UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN
FACULTAD DE INGENIERÍA MECÁNICA Y ELÉCTRICA

DESIGN AND SIMULATION OF MECHANICAL COMPONENTS OF A ROBOTIC CELL FOR THE AUTOMOTIVE INDUSTRY

POR

JOSÉ ISRAEL REYNA MARTÍNEZ

**COMO REQUISITO PARCIAL PARA OBTENER
EL GRADO DE MAESTRÍA EN CIENCIAS
DE LA INGENIERÍA AUTOMOTRIZ**

JUNIO, 2018

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SUBDIRECCIÓN DE ESTUDIOS DE POSGRADO

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Los miembros del Comité de Tesis recomendamos que la Tesis "Design and Simulation of Mechanical Components of a Robotic cell for the Automotive Industry" realizada por el alumno José Israel Reyna Martínez, con número de matrícula 1494729, sea aceptada para su defensa como opción al grado de Maestria en Ciencias de la Ingeniería Automotriz.

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San Nicolás de los Garza, Nuevo León, a 7 de Junio del 2018.

Agradezco a Vitro por darme la oportunidad de realizar este proyecto. Al Dr. Carlos Vazquez quien, con su conocimiento, experiencia y su paciencia, me ayudo al desarrollo de este trabajo.

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A mis padres, a todos los que me apoyaron y a las personas que conocí durante el desarrollo de este trabajo.

¡GRACIAS TOTALES!

Content

Chapter 1 Introduction

1.1 Introduction

Process automation is very common in industries that seek to increase quality and reduce costs, these companies often bet on generating their own technology to ensure that they consider all the requirements that need to be met and also, they allow can adapt the technology to the requirements that arise.

The design of work cell will allow maintaining the production of current models of glass, but in turn, will be adjusted for the manufacture of new models of automotive glass.

To be sure that the process automation is effective, an appropriate design is required, as well as an analysis to optimize the models and verify that the design meets the requirements.

This work will try to comply with the design of an automated work cell flexible in production, current, and future, but also optimized in size and cost, all using a set of design and simulation tools for process validation that will be generated at the end of the work.

1.2 Objective

The design of the process of an intelligent system for the assembly of components for automotive glass.

1.2.1 Specific Objectives

- Design a tool and optimize it using industrial and free software, Finite Element software for the assembly of components of the various types of glasses.
- Design of an automotive glass conveyor which is used in the assembly process of components, with the objectives of maintaining the same position of the glasses to achieve a correct assembly of components, different types of glasses.
- The design of a working cell.

1.3 Hypothesis

Space savings of 20% can be achieved with respect to current methods of operation whit savings of at least 30% in the work cell components for the assembly process of automotive glass, whit the help of a methodological process of design and Finite Element Analysis, in addition to the use of tools for the visualization of the process.

Chapter 2 Industrial Automation

The industry aims to provide a useful and quality product, with the lowest production cost to increase profitability. Previously, manufacturing was more traditional, where production speed and quality depended on the capabilities of people and their mood, production varied in quantity and quality.

Automation is the use of technological equipment to replace the manual work done by human beings. The manual activities were assisted by mechanisms to facilitate tasks that required physical stress, but people were the ones who operated and made the decisions when carrying out the activities, so it was not free of errors. Automation allows all these mechanisms to be used with the least possible human intervention [1].

Industrial automation involves the application of control systems equipment, sensors, actuators with a predefined logic for decision making activity being done and also, it is possible to give information about the process and equipment being used, useful information for production, quality and maintenance areas. With these intelligent systems, human intervention is minimal, which makes the tasks performed faster and with precision.

Automation typically uses a combination of technologies from different areas such as robotics, mechanical, electrical, electronic, hydraulic, pneumatic and computer.

Figure 1 shows an example of automation, the palletizing process uses a robot to accommodate boxes, the robot has a tool that has pneumatic pistons for the movement of the mechanism that hold the boxes, the boxes move with rollers driven with electromagnetic motors, use electronic sensors to know if the 4 boxes are in position and the programmed logic decides the actions to be carried out in the process.

Figure 1. Robotic automated palletizing.

2.1 History of Automation

The term automation is believed to have appeared for the first time in the Ford Motor Company in the 1940s, in which there was a small market with a lot of competition, cost reduction was needed to make the price of the vehicles competitive, Henry Ford changed its production method for its Ford Model T by introducing the conveyor belt, as shown in figure 2, which eliminated the need to manually transport the chassis to different work areas, its employees were assigned specific and repetitive tasks that would be carried out on the chassis when it reached its work zone, eliminating transfers of workers, also added control devices through the use of timers, relays, buttons, sensors, motors and actuators to perform specific tasks. With these tasks, an automatic and continuous production was achieved, with reduced Manufacturing time and costs [1].

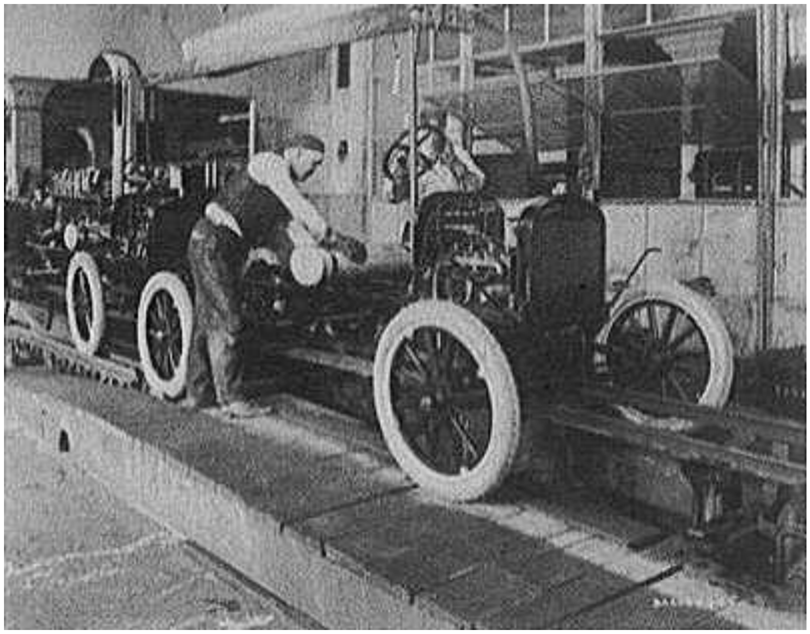


Figure 2. Ford Motor company assembly Line.

At first the control was made with complex relay systems that did not allow flexibility of the processes. In 1968 GM launched a proposal to change these systems, as a result of this Bedford Associates developed the MODICON (Modular Digital Controller) that would be the first PLC (Programmable Logic Controller). Nowadays the PLC is the basis for the control of industrial automated systems.

2.1.1 Advantages and Disadvantages of Automation

Automation in industry is common today because of its advantages, makes companies grow giving more confidence to the processes [1].

<u>Advantages</u>

- Repeatable repetitive tasks: Human operators who perform repetitive tasks can be easily replaced.
- Low operation costs: Automation eliminates the need for human intervention in processes, salary costs, vacations, insurance, protective equipment, food, pensions, etc.
- Increase of production: The machines do not take vacations, they do not have holidays, they do not get sick, they do not lack. Ideally if a company were 100%

automated, it could produce every day at all hours. However, maintenance must be considered; systems can now detect if it is necessary to change any component, but with good maintenance planning the time of this process can be reduced. With all these time savings the production increases.

- Higher quality: Automating a repetitive process can eliminate human errors caused by fatigue, stress, distraction, among other factors. The current machines can make such precise movements even at high loads. In addition, these systems can check the quality of the parts, which allows keeping records in a simple way and allows to reduce the number of parts out of tolerance.
- Safety: It is avoided to put human operators in risky areas, such as in places with high temperatures, radioactive, toxic. It also prevents them from doing work that could hurt them such as carrying heavy objects or handling dangerous objects.
- Greater Flexibility: The machines can be easily reprogrammed to perform new tasks.

Disadvantages:

- High initial cost: The investment in equipment, modification and preparation of the plant, has a high cost at the beginning, in addition to the training of employees to manage the equipment.
- Non-automatable processes: There are tasks where automation is not possible. Automation is best applied in repetitive tasks and large volumes.
- Development costs: The automation also requires a previous investment for planning the development of the automated process.

2.2 Work cell

A work cell gathers all the necessary equipment to carry out the operations to constantly produce a product as well as feedback process information, having as a requirement to be compact to minimize the execution time of any activity [2, 3].

Currently, with the demand of increasing products in all industries, these have the objective to satisfy the demands and need to be prepared for future needs, so automatic systems with flexibility in the process to generate more and new products is a necessity. Work cells have the need to reduce manufacturing work times, so they must reduce configuration times to move from one product model to another, work times within the cell, movements within the cell and transfers to other processes [4].

2.2.1 Basic elements of a work cell

In a work cell, automatic activities are carried out, basic elements that a work cell requires are presented below:

- PLC: is the system that controls the entire process of the cell, it is where the actions to be taken are programmed, it monitors the sensors, stores the information of the process, drives motors, valves, among other elements.
- Power module: It supplies electrical energy for the operation of the electronic components of the cabinet.
- Input and output modules: They serve for communication between the control devices of the work cell.

These 3 elements are basic in any system and are usually placed together, in figure 3 a control cabinet is shown where basic elements are shown.

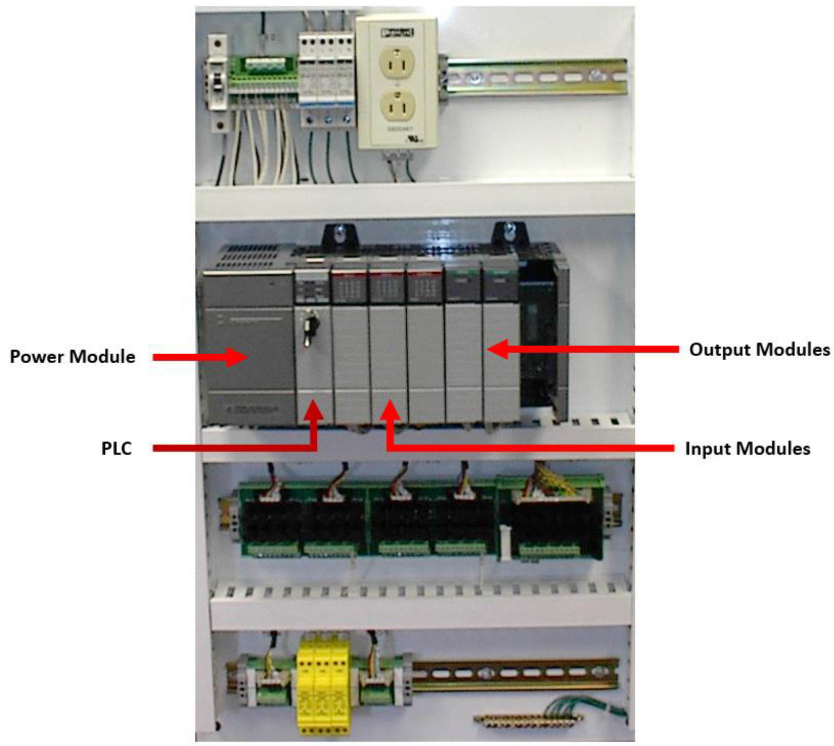


Figure 3. Basic control cabinet.

- Drivers: Control the motors and other components used in the cell.
- Sensors: Essential elements for a system to be automatic, allow to measure or detect different variables such as presence, temperature, strength.
- Supply systems: Are those that supply in a controlled manner the elements that the equipment needs to operate, such as, air tank for pressurized air supply.
- Security fencing: Prevents human operators from entering the work area of the cell, to prevent movement of dangerous machines or tools to injure them.
- Interlocks: These are electronic locks that restrict the opening of the door during the operation and prevent it from being activated if it is open, when programming work is carried out within it, such as maintenance work.
- Security curtains: In the work cells the material enters and leaves the cell, the enclosure has areas, spaces such as doors or windows, large enough for people

to enter, the curtains are elements that detect if something goes through these areas and warns the PLC to act.

- Turrets: Elements that inform the state of the cell.
- Emergency stops: These are buttons that stop all the elements of the cell, it is the security device activated by the operators.

2.3 Industrial Robots

Currently, one of the most common equipment to achieve automate processes are the Industrial Robots, since they allow great mobility, speed, load capacity and precision, which for a company become greater productivity, quality and flexibility of processes.

2.3.1 History of Industrial Robots

In 1921 the word "robata" appears in the novel "Rossum's Universal Robots" by the author Karel Capek, this is where the word "Robot" has its origin [5].

The first Industrial Robot was used at the General Motors plant in 1961, manufactured by Unimation, the first robot company, founded by George Devol and Joseph Engelberger. In 1973 the company ASEA presents its robot IRB-6, the first fully electric robot. In 1978 Hiroshi Makino invents the SCARA Robot [6].

The first Unimation robot performed a rather simple handling task in 1961 at a General Motors plant, the figure 4, shows the first robot installed in plant. The application of the robots in the industry validated their operation reliably and guaranteed a uniform quality, which encouraged its use in other companies.

Figure 4. The first Unimation performed a rather simple handling task in 1961. [6]

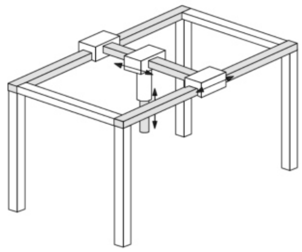
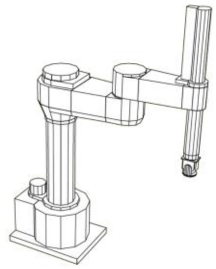
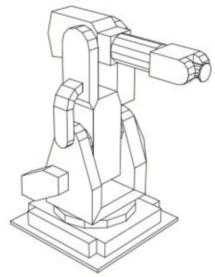
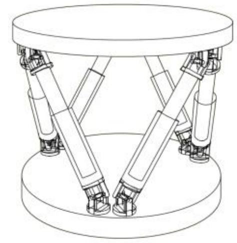
In the 1980s, parallel robots showed great speed for small loads, the first joysticks and teach pendants facilitated programming and also first vision systems were introduced [5, 6].

In the 1990s, the first communication protocols were established in robots, the first graphical interfaces for offline programming were created, and collision detection systems were implemented. In 1998, RobotStudio appeared as the first virtual simulation tool [5].

Currently, the trend of robots is to lower prices, improve speed and accuracy, facilitate the tasks of simulation and programming.

2.3.2 Different structures of Industrial robots

There is a wide variety of robots, each with its own configuration of movements that can be prismatic, rotational or a combination of both, each one has its utility and depending on which task needs to be automated there is a suitable robot for the job. Figure 5 shows the 4 most common types of robot configurations as well as their workspace.

Gantry	SCARA	Serial Articulated	Parallel
			
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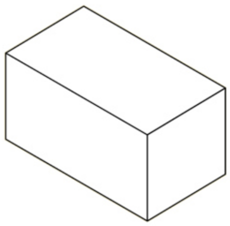
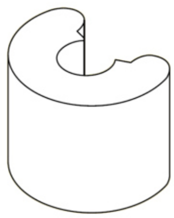
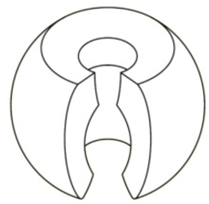
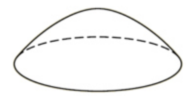
			

Figure 5. Common types of industrial robots [6].

In the industry the most common type of robot is the articulated serial, it is an anthropomorphic robot that resembles a human arm, one of the main reasons for use is its mobility; they have great scope and give great freedom of movement to the end effector, which gives great flexibility to perform many different types of jobs. This mobility is due to the number of axes of the robot. Normally a robot of this type has 6 rotation axes, as shown in figure 6, in addition, there is a wide range of models ranging from capacities of 3 kg to 1000 kg,

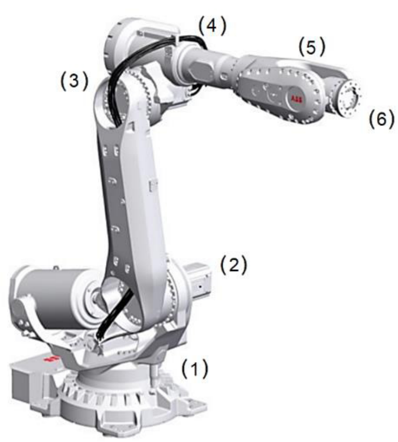


Figure 6. Robot axes example, rotation axes (1) to (6) [7].

2.3.3 End-Effector

The End-effector is the element that is placed on the flange of the robot, see figure 6 rotation axe number 6. It interacts with the workpiece. This tool is what marks the purpose of the robot.

