 bar is translated to a theoretical force of 482 N. Thus, to verify if the guided actuator can withstand the moment generated by this vertical actuator and the weight of the nest, the calculations necessary were made following the MXS actuators catalog, which states that to calculate the moment the following equation should be used:

$$M = F \times (Ln + An) \tag{21}$$

Where,

M – Moment [N·m]

F – Load [N]

Ln – Overhang [mm]

An - Correction value of moment center position distance [mm]

In Figure 96 the free body diagram of the problem is presented.

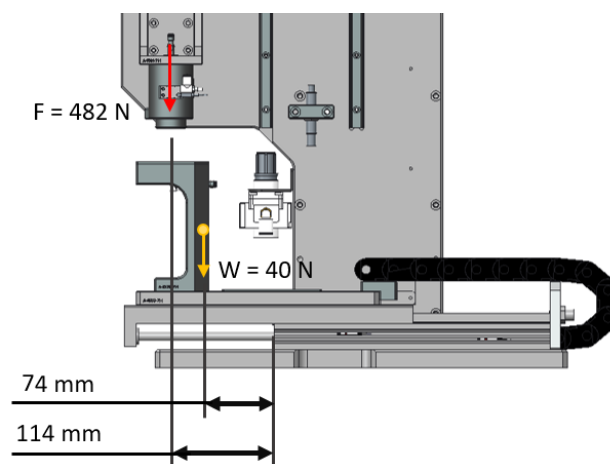


Figure 96 - Free body diagram of the efforts withstand by the guided actuator

With all the information gathered, is now possible to calculate the moment exerted on the guided actuator:

$$M = 40 \times (0,074 + 0,034) + 482 \times (0,114 + 0,034) \approx 75,65 \text{ N} \cdot \text{m} \quad (22)$$

In the catalog of the actuator is given that the maximum allowable moment for this case is 50,5 N·m. This means that the actuator is not suitable to operate under these conditions. One solution to this problem, without redesigning any part of the systems, is to reduce the pressure at the entry of the vertical actuator, which consequently reduces its load. If the pressure is reduced to 3 bar, the actuator will perform half the load, 241 N. Performing the moment calculations once again with this load value, the result achieved is:

$$M = 40 \times (0,074 + 0,034) + 241 \times (0,114 + 0,034) \approx 39,99 \text{ N} \cdot \text{m} \quad (23)$$

This new result validates the usage of the guided actuator selected. If possible, the vertical cylinder should be regulated to an even lower pressure to reduce the load applied to the guided actuator and consequently increase its lifespan. Furthermore, the vertical cylinder of the retaining ring insertion tool was not considered for this dimensioning because it is not supposed to transfer any load onto the guided actuator. The vertical motion of the retaining ring insertion tool is limited by a shock absorber in such a way that a small gap exists between the retaining ring and the bearing so that the retaining ring can open freely. Thus, since there is no contact there is also no load transmission onto the bearing and consequently the guided actuator.

Linear actuator from the nest wedge

This actuator must produce enough load to push the subassembly 1 against the nest. To validate this actuator is necessary to calculate the friction force created by the subassembly 1 weight, which is around 0,35 kg. The frictional coefficient used was 0,8 which is the worst-case scenario between two steel parts.

The friction force (F_f) of the subassembly 1 is:

$$F_f = \mu \times W \times g \quad (24)$$

$$\Leftrightarrow F_f = 0,8 \times 0,35 \times 9,81 \approx 2,75 \text{ N}$$

With the value of the friction force established is possible to compare this value to the load exerted by the actuator, which through the catalog is known that at 6 bar the theoretical force is approximately 47,1 N. In this case, the actuator's load is transferred from the wedge to an external diameter of the housing through a 45° face, thus it is necessary to calculate the

resultant force that is parallel to the direction of movement. In Figure 97 the information necessary to calculate the resultant force is given, followed by the calculations (equation (25))

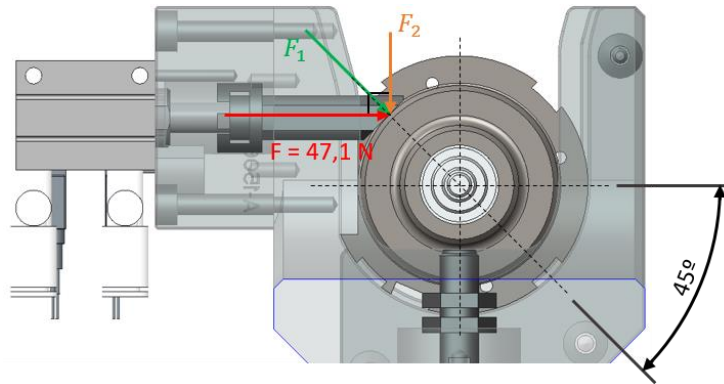


Figure 97 - Dimensions required to calculate the push force

$$\begin{cases} F_1 = 47,1 \times \cos(45) \\ F_2 = F_1 \times \cos(45) \end{cases} \Leftrightarrow \begin{cases} F_1 \approx 33,30 \text{ N} \\ F_2 = 33,30 \times \cos(45) \end{cases} \Leftrightarrow \begin{cases} F_1 \approx 33,30 \text{ N} \\ F_2 \approx 23,55 \text{ N} \end{cases} \quad (25)$$

Comparing the value F_2 to the friction force, is possible to confirm that the actuator selected can produce almost 9 times the force necessary to push the subassembly, which validates the actuator for this application. This also means that if the operator tries to remove the subassembly with the wedge under pressure he will need to apply at least 26,3 N of force.

Remaining actuators

All the remaining actuators were not dimensioned, meaning they are not as critical and most of them are models already available in the CAD library from IPTE and were chosen based on their dimensions. Most of them are over-dimensioned for their application, for instance, the actuator used to lift the retaining ring inserter (SMC CDQ2A40TF-100DZ) is capable of producing a return force of 633,5 N at 6 bar but is only moving a load inferior to 150N.

Of all the actuators included in this group, only the linear actuator used to lock the subassembly 1 in the insertion tool has a critical function. This actuator has already been dimensioned in the subchapter 4.3.3.4.4. In station 1.B the contact point with the shaft is made with a rubber tip and the subassembly weighs around 0,205 kg (0,143 kg more than the first case studied), but, predictably, the actuator is still suitable for the application since in the previous case, where the contact was metal to metal, the actuator was producing around 60 times more force than required to hold the bearing.

Linear guides

For this station, no linear guides were dimensioned. The application cases are similar to the ones found on the presses' guiding system. The loads are attached to the actuators through floating joints, which means that all the strains and weights are being supported by the actuators themselves and the linear guides only serve the purpose of guiding the components, therefore, the forces to which they will be subjected are residual and can be despised. Thus, the guides selected were the standard type commonly used at IPTE, the HGW15CCZ0H from HIWIN.

Finger FEM analysis

To confirm if the fingers designed are capable of withstanding the load generated while the retaining ring is being closed, a FEM analysis was performed. First, it is necessary to calculate the final resultant force on the finger produced by the actuator selected, which generates a M_E of 11,2 N·m. Through the previous calculation, it is possible to assume that M_A is the same as M_C , thus, adjusting the equation (20) is given:

$$\begin{aligned} \sum M_t &= 0 & (26) \\ \Leftrightarrow M_A + M_A + M_E &= 0 \\ \Leftrightarrow M_A &= \frac{-11,2}{2} = -5,6 \text{ N} \cdot \text{m} \end{aligned}$$

It is now possible to calculate the new F_R , which will be used in this study:

$$\begin{aligned} \sum M_A &= 0 & (27) \\ \Leftrightarrow M_A + F_A \times d &= 0 \\ \Leftrightarrow F_A &= -\left(\frac{-5,6}{26,25 \times 10^{-3}}\right) \approx 213,33 \text{ N} \end{aligned}$$

$$\cos(17) = \frac{F_R}{F_A} \quad (28)$$

$$\Leftrightarrow F_R = \cos(17) \times 213,33 \approx 204,01 \text{ N}$$

With the new F_R calculated it is now possible to perform the FEM analysis. Only one finger will be studied since the fingers are symmetrical, as well as the resulting loads they will need to withstand.

Just like all the studies done so far, all the parameters that influence the results must be inserted, which include the definition of the material, fixtures, and external loads. The parameters used for this study are presented from Table 84 to Table 86. In this FEM analysis, the connections were not considered since the component being studied is a single part. The fixture was also simplified. In reality, the fingers also have some lateral support from the shaft’s cavity where they are installed, while in the case study the screw hole was defined as the fixed geometry. Finally, the gravity effect was not considered since the part is very small and the influence of its weight is negligible.

Table 84 - Finger material properties

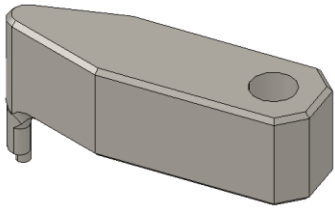
Illustration	Properties	
<div style="display: flex; align-items: center;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg); margin-right: 10px;">Press frame</div>  </div>	Material	X153CrMoV12 (1.2379)
	Yield strength	1034 MPa
	Tensile strength	1158 MPa
	Elastic modulus	200 GPa
	Poisson’s ratio	0,27
	Mass density	8000 kg/m ³
	Shear modulus	80 GPa

Table 85 - Fixture applied for the finger analysis

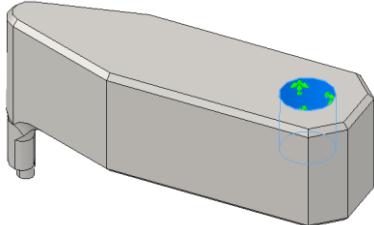
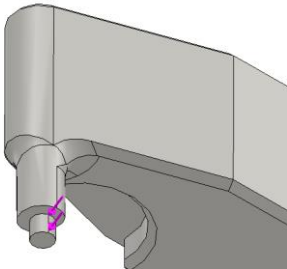
Illustration	Fixture details
	<ul style="list-style-type: none"> • Entities: 1 face; • Type: Fixed geometry.

Table 86 - External loads applied regarding the finger analysis

External loads	Illustration	Properties
<p>Load</p>		<ul style="list-style-type: none"> • Entities: 1 edge; • Type: Normal load; • Value: 204,01 N.

With all the conditions for the study defined, it is still needed to define the mesh type and parameters. The most important information regarding the mesh used can be seen in Table 87 and a representation of the mesh generated can be seen in Figure 98.

Table 87 Information regarding the mesh used for the finger analysis

Mesh type	Solid mesh
Mesher used	Standard mesh
Element size	0,67 mm
Tolerance	0,03 mm
Total Nodes	72 480
Total elements	49 254

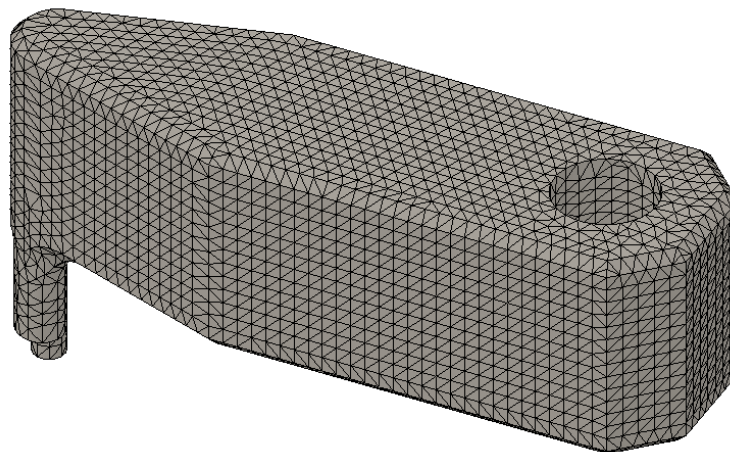


Figure 98 - Mesh generated for the finger analysis

With all the conditions and mesh defined, the FEM analysis was performed. The results achieved for the von Mises equivalent stress and displacement can be seen, respectively, in Figure 99 and Figure 100.

Analyzing the values obtained, it is possible to notice that the maximum von Mises equivalent stress registered is still far from the yield strength of the material, which means the fingers can withstand the load, being that the safety factor is around 1,6. It is possible to see that the stress is concentrating in one area of the finger. In some cases, this could lead to a redesign of the component to improve the stress distribution, but in this case is not possible to add material around the most critical area, because, as already mentioned, the fingers need to work around the housing shape and fit the retaining ring in the picking and insertion position.