There are endless tools for different jobs, including welding, painting, drilling, blades, sensors, but the most common are pick-and-place jobs, where grippers are designed specifically to take different kinds of objects. Figure 7 shows a simple pneumatic gripper, mounted on the flange of a small robot. The pneumatic systems are the most commonly used because the grip force is easily adjustable.

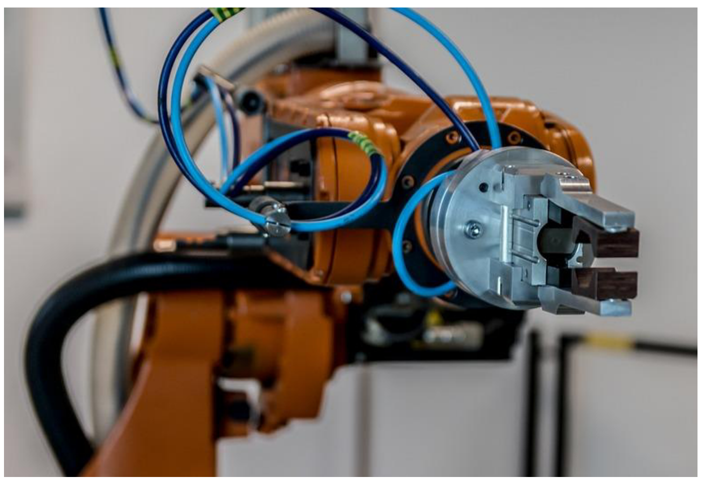


Figure 7. Simple gripper mounted on a robot.

The use of robots in pick-and-place jobs is due to their characteristics, they can move large loads with speeds up to 10 m/s, acceleration of 100 m/s^2 and accuracies of 0.1mm, but to take advantage of these characteristics a correct design of the system is important along with a correct selection of the robot to use [8].

In addition to the object that takes things, there is a structure that supports the elements necessary to perform the actions, such as force sensors to avoid applying too much force and break some parts, systems of actuation of the clamp, which would be valves for the pneumatics, camera for detection, and sensors for validation and at the end the clamps, see figure 8.

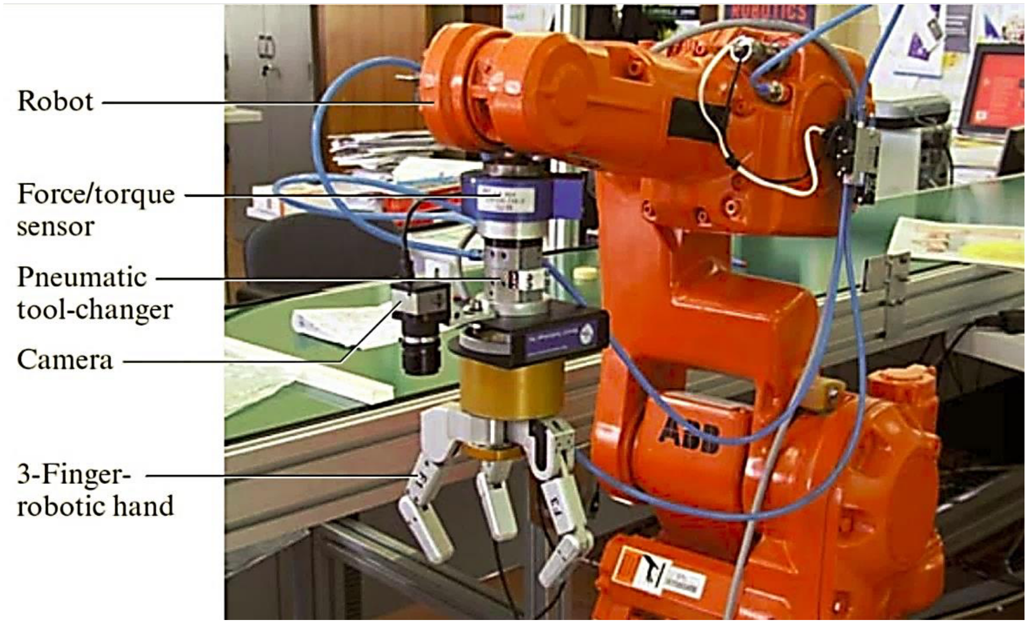


Figure 8. End-effector structure [6].

Chapter 3 CAD

Current automation process is faster than in past decades, this is due to the application of computational tools and the constant evolution of technology. One of the areas that benefit the most with this technological evolution is Design, moving from large drawings made by hand, to computer in order to create designs in less time.

CAD (Computer Aided Design) is the use of computational tools for the generation of 2D and 3D elements, work that previously made large groups of technical designs, now can be done faster by a small group. In addition to the generation of elements allows to easily change, scale and manipulate the virtual parts.

CAD software allows to create 3D elements from drawings in views of the part, but also allows the generation of assemblies, which is the union of various objects.

3.1 History of CAD

Leonardo Da Vinci is one of the most recognized people of antiquity for his engineering drawings, where he exhibited machinery and its operation, his original plans continue to exist and can be seen in some museums. Figure 9 shows one of the old drawings of a giant crossbow, Da Vinci repeatedly created models of weapons of war, but also drew art and other non-warlike mechanisms.

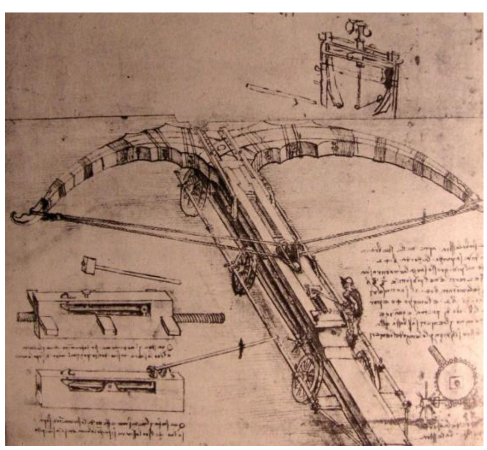


Figure 9. Leonardo da Vinci design for an enormous crossbow.

The modern design has its origins in the works of descriptive geometry of René Descartes and Gaspard Monge. The technical drawings were created by hand, with simple tools such as T-square, triangles, scales, compasses and other basic tools. In 1901, Charles H. Little invented the Drafting Machine (Figure 10), this machine had all the necessary tools to draw, in addition that its head allowed a free movement of these tools throughout the drawing board, allowing to set positions for accurate line drawing [9].

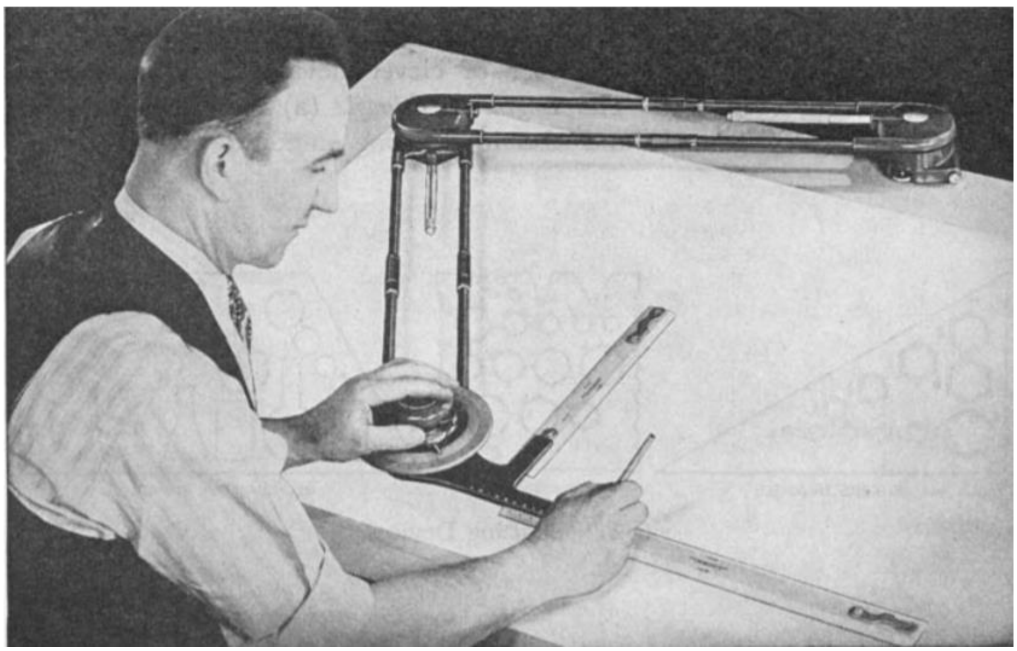


Figure 10. Drafting Machine [9].

But it was not until after the World War I that it became important and in 1935 the first standard for technical drawings was created. With the appearance of aeronautics 1:1 representations of the elements were needed and since there was no way to pass small drawings to the required size, these were made by hand by several people (Figure 11). During the World War II, new tools were introduced to improve productivity in the drawing process [9].

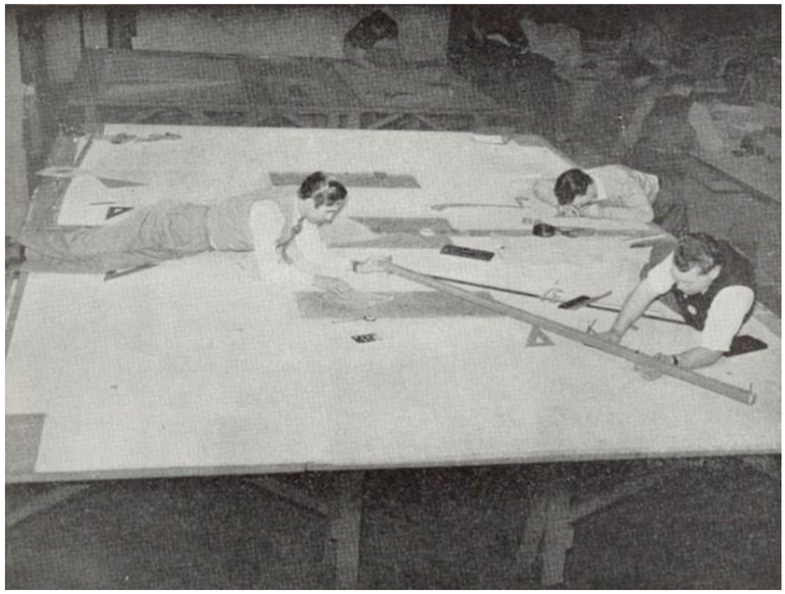


Figure 11. Creating an Aircraft Master Layout [9]

One of the pioneers in computer drawing was General Motors who together along with IBM launched a secret project called "Digital Design", with the beginning of the project they gave it the name "Design Augmented by Computer". It was until 1964 that it was presented in Fall Joint Computer Conference the DAC-1 (Figure 12), this system had advanced functions such as transformations in geometric objects to display, rotate, enlarge, crop and is considered by many as the first CAD system [10].

Figure 12. First interactive CAD system, DAC-1 [10].

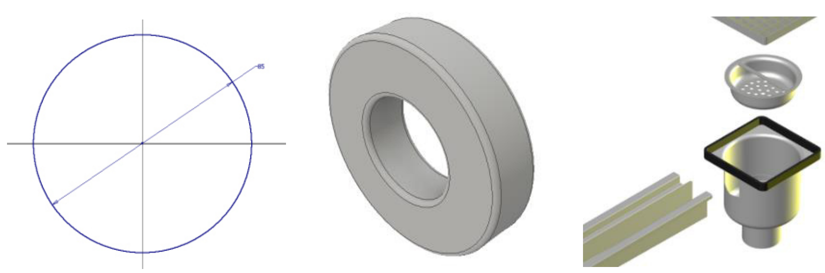
In 1982 Autodesk was founded by John Walker, the first important product was AutoCAD, software that came from a program written by Mike Riddle. The program, designed to work with the new low-cost computers, revolutionized the industry.

Currently, CAD software is widely used in the industry for the creation of sophisticated equipment, where in addition to the design technical data of the created elements are obtained, even with a good database it is possible to estimate costs, they also allow to create photorealistic images to show an approximation of how it would look in reality. There is a wide variety of CAD software and it is possible to use them in not very expensive computers.

3.2 The industrial CAD software

Software is used in engineering design to produce and improve new products, while in programs such as AutoCAD, only design dimensions are conducted. A parametric modeler allows to model the geometry, dimension and material so that if the dimensions are altered, the geometry automatically updates based on the new dimensions. This allows the designer to store his calculation knowledge within the model.

The design of parts begins with 2D drawings that are extruded to generate 3D geometries. The machines are not solid parts, they are the union of many individual parts. The CAD software allows to create these unions in models called assemblies, that by means of contacts and constraints. The figure 13 shows the 3 states in the mechanical design process.



Sketch Solid Assembly

Figure 13. Sketch, solid part and an assembly.

Chapter 4 Numerical Methods

To solve problems where the system is simple, analytical solutions are usually applied. They have the capacity to obtain the result in any state of the system, using for this, mathematical equations that govern the problem.

The problem with using this method is that by increasing the complexity of the problem, also solving them becomes complicated. Therefore, techniques have been designed and improved where the system is divided and resolved into sections. These techniques are called numerical methods and have for example the finite difference method and the Finite Element Method.

4.1 Direct Approach Method (Analytical solution)

This method is used to solve simple problems, widely used in one-dimensional systems. This method uses concepts of physics directly, it does not demand a rigorous mathematical analysis [11].

The result of this analysis is a matrix system of the form $[K]\{d\} = \{F\}$, where F is called the global nodal force matrix, the d is called global nodal displacement matrix and K is called system stiffness matrix, with which the system can be solved in any state.

A simple example of this method is shown below, a system of 2 springs joined where each have their own elastic constant. Hooke's law helps to obtain the relationship between force and displacement.

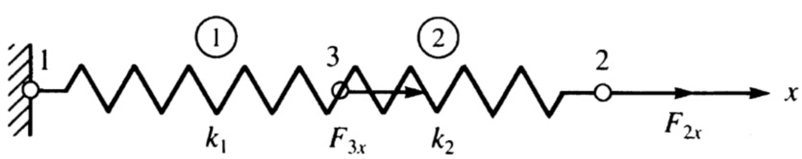


Figure 14. Two springs assembly [12].

Node 1 is fixed and apply forces for F_{3x} at node 3 and F_{2x} at node 2.

$$\text{Hooke's law} \qquad F = kx \qquad \textit{Eq. 4-1}$$

Applying Hooke's law in each of the nodes and applying equilibrium gives the following:

$$F_{1x} = k_1 d_{1x} - k_1 d_{3x} \quad \text{Eq. 4-2}$$

$$F_{2x} = -k_2 d_{3x} + k_2 d_{2x} \quad \text{Eq. 4-3}$$

$$F_{3x} = (-k_1 d_{1x} + k_1 d_{3x}) + (k_2 d_{3x} - k_2 d_{2x}) \quad \text{Eq. 4-4}$$

Grouping terms:

$$F_{1x} = k_1(d_{1x} - d_{3x}) \quad \text{Eq. 4-5}$$

$$F_{2x} = k_2(d_{2x} - d_{3x}) \quad \text{Eq. 4-6}$$

$$F_{3x} = -k_1 d_{1x} - k_2 d_{2x} + (k_1 + k_2) d_{3x} \quad \text{Eq. 4-7}$$

Equations 4-5 to 4-7 can be reordered in matrix form:

$$\begin{Bmatrix} F_{1x} \\ F_{2x} \\ F_{3x} \end{Bmatrix} = \begin{bmatrix} k_1 & 0 & -k_1 \\ 0 & k_2 & -k_2 \\ -k_1 & -k_2 & k_1 + k_2 \end{bmatrix} \begin{Bmatrix} d_{1x} \\ d_{2x} \\ d_{3x} \end{Bmatrix} \quad \text{Eq. 4-8}$$

The Equation now is in the form $\{F\} = [K]\{d\}$

$$\{F\} = \begin{Bmatrix} F_{1x} \\ F_{2x} \\ F_{3x} \end{Bmatrix} \quad \text{Eq. 4-9}$$

$$[K] = \begin{bmatrix} k_1 & 0 & -k_1 \\ 0 & k_2 & -k_2 \\ -k_1 & -k_2 & k_1 + k_2 \end{bmatrix} \quad \text{Eq. 4-10}$$

$$\{d\} = \begin{Bmatrix} d_{1x} \\ d_{2x} \\ d_{3x} \end{Bmatrix} \quad \text{Eq. 4-11}$$

4.2 Finite Difference Method (FDM)

It is a numerical method commonly used to find approximate solutions, based on the approximation of the partial derivatives by Taylor series.

The concept of discretization is fundamental for the FDM, the system must be divided into many points where the solution is evaluated. The division of the domain results in a structured mesh with rectangular pattern [13].

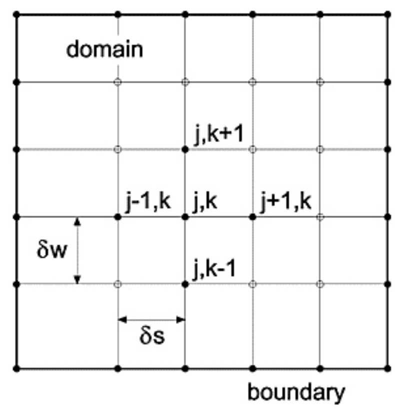


Figure 15. FDM Discretization. [14]

The disadvantage of this method is that it becomes difficult to use in systems with complex geometry.

4.3 Finite Element Method (FEM)

The Finite Element Method is a numerical method used in engineering, physics and mathematics to solve problems in topics such as structural, heat transfer, fluid flow, mass transport, electromagnetic potential, etc.

4.3.1 Discretization

The discretization is the first step of the FEM. It consists in dividing the structure in a finite number of elements. Unlike the FDM, the FEM allows analyzing complex geometries; the elements adapt to geometry regardless of the complexity. In Figure 16 it can be seen the comparison of the discretization by the FMD and FEM methods.

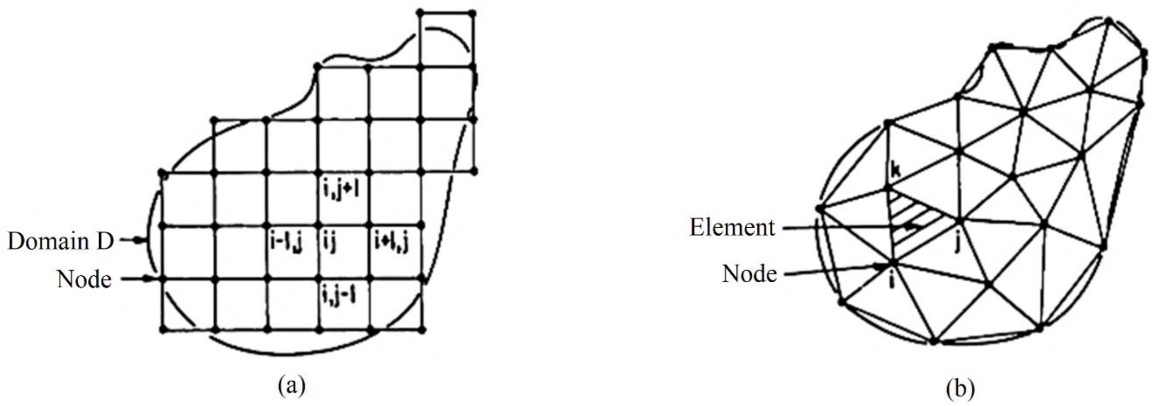


Figure 16. Finite difference and finite element discretization schemes. a) discretization using regular finite difference net; b) discretization using triangular finite elements [13].

The system can be divided in one-dimensional, two-dimensional or three-dimensional elements as shown in figure 17.

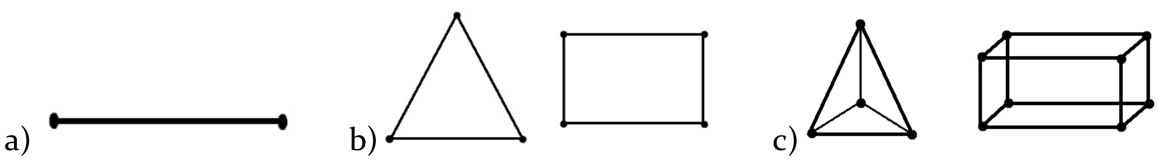


Figure 17. Discretization Elements a) 1D; b) 2D; c) 3D

Figure 18 shows an example of discretization process for a 1D system, which simplifies the task of solving the system.

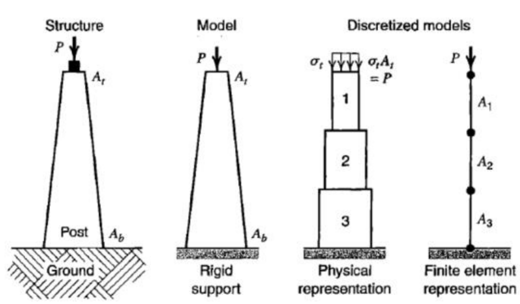


Figure 18. 1D Discretization method [15].

Figure 19 shows a 2D element before and after being discretized.

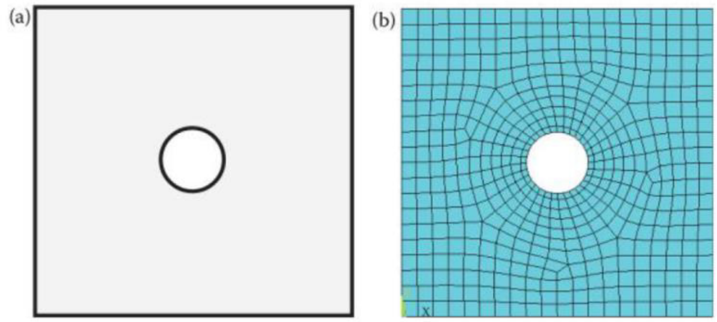


Figure 19. a) 2D CAD part; b) FEM discretization [16].

Figure 20 shows an assembly after being discretized.

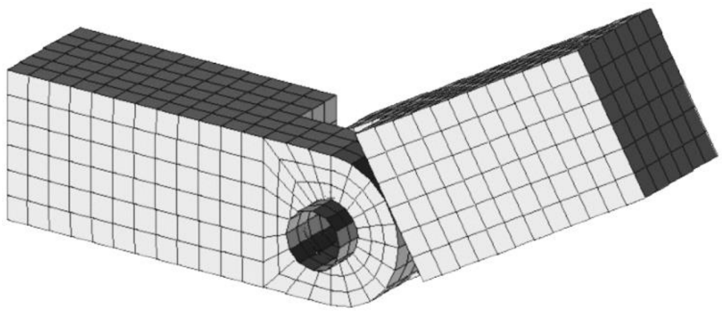


Figure 20. 3D Discretization of an assembly [17].

4.3.2 Brief history of Finite Element Method

The Finite Element Method used today has its origins in the 20th century. In 1909 Ritz developed a method using interpolation functions to approximate solutions of differential equations but as a restriction, they should satisfy the boundary conditions of the problem [18, 19].

In the work of Hrennikoff in 1940s, it was demonstrated that replacing small portions of the continuous system with an arrangement of simple elastic bars, could solve elastic problems [20].

In 1943 Courant increased possibilities of the Ritz. Courant suggested the use of piecewise continuous functions defined over triangular regions. This also eliminates the restrictions that Ritz had previously [19, 21].

Argyris and Kelsey in 1954 demonstrated the important role that energy principles in the Finite Element Method [12]. Turner and Clough developed the stiffness method in 1956. In 1960 The term *finite element* was coined by Clough. [21, 16]. Zienkiewicz and Cheung in 1965 solved field problems, such as determination of the torsion of a shaft, fluid flow, and heat conduction. In 1967 they published "The Finite Element Method in structural and continuum mechanics", the first book on FEM [12, 19]. In 1960's the FEM was facilitated due to the possibility of using the computers to perform the calculations. With this there were many mathematicians, whose research showed that as the number of elements increases, the solutions improve getting closer to the exact solution [19, 22]. Computer implementation of FEM programs emerged during the early 1970s. E. Wilson developed one of the first Finite Element in early 1960s. In 1965, NASA funded a project to develop the program which came to be known as NASTRAN. In 1969, John Swanson started marketing a program called ANSYS. ABAQUS was developed by a company called HKS, which was founded in 1978 [22].

Nowadays, the Finite Element Method has become one of the most used and versatile tools applied by engineers and scientists. It has also been successfully applied for the solution of several other types of engineering problems such as heat conduction, fluid dynamics, electric and magnetic fields, and others [19, 21, 16].

4.4 Mechanical Properties

The materials have different mechanical properties inherent to them, these determine the behavior of the material with respect to the external forces that are exerted on them. It is also necessary to consider the behavior that a material can have in the different mechanization processes that it may have. Some mechanical properties are: modulus of elasticity (Young's modulus), Poisson's ratio, yield strength and tensile strength.

The stress-strain curve graphically shows the mechanical properties where various properties can be observed, it can be used to determine the behavior of a material. In Figure 21, a strain-strain curve for an aluminum alloy is shown as an example.

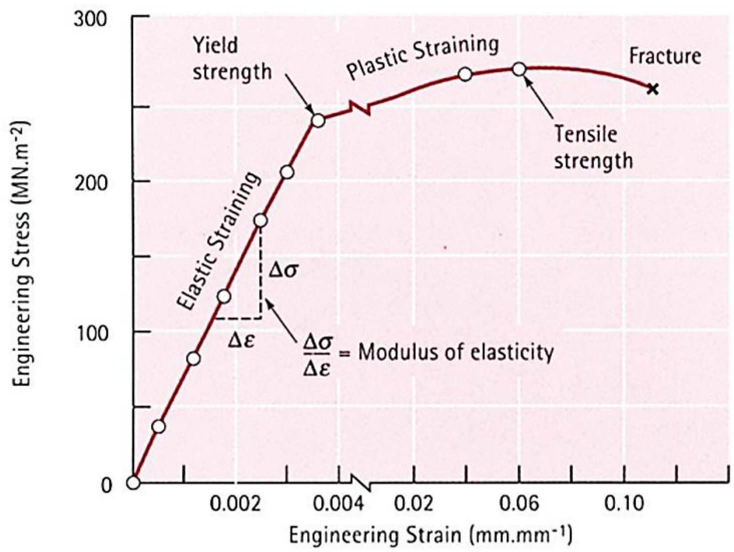


Figure 21. The stress-strain curve for an aluminum alloy [23].

4.4.1 Modulus of elasticity (Young's modulus)

The modulus is a measure of the stiffness of the material. A stiff material, with a high modulus of elasticity, maintains its size and shape even under an elastic load. Rigid materials have a higher value of young's modulus, as seen in Figure 22 comparing 2 different metals.

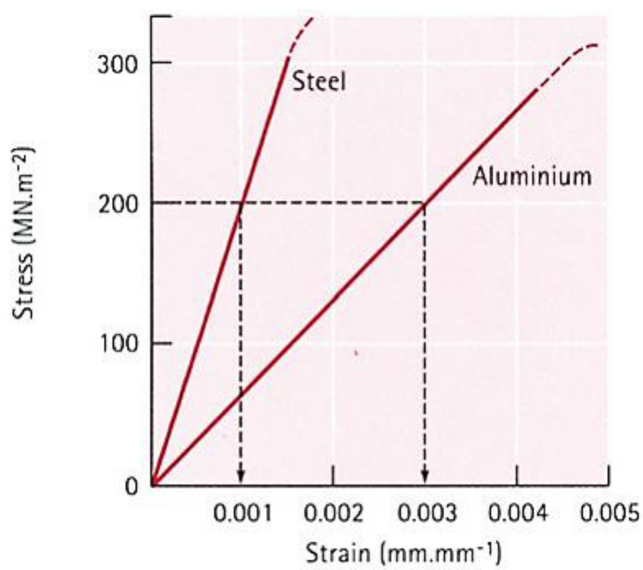


Figure 22. Comparison of the elastic behavior of steel and aluminum [23].

4.4.2 Poisson's ratio

Relates the longitudinal elastic deformation produced by a simple tensile or compressive stress to the lateral deformation that occurs simultaneously

$$\mu = \frac{-\varepsilon_{lateral}}{\varepsilon_{longitudinal}} \qquad \textit{Eq. 4-12}$$

Poisson's ratio is typically about 0.3 for metals [23].

4.4.3 Yield Strength

Yield Strength is the stress at which plastic deformation becomes noticeable. In metals, this is usually the stress required for dislocations to start to slip. The yield strength therefore is the strength that divides the elastic and plastic behavior of the material. When designing a part that will not plastically deform in service, we must either select a material that has a high yield strength or make the component large so that the applied force produces a stress that is below the yield strength

4.4.4 Tensile Strength

Is the maximum stress on the engineering stress-strain curve. In many ductile materials, deformation does not remain uniform. At some point, one region deforms more than others and a large local decrease in the cross-sectional area occurs. This locally deformed region is called a neck. Because the cross-sectional area becomes smaller at this point, a lower force is required to continue its deformation, and the engineering stress, calculated from the original area, decreases. The tensile strength is the stress at which necking begins in ductile materials.

4.5 ANSYS

ANSYS structural analysis software enables to solve complex structural engineering problems and make better, faster design decisions. With the finite element analysis (FEA) tools available in the suite, it is possible to customize and automate solutions for structural mechanic's problems and parameterize them to analyze multiple design scenarios. It can connect easily to other physics analysis tools for even greater fidelity. ANSYS structural analysis software (figure 23) is used throughout the industry to enable engineers to optimize product designs and reduce the costs of physical testing [11].

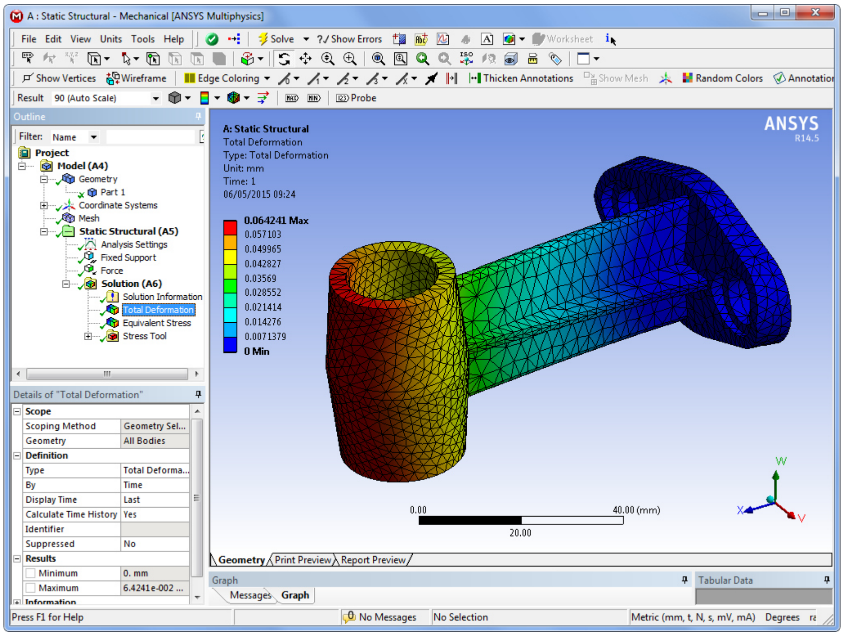


Figure 23. Ansys Workspace.

4.6 Stress Analysis in CAD´s software

Industrial software whose main function is not FEM analysis, such as design software, generally has simpler FEM analysis tools, but integrated within the same design software, which allows simulations to be carried out quickly with limitations.

Free software allows the use, modification and distribution of software, regulated by the GNU General Public License, with different types of licenses [24].

With free software it is also possible to perform processes for FEM analysis. Systems can be constructed, calculated and post-processed, but with many limitations and without guarantees of adequate operation. It is usually difficult to work with this software in comparison with industrial software.

Chapter 5 Development

For the development a methodology is followed this is shown in figure 24.

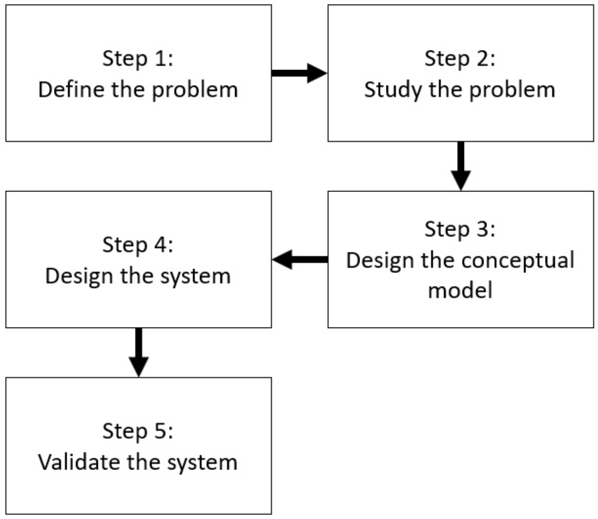


Figure 24. Detailed steps of development

5.1 Development Phase 1

The first step for the development of the cell is to know the requirements, seeing the process currently used to understand what they do, how it works, take the times and know more of the process by the experience of operators, talk to the person requesting the project to know what he wants and time frame of the project. With this information a basic idea of the process can be generated.