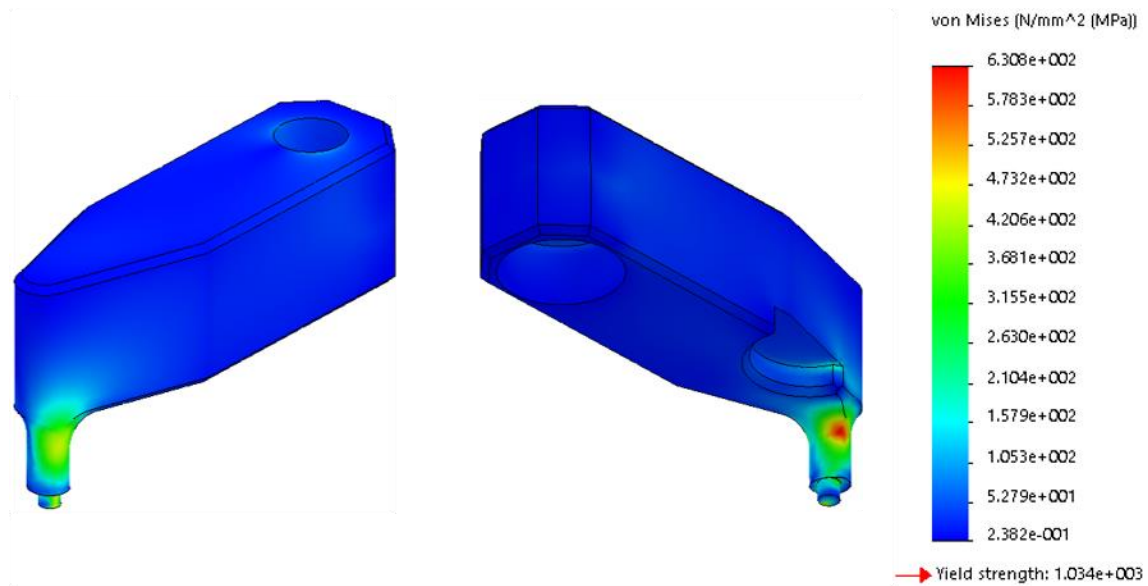


Figure 99 - Von Mises equivalent stress from the finger analysis

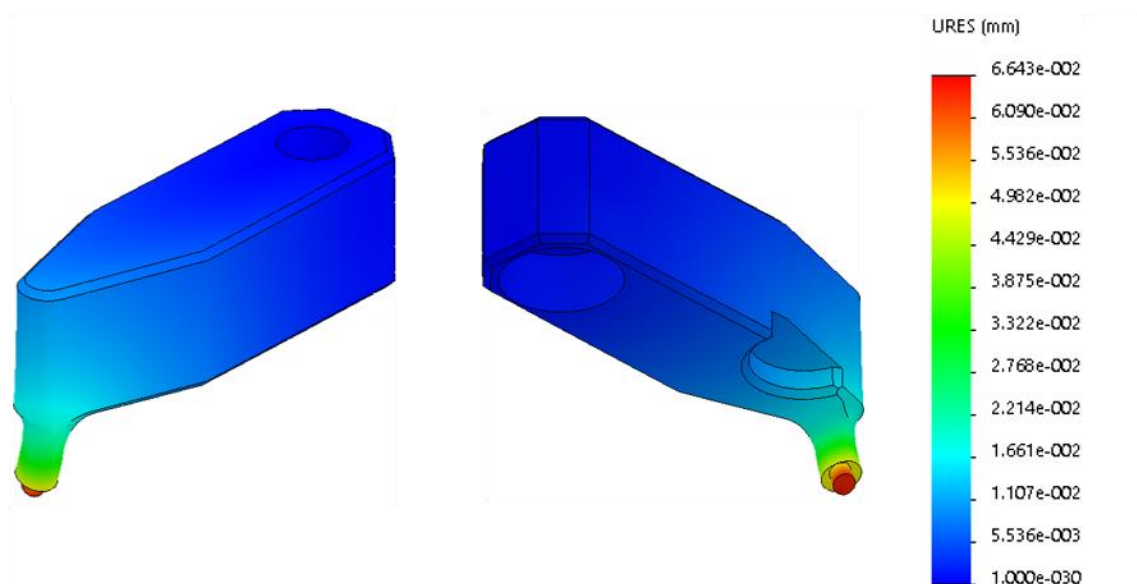


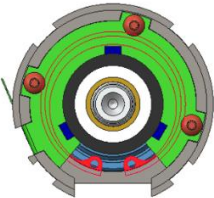
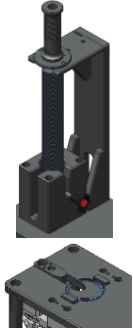
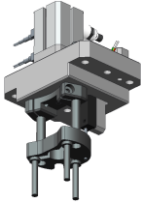
Figure 100 - Displacement from the finger analysis

The last concern regarding the finger is the wear resistance. It is impossible to prevent the fingers from being worn over time but is necessary to delay this process. When the fingers are worn out they will not be able to hold the retaining ring and they will most likely jump out of the fingers due to the spring load created upon closing. For this reason, the fingers were tempered and quenched to achieve a hardness of 54 to 56 HRC. This should increase their lifespan, but only when in continuous production it will be possible to evaluate how many parts they can produce before needing replacement. If needed, is possible to increase the heat treatment hardness even further or add a surface treatment such as nitriding or hard chrome plating.

4.3.4.5 Final remarks

Station 1.B presented the most complex challenge from the entire assembly line and consequently is also where the most novel solution was implemented. The system used to lock subassembly 1 onto the tool is based on the solution used to lock the bearing in Station 1.A, with the same logic in the selection of valves and isolation from the safety light curtains. The most outstanding system developed in station 1.B was the retaining ring insertion mechanism. Some of the main challenges and innovative solutions found are presented in Table 88.

Table 88 - Main challenges and solutions from Station 1.B

Problem	Illustration	Solution
<p>How can the orientation of the retaining ring holes be guaranteed during the insertion of this component?</p>		<p>The typical solution used to the automated insertion of retaining ring is through compressing them along a tapered bore, but this does not guarantee the orientation. To circumvent this problem a solution was developed from scratch, based on the vulgar retaining ring pliers. A set of gears, in combination with a rotary actuator and a pair of custom design fingers, can simulate these pliers and always have the retaining ring oriented by its holes, ensuring a precise positioning of the part upon installation of the motor's housing.</p>
<p>How is it possible to orient the part for picking them with the fingers since they are produced with very poor tolerances?</p>		<p>A dimensional study was performed to different production batches of the retaining ring. This study allowed to establish relations between the different dimensions of the retaining ring and predict the maximum expected dimensions. Through this study, a cartridge and a wedge mechanism were designed to always guarantee the orientation of the retaining ring and position of the holes for the picking operation.</p>
<p>How is it possible to confirm the correct installation of the retaining ring and the correct upwards orientation of the chamfer?</p>		<p>To avoid complex and expensive solutions to verify the orientation of the chamfer before installation, a probe system was designed to confirm the positioning of the part after installation. Since the manual replacement of the part, when poorly inserted, is a fast and easy operation, this solution was adopted due to its simplicity and lower cost.</p>

When the station 1.B finishes its operating cycle, the operator collects the subassembly 3 from the nest and moves to station 2, where the next components will be assembled.

4.3.5 Project common to station 1.A and 1.B

In this subchapter, the parts of the project common to station 1.A and 1.B will be discussed. Although these stations perform independent operations, they are installed in the same cell, and consequently, there are some parts of the project that are related to both stations, such as the pneumatic project, budgeting, and parts list.

4.3.5.1 Pneumatic project

The pneumatic project of these stations is common since there's only one PLC and air treatment unit. The system is divided into three ramifications after the air treatment unit, a group of valves for the station 1.A (valve block 2), a group of valves for the station 1.B (valve block 3), and another group common to both stations that contain the valves that need to stay pressurized if the safety light curtains are interrupted (valve block 1). In this equipment, there are also 3 pairs of residual pressure release valves, which release all the air of the system in case of an emergency trigger (safety light curtains or emergency button). These valves are organized in pairs to obtain redundancy. This means that if one fails to release the residual pressure from the system, the other one will do the job. They are also monitored through safety limit switches to make sure they are operating correctly and exhausted the air.

These pairs of residual pressure release valves can be seen in Figure 101. The first pair is integrated into the air treatment unit and will release all the air from the system if the emergency button is pressed, stopping both stations. The second pair is located before the valve block 2 and if the safety light curtains of station 1.A are interrupted, it will cut the air supply to this block. The last pair is located before the valve block 3 and will cut the air supply of this block if the safety light curtains of station 1.B are interrupted. The valve blocks already mentioned are described in Table 89 to Table 91.

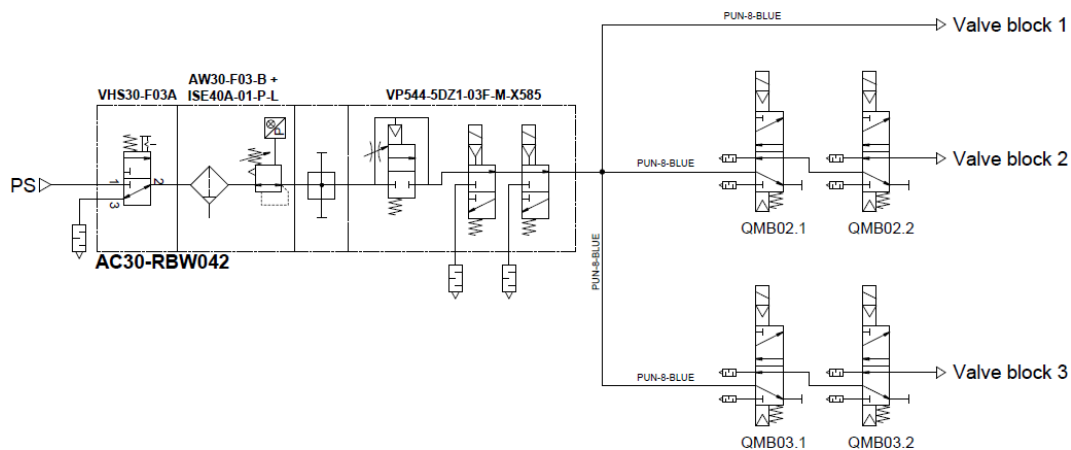


Figure 101 – Emergency air pressure release system

The valve block 1 contains the valves that control the actuators which hold parts and would drop them if the air was cut-off. To avoid this, the air supply of these valves is kept open, even if the safety light curtains are interrupted. Additionally, the actuator MMB501 and MMB502 need to move when the operator is loading the machine, and at this point, the safety light curtains are interrupted, meaning these actuators need to be outside the safety circuit of the light curtains.

This valve block only has its air supply interrupted when the emergency button is pressed since in this scenario all the power supplies need to be shut-off. For this reason, the valves that control the MMB501 and MMB502 are also closed-center, so that even in the case of the emergency button being pressed the parts do not fall. The actuator MMB503, has explained previously in Table 80, needs to be 5/3 open center for the mechanism to operate correctly, which could lead to the release of the retaining ring from the fingers.

The other two valve blocks control the remaining actuators and will have their air supplied cut every time the safety light curtains are interrupted or the emergency button is pressed.

Table 89 - Valve block 1 configuration

Slot	Actuator ID	Valve type	Tube size (mm)	Description
1	MMB501	5/3 Closed center	Ø4	Bearing lock
2	MMB502	5/3 Closed center	Ø4	Subassembly 1 lock
3	MMB503	5/3 Open center	Ø6	Retaining ring gripper (fingers)

Table 90 - Valve block 2 configuration

Slot	Actuator ID	Valve type	Tube size (mm)	Description
1	MMB511	5/3 Open center	Ø6	Shaft carrier

Table 91 - Valve block 3 configuration

Slot	Actuator ID	Valve type	Tube size (mm)	Description
1	MMB521	5/3 Open center	Ø6	Subassembly 1 insertion
2	MMB522	5/3 Open center	Ø6	Retaining ring insertion
3	MMB523	5/3 Open center	Ø6	Nest carrier
4	MMB524	5/3 Closed center	Ø4	Housing lock
5	MMB525	5/3 Open center	Ø6	Retaining ring carrier
6	MMB526	5/2 Bistable	Ø4	Retaining ring wedge
7	MMB527	5/2 Bistable	Ø4	Retaining ring holder
8	MMB528	5/2 Bistable	Ø4	Retaining ring position check

The full pneumatic scheme can be found in Annex IV.

4.3.5.2 Budgeting

A resume of the costs associated with station 1 can be seen in Table 92. In this table, the costs are divided into different categories and the values presented are a close approximation of the real cost. Due to confidentiality issues, a detailed version of this budget will not be provided.

Table 92 - Station 1 budget

	Description	Cost (€)
Human labor	Mechanical project	17 500
	Electrical project	8000
	Software & application	10 500
	Mechanical assembly	7000
	Electrical assembly	4000
Materials	Cell	16 500
	Pneumatic & mechanical standard parts	20 000
	Electrical	33 000
	Mechanization	15 000
Other costs	Project management related costs	3000
	Packing and shipment	600
	Installation	1400
	Training (1 week)	1200
	Production support (3 weeks)	1800
Total station cost		139 500 €

4.3.5.3 Bill of materials

The bill of materials is available in the Annex V. The list of parts is divided into two main parts, the custom manufactured parts, and the standard parts. Within these two parts, there are different categories in which the parts are organized. The custom manufactured parts are divided according to their manufacturing process, being the categories acrylics (parts produced mainly from polycarbonate), machined parts (all the parts that need to be produced in a CNC or lathe), sheet metal (includes parts produced by laser cutting, bending, and parts produced with sheet metal) and welded (structures and sheet metal parts that need to be welded to achieve the final part). The standard parts are divided into three categories, pneumatic, mechanical standard parts, and electronic.

4.4 Station 2

4.4.1 Operation and main considerations

Station 2 is the only fully manual station in the assembly line. This station is where the nut and PCB will be installed onto subassembly 3. The nut is needed to stop the play between the shaft and the bearing 1 and will be the first component to be installed. The other component is the PCB, which will be positioned and oriented on the housing by the operator. In the end, 3 screws need to be assembled to fix the PCB onto the housing. The resultant product of this station is the subassembly 5. An exploded view of this subassembly can be seen in Figure 102.

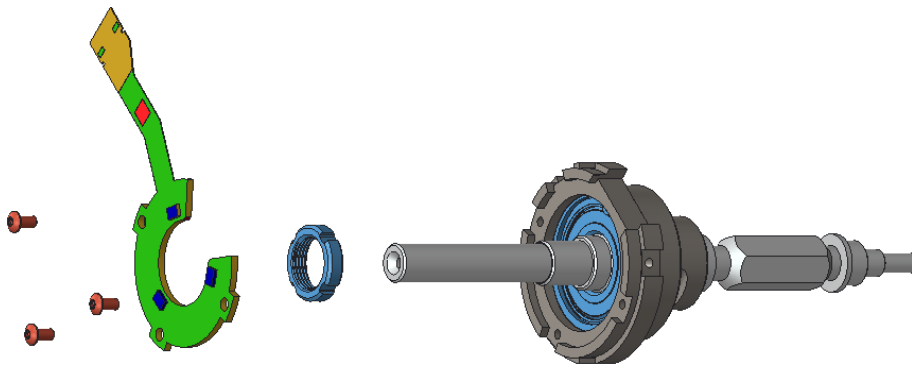


Figure 102 - Exploded view of subassembly 5

Since all the manipulation of the parts is done by the operator in this station, it is his/her responsibility to carefully handle them. Adding to the shaft zone that cannot be touched, the operator now needs to be careful with the PCB components and its flat connector, in order to not damage or over bend it. From the three components to be assembled, only the PCB comes oriented in plastic trays, the others come packed at random inside packages. Also, both the nut and the screws come with a pre-applied coating on the threads (example in Figure 103) for the self-locking of these components. When being tightened, this coating breaks, and the curing process of the adhesive begins. During this breakage, particles are released to the subassembly, which is a factor to take into consideration during the project.



Figure 103 - Pre-applied coating on the fasteners [112]

4.4.2 Specifications

The requirements imposed by the customer for this station are listed in Table 93.

Table 93 - Station 2 specifications

Specification	Description
Parts loading	<ul style="list-style-type: none"> • Manual loading of subassembly 3 on the tool; • Manual assembly of the PCB; • A screw feeder to orient them must be provided (NSBI Quicher); • Manual loading of the nut.
Part detection	<ul style="list-style-type: none"> • Detection of subassembly 3 on the nest;
Process	<ul style="list-style-type: none"> • The screwdrivers must be from Desoutter; • The screwdrivers must possess torque and angle control; • The screwdrivers must be installed in ergonomic tool arms; • Torque required for the nut: 14 N·m; • Torque required for the screws: 1,5 N·m; • A mask is required to prevent damage on the PCB; • The PCB has a 2D code engraved and it must be read at the end of the operation; • Vacuum is required.

4.4.3 Brainstorm

The design of this station is somewhat defined beforehand. The screwdrivers will be installed in ergonomic tool arms and there will be a screw feeder, thus is still necessary to design the nest, vacuum system, and mask. This station needs special attention to conceive an ergonomic design since all the operations are manual and there are a lot of components that the operator needs to interact with. This station will also be designed within a cell with the smallest dimensions available, therefore a careful placement of the components needs to be taken into consideration.