The objective of this process is the assembly of automotive glass. A glass is added several parts, such as moldings, supports and pins, necessary to install in the car. Figure 25 shows an assembly as an example.

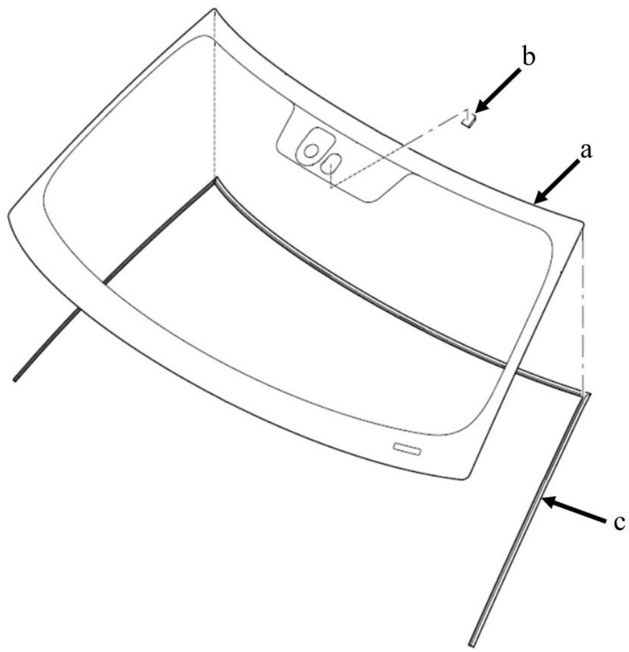


Figure 25. Automotive glass elements, a) automotive glass, b) bracket, c) moldings [25].

5.2 Phases of Manual Operation

Knowing the process to be automated gives details such as the areas of opportunity and other requirements of the process.

The process to be automated can be described in several points:

1. Placing the glass on a turntable:

The glass exits a previous process, which is not considered in the development of this project. The glass is mounted on a table, which allows free rotation of the glass, in preparation for the next step.

2. Application of the primer

In this stage, they apply a primer on the edges of the glass that is required to be able to perform the assembly process of the subassemblies.

For the application of the primer, a table is used allowing to turn the glass freely; as the glass is rotated, the primer is applied quickly and easily, the table has a flannel coating to protect the glass.

3. Loading the glass on the fixed table for bracket assembly

A movement of the glass is made, this time the glass is mounted on a table to assemble the bracket manually

4. Bracket assembly

Using a guide, the bracket is placed, this is a support for the devices required by the vehicle, such as the rear-view mirror, the GPS, etc.

5. Visual inspection of bracket

Leaving the cell an operator visually inspects the bracket to find some defects in the glass and verifies the position of the bracket.

After the bracket assembly, the required missing subassemblies are added to the glass by an extra machine. This machine requires 2 operators to place the parts to be mounted on the glass, these parts are moldings, and pins; The parts are kept in the machine by vacuum. This placing process is performed before the glass is loaded into the machine when the glass is in the process of bracket assembly or inspection.

6. Loading the glass onto the subassembly machine

After bracket inspection process, the glass performs another movement to be mounted on the subassembly machine, which already has the parts to be assembled.

7. Second assembly process

Here the machine centers the glass with the use of rollers, and is held by suction cups, the glass is pressed against the subassemblies and pistons apply extra pressure to achieve a correct assembly.

8. Loading glass on a turntable

Once assembled the glass, the glass passes again to a turntable for inspection.

9. Complete Assembly inspection

The operator inspects the assembly of the molding and pins.

10. Loading glass to rack

It is the final process, here depending on the inspections, the glass is placed in its respective rack.

Figure 26 shows this process.

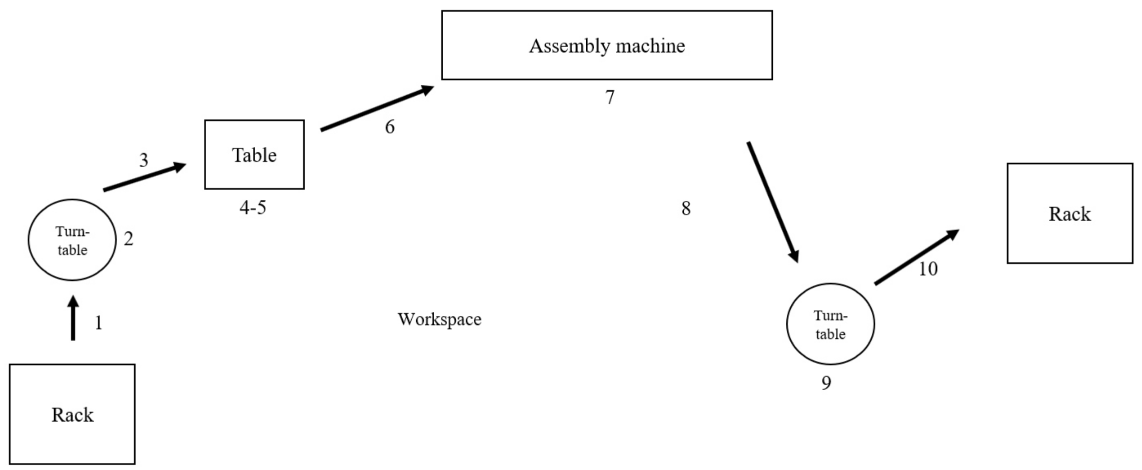


Figure 26. Manual assembly process.

5.3 Process requirements

The requirements for the project are:

- Correct assembly of subassemblies.
- The process can be adapted different models of glass.
- Do not exceed the budget.
- Operation Manual.
- Maintenance Manual.
- Same or less cycle time.

5.4 Work cell Design

Conceptual design

The process that was planned according to the requirements can be numbered in 3 stages, each stage is described below, in addition figure 27 shows the process diagram.

- Load operation.
- Subassembly feed operation
- Unload operation.

Loading process:

1. The operator shall load a glass into the loading conveyor.
2. With the aid of a centering system, the operator will center the glass, the glass will be attached to the conveyor.
3. The load operator will apply the primer assisted by a system that allows the glass to rotate. When finished, the glass returns to the original position.
4. The glass will enter the cell, which will pass the glass to the central support of the cell.

Assembly process:

5. With the glass inside the cell, in the central support, 2 operators will place the subassemblies in the tool.
6. The robot will apply adhesive to the bracket.
7. The robot will assemble the parts in the glass.
8. The robot inspects the placement of the bracket.

Unload process:

9. Having the glass assembled, the glass will leave the cell.
10. The operator inspects the glass.
11. The operator will discharge the glass and place it according to previous inspections.

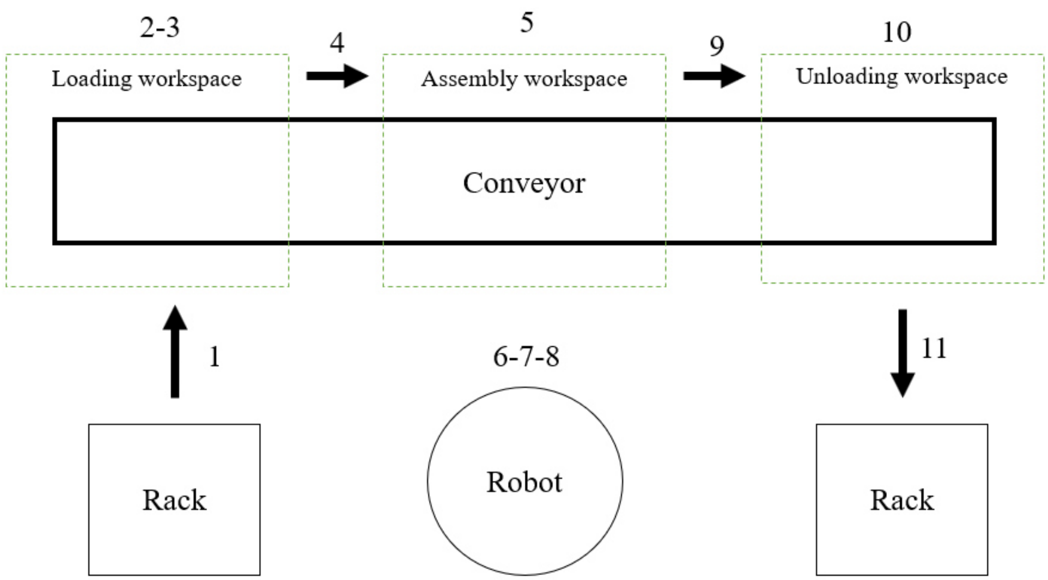


Figure 27. Automatic assembly process.

System requirements

The conveyor needs to meet several points:

- Simple design.
- Simple and modifiable.
- Lightweight.
- Resistant.

5.4.1 Work cell design

The tool must meet several requirements that depend on what the project requires, as well as the technical limitations:

- The tool must assemble all the subassemblies in a single action
- Lightweight
- The tool must be able to be used for several models of glass.

The project was divided into 2 phases:

The first would cover the design of the cell fence, the design of the conveyor and the design of a tool for bracket assembly only.

The elements would be made. The cell would operate with the sequence marked in conceptual development by assembling only the Bracket to the glass.

The second phase would concentrate on the design of the tool for the assembly of all subassemblies, the manufacture of the same and their implementation in the cell.

5.5 Fencing design

At this stage of design, the available space, the tasks to be performed, the location of the cell components, and the security systems to be integrated into the cell are considered.

Essential elements of the cell:

- Main Cabinet: it has the power supply system, which will feed the cell with the electric power required, here also the PLC, to control the operation of the cell, is located.
- Robot Industrial: The cell requires the use of an industrial robot with the necessary characteristics for the use of the tool, the robot to use is an IRB 6700 (specify model), for robot control a cabinet is required, this will also be taken account for the work cell layout.
- Pneumatic tank: it will feed the pneumatic systems to be used in the cell.
- Adhesive Application System: This system consists of a pump that will inject the adhesive into the subassemblies for the assembly process of the glass, this system also has a cabinet for control.
- HMI: This is the interface of the cell used by the operator to obtain operation information, also for the configuration of the cell work.

Layout

Using the dimensions of the glasses to be used in the working cell, the working space of the robot and the space of the other elements, it was possible to design the layout of the dimensions of the cell.

Having this concept, elements where located in the places needed.

3D design

CAD models of these elements were searched, where most can be found on the official web pages of the suppliers. If they did not have the official CAD models, simple models would be made according to the information in the datasheets of those elements.

Figure 28 shows the distribution of the cell and the main elements that make it up.

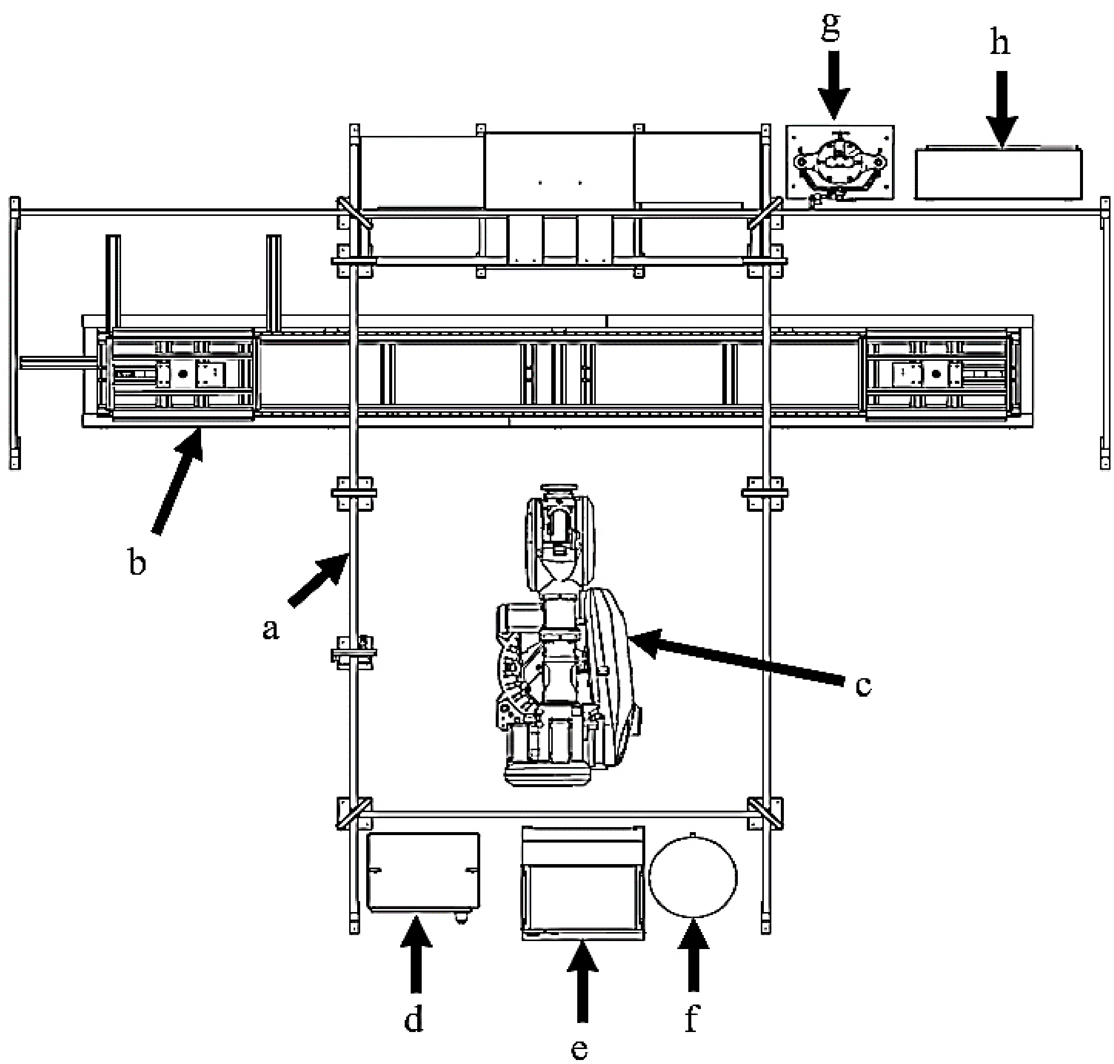


Figure 28. Layout of work cell.

Table 5-1 shows the basic elements of the work cell.

Table 5-1. Work cell elements

a	Fencing	e	Robot Controller
b	Conveyor	f	Pneumatic tank
c	Industrial robot	g	Adhesive dispenser
d	Main cabinet	h	Adhesive dispenser cabinet

At the top of the fence, a support was added which would serve to transport the signal cables only, separate from the power cables and the pneumatic system.

Safety

Every automation process requires security, to avoid causing damage to people or the same system, inside a robotic cell there are usually fast movements, heavy loads, tools for cutting or welding and other elements that would put an operator at risk.

There are also dangers to cell elements, when unplanned actions are performed in the process, or when the cell operations are being programmed, there is a danger of damage.

Having the conceptual design of the cell elements of security in the cell can be added, and they are described below:

The interlock: it is a locking switch commonly used in the doors that will have the working cell, its function is to block access during the operation of the cell. In addition, it prevents the operation of the same if the door is open, as this indicates that there may be someone inside.

Emergency Stop: As its name indicates serves to stop the whole cell, at any time, they have interlocking to prevent accidental reestablishment of the operation.

Safety curtains: These elements are presence sensors, detect if someone is in a zone, with this information, and depending on the cell, it can command to stop the operation if at that time there should be something in the zone.

Turrets: Their function is to indicate the working state of the cell, among them are mainly:

- Automatic Operation.
- Manual operation.
- Emergency stop.

5.6 Conveyor

The activities of the conveyor can be divided into 3:

1. Loading process
2. Assembly process
3. Unload process

5.6.1 Base

The base is the main structure of the conveyor, in it will be mounted all the elements to be used in the 3 processes mentioned.

It has 2 profiles of 5.2m running along the conveyor, 5 pairs of equidistant legs to avoid buckling in the main profiles, and crossbars to give resistance to the base.

Due to the weight of the carriage and the glass, the use of linear bearings that support the weight of the cart and the glass was added, where servomotors only have the task of moving the carts.

5.6.2 Load process system

Because the glass should be allowed to turn the cart was designed in 2 parts.

Lower part of the cart

The lower part uses aluminum profiles, to connect with the bearings of the linear guides were designed aluminum parts that also provided the necessary height to connect the servomotors with the carriage

The lower part would allow the rotation of the upper part where in addition the upper part should be provided with pneumatic pressure for the system of suction cups that would hold the glass.