In this station, to orient the subassembly 3 the predicted half holes of the housing can be used. Thus, the nest will have two pins that will align with these holes, as well as a face to reference one of the external diameters of the housing. To have the screwdrivers at an ergonomic height for the operator, the nest needs to be as low as possible, but at this height, the operator loses

visual contact with the orientation pins. This could create difficulties for the operator to align the half holes with the pins, thus, to avoid this problem and ease the alignment of the subassembly, the nest can be placed in a rotary system that will alternate between a loading position and a position to assemble the components. The load position will be angled in such a way that the orientation pins will face the operator and the assemble position will be parallel to the workbench so that the nut and screws can be installed vertically. A representation of this mechanism can be seen in Figure 104.

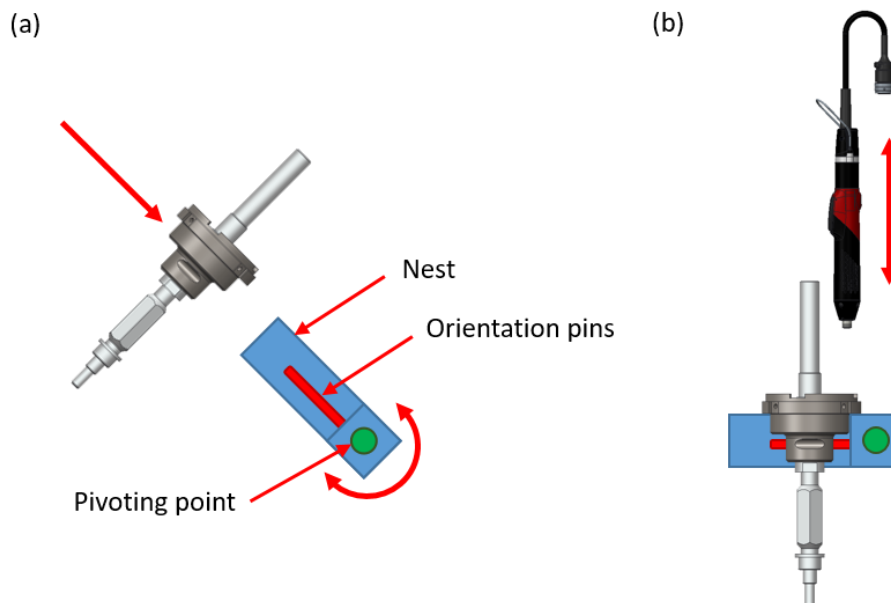
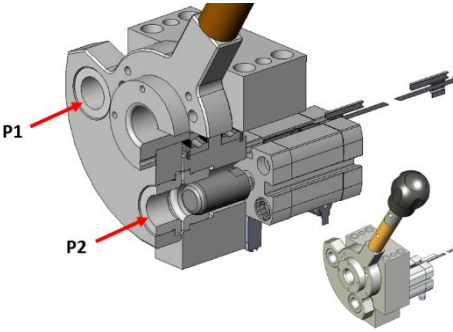

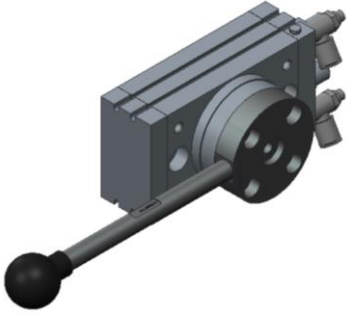


Figure 104 - Schematic representation of the nest: a) Loading position; b) Assemble position;

With this nest, it is also necessary to lock the subassembly so it does not move during the operation. To achieve this, the design used in station 1.B to lock the housing will be adapted, since the system is already designed, it is easier to adapt it than designing a new system from scratch. It is important to keep in mind that this station does not have safety light curtains and that this cylinder will move with the operator exposed to it, creating the possibility of the operator getting his finger squeezed between the wedge and the housing. Taking this into consideration it is also important to mention that the actuator selected for this job can only produce a force of around 47 N at the pressure of 6 bar. This force is not enough to cause injuries and the operator can easily remove the finger or push the wedge back. Even so, to reduce this force, a pressure regulator was installed to adjust the force of the actuator for the bare minimum needed to still push the subassembly against the nest and hold it snugly.

Also, with this rotary mechanism, it will be necessary to design a locking system so that the nest stops in both positions. For this mechanism, three different systems were considered, a pneumatic pin lock, a spring plunger lock, and a rotary pneumatic actuator. These systems are presented in Table 94, as well as their pros and cons.

Table 94 - Rotation lock options

	Example	Pros and cons
Pneumatic pin lock		<p>Pros:</p> <ul style="list-style-type: none"> • Mechanical and pneumatic lock; • Good process control. <p>Cons:</p> <ul style="list-style-type: none"> • Higher cost; • Most complex out of the three options.
Spring plunger	 <p>(Same system as the pneumatic pin lock but with a manual spring plunger)</p>	<p>Pros:</p> <ul style="list-style-type: none"> • Lower cost; • Simple system; • Mechanical lock. <p>Cons:</p> <ul style="list-style-type: none"> • Needs external position detection; • Another step to be executed by the worker.
Rotary actuator		<p>Pros:</p> <ul style="list-style-type: none"> • A shelf-ready and simple solution; • Good process control. <p>Cons:</p> <ul style="list-style-type: none"> • May present a danger for the operator; • Non-mechanical lock.

Analyzing Table 94 the option that is more attractive in a mechanical design point of view is the rotary actuator. Having a shelf-ready solution is a huge advantage in terms of simplifying the design and reducing the design and manufacturing time. In comparison to the other options, the biggest disadvantage is the danger that this system may present for the operator. The system cannot move by itself and the chambers of the actuator should only be pressurized when the actuator is in its final positions. This control can be done pneumatically and more than one sensor and valve can be added to the system to create redundancy and make sure the actuator will never move by itself even if one of the components malfunctions.

Regarding the other two options, the pneumatic pin lock is an attractive option in terms of functionality but would need more time for the design and manufacturing which would result in a greater cost in human labor, as well as parts costs. The spring plunger is the simplest, safest, and cheaper solution, but adding another manual task for the operation in a machine where all the tasks are manual did not please the customer, thus this option was discarded.

For these reasons, the option chosen was to design the nest rotation system using a rotary actuator, but as established before, with special attention to make sure the actuator is only pressurized when necessary.

Regarding the mask, the goal is to create a shelter for the PCB so that the operator cannot accidentally damage its components during the screwing operation. The mask should cover the whole PCB and only have three holes that will help guide and install the screws. This mask needs to be removable since the nut must be installed before the screws, as well as the PCB. This being said, the mask needs a guiding system to make sure that when needed it is easily positioned and that it stays in the correct position during the operation.

Two options were considered, a pivoting mask and a linear guided mask. A representation of these two options can be seen in Figure 105.

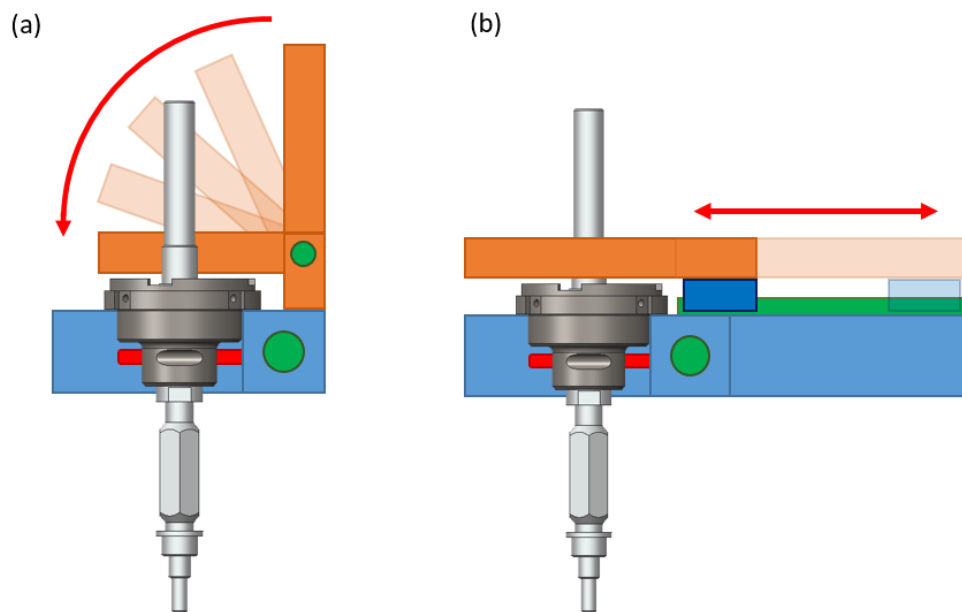


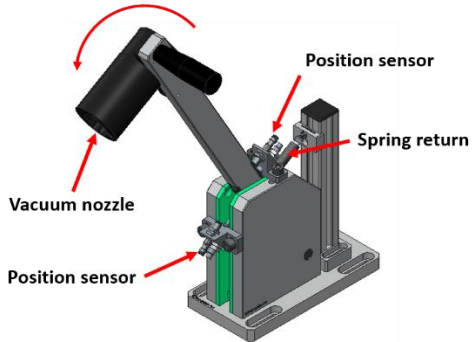
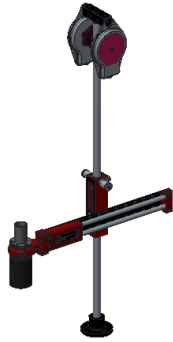
Figure 105 - Mask options: a) Pivoting mask; b) Linear guided mask

These two options are very similar in terms of costs and functionality, but shortly after considering these two options, the pivoting mask was excluded. With this pivoting option, for the mask to be easily accessible, it needs to stay in a vertical position when not in use, and this would interfere with the screwdrivers and the space to maneuver them freely. With the linear guide system, this problem is eliminated, the mask stays in a low position and as close as possible to the housing.

This mask will be guided with low profile linear guides and blocks and it will be manually activated. To lock the mask in place, since the positioning is not very critical due to the large manufacturing tolerances of the screws, a simple combination of a spring plunger and a groove will be used to secure the mask in both the rest and operating positions.

Finally, for the vacuum system, is necessary to verify if the operator cleans the subassembly being produced, and if so, for how much time. To achieve this, the vacuum can be either attached to a fixed nest or have a movable nozzle. Taking into consideration all the tasks that the operator already needs to perform and, since the subassembly is already oriented on a nest, it is better to eliminate another handling operation of the product and have a movable nozzle that can move up to the nest and clean the particles produced by the screwing operations. Established this, the movable system needs to have a position control so that the PLC can verify that the nozzle was placed on the product and for how long it stayed there. For this mechanism, two options were considered, a rotary lever and an ergonomic tool arm. Both these options are presented in Table 95, along with their pros and cons.

Table 95 - Vacuum system options

	Example	Pros and cons
Rotary lever		<p>Pros:</p> <ul style="list-style-type: none"> • Single-axis movement to engage the nozzle; • Good process control. <p>Cons:</p> <ul style="list-style-type: none"> • Occupies space near the nest and may constrain the operator’s movements; • Most complex out of the two options.
Ergonomic tool arm		<p>Pros:</p> <ul style="list-style-type: none"> • A shelf-ready and simple solution; • Good process control. <p>Cons:</p> <ul style="list-style-type: none"> • Two-axis movement to engage nozzle; • Higher cost in components.

Analyzing the two options, the best solution seems to be the ergonomic tool arm. Although an ergonomic tool arm can be a costly component, the savings made in the design and manufacturing time easily compensate for its cost. Even more, and as established before, space is scarce in this station, and having a solution that constrains movements is not a feasible option.

To this ergonomic arm, an anti-rotation system can be added to only allow movement in two axes, as well as a sensing mechanism to detect its position on the nest and control the cleaning process.

4.4.4 Project

4.4.4.1 Overview

In Figure 106 an isometric representation of station 2 can be seen. The components are identified with balloons, and their legend is presented in Table 96. Additionally, other views of this station can be found in Annex II.

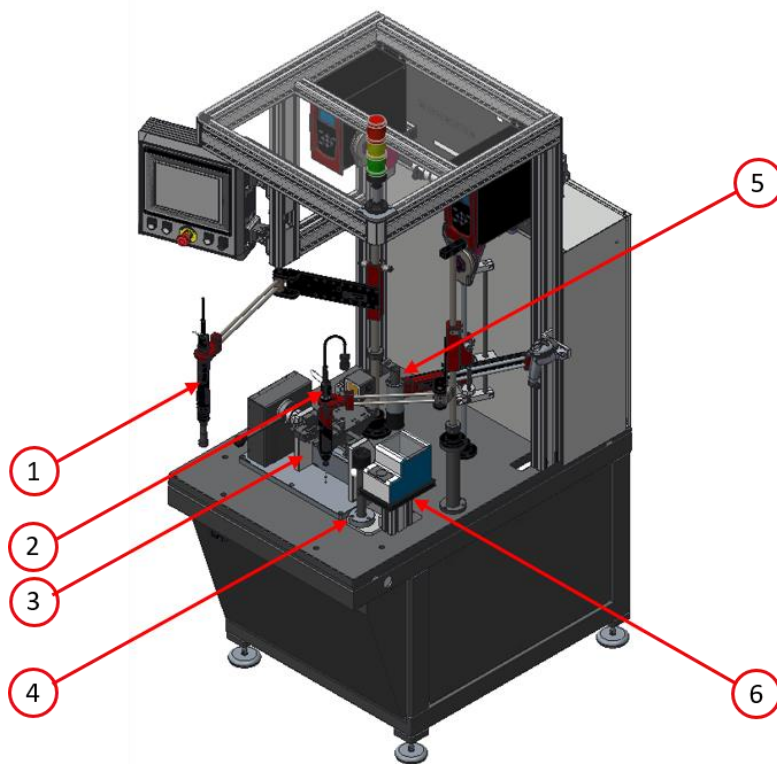


Figure 106 - Isometric view of station 2

Table 96 - Station 2 components

Number	Reference	Description
1	A-A210-99	Nut screwdriver
2	A-A220-99	Screws screwdriver
3	A-A205-99	Nest
4	A-A216-99	Nut positioner
5	A-A245-99	Vacuum system
6	A-A225-99	Screw feeder

4.4.4.2 Focal points

As already mentioned before, the space available in this station is very limited and there is a significant amount of components that need to be installed. This created a challenge since everything needed to be placed ergonomically. In the end, it was possible to achieve an ergonomic design with minor compromises in some handling points. In Figure 107 the points of interaction between the operator and the equipment are highlighted and it is possible to see the layout achieved following the orientations of the standard ISO 14738.