To allow free rotation of the glass, a bearing was used on a steel base that would connect to the bottom of the carriage

The steel base would also serve to hold the vacuum generator to be used to hold the glass.

Top of the cart

The top was designed with aluminum profile. For the subjection of the glass 4 suction cups were used along with a generator of vacuum.

To fulfill the requirement of rotation, a rectangular base of steel was used where in its center was welded a steel tube that would serve as the axis of rotation along with the bearings, besides where it would pass the pneumatic hose. In figure 29, a representation of the armed cart, can be seen.

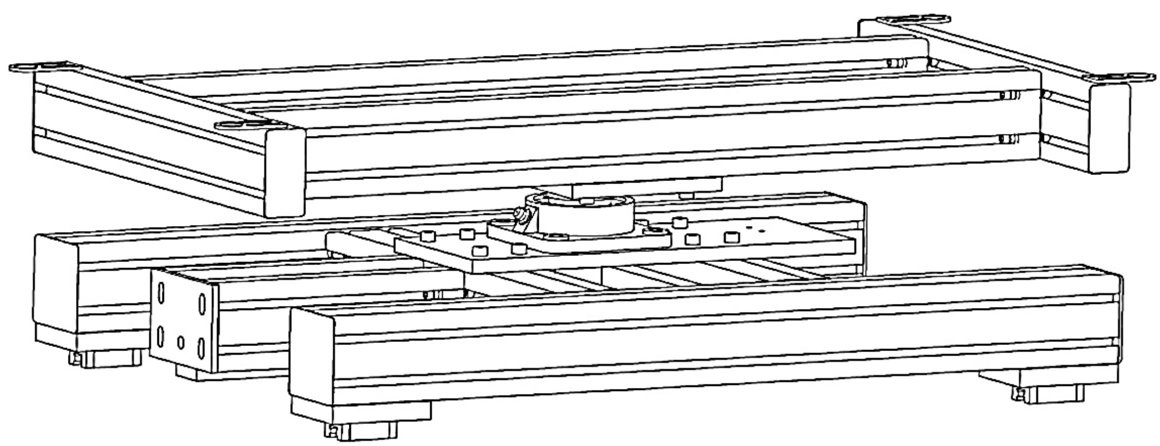


Figure 29. Conveyor cart.

Anchoring system:

The rotation of the glass in the conveyor is necessary, but only in some parts of the process, while the conveyor is in motion or when it is desired to maintain the position for the assembly of the subassemblies the rotation must be avoided. To achieve this, an anchor system was designed, consisting of a fixed aluminum part at the top and a fixed piston at the bottom of the carriage.

To simplify the anchoring process for the piston, a piece of nylamid with semi-conical tip was designed to allow anchorage even with the carriage slightly moved

The servomotor is located so that it is away from the center because if it was placed in the lower part the car could not reach the center of the conveyor.

System for glass centering:

The assembly process requires that the glass is positioned within the range where the chamber can detect the position where the subassemblies are assembled, in addition, it is required that in the process of loading and accommodating the glass there is repeatability.

A system of bumpers that serve to center the glass at the moment of placing the glass of entry, the bumpers have a piston and a roller of nylamid, to fulfill its objective, the ceilings had to rise to the moment that the glass is loading but be down to allow the glass to spin.

Load system

It was planned that the glass was mounted directly on the carriage where the suction cups blow air to allow the movement of the glass for its centering when performing several tests of this type of systems. It was concluded that it was not easy to move the glass so a new system for glass loading was necessary.

For the load, a system was designed with spherical bearings that would allow a smooth movement of the glass, in this system they had as base a piston identical to one of the bumpers, in it was had a frame of steel in which were 2 spherical bearings, There were 2 of these supports, one at each end of the glass; they were required to have the same stroke as the stops since they required equal movement and speeds.

Figure 30 shows the basic structure for the load system.

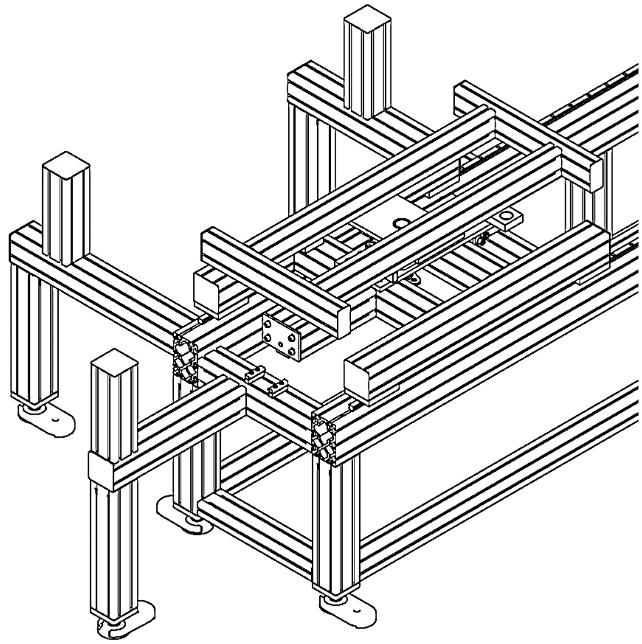


Figure 30. Load system.

Mechanical simulation

To calculate the maximum bending generated by the load of the glass, equation 5-1 was used [26]:

$$f = \frac{(F)(l^3)}{(3)(E)(I)(10^4)} \qquad \textit{Eq. 5-1}$$

Where f (mm) is the generated bending, F *(N)* is the applied force, I *(cm⁴)* is the moment of inertia, l *(mm)* is the length of the profile and E (N/mm²) modulus of elasticity.

With this equation and the data of the system, a maximum bending of 0.15 mm was calculated. In addition, a simulation was performed (figure 31) to validate that structurally the system would support the forces, a safety factor of 1.61 was obtained in the weakest elements that are those that hold the suction cups.

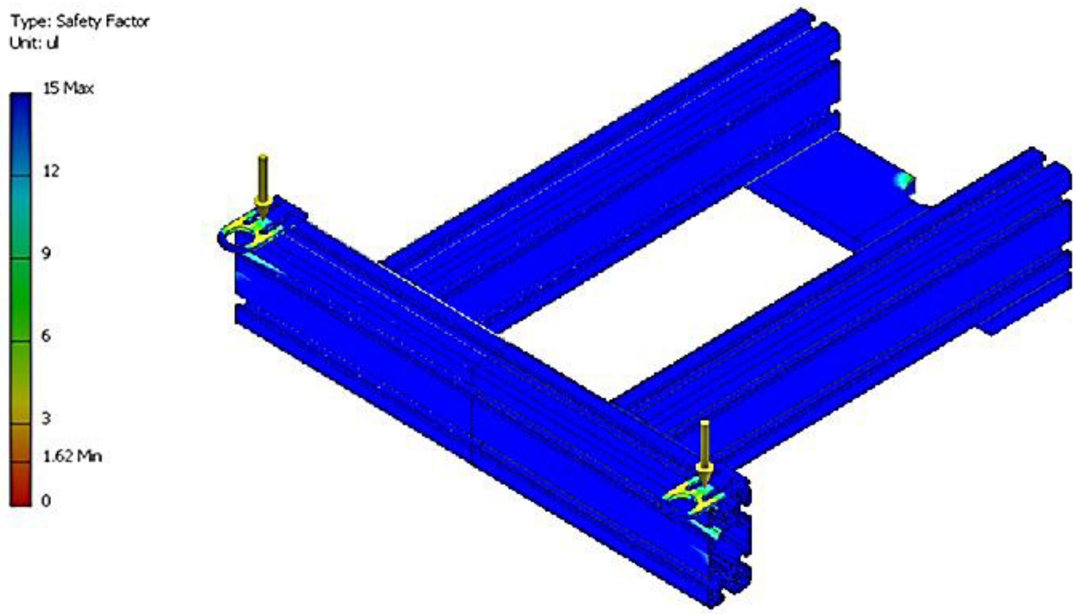


Figure 31. FEA of the top of the cart.

5.6.3 Assembly process system

Conveyor Center Support

The conveyor has the purpose of providing the cell with a glass with the proper position. The cart of the load conveyor moves it to the center of the cell, here the central support holds the glass, the robot attaches the bracket and the central support mounts the glass to the exit conveyor.

The glass from the conveyor is placed on the central support (figure 32), with the help of pistons they rise to be held on the load conveyor, which allows him to leave the cell.

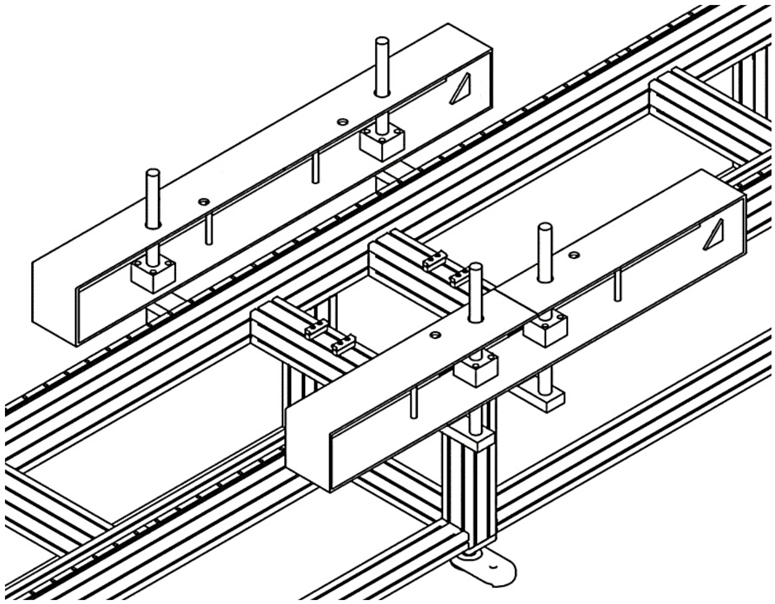


Figure 32. Central conveyor system for assembly.

The base of these supports is a steel frame; internal supports were added to prevent the supports from sagging by weight. This stage is critical for the process, since it must maintain the position of the glass, so it required a system of guides that allowed to rise without having movements, was designed a system of steel guides attached to the base of the Transporter where the supports with the help of a few pieces of nylamid would restrict the movement.

To hold the glass, 4 suction cups identical to those of the conveyors were used along with its vacuum generator. Also has 8 parts to give support when assembling moldings, these parts can vary their height, to adapt to different types of glass, with a threading system.

The system required a backlight to assist the inspection process with the camera, it was adapted to the support, some dimensions were modified to allow the conveyor to enter and exit the cell without colliding with the backlight.

5.6.4 Unload process system

The unload system is identical to the loading system, omitting the bumpers as they are unnecessary at this stage, the unload conveyor is a mirror of the load conveyor, with the same turning, anchoring, vacuum holding systems and also use the spherical bearings, but in this case to remove the glass from the conveyor.

5.7 Robot tool

It is increasingly common for robotic grasping systems to replace manual labor in industry. These systems have to meet requirements on efficiency and reliability, in order to be economically viable. The gripper design is a critical part of implementing such a robotized solution. Nowadays, it is most common to use parallel-finger grippers in industrial settings. The fingers are developed by experienced engineers, with design choices based on human expertise, and a costly and time-consuming trial-and-error process [27].

The purpose of this tool is to fasten the bracket in addition to having a support so that the assembly will be performed correctly

The base of the tool was designed in steel with holes with box for the screws that will be attached to the flange, the base has a lateral support for the camera, an identical support was added to the other side of the base to have a symmetrical tool trying to keep the center of gravity as stable as possible.

To hold the bracket a gripper is used in which some elements will adapt, called fingers. These fingers will have the inner shape of the bracket so that when the gripper actuates its opening the fingers press the inner walls of the bracket holding it.

Placed to one side of the gripper was adapted an aluminum parts that would aim to press the bracket at the time of assembly.

Sensor integration

Fingers are added inductive sensors to detect the finger being used. These sensors are fixedly mounted to the movable part of the gripper with the aid of a pair of fastening pieces.

5.8 Robot tools design

The tool has the task of assembling with precision the elements in the glass, but it has the following limitations:

- It must be light enough to be manipulated by the robot, without exceeding its capacity with respect to the center of gravity of the tool.
- Must be able to take the elements properly and in a constant position.
- Can make small positioning corrections for proper assembly.
- It should have a size that fits the size of the cell.

For the first phase of the project, it is contemplated that the tool will be able to assemble only the different types of brackets in the glass to obtain the necessary information to create the complete tool in a subsequent process.

The first version (figure 33) that was made was very simple, it consisted of a steel base, in the center it had a gripper with 2 elements that we called "fingers", that fulfilled the function of taking the bracket.

It had a camera on one side with the function of detecting if it could proceed to take a bracket and also to correct the position of the robot for the correct assembly of the bracket.

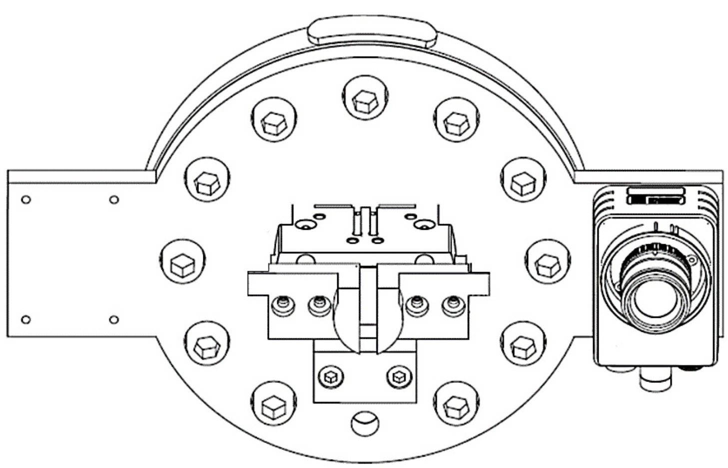


Figure 33. Robot tool V1.

This tool was used to find the variables of the process, among which the most important ones are mentioned below.

- The camera needed its own and stable lighting, since the ambient light caused problems in the recognition.
- The wiring that came out of the tool to the control system gave problems.
- The camera being almost level with the gripper could collide and damage the lens of the camera.
- A control of the force with which the elements were assembled was needed.

The simulation (figure 34) was performed to obtain the maximum stress present in the fingers, 2 forces are present, one applied when the Gripper is opened to take the bracket and the other to perform the bracket assembly.

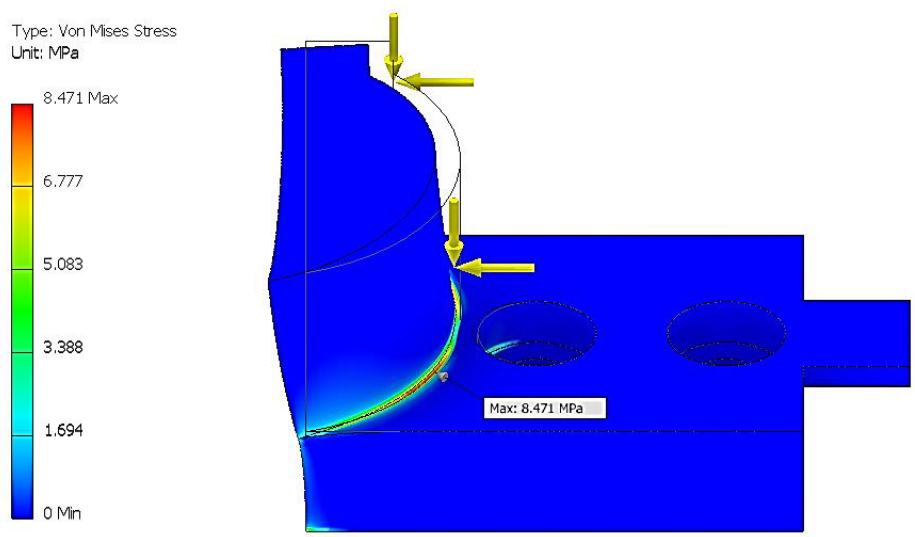


Figure 34. FEA of the finger to hold the brackets.

The maximum stress was 8.471 MPa, the Yield Strength is 350 MPa, therefore the piece resists without problems the task.

A new tool (figure 35) was designed to solve these problems, with the following solutions.

- A ring of light was added to the camera.
- A system was added that received all the information of the process within the tool to send the information in a simpler way to the controller.
- A force sensor was added to control the assembly, and this helped to separate the level between the camera and the gripper.