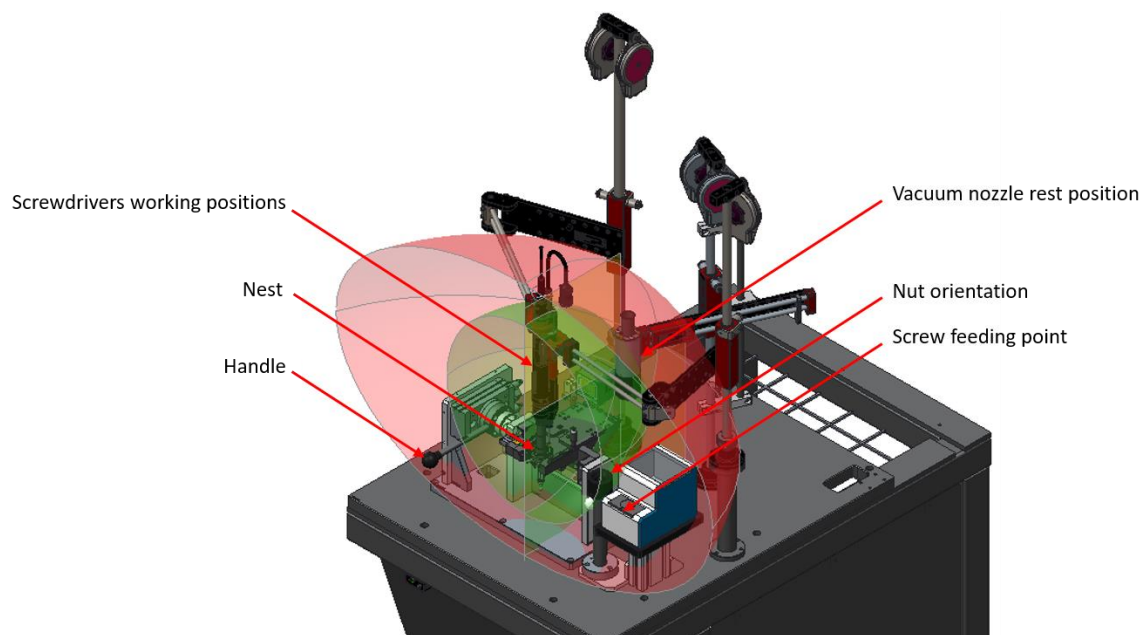


Figure 107 - Station 2 components

The compromises were made on the screw feeding point and the vacuum nozzle position, they slightly outside the desired work area, but they are still within ergonomic reach. The screw feeding point is right on the edge of the desired work area, but since the operator will need to reach this position three times per cycle it would be preferable to have inside it. Regarding the handle, when the nest is in the working position it also stays in a not ideal position but, like the vacuum nozzle, the operator will only reach this position one time per cycle.

It is important to add that the dimensions used from the ISO 14738, were applied while disregarding the movement of the operator, it is assumed that the operator stands still in the same spot during the operations.

In Figure 108, additional views of the ergonomic analysis are presented.

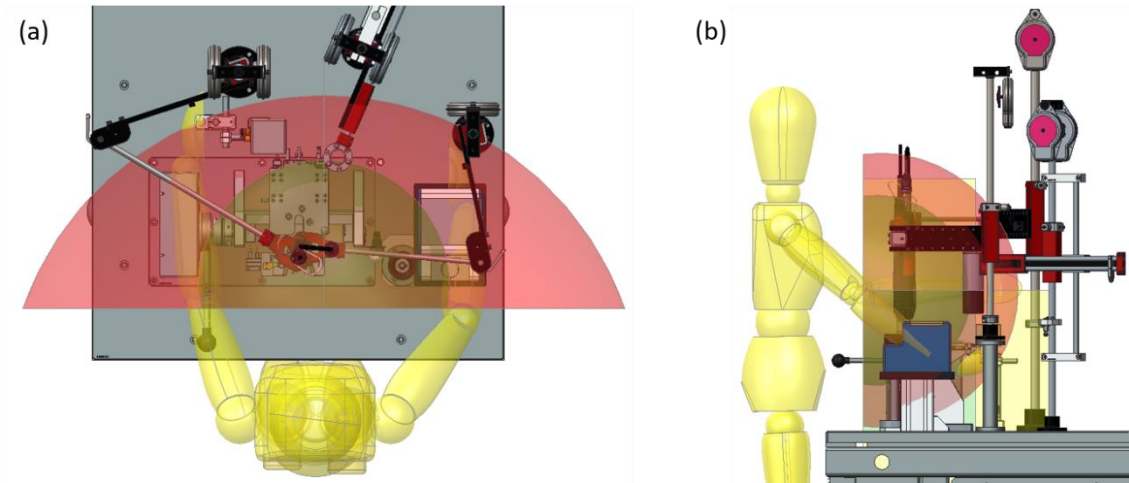


Figure 108 - Station 2 ergonomic analysis: a) Top view; b) Right view

It is also important to add that the rest position of the screwdrivers was ignored. The ergonomic tool arm has three degrees of freedom (one vertical linear axis and two rotation axes) and their rest position is not constant, mostly depending on the operator.

Taking into consideration all these points and despite the efforts made to make this station as ergonomic as possible, it is recommended that the operator assigned to this station changes from hour to hour. Since there are a lot of movements and reaching points in this station, in comparison to the rest of the assembly line, it is clear that this station has the largest workload, thus, to avoid excessive physical effort and possible burnout of the operator, this schedule rotation is highly recommended.

The remaining focal points of station 2 are presented in Table 97.

Table 97 - Focal points of station 2

	Illustration	Focal points
2D code scanner		<p>In this station, the first component with a 2D code is assembled. From this point onwards all the production information will be related to the motor being produced through the reading of this code. At this point, the production data from station 1 will also be related to the product read in station 2. The reader chosen for this job is produced by IFM and its reference is O2I304. The code will be read at the end of the operation in case the motor produced is OK.</p>

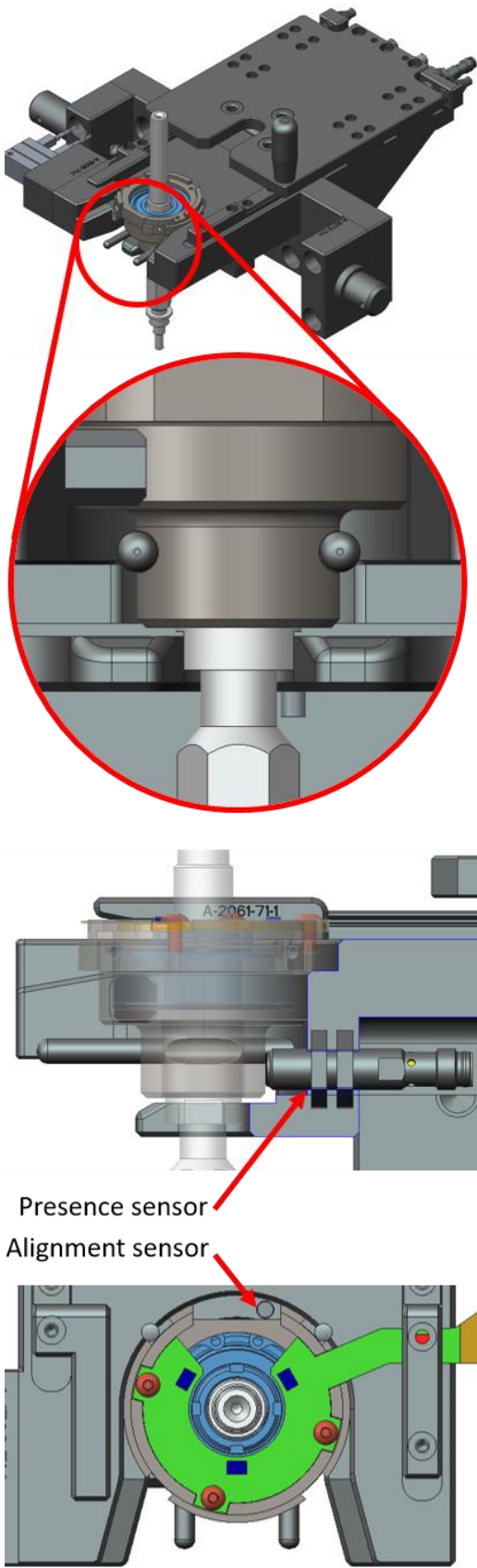
	Illustration	Focal points
<p>Nest</p>		<p>The nest is responsible to align and hold the product during the screwing operations and is also where the mask and its guiding system are mounted. A rod was installed on each side of the nest to be supported by the bearings of the rotary system, only allowing the nest to move within its rotation axis.</p> <ul style="list-style-type: none"> <p>Orientation: In this nest, it is necessary to orient the housing and the shaft. The housing is oriented through the half holes and one of its outside diameters, which are the references that will align the entire subassembly in the nest and consequently with the mask. Regarding the shaft, it spins freely since it is only attached to the bearing, thus, to tighten the nut, this rotation needs to be restrained. The shaft has two flat faces for this purpose and this is where the nest will lock it. During the insertion, the subassembly first aligns by the half holes, and afterward, the operator must turn the shaft until the flat faces align with the groove on the nest. If the flat faces are not aligned it is not possible to insert the subassembly completely.</p> <p>Inductive sensors: An inductive sensor is used to sense the presence of the housing on the nest and it will only detect it when fully inserted. A second sensor was installed to make sure the subassembly is in the correct orientation (With the housing relief facing the operator) since it can be inserted in both ways, but the mask will only align when correctly inserted.</p> <p>Wedge: The wedge follows the same principle as the one from station 1.B, but it will work with a slower movement and a lower pressure to present the smallest risk possible for the operator.</p>

	Illustration	Focal points
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Rotary system</p>	<div data-bbox="309 322 810 766" data-label="Image"> </div> <div data-bbox="300 824 817 1377" data-label="Image"> </div> <div data-bbox="306 1505 817 1930" data-label="Image"> </div>	<p>The rotary system consists of a rotary pneumatic actuator, handle, floating joint, and a pair of bearings. The two rods of the nest are installed on the bearings, blocking all the movements except the rotation pretended. The actuator rotation axis is aligned with the rods of the nest and connected through a flexible coupling. Finally, the handle is connected to the actuator and has a length of roughly 220 mm from the knob sphere center to the rotation axis of the actuator.</p> <ul style="list-style-type: none"> Rotary actuator: The rotary actuator chosen for this application was the MSQB50A from SMC. This actuator produces a torque of 5,57 N·m at 6 bar and 1,85 N·m at 2 bar. Since the center of the knob is located at approximately 220 mm from the center of the actuator, this means that the operator, at 6 bar, needs to apply around 25 N of force to move the nest and at 2 bar only needs approximately 8 N (these forces do not take in consideration the effect of the center of gravity). Flexible coupling: In order to not reduce the lifespan of the rotary actuator, a coupling is added between the rods of the nest and the actuator. This coupling will absorb minor deviations and eliminate possible tensions that would be created. Operation: After designing the nest and the mask in was possible to observe that the center of gravity is off-center in relation to the rotation axis. In the image beside is possible to see a rough location of the center of gravity. This means that the nest, when the actuator is unpressurized, will tend to fall to the loading position. Since the goal is for the nest to only move when the operator intervenes, a solution for this was found and will be explained in the subchapter 4.4.4.5.

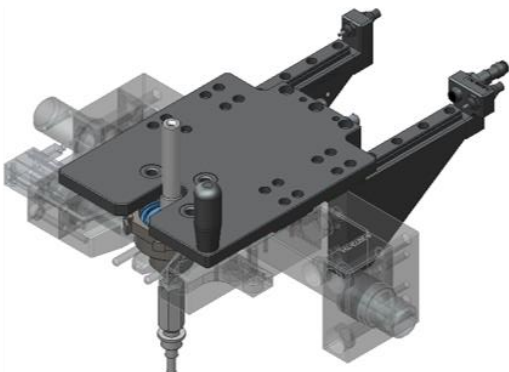
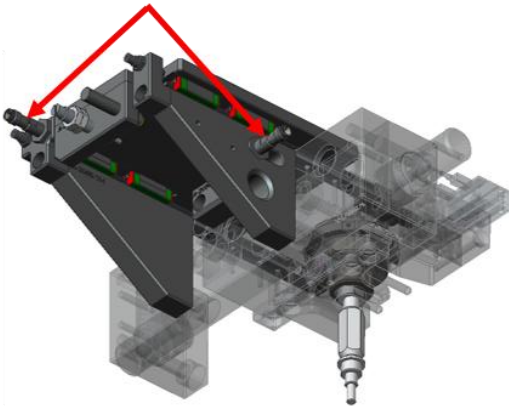
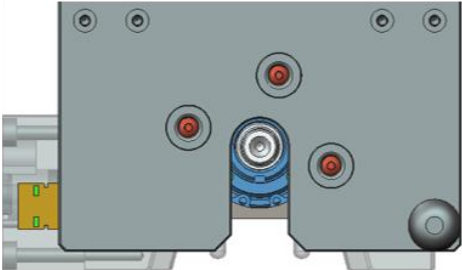
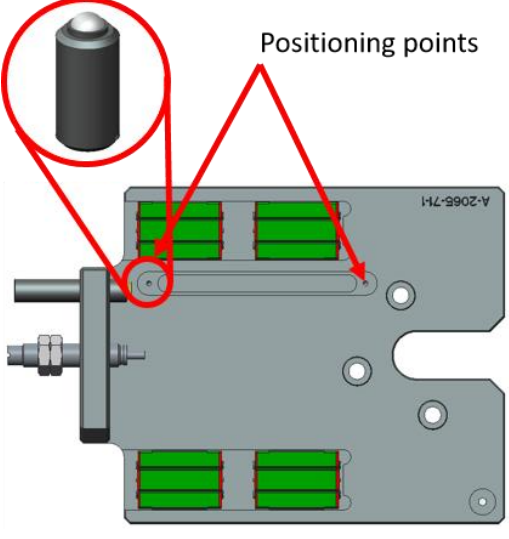
	Focal points
<div style="display: flex; align-items: center;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg); font-weight: bold; margin-right: 10px;">Mask</div> <div style="flex: 1;"> <p style="text-align: center;">Illustration</p>  <p style="text-align: center;">Position sensors</p>   <p style="text-align: center;">Positioning points</p>  </div> </div>	<ul style="list-style-type: none"> • Linear guides: The linear guides used on the mask are different from the ones used so far. Since the purpose of the guides is to only guide the movement and not bear any load, to keep the system light and compact a linear guide from the miniature series of Hiwin was used. The model chosen was the MGN09CH and, to avoid large accidental moments, four blocks were installed. • Sensors: The mask has two inductive sensors to control its position. The PLC monitors these sensors to know when the mask is engaged and disengaged, making sure the operator is following the operation procedure step by step. • Shock absorbers: To smooth the stopping movement of the mask, two shock absorbers were installed, one in each of the final positions. • Bushings: The part of the mask that will suffer the greatest wear are the holes that guide the screws. To avoid a complex spare part, three DIN172A drill bushings were installed, making the spare parts a standard component, easier to purchase, and for a fraction of the mask plate price. • Positioning: To guarantee the position of the mask a simple track system with two positioning tapered holes was used. To lock the mask, a spring plunger with a metallic sphere tip is used, which is only tensioned when the mask reaches the final positions. The spring plunger is gradually compressed through a chamfered face and then decompresses inside the tapered holes, positioning the mask. Between these two points, the mask does not take any force from the spring plunger and can move freely and smoothly.