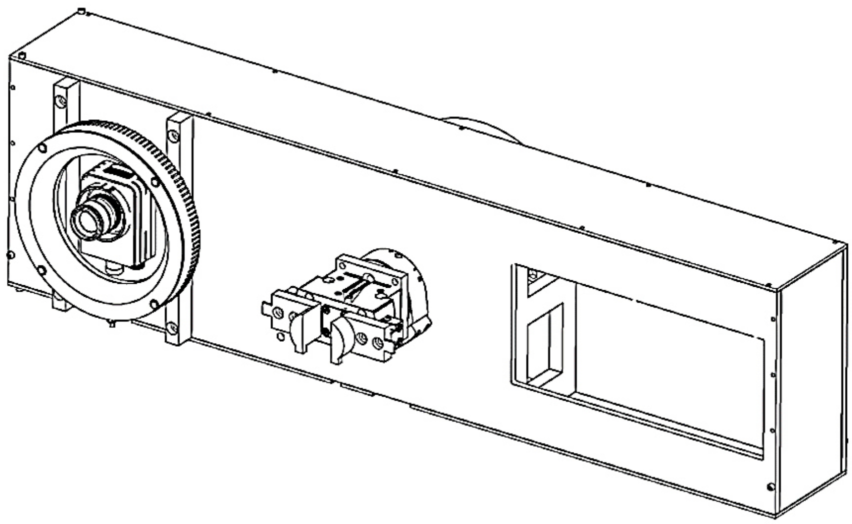


Figure 35. Robot tool V2.

For the tool, a simulation (figure 36) was performed to know if the structure of the box would resist the force of the assembly, it is observed that the maximum stress was very small because no extreme force is applied to the assembly of the glass.

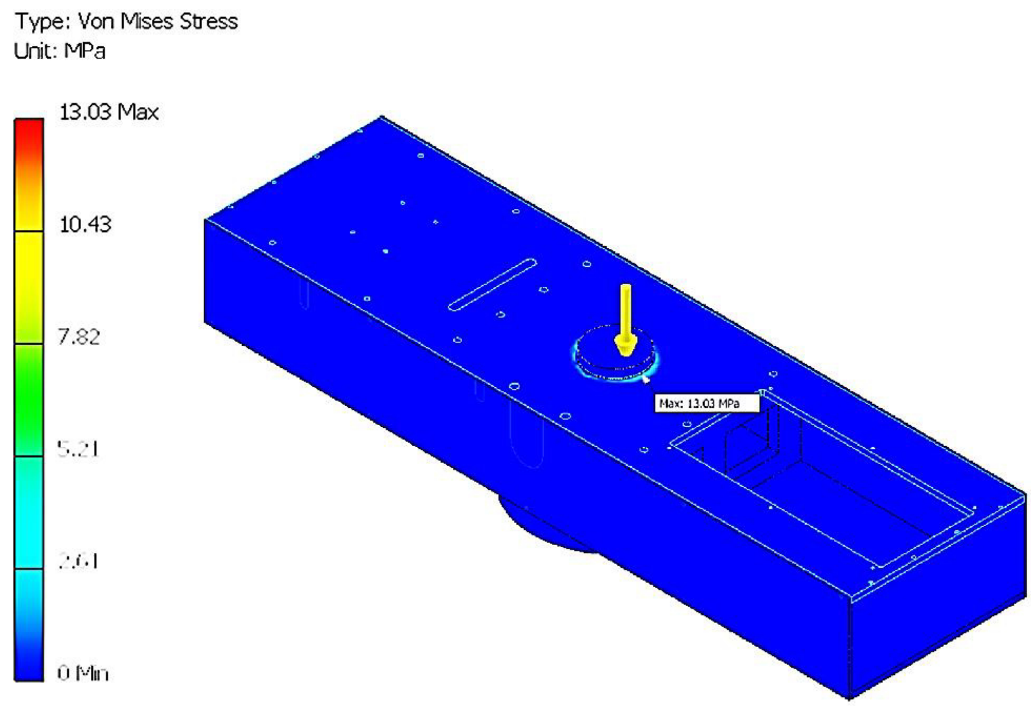


Figure 36. FEA of the robot tool V2.

The maximum stress is located under the force sensor in the aluminum plate and is 13.03 MPa, the material of the plate is AL 6061 T6, which has a Yield strength of 276 MPa, so the tool would easily support the assemble.

5.9 Manufacture and assembly of the cell

Having designed all the components of the cell detailed drawings were created with tolerances, materials, etc., for its manufacture.

The fence was the first to be built, it was assembled without complications in the area planned, then started the placement of the robot in the cell.

The next thing that arrived was all the aluminum profile of the conveyor, the base of this one was anchored in the required position, having this base and the robot inside the cell had everything necessary to be able to finish with the enclosure of the cell, closing.

It followed the process to place the servo motors, they required the positioning, they needed to be at a distance and they were parallel to the guides since any angle would cause some damage to the servo motors.

With the servo motors in place, the carriages of the conveyors were assembled, the bearings of the linear guides were placed, the lower part of the carriage was placed on them and in the bearing, the pistons of the anchorage system were added.

The top of the car was assembled with suction cups and anchoring parts, the tubular support was placed, and all these elements were attached to the bottom of the car.

The rotation and anchoring systems were checked to see possible problems, the movement of the carriages in the guides was also verified, and the carriages were connected to their respective servo motors.

Pistons were assembled, together with their Reed sensors, for the system of loading, assembly, unload, and centering. The rollers were placed for the centering system, the supports were placed for the loading and unloading process

5.10 Implementation of phase 1

By having the cell built, where the elements were already connected so that they could be moved by a controller, movement tests were performed to verify the correct assembly of the components.

The conveyors moved inside and outside the cell to confirm the correct operation of the servomotors and confirm that the movement was carried out in a simple way with the carriages mounted on the linear guides.

Tests were also carried out for the system of rotation of the table of the car, in such a way that the rotation of the glass was allowed without damaging the system of pneumatic hoses that serve for the suction system of the suction cups.

5.11 Load conveyor system

The pistons of the loading system were tested and adjusted to verify that the height and speed were the same for the correct functioning of the system, a test was carried out of how the operators would mount and unload the glasses on the conveyor.

For the loading system, in addition, the positions of the stops and speeds of the pistons were adjusted so that the fastening of the glass in the carriage would be carried out in a correct and repeatable manner.

5.12 Central support

Tests were performed to see the movement of the pistons and brackets for the central support system

Problems were found for this system since the design guides did not fulfill their function because the guides did not allow a little freedom of movement which caused the problem.

An auxiliary guide system (figure 37) was designed, replacing the existing system, consisting of guide profiles and their respective trolleys located at the ends of the supports.

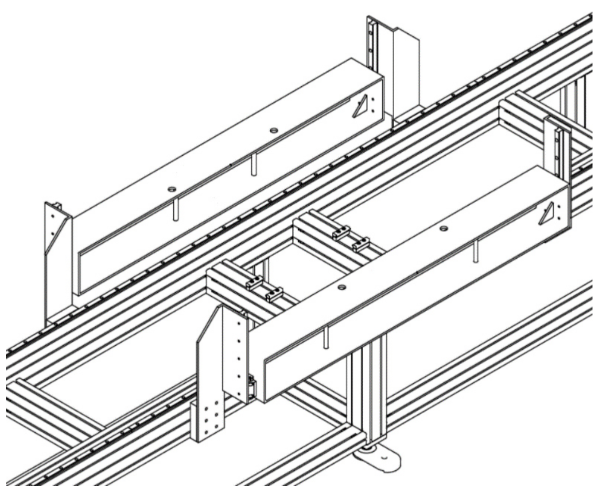


Figure 37. Changes in the central system

This system allowed a better movement of the system, eliminating the problems of the previous guides.

5.13 Development phase 2

The tool had the following requirements:

- Light tool to be used by the robot.
- Base of the tool made of aluminum profile to serve for new models of glasses.
- Assemble all components properly.
- The assembly of the glass requires an application of 200 N.

The tool (figure 38) was designed with aluminum profiles as a base, for the assembly of the glass an aluminum part was created with the male form of the glass with grooves to hold the moldings and pins.

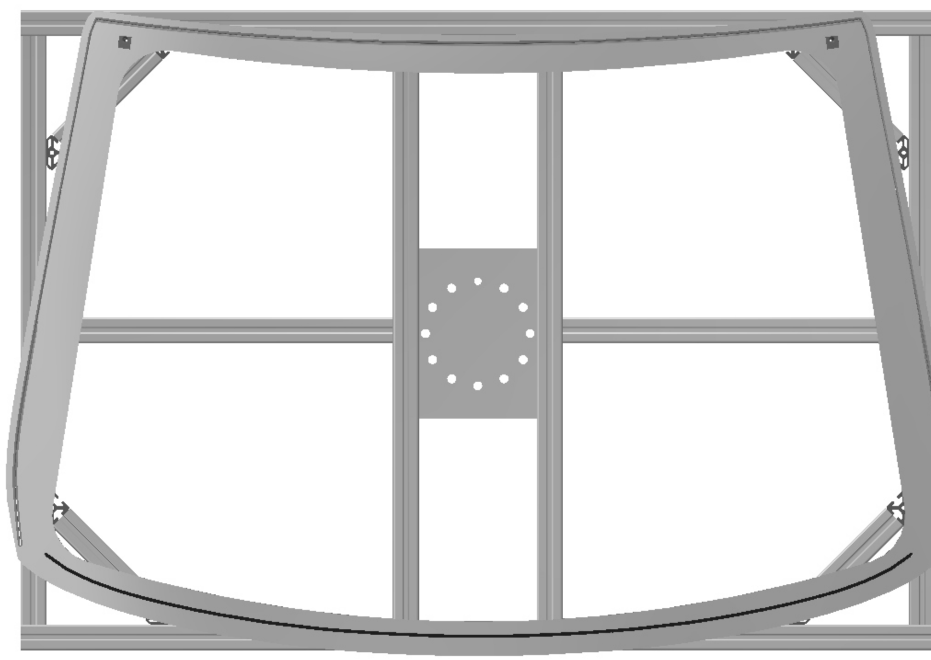


Figure 38. Complete robot tool.

5.13.1 Aluminum profiles

The tool will be based on aluminum profiles, 3 tools were created that each had a different type of profile to analyze.

Solid profile

This profile (figure 39) is the most resistant, expensive and heavy of the 3, with a mass of 4.53 kg/m.

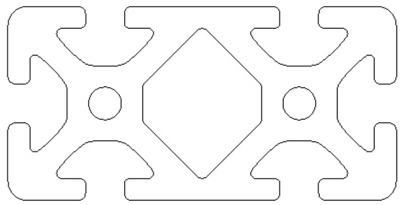


Figure 39. Solid profile.

Light profile

This profile (figure 40) is lighter and more economical than solid, but has a lower strength, its mass is 3.04 kg/m

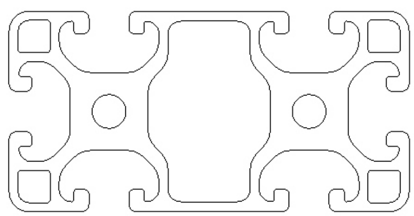


Figure 40. Light profile.

Economic profile

This profile (figure 41) is the cheapest and lightest profile, but also least resistant, it has a mass of 2.42 kg/m.

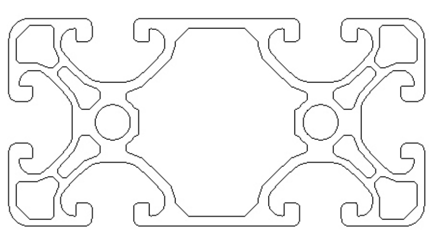


Figure 41. Economic profile.

5.13.2 Materials

The profiles are made of an Al 6060 T6 alloy with mechanical properties shown in table 5-2 [26].

Table 5-2. Al 6060 T6 Proprieties.

Property	Value	Unit
Density	2700	Kg m^{-3}
Young's Modulus	70,000	MPa
Poisson's Ratio	0.33	-
Tensile Yield Strength	195	MPa
Tensile Ultimate Strength	254	MPa

The material that was selected for the other elements of the tool was an aluminum Al 6061 T6, which is a common material used in the company and is easy to machine. Table 5-3 shows the physical properties of this material [28].

Table 5-3 Al 6061 T6 Proprieties.

Property	Value	Unit
Density	2700	Kg m^{-3}
Young's Modulus	68,900	MPa
Poisson's Ratio	0.33	-
Tensile Yield Strength	276	MPa
Tensile Ultimate Strength	310	MPa

5.14 Information of the tools

The mass and the center of gravity are very important points to consider when designing the tool, since it depends on whether the robot will be able to maneuver it without problems. The information on the center of gravity of the tools is shown below.

Table 5-4. Center of gravity and mass of tools.

	Mass (Kg)	L-X (mm)	L-Y (mm)	Z (m)
Solid	73.5	0	0	0.086
Light	60	0	0	0.09
Economic	55.5	0	0	0.094

Figure 42 shows the load diagram of the robot that will be used in the cell, as shown, the maximum load that can be loaded is when the center of gravity of the tool is closest to the flange. In addition, in the graph the location of the center of gravity of the tools is indicated with a red dot, the 3 tools have a distance in the z-axis of the center of gravity practically identical.

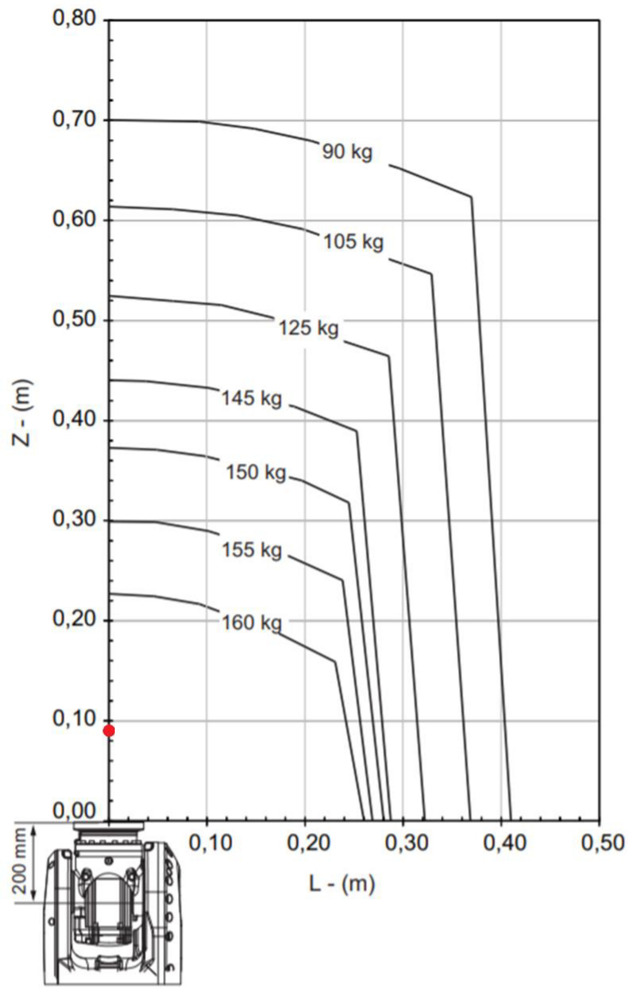


Figure 42. Load diagram Robot [7], red dot indicates where the center of gravity of the 3 tools is located.

With these data the robot would be able to work with the tool independently of the profile to be used. Therefore, the other factors that will determine the best profile to use in the tool will be reviewed later.

5.15 Finite Element Analysis (FEA)

The FEA analysis will simulate the adhesive force present in the tool, to see the displacements and tensile forces, to check the performance of the tool. The FEA analysis will simulate the adhesive force present in the tool, to see the displacements and tensile forces, to check the performance of the tool.

5.15.1 Simplification

Symmetry

The simplification by symmetry generates a computational advantage, since instead of analyzing the whole system, it is only possible to analyze a portion that represents the entire system, which lightens the computational load by having fewer calculations to be performed, which generates faster analyzes.

To be able to apply analysis by symmetry it is necessary to comply with certain conditions, where in the system there must be symmetry in geometry, in the physical properties and in the loads applied, in addition, to the portion of the system to be analyzed, movement restrictions must be applied such that represent the total system properly [29].

In the figure 43 it is shown that due to the geometry of the system and its applied loads the system can be simplified in such a way that it is possible to analyze only a quarter of the system.