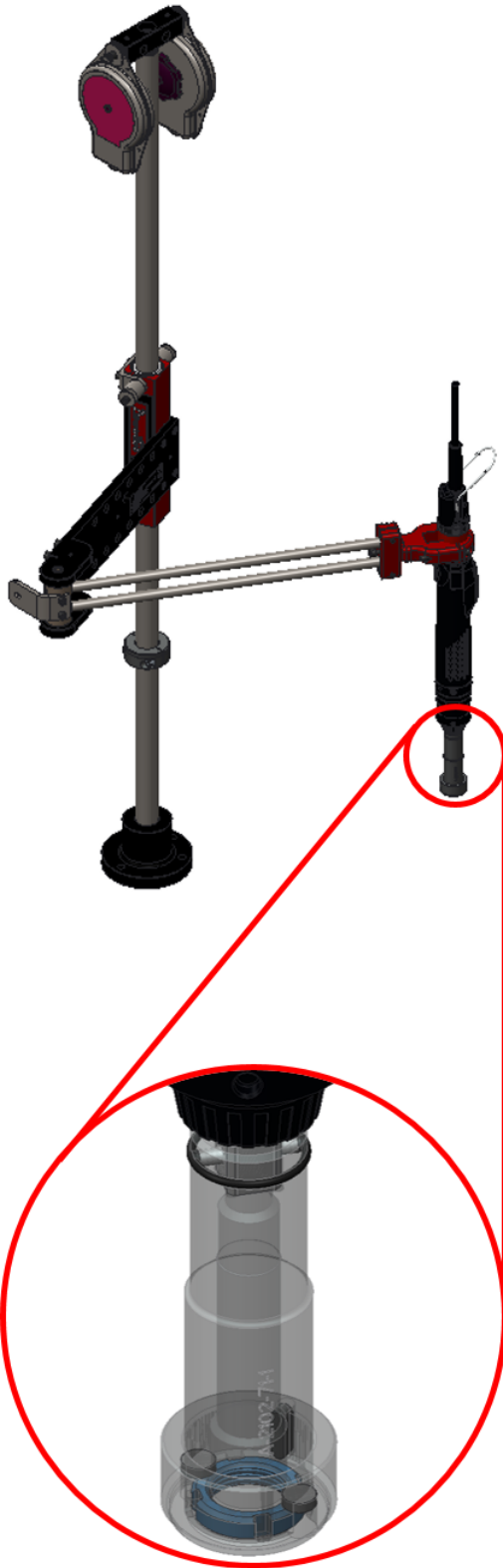
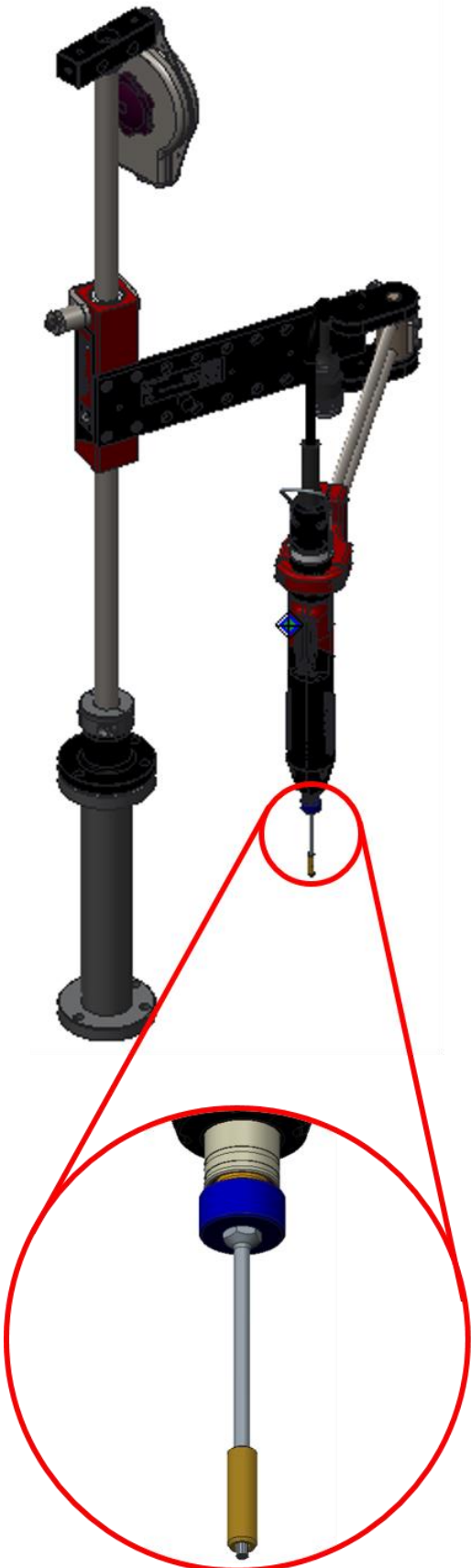
	Illustration	Focal points
<p>Nut screwdriver</p>		<ul style="list-style-type: none"> Ergonomic tool arm: The ergonomic tool arm selected for this screwdriver, by request of the customer, is produced by Desoutter. This brand has two types of ergonomic arms, the linear and the pantograph type. At their production site, the customer typically uses the pantograph type, thus, to use components already present on their factory floor it was implemented the pantograph D53-25S. This arm is capable of absorbing a torque reaction up to 25 N·m and holding a tool weight of 2,5 Kg, which is more than enough for the application in question. Screwdriver: At IPTE, electronic components are normally chosen by the electric department, and the electric screwdrivers are no different. Thus, the screwdriver selected was the ERS22-M20 by Desoutter. This screwdriver is capable of producing torques between 6 and 22 N·m and weighs 1,05 kg (this weight validates the capacity of the ergonomic tool arm). The output connection of the screwdriver is a 3/8" square connector. Tool: The tool was custom designed for this application. To be capable of installing the nut onto the shaft, the tool needs to have enough height and a hollow interior so that it can circumvent the shaft and reach the threads where the nut will fasten. This tool has four teeth that will enter the grooves of the nut and guarantee the transmission of the torque. The nut will stay attached to the tool during the manipulation thanks to two magnets installed on the interior of the tool. This is not ideal since they will collect metallic particles over time, but other solutions would be more complex and expensive.

	Illustration	Focal points
<p>Screws screwdriver</p>		<ul style="list-style-type: none"> <p>Ergonomic tool arm: Just like the ergonomic tool arm chosen for this screwdriver, this one will also be a pantograph type from Desoutter, exactly for the same reasons. Since the torque needed for the screws is only 1,5 N·m the smallest pantograph from this series can be used, which is the D53-5S. This arm is capable of absorbing torque reactions up to 5 N·m and holding a tool weight of 0,8 Kg, meaning the torque absorption is more than enough for the application in question, but the max weight for the tool is close to the screwdriver weight.</p> <p>Screwdriver: For this operation, the electric department selected the electric screwdriver ERS2 by Desoutter. This screwdriver is capable of producing torques between 0,6 and 2,5 N·m and weighs 0,7 kg. Has stated before, the weight of the screwdriver is close to the max weight that the ergonomic arm can handle. If latter this becomes a problem, it is possible to add a stronger tensioner to the arm to support larger weights and hold this screwdriver. The output connection of the screwdriver is a female 1/4" hexagonal connector.</p> <p>Tool: For the tool of this operation, since the output connection is a standard type for fasteners, it is possible to use market-ready components. The bit selected only needs to be long enough so that the screwdriver stays in a higher position than the tip of the shaft. To hold the screw, a standard magnetic accessory was used to magnetize the bit and it was also added a brass sleeve to help center it on the bushing and ease the aligning and insertion of the screws.</p>

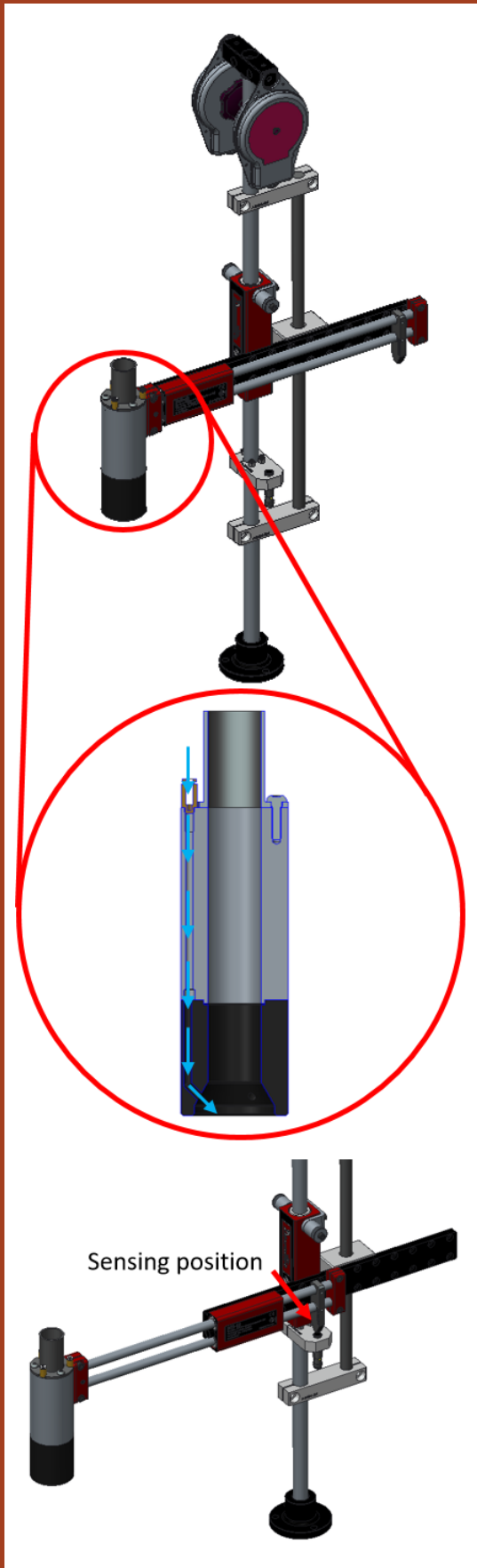
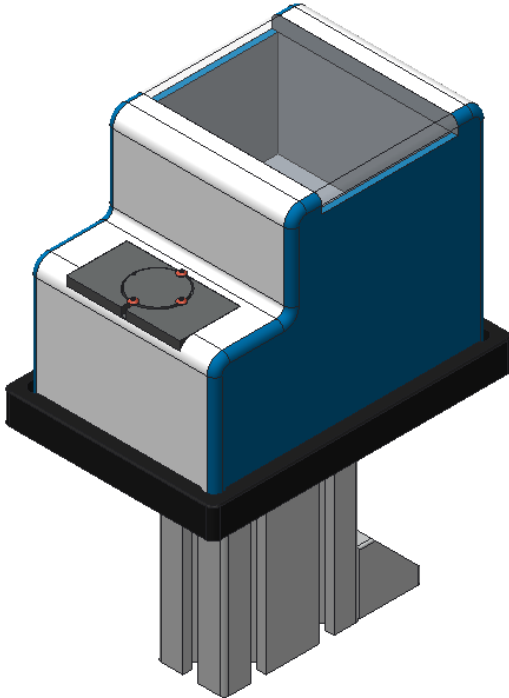
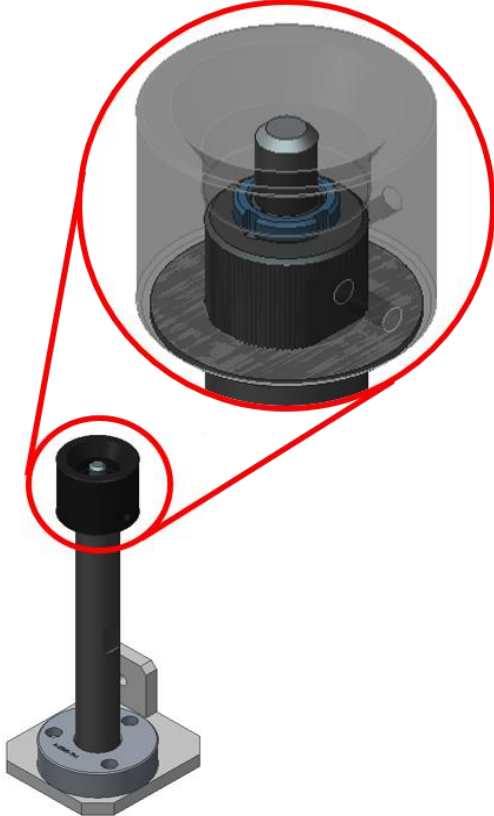
	Focal points
<p data-bbox="245 1032 272 1205" style="writing-mode: vertical-rl; transform: rotate(180deg);">Vacuum system</p> <div data-bbox="288 237 826 1995"> <p data-bbox="496 208 619 230" style="text-align: center;">Illustration</p>  </div>	<ul style="list-style-type: none"> <li data-bbox="855 275 1361 808"> <p>• Ergonomic tool arm: For the vacuum system it was also decided to use an ergonomic tool arm. This arm, which is also from Desoutter, is not a pantograph type like the others. Since a controlled movement was desired, a linear-type ergonomic arm was better, besides, the space available was not sufficient for another pantograph. Thus, since this ergonomic arm will not need to withstand any torque, it was selected based on its dimensions. The model chosen was the D53-12.</p> <li data-bbox="855 842 1361 1167"> <p>• Anti-rotation: To this ergonomic arm an anti-rotation system was added. Since the vacuum nozzle only needs to reach 2 positions (vacuum position and rest position) it only needs two degrees of freedom. Any additional degrees of freedom will make it more difficult to align and control the tool.</p> <li data-bbox="855 1200 1361 1648"> <p>• Vacuum nozzle: The vacuum nozzle was custom designed for this operation in order to attach directly to the ergonomic arm and better fit the product. This vacuum nozzle has three channels equally spaced around its axis. These channels will burst blows of air during the Vacuum operation. The goal is to agitate any particles deposited in areas where the vacuum cannot reach with sufficient power to extract them.</p> <li data-bbox="855 1682 1361 1962"> <p>• Sensing position: A sensor is needed to monitor the position of the arm during the vacuum operation, which was achieved with an inductive sensor and a metallic pointer. This was designed in such a way, that the sensor is only activated when the arm reaches the required position.</p>

	Illustration	Focal points
Screw feeder		<ul style="list-style-type: none"> • Screw feeder: The screw feeder was specified by the customer, being the model NSBI by Quicher. This equipment is capable of orienting and feeding the screws individually, making sure the operator will always have a screw ready to pick up when needed. This feeder also comes with an adjustable metallic guide that helps the operator to insert the bit into the screw head easily. • Support: If the Quicher was resting on the workbench, the height at which the operator would pick up the screws would not be sufficiently good regarding ergonomics. As seen in Figure 108, the Quicher is already slightly off the desirable area and if it was sitting on the workbench it would be even worse. Thus, to bring the Quicher to a more desirable height, a support was designed to raise it.
Nut aligner		<ul style="list-style-type: none"> • Nut aligner: As mentioned in the subchapter 4.4.1, the nut will reach the station randomly displaced inside packs. To help the operator insert the nut into the tool a support was provided. This support has a pin to center the nut and an external guide for the tool. The operator will drop a nut on the pin and, through gravity, the nut will center itself. The operator then moves the screwdriver to this aligner and inserts the tool into the guide, which will center the tool with the nut. Finally, to align the tool's teeth with the grooves on the nut, the operator will activate the screwdriver, which will turn counter-clockwise, until the teeth enter the grooves. At this point the operator will feel the whole screwdriver drop a few millimeters, meaning that the teeth entered the grooves of the nut.

4.4.4.3 Operation sequence

In this subchapter, a list of all the sensors and actuators will be presented, including the sensors that detect the actuators’ positions, which are available in Table 98 and Table 99. In these tables, the brands and references of the components will also be mentioned as well as a description of their function. This will help to better understand how the operation sequence functions, as well as connect this sequence with the information present in the pneumatic diagram.

Table 98 - Station 2 sensors

Sensor ID	Brand	Reference	Description
BRC19	Omron	E2E-C04S12-WC-B1	Subassembly 3 in the correct position
BRC20	Omron	E2A-S08KS02-M5-B1	Subassembly 3 Presence
BRC21	Omron	E2A-S08KS02-M5-B1	Mask on screwing position
BRC22	Omron	E2A-S08KS02-M5-B1	Mask on the rest position
BRC23	SMC	D-F8PSAPC	Subassembly 3 lock (front)
BRC24	SMC	D-F8PSAPC	Subassembly 3 lock (back)
BRC25	SMC	D-M9PSAPC	Nest on screwing position
BRC26	SMC	D-M9PSAPC	Nest on the rest position
BRC30	Omron	E2A-M12KS04-M1-B1	Vacuum cleaner Valve (open)
BRC31	Omron	E2A-M12KS04-M1-B1	Vacuum nozzle in position
BRC32	Multicomp Pro	PSF109S-81-330	Vacuum cleaner pressure ok

Table 99 - Station 2 actuators

Actuator ID	Brand	Reference	Description
MMB501	SMC	CDUJB10-10D	Subassembly 3 lock
MMB502	FESTO	VZPR-BPD-22-R112	Vacuum on/off valve
MMB503	SMC	MSQB50A	Nest position lock

Apart from these three actuators and their control valves, on the valve group, there is also a dedicated valve to control de air burst during the vacuum cleaning operation. This valve releases three bursts with a duration of 0,5 seconds, and the whole vacuum operation takes approximately 5 seconds. This valve will be latter referenced again in the subchapter 4.4.4.5.

Upfront, in Table 100, the operation sequence will be explained step by step. It is important to keep in mind that this station is fully manual and the operator is responsible for following this sequence in order to produce a successful subassembly. The PLC will monitor all the steps and will alert the operator when he misses a step or concludes it unsuccessfully as well as block the screwdrivers from working if necessary.

Table 100 - Station 2 operation sequence

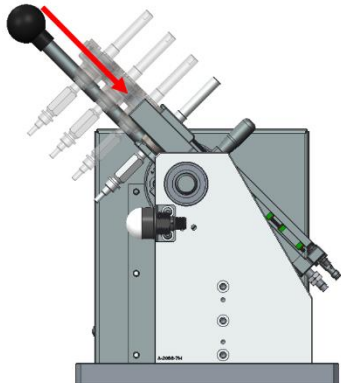
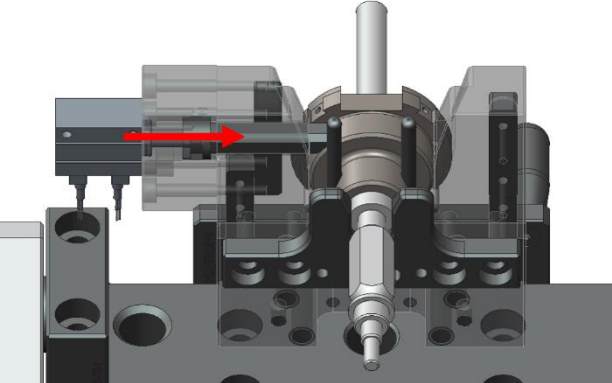
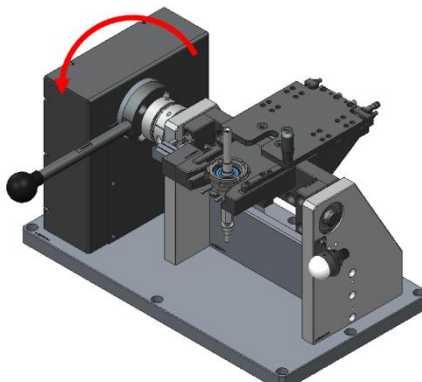
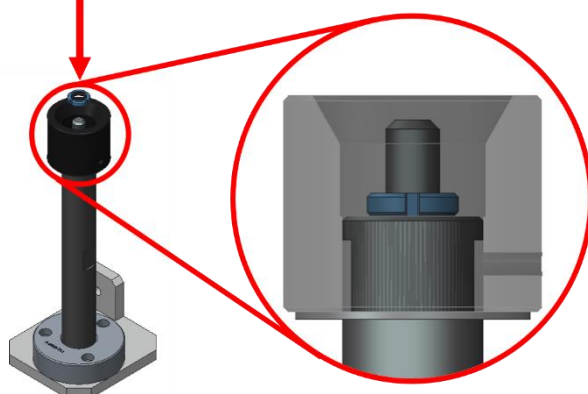
	Illustration	Description
Step 1		<p>The operator loads the subassembly 3 into the nest. Upon the loading of this subassembly, and if it is loaded in the correct orientation, the sensor BRC20 will be activated and the sensor BRC19 will stay deactivated.</p>
Step 2		<p>When the PLC receives the signal of the sensor BRC20 and no signal from the sensor BRC19, it orders the actuator MMB501 to move forward and lock the subassembly 3 in the nest, which consequently activates the sensor BRC23. This movement will be made slowly and at low pressure.</p>
Step 3		<p>With the signal from the sensor BRC23 and BRC20, the actuator MMB503 is depressurized. The operator then rotates the nest to the screwing position, and, upon reaching this position, the sensor BRC25 is activated, which triggers the pressurization of the actuator MMB503 and consequently locking the nest in position.</p>
Step 4		<p>If not already done, the operator drops a nut on its aligner.</p>

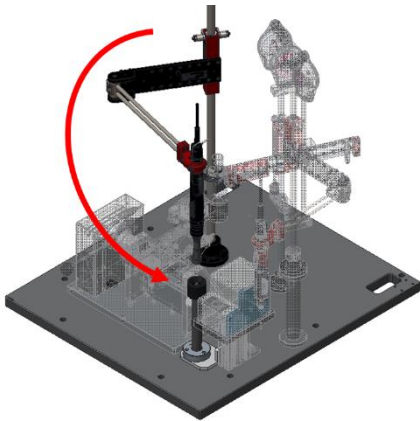
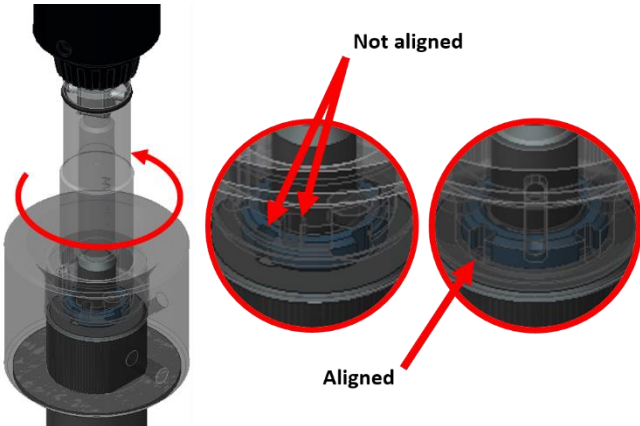
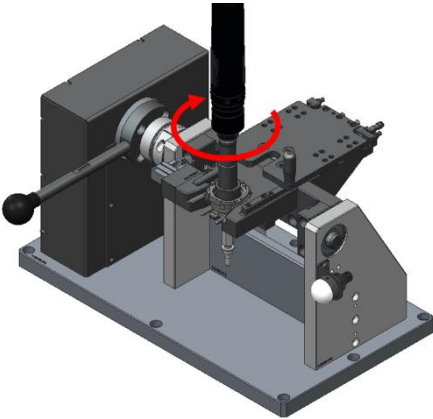
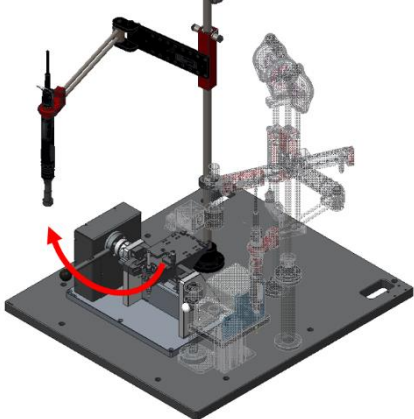
	Illustration	Description
Step 5		<p>The operator grabs the nut screwdriver and goes to the aligner to collect the nut previously placed there.</p>
Step 6		<p>The operator activates the screwdriver, which is programmed to execute a counter-clockwise rotation so that the tool teeth can align with the nut. When the nut enters the tool, the operator will feel a slight downwards motion of the screwdriver and can now stop the screwdriver.</p>
Step 7		<p>The operator inserts the tool onto the subassembly 3 and activates the screwdriver, which will now rotate clockwise, tightening the nut. The screwdriver controller will read the torque and angle achieved on the nut and will signal the PLC if the operation was OK or NOK.</p>
Step 8		<p>The operator removes the tool from the subassembly 4 and moves the screwdriver out of the way to free the space for the remaining operations.</p>

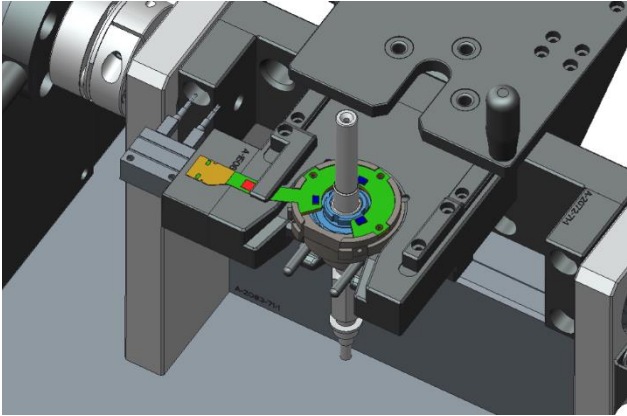
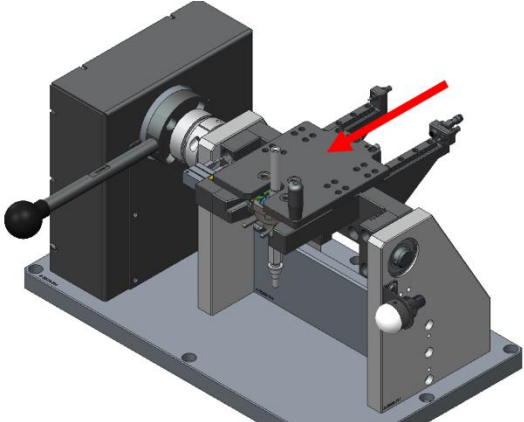
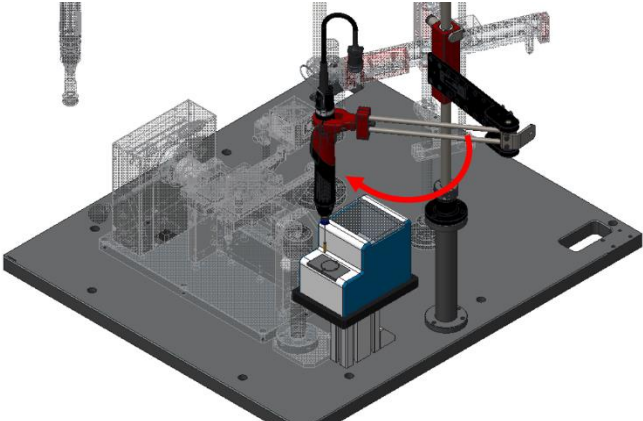
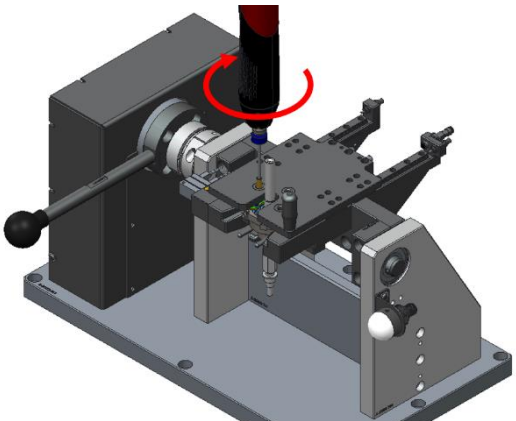
	Illustration	Description
Step 9		<p>The operator will now place the PCB onto the subassembly 4. This placement must be done carefully to not damage the flat connector or any other component of the PCB. The flat connector must be placed under the existing guard on the nest to protect it from the mask movement.</p>
Step 10		<p>The operator can now move the mask to the screwing position to protect the PCB during the screws fastening. When the mask is in the desired position, the sensor BRC21 is activated.</p>
Step 11		<p>The operator grabs the second screwdriver and goes to the NSBI Quicher to grab a pre-aligned screw.</p>
Step 12		<p>The operator inserts the bit and screw into the bushing and activates the screwdriver, tightening the screw through the PCB and onto the housing. The screwdriver controller will read the torque and angle achieved on the screw and will signal the PLC is the operation is OK or NOK.</p>