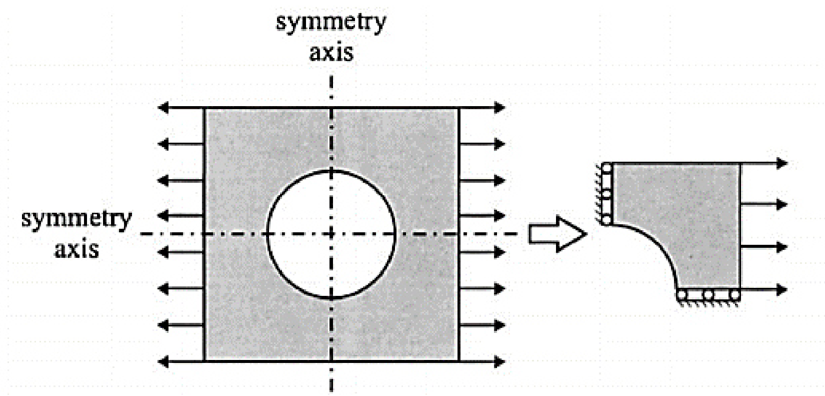


Figure 43. Example of quarter-symmetry [29].

The system of the figure 44 allows the symmetric analysis but due to the type of applied loads it is only possible to half of the symmetry.

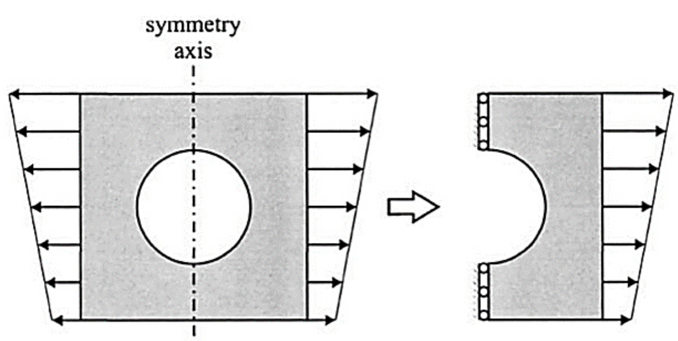


Figure 44. Example of half-symmetry with respect to vertical axis [29].

Figure 45 shows a system similar to that of the figure 46 but being composed of 2 materials, the simplification by symmetry can only be done as follows.

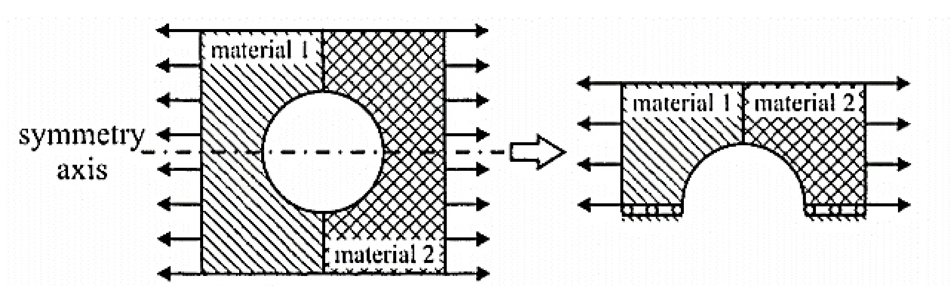


Figure 45. Example of half-symmetry in 2 material system [29].

The system shown in figure 46 does not allow analysis by symmetry due to the characteristics of the system, its variable loads and its 2 types of materials.

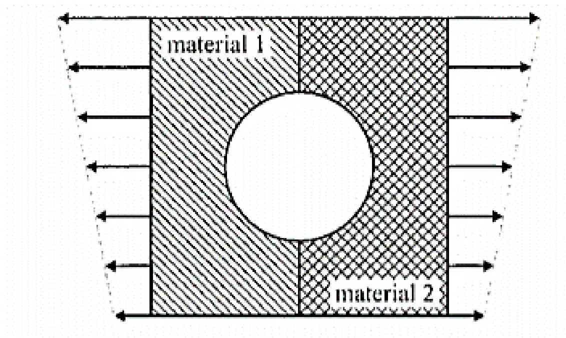


Figure 46. Example of no symmetry [29].

To perform the FEA analyzes without taking much time, it was decided to perform the simulation by symmetry, for this, half of the tool was analyzed by placing the necessary supports and forces. Figure 47 shows the axis of symmetry that was considered in the tool and the sample to be studied from the tool.

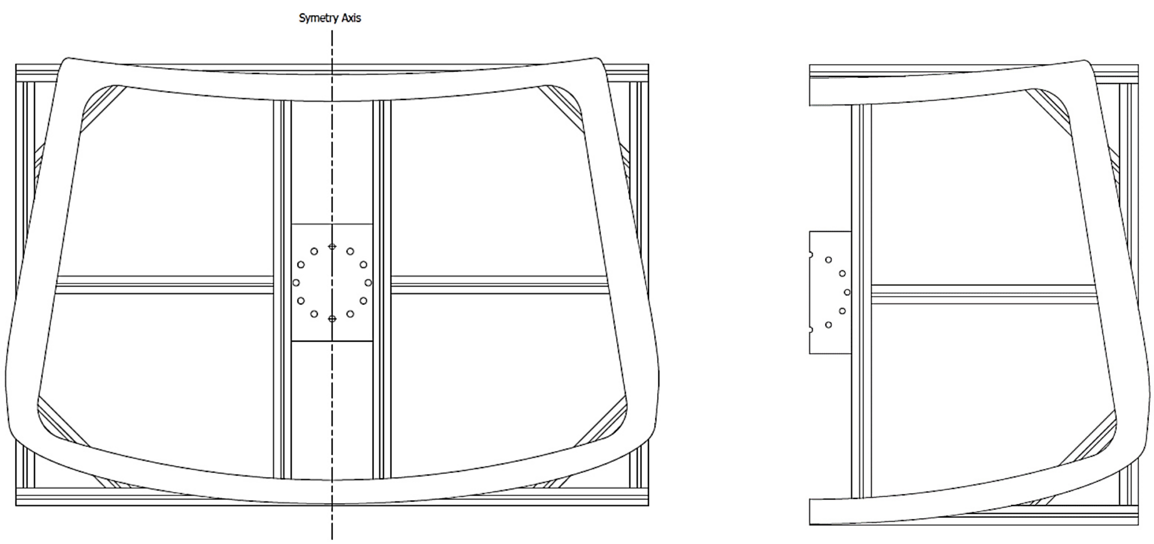


Figure 47. Tool's symmetry axis.

In addition, the 45 ° connections were removed (figure 48) by an extension of the profile.

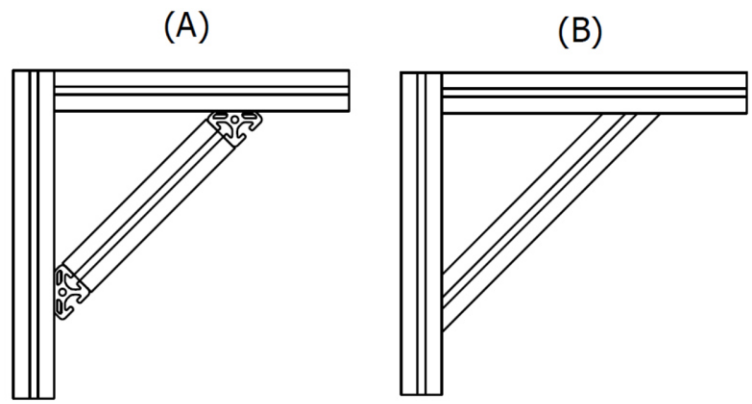


Figure 48. Connections. (A) Real. (B) Simplified.

A simulation (figure 49) was carried out to verify that the simplification of the connectors did not affect the simulation, a force like that which would support both types of connections was applied.

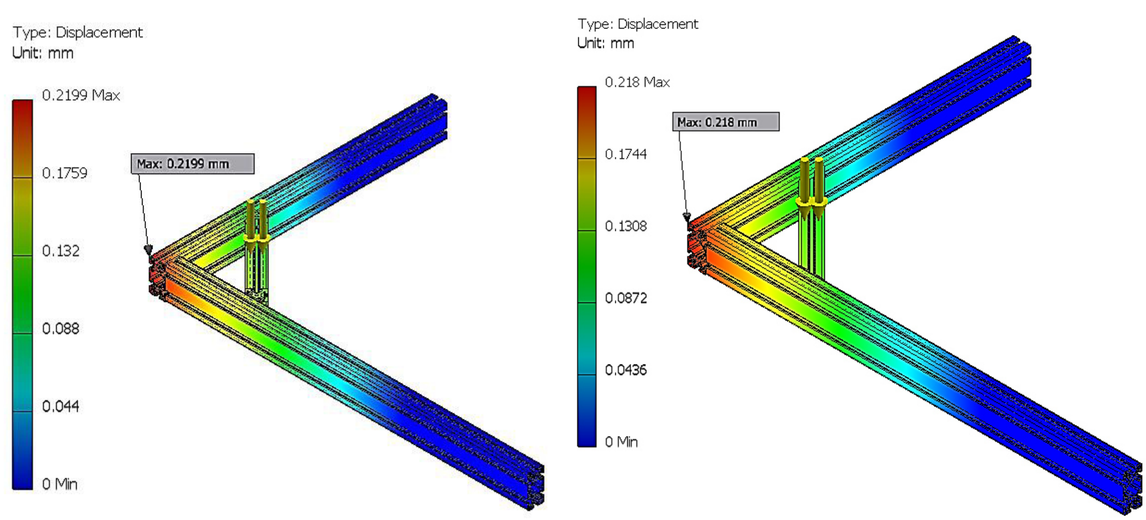


Figure 49. Comparison of the analysis of the connections of the profiles.

5.16 Boundary conditions

The Boundary Conditions serve to simulate the physical limits in the tool, such as the joints of the different pieces that make up the tool, also where the tool is to be held, and the forces that will be applied to it.

5.16.1 Frictionless constraint

To perform the FEA analysis with symmetry it was required to apply a Frictionless constraint, this constrain prevents motion of a face in the direction to the face, as shown in figure 50.

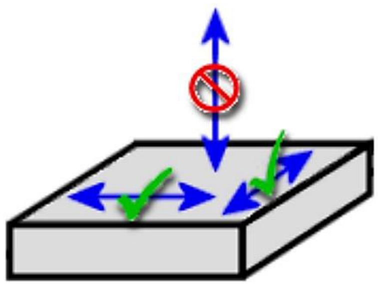


Figure 50. Frictionless constraint [30]

5.16.2 Fixed Constraint

This support constraints motion in all directions for the selected geometry.

5.17 Simulation process

The simulations of the tools were carried out with 3 different programs to compare their practicality, ANSYS, another industrial software and one free software.

5.17.1 Stress analysis preparation

Contacts

The first step to configure the simulation is to register all the contacts between the parts that make up the assembly, so that at the time of the simulation it behaves properly.

Material

To select the material of the parts, the first step is to register a new material, mechanical properties of the material are introduced in the software. Then assign the corresponding material.

Boundary conditions

In this case the analysis considers two types of constraints:

- Frictionless support

the frictionless support was applied to the faces resulting from the cutting of the symmetry of the tool as shown in figure 51.

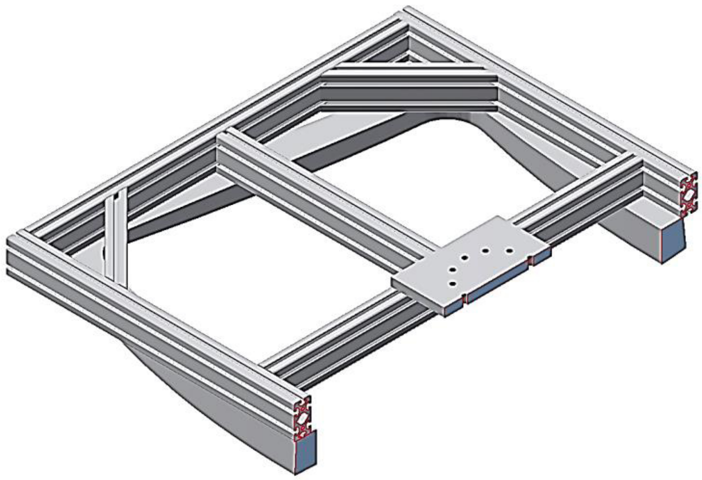


Figure 51. Frictionless support.

- Fixed support

The fixed constrain was applied in the part that joins the tool to the robot as shown in figure 52.

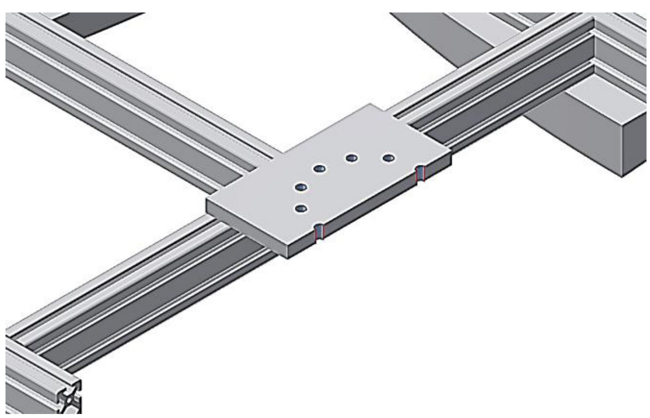


Figure 52. Fixed support.

- Force

For the FEA simulation of the tool a force of 200 N was applied to simulate the assembly as shown in figure 53.

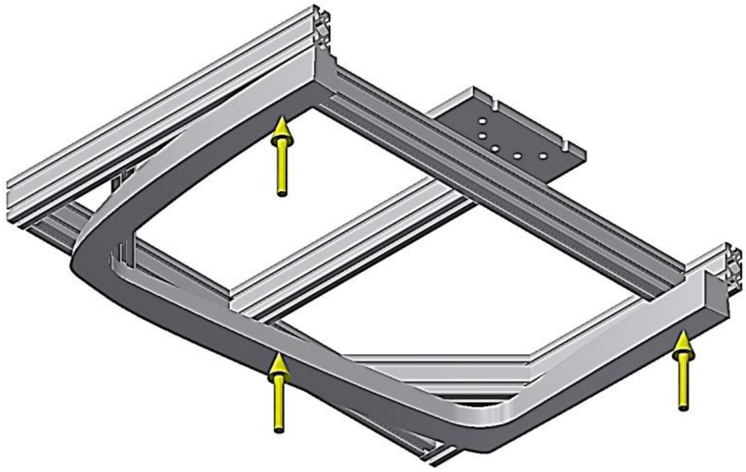


Figure 53. Force.

5.18 Analysis information

The FEM analysis was performed to find important information to see if the tool can support the applied forces.

To carry out the analyzes, 3 different methods were used, one using the simulation tools provided by the industrial software, another will be the application of ANSYS, a specialized tool for the FEM simulation, and finally it will be the free software, a free license tool for the analysis. The basic process to perform the simulations in each software are shown in the annexes.

Obtaining the present stress in the tool and with the data of the material mechanical its behavior can be obtained. If the stress exceeds the Yield Strength, the tool will not be useful since the loads will permanently modify its geometry or it could result in a fracture.

In addition, the displacements must be checked since the tolerance of assembly is ± 1mm.

Chapter 6 Results

6.1 Work cell implementation

The cell was released in the plant for continuous production use, the staff was trained to manage the cell and the process to be carried out. In addition to creating manuals for the process and maintenance.

The work times in the cell were kept constant for production.

The loading system worked properly, the turn for the priming also worked as expected and once the operator got used to mentioning that it was comfortable to work.

The transport system of the glass for the entrance had the correct precision and the system of linear guides allowed a very smooth movement, the out of phase connection of the engine worked, but it was decided to change the connector by one with a ball joint to allow absorbing any movement and not forcing the engines.

The load system for bracket assembly worked properly with the adapted linear guides, if the positioning in the load was carried out properly the glass lay in position for the assembly of the bracket. The tool for bracket assembly (version 1) worked properly for gluing together with the bracket feeding system.

For the discharge of the glass, the movement system for the glass outlet and the system for unloading the glass worked properly.

6.2 Robot Tool FEA

Simulations of the structural static type were carried out, to the 3 tools, to obtain necessary information of the maximum deformation type and maximum stress, to verify if they can support the assembly tasks.

6.2.1 Ansys stress results

Solid Profile

The simulation shows (figure 54) that stress is concentrated in the profile where it comes into contact with the plate that connects the flange of the robot with a maximum stress of 1.69 MPa, the material of the profile has a resistance of 195 MPa, with which can see that the tool would resist the task of assembly without any problem.