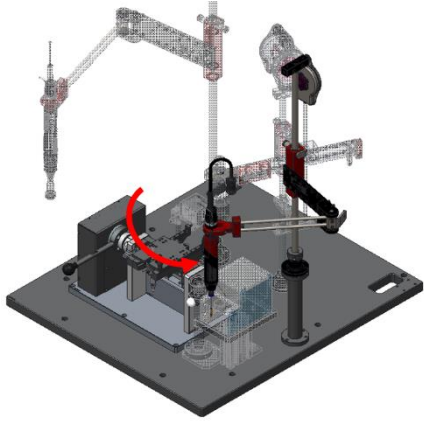
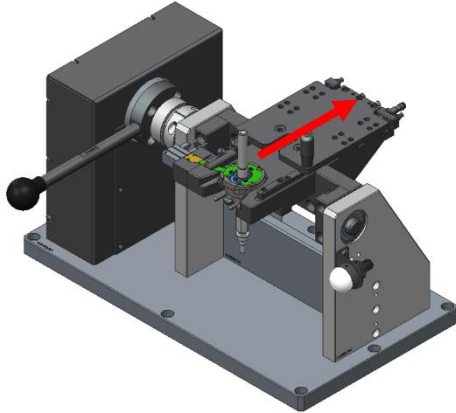
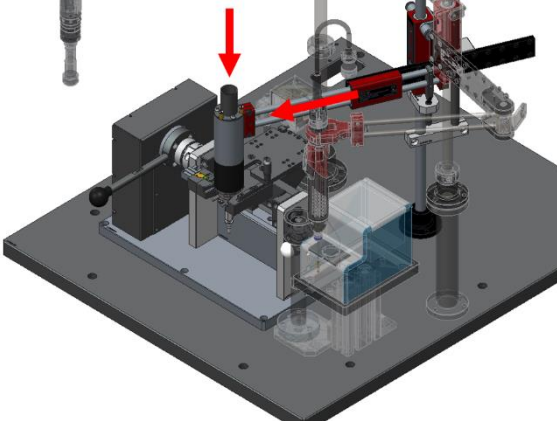
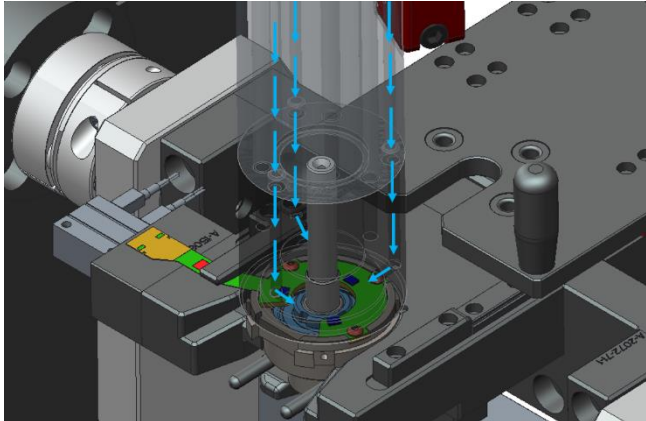
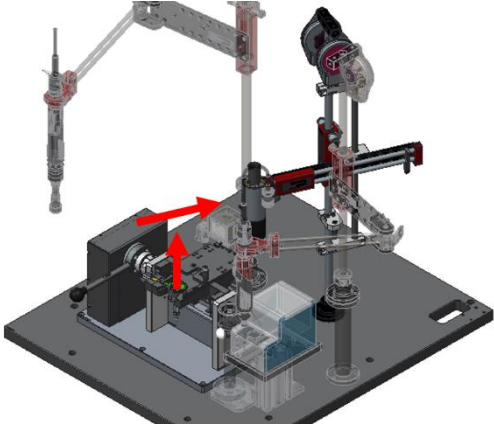
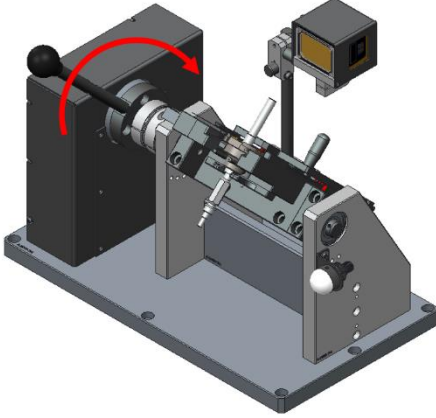
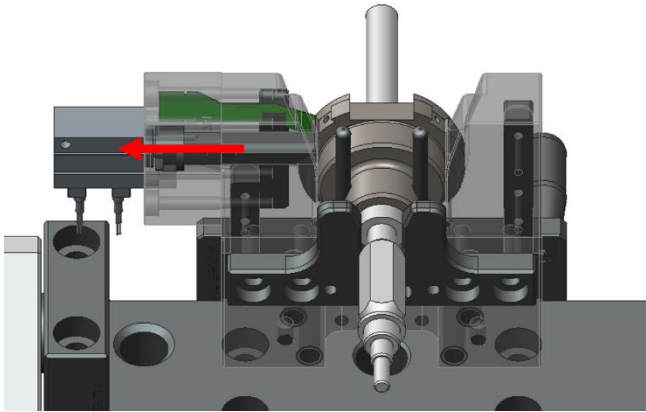
	Illustration	Description
Step 13		<p>After the operator executes the steps 11 and 12 three times, it will move the screwdriver out of the way to free the space for the remaining operations.</p>
Step 14		<p>The operator can now move the mask to the rest position and expose the subassembly for the vacuum cleaning operation. When the mask is in the rest position, the sensor BRC22 is activated.</p>
Step 15		<p>At this stage, the operator grabs the vacuum nozzle and places it over the subassembly 5. This placement is done with two different movements, first a horizontal movement and after a vertical one. When the vacuum nozzle is in the desired position, the sensor BRC31 is activated.</p>
Step 16		<p>With the activation of the sensor BRC31, the cleaning cycle begins. The actuator MMB502 opens the vacuum line valve, activating the sensors BRC30 and BRC32. This cycle takes 5 seconds and there are three air bursts (0,5 second each) 1,5 seconds apart from each other.</p>

	Illustration	Description
Step 17		<p>After the vacuum cycle finishes, the actuator MMB502 closes the vacuum line valve, deactivating the sensors BRC30 and BRC32. The operator can now remove the vacuum nozzle from the nest and store it on the rest position. When the operator removes the nozzle, the sensor BRC31 is deactivated.</p>
Step 18		<p>After the cleaning cycle, the pressure inside the actuator MBB503 is reduced to 2 bar and the operator can now move the nest to the rest position. When the nest reaches this position, the sensor BRC26 is activated, which triggers the PLC to read the 2D code of the PCB and to increase the pressure of the actuator MMB503 to 6 bar, locking the nest in this position.</p>
Step 19		<p>After the PLC receives the information from the code reader, the actuator MMB501 moves back, releasing the subassembly 5 and activating the sensor BRC24. The operator can now remove the subassembly 5, which deactivated the sensor BRC20, and resets the machine.</p>

The GRAFCET of station 2 can be found in Annex III and is divided into two separate charts. The first chart (X600) describes the normal operating cycle of the machine. The other chart is the X700, which describes the safety cycle executed when the emergency button is activated.

4.4.4.4 Command system

Besides the PLC and HMI, this station integrates two additional controllers, one for each screwdriver, which will drive, monitor, and control them. The controllers used are the CVIR II from Desoutter and they are highlighted in Figure 109.

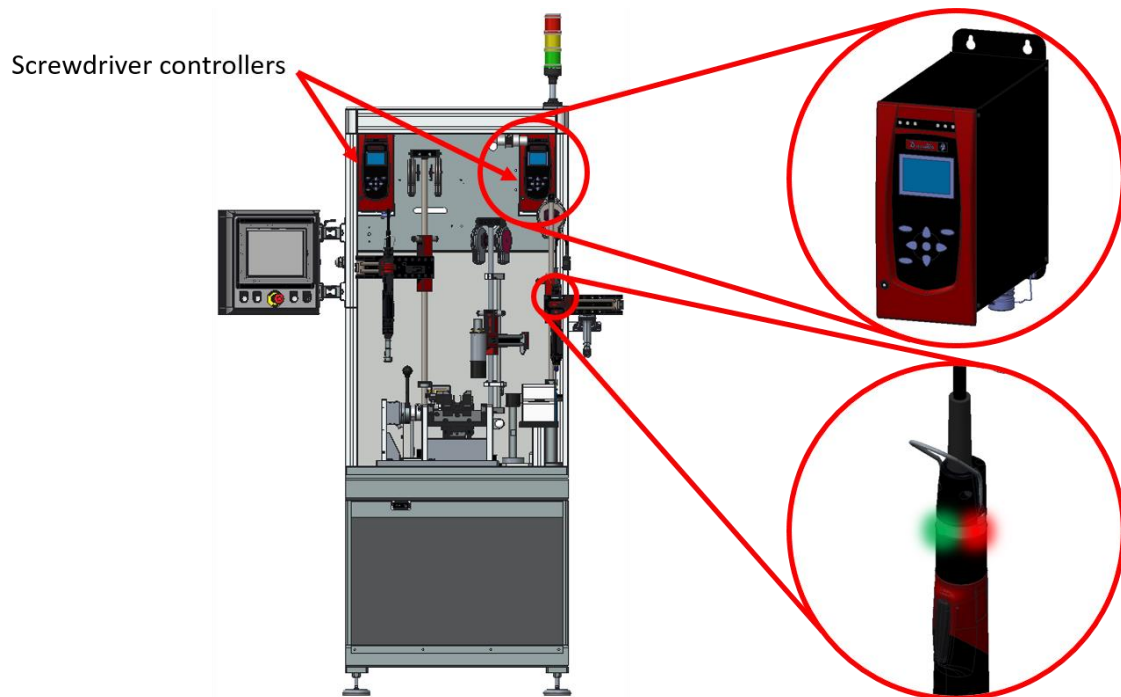


Figure 109 - Screwdriver controllers

These controllers allow setting the torque and angle desired for the operation, as well as the acceptable maximum and minimum values. During the operation, the controllers read the values from the screwdriver and stop them when they reach the desired values. If the operation does not comply or cannot reach the predefined values, the screwdrivers will also be stopped and the operation signaled as NOK (the controllers communicate directly with the PLC, informing the outcome of the operation). The PLC will store the values achieved and relate them to the 2D code read. In case of faulty operation, the PLC can also prevent the screwdrivers from keeping on running and consequently inform the operator that the product must be rejected.

Apart from the communication with the PLC to inform the state of the operations, each screwdriver possesses a feedback light. The controller is in constant communication with the screwdrivers and at the end of the fastening operation, the controller will light this feedback light according to the outcome of the operation, being that a successful fastening will be signaled with a green light and an unsuccessful one will be signaled with a red light.

4.4.4.5 Pneumatic project

Overall, the pneumatic project of station 2 is quite simple. It possesses an air treatment unit, a valve block, and a standalone valve. The pneumatic diagram for station 2 can be seen in Figure 110 and the configuration of the valve block in Table 101.

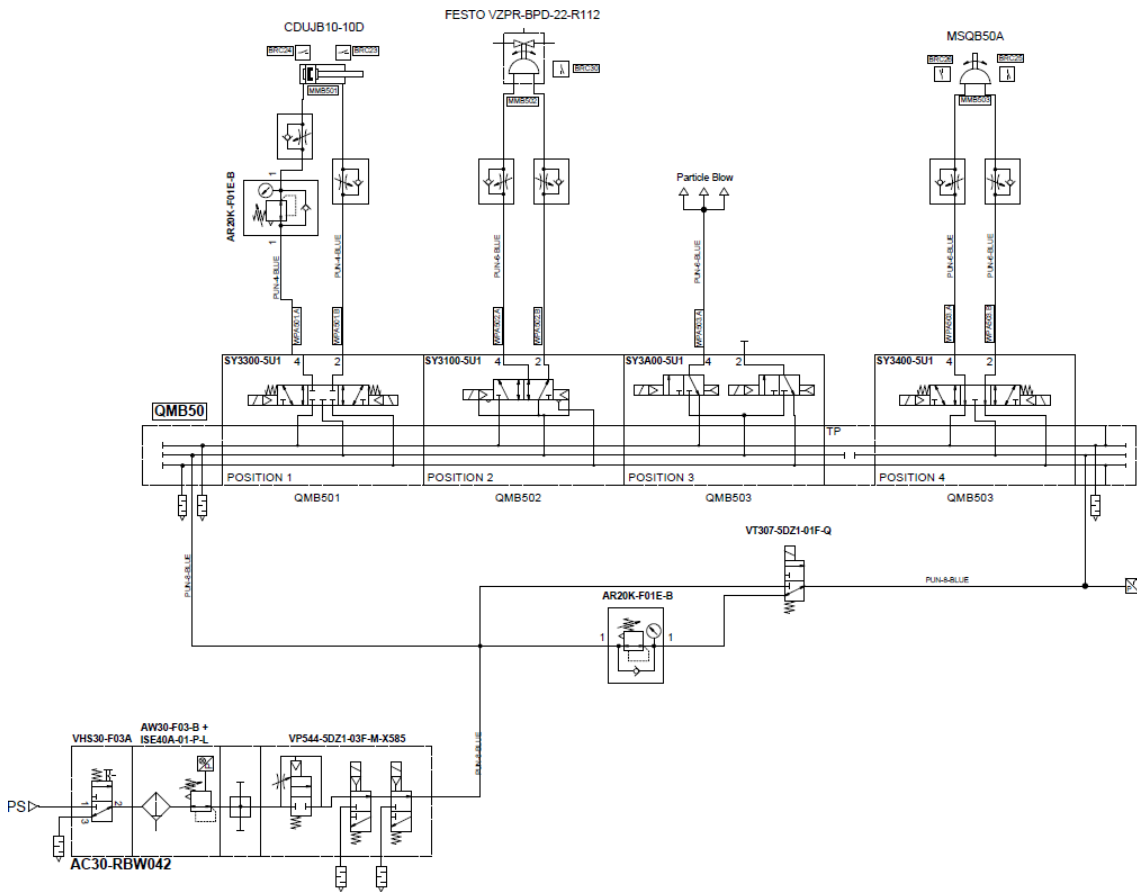


Figure 110 - Station 2 pneumatic diagram

Table 101 - Station 2 valve block configuration

Slot	Actuator ID	Valve type	Tube size (mm)	Description
1	MMB501	5/3 Closed center	Ø4	Subassembly 3 lock
2	MMB502	5/2 Bistable	Ø6	Vacuum on/off valve
3	-	Dual 3/2 NC	Ø6	Air bursts control valve
-	-	-	-	Pressure separation
4	MMB503	5/3 Open center	Ø4	Nest position lock

The most peculiar part of station 2, in terms of the pneumatic project, is the air pressure feeding for the actuator MMB503. In the valve block, a pressure separator was installed to separate the intake airline of this actuator from the main 6 bar line. This actuator will be fed through an external 3/2 valve (SMC VT307-5DZ1-01F-Q), which will select the pressure line that will reach the actuator, either 6 bar or 2 bar. At the entry of the valve, there are two feed lines, one is directly connected to the air treatment unit (6 bar), and the other passes through an air pressure regulator (SMC AR20K-F01E-B) which will reduce the pressure to 2 bar. As already mentioned in Table 97, the center of gravity of the nest is off-center in relation to the rotation axis, which will make it naturally want to fall back to the loading position, if not already there. The lower pressure will guarantee that, when the nest is in the screwing position, it will never go to the loading position without the operator intervention. The 2 bar produces enough force to hold the nest in position while making sure that the operator will need to apply a despicable force to move the nest to the loading position.

By default the feeding pressure is 2 bar and will only increase to 6 bar if the 3/2 valve is activated by the PLC. In the absence of an electric signal on the solenoid, the valve is normally feeding the actuator through the 2 bar line, since the 3/2 valve is spring-loaded to this position. This was purposely made so that if there is a failure in this system the pressure being fed is low and presents a lower risk to the operator. A pressure sensor was also added to the system so that the PLC knows at all times the pressure being supplied to the rotary actuator. If at any given time the pressure being fed is different from expected, the PLC will cut the air and alert the operator of a malfunction and the need for a maintenance intervention to verify and fix the system. The conditions that the PLC will monitor are present in Table 102.

Table 102- Air pressure conditions for the rotary actuator

Action	Valve position	Pressure
Nest ready to be loaded	Port 4	6 bar
Nest ready to move for the screwing position	Open center position	0 bar
Nest in the screwing position ready for the operation	Port 2	6 bar
Nest ready to move for the loading position	Port 2	2 bar
Nest ready to be unloaded	Port 4	6 bar

4.4.4.6 Dimensioning and selection criteria

Rotary actuator from the rotary system

The rotary actuator for this system has the main function of securing the nest in position, during the loading and screwing operations. It is important to keep in mind that this station is manual and does not have any safety light curtain, thus, the movement of the actuator should be

carefully monitored and the risk for the operator, in the case of a malfunction, should be mitigated. For these reasons, the actuator selected should not be able to generate large forces, only enough to guarantee a smooth operation of the equipment. The forces that the operator will be subjected at the handle will be calculated and commented on within this subchapter. In Figure 111 the dimensions needed for these calculations are presented.

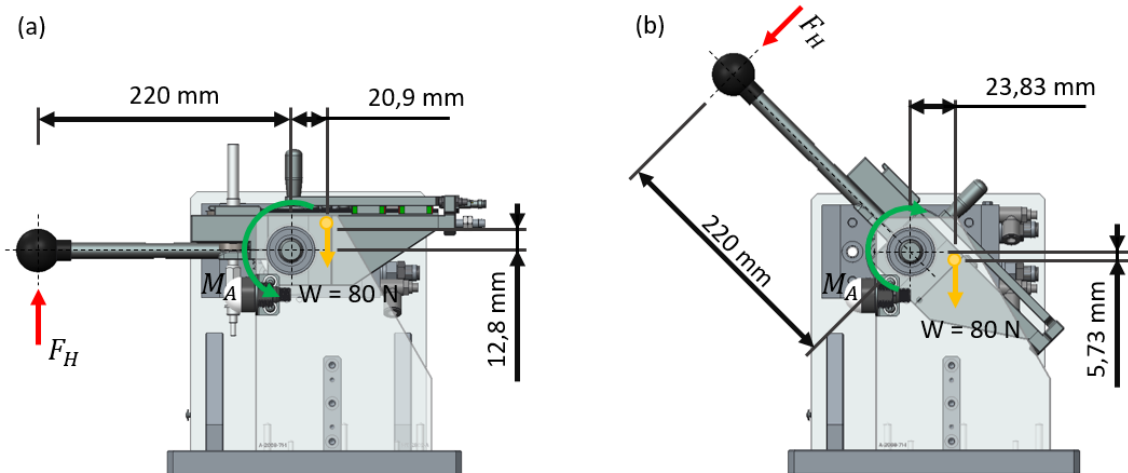


Figure 111 - Dimensions required to calculate the forces at: a) Screwing position; b) Loading position

The nest and mask together have a mass of approximately 7,5 kg and the subassembly 3 is around 0,35 kg. To simplify the calculations the whole weight to be moved will be considered to be 80 N. Also, according to the supplier’s catalog, the actuator is capable of producing 1,85 N·m at 2 bar and 5,57 N·m at 6 bar.

First, it will be calculated the load needed to move the nest from the loading position to the screwing position:

$$\begin{aligned} \sum M &= 0 & (29) \\ \Leftrightarrow M_W + F_H \times 0,22 &= 0 \\ \Leftrightarrow F_H &= \frac{80 \times 0,02383}{0,22} \approx 8,67 \text{ N} \end{aligned}$$

The load needed to try moving the nest when locked on the loading position is calculated at equation (30).

$$\begin{aligned} \sum M &= 0 & (30) \\ \Leftrightarrow M_W + M_A + F_H \times 0,22 &= 0 \\ \Leftrightarrow F_H &= \frac{80 \times 0,02383 + 5,57}{0,22} \approx 48,27 \text{ N} \end{aligned}$$

When the actuator is pressurized with 2 bar and is time to move the nest from the screwing position to the loading position the operator will need to apply the load calculated at equation (31).

$$\begin{aligned} \sum M &= 0 & (31) \\ \Leftrightarrow M_W + F_H + M_A &= 0 \\ \Leftrightarrow F_H &= - \frac{80 \times 0,0209 - 1,85}{0,22} \approx 0,81 \text{ N} \end{aligned}$$

If the actuator is pressurized at 6 bar in the screwing position, if the operator tries to move the nest he will need to apply the load calculated at equation (32).

$$\begin{aligned} \sum M &= 0 & (32) \\ \Leftrightarrow M_W + F_H + M_A &= 0 \\ \Leftrightarrow F_H &= - \frac{80 \times 0,0209 - 5,57}{0,22} \approx 17,72 \text{ N} \end{aligned}$$

In short, the operator will need to apply a force of 8,67 N to move the nest from the loading position to the screwing position and a force of 0,81 N to move the nest from the screwing position to the loading position (this force can be adjusted by slightly increasing the pressure fed to the actuator). When the operator tries to move the nest when he is not supposed to, he will need to apply a larger force in both cases. The operator is still able of moving the nest, but the higher force required should be interpreted as a sign that the nest is not ready to rotate and he should not proceed. Also, the PLC will know if the nest moved when it was not supposed to and act accordingly, either to avoid risk for the operator or alert the operator that he is making a mistake in the operation sequence.

Linear actuator from the nest wedge

The linear actuator and the wedge design are the same as the one used in station 1.B. Since the previous calculations have shown that this actuator produced a load almost 9 times superior to the required to push the subassembly, it is possible to assume that the actuator can push the subassembly 5, since it only weighs a few grams more than subassembly 3. This actuator, as it can be seen in Figure 110, was installed with a pressure regulator in order to work with a pressure under 6 bar and reduce the load applied by the actuator to the minimum necessary. This way, if the operator pushes a finger on the wedge it would not experience the full resistance offered by the actuator. The 26 N of force would not cause injuries to the operator, but it is better to reduce the load to not hurt the operator in the eventuality of this happening.

Linear guides

The linear guides for the mask only need to support the weight of the mask components and guide the movement. They will not be subjected to torque from the screwdrivers or any other efforts. According to the catalog, each block MGN09CH from HIWIN can withstand a dynamic load of 1,86 kN and the mask only weighs around 1,5 kg, which means that the guides selected are more than suitable to support and guide the mask, thus, no calculations were performed

4.4.4.7 Budgeting

A resume of the costs associated with station 2 can be seen in Table 103. In this table, the costs are divided into different categories and the values presented are a close approximation of the real costs. Due to confidentiality issues, a detailed version of this budget will not be provided.

Table 103 - Station 2 budget

	Description	Cost (€)
Human labor	Mechanical project	10 000
	Electrical project	7000
	Software & application	10 000
	Mechanical assembly	4000
	Electrical assembly	4000
Materials	Cell	11 000
	Pneumatic & mechanical standard parts	20 000
	Electrical	40 000
	Mechanization	6000
Other costs	Project management related costs	3000
	Packing and shipment	600
	Installation	1400
	Training (1 week)	1200
	Production support (3 weeks)	1800
Total station cost		120 000 €

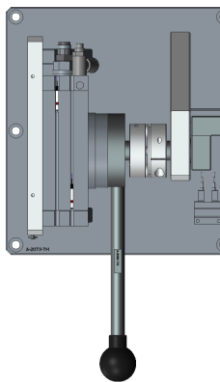
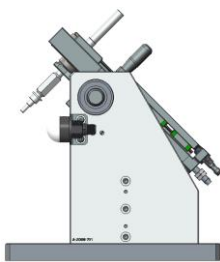
4.4.4.8 Bill of materials

The bill of materials of station 2 is available in the Annex V. Just like the parts list of station 1, the list is divided into two main parts, the custom manufactured parts, and the standard parts.

4.4.5 Final remarks

Station 2 is a perfect example to demonstrate the considerations necessary to design an ergonomic workstation. A lot of components needed to be installed in this station and, through an ergonomic study based on the standard ISO 14738, a solution able to optimize their location was found, guaranteeing that all the components would be ergonomically accessible to the operator. Some of the main challenges presented by this station and the innovative solutions found to solve them are presented in Table 104.

Table 104 - Main challenges and solutions from Station 2

Problem	Illustration	Solution
<p>How is it possible to have a pneumatic actuator operating freely without presenting a hazard to the operator?</p>		<p>As previously mentioned multiple times, this station does not have safety light curtains to protect the operator from the pneumatic actuator, thus, these actuators needed to be carefully monitored and meticulously controlled. The usage of lower pressures and flow regulators, as well as pressure sensors, allowed to continuously monitor the actuators and control their movements in such a way that the system would fail before presenting a hazard to the operator.</p>
<p>How is it possible to avoid operation zones with very low visibility and ergonomically solve them?</p>		<p>The nest where the subassembly 3 is installed has two orientation rods and if the nest was to be fixed, these rods would be installed in a zone with low visibility. To solve the problem and allow the operator a direct angle of vision to this points, the nest was designed with a pivoting system that allows the operator to rotate the nest between the load zone and the horizontal plane on which the components will be assembled, thus improving the ergonomics of this station</p>

Additionally, it was recommended to create a rotation schedule for the operator allocated to this station in order to reduce the accumulation of stress and fatigue due to the high number of tasks that need to be performed in this station

When the operating cycle of this station is finished, the operator collects the subassembly 5 from the nest and moves it to the pallet present in the conveyor stopper, which will transport the product to station 3.

CONCLUSIONS

5 CONCLUSIONS AND PROPOSALS OF FUTURE WORKS

When placing a new product into the market, the manufacturer needs to estimate how many units it will produce and define all the production processes required to achieve the final product. With this information, a decision can be made on the level of automation more adequate and the best plant layout to use. The customer initiated the conversations with IPTE wanting a semi-automated production line, and through discussion and input from both parties, a cellular assembly line was defined as the route to follow.

As previously mentioned, this dissertation had a main focus on the first two stations. The cellular assembly line is generically explained, but it is still made clear what is the thought pattern required to define a layout and group tasks, in order to create a functional and efficient assembly line. All the other stations not deeply analyzed in this dissertation followed a design process similar to the two stations presented. Both stations 1 and 2 were selected for knowledge demonstration reasons, and not because they are the first two stations of the assembly line.

At the beginning of the work presented in this dissertation, a list of goals was defined, which are listed once again in Table 105, along with the conclusions achieved through this work.

Table 105 - Analysis of compliance with the proposed goals for the project

Goal	Conclusion
Study of the product and production processes	A lot of knowledge was passed from the customer to IPTE regarding the product and the production process. With this knowledge, physical parts, and drawings, the product was deeply studied in order to design the most adequate solutions for its peculiarities.
Group the assembly steps into different stations	In collaboration with the customer, the assembly steps were grouped into stations, allowing to define and create the cellular assembly line concept that was developed during the work presented in this dissertation.
Automate the maximum amount of assembly processes, minimizing manual assembly operations	All the assembly processes were automated, with exception to the ones related to station 2. These operations were not automated because the customer did not see a good enough economical advantage in automating them.
Ensuring the safety of the operator at all times	Regardless of a station being based on a single operation cell, multiple operation cell, or manual operation cell, the safety of the worker was always the number one priority, and, with or without safety light curtains, the safety hazards were reduced to the maximum, resulting in extremely safe workstations.

Goal	Conclusion
Ensure an ergonomic design of the equipment	All stations were studied ergonomically according to the standard ISO 14738, always ensuring the best possible working conditions for the operator.
Ensure the traceability of the production history and associate with the part number of the product produced	In this dissertation, it was only possible to verify this is station 2, but from station 2 onwards, the 2D code of the product is always read before the assembly operations, and all the production information is related to this code, ensuring complete traceability of the production history of any part.
Minimize the risk of product damage and dirt accumulation during production	This relies heavily on the operator and on the way he/she handles the product, but regarding the design, many decisions and solutions were applied in order to mitigate these risks, as well as the installations of multiple vacuum cleaning points across the assembly line to eliminate the accumulation of debris.
Guarantee that the station possesses ESD (Electrostatic Discharge) properties	All the materials used for the components that integrate the mechanisms that handle the product have ESD properties. The operator is also connected to an antistatic wristband.
Comply with the cycle time of 40 s	All the stations comply with the cycle time.

In short, all the goals proposed at the beginning of the work were completed with success. The assembly line was designed, approved, manufactured, tested, and delivered to the customer on time, always complying with their requirements and even exceeding the initial expectations. Still, as in all projects, especially in custom projects like the one presented in this dissertation, there is always room for improvement. With the start of the mass production and continuous operation of the equipment, it is guaranteed that the customer will find bottlenecks and inefficiencies in the process, which are points that can be later addressed in order to improve the productivity and efficiency of the assembly line.

On a more personal note, working on this project was a great challenge due to its size and complexity. However, the greater the challenge the greater the opportunity to learn. This project allowed me to better understand and implement the knowledge obtained during my academic career, as well as follow and observe the whole process of producing an assembly line, from the design, to the machining of components and assembly of the stations, and the tutoring given by the company was impeccable. The experience obtained will certainly be a relevant aspect for my future working career.

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6 REFERENCES AND OTHER SOURCES OF INFORMATION

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ANNEXES

ANNEX I – MATERIAL PROPERTIES

ANNEX II – GENERAL VIEWS OF THE EQUIPMENT

ANNEX III – GRAFCET

ANNEX IV – PNEUMATIC DIAGRAM

ANNEX V – BILL OF MATERIALS

ANNEX VI – DATASHEETS

ANNEX VII - DRAWINGS