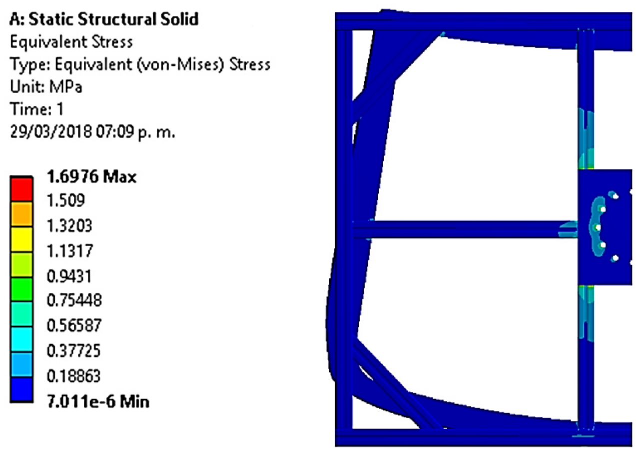


Figure 54. Stresses in the solid profile tool.

The deformation presented by the tool is another point to consider, because if it is too large it could affect the assembly position of the element, which would cause it to be out of tolerance. The resulting deformation of this effect is 0.015 mm, which is too small to have a negative impact on the assembly, as shown in figure 55.

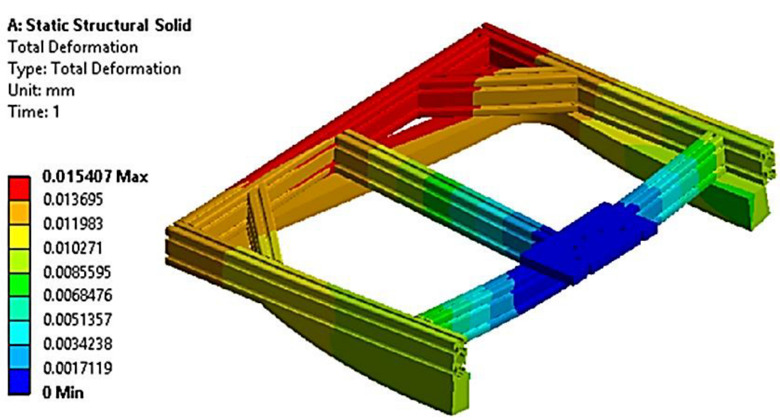


Figure 55. Results of deformation in the solid profile tool.

Light Profile

As in the tool with solid profile, the stress is concentrated in the part where the profile comes in contact with the plate of the robot flange. The maximum stress is 1.99 MPa (figure 56), it increases with respect to the solid profile, but it is still much lower than the 195 MPa that the material supports.

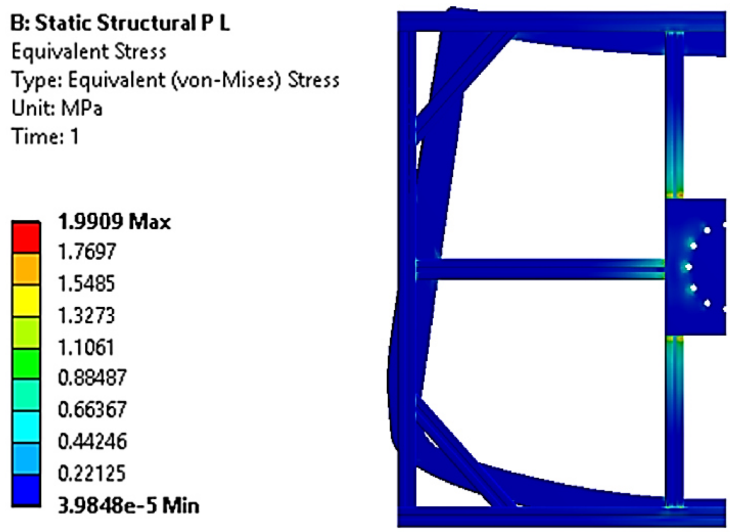


Figure 56. Stresses in the light profile tool.

The deformation also had an increase with respect to the simulation of the solid profile, but it is also still less than 0.1 mm as shown in figure 57, so the impact of the deformation of the tool is negligible.

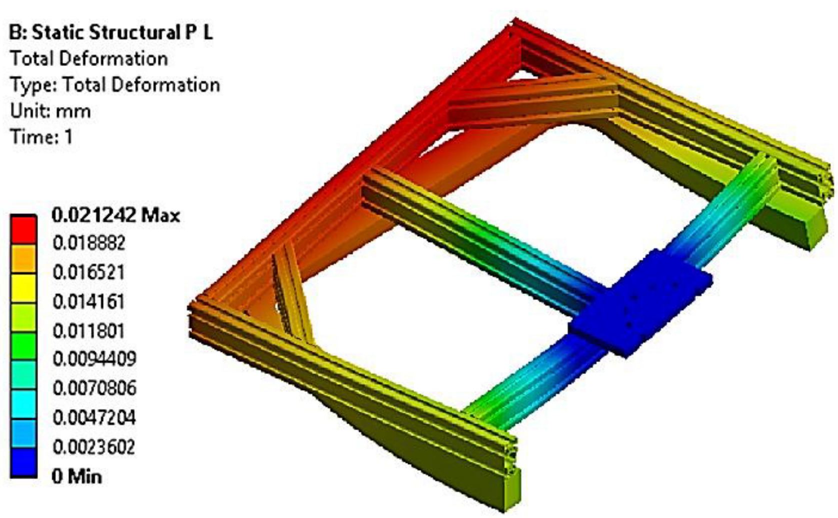


Figure 57. Results of deformation in the light profile tool.

Economic profile

The tool of economic profile has the same behavior as the other 2 tools, are concentrated in the area near the flange of the robot, the maximum stress is the highest in the 3 tools with a maximum stress of 2.75 MPa (figure 58), but this stress is also very small compared to the strength of the material.

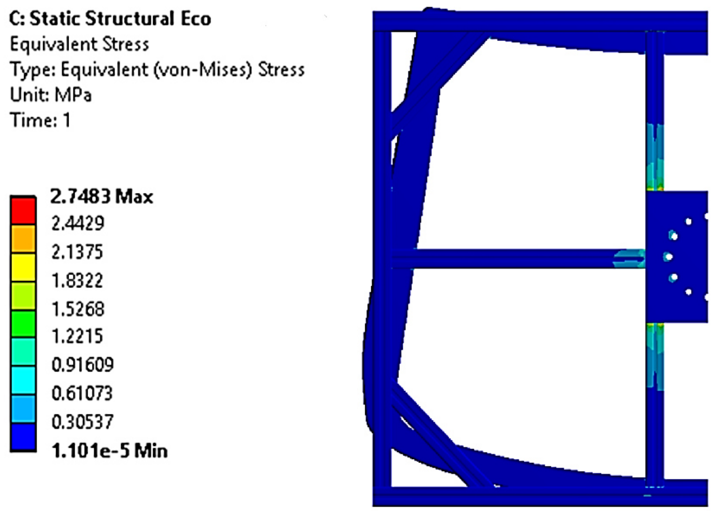


Figure 58. Stress in the Economic profile tool.

The deformation is greater than the other 2 tools with a maximum of 0.025 mm (figure 59), but even so it is very small for about a great way the assembly.

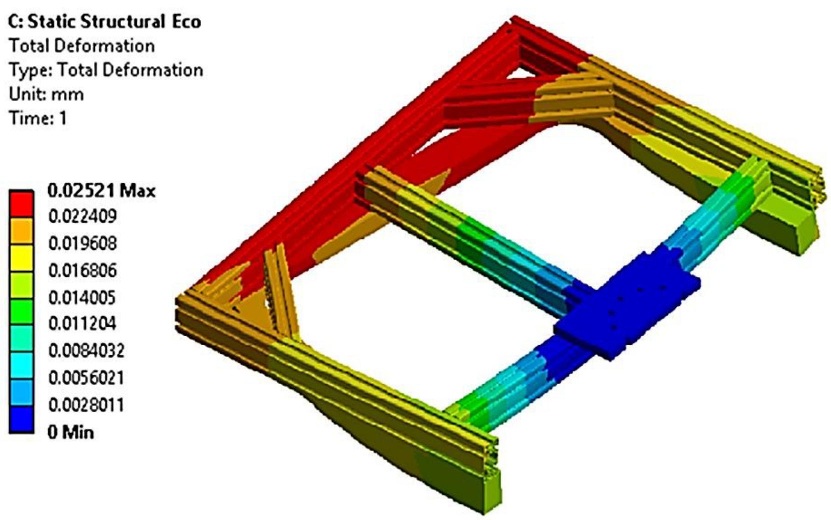


Figure 59. Results of the deformation in the economic profile tool.

Chapter 7 Discussion & Conclusion

7.1 Work cell

The cell was completed with the elements necessary for its operation. The conveyor was left in operation with the improvements applied, the correct functioning of the components of the cell were shown, and the process was left in operation, with the task of assembly the bracket with the tool v1 shown in Figure 33.

The cell process, where the activities are optimized, and several tasks are carried out at the same time, allowed to reduce the area in which the same activity was carried out manually, with which the cell (figure 28) reduced by 38% the area occupied for the assembly operation with regarding the space occupied in the manual process (figure 26). These data were obtained by comparing the actual measurements of the cell and the space occupied in the manual process.

7.2 FEA software comparison

For practical reasons a comparison was made between Ansys, industrial software and a free one, to compare the advantages and disadvantages.

7.2.1 Data comparison

Table 7-1. Solid Profile Results comparison.

Solid Profile	Max. Displacement	Max. Von Misses Stress
Industrial software	0.01601 mm	1.693 MPa
Ansys	0.015407 mm	1.6976 MPa
Free software	0.0149 mm	1.29 MPa

Table 7-2. Light Profile Results comparison.

Light Profile	Max. Displacement	Max. Von Misses Stress
Industrial software	0.02086 mm	2.761 MPa
Ansys	0.021242 mm	1.9909 MPa
Free software	0.021 mm	1.5 MPa

Table 7-3. Economic Profile Results comparison.

Economic Profile	Max. Displacement	Max. Von Misses Stress
Industrial software	0.02623 mm	3.872 MPa
Ansys	0.02521 mm	2.7483 MPa
Free software	0.022 mm	1.29 MPa

Comparing the results of the simulations of the 3 software, it can be observed in figure 60, they have a similar behavior in the 3 software, with the exception of the simulation of the economic profile tool in the free software, this may be due to the fact that the mesh was not fine enough because the free meshing software has limitations, had problems meshing the internal geometry of the profile, as the geometry was relatively, mesh did not match the original geometry.

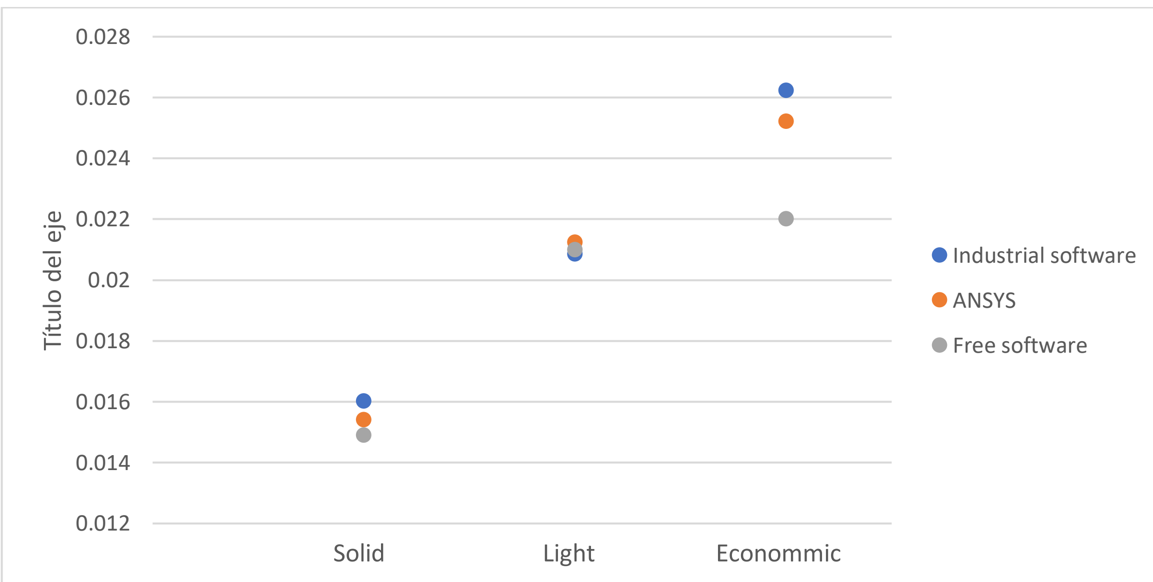


Figure 60. Software displacement comparison.

The behavior of the software is different when comparing the results of the maximum stress (figure 61), in the case of the solid profile they have a similar behavior, but in the case of the other 2 there is a difference, which is due to the type of predominant elements in the mesh, in the case of Ansys are Hexahedrons and in the case of the industrial software is Tetrahedrons and it was not possible to change it. In addition to the quality of the mesh created.

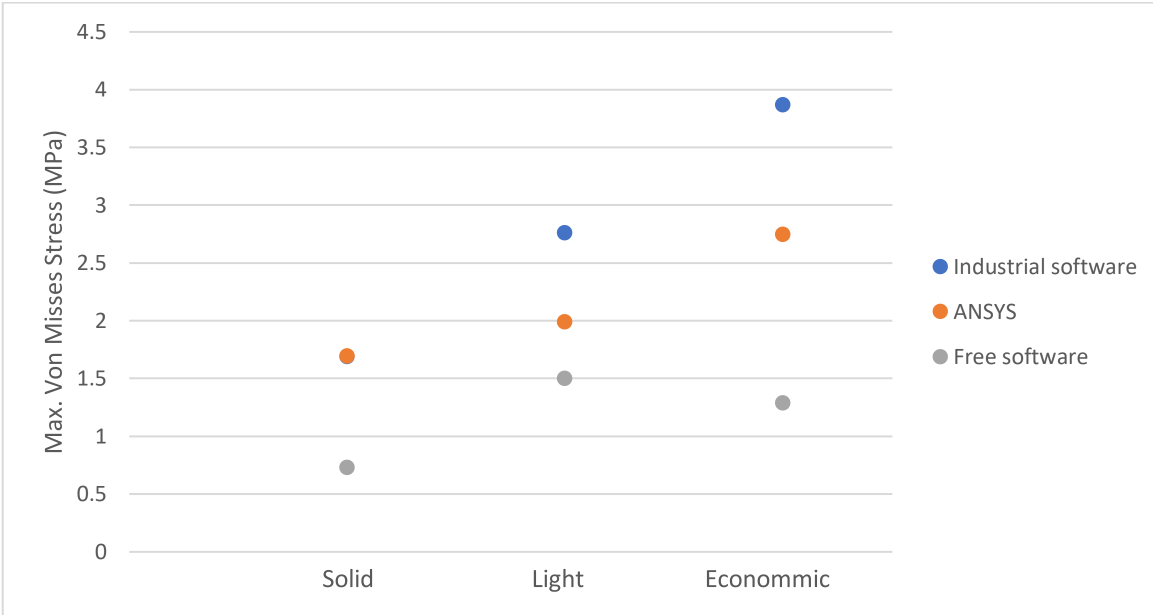


Figure 61. Software stress comparison.

With the data obtained from the simulation with the different software and with the physical data of the 3 different tools seen in section 5.14, any of the 3 tools meet the weight restrictions and resist the assembly activities of components.

The advantage of the economic profile tool with respect to the other 2, in addition to the mass, is the price of the profiles, in which economic profile was 40% cheaper than the solid profile. So, the most viable option would be the tool with economic profile since it is used for the assembly activity, and it is lighter.

7.2.2 Benchmarking FEM software

In this section Ansys was compared with industrial and free software.

Table 7-4. Benchmarking FEM software.

	Industrial software	ANSYS	free software
Design tools	Yes	Yes	Yes
Surface elements design	Yes	Yes	Yes
Solid elements design	Yes	Yes	Yes
Geometry import	Yes	Yes	Yes

Second order elements	No	Yes	Yes
Local mesh control	Yes	Yes	No
Types of loads available	5	15	2
Boundary conditions available	3	7	4
Physical material properties	10	+50	4
Contacts creation	Automatic	Automatic	Manual
2d analysis	Yes	Yes	Yes
3d analysis	Yes	Yes	Yes
Types of analysis available	3	+20	1
Reports available	Yes	Yes	No
Price	100%	400%	Free

Table 7-5.Time in activities for each simulation.

	Pre-processing	Processing	Run Time
Industrial software	20 min	30 min	2 hours
ANSYS	20 min	30 min	1.5 hours
Free software	4 hours	50 min	4 hours

ANSYS, being a software specialized in the analysis, has simple tools for design, which is why external software is generally used to create the geometries that are then imported, except in very simple geometry that can be worked within Ansys itself.

It is a tool that also allows other types of analysis, also takes into account many physical properties of the materials, also allows an interconnection of data from different simulations, which allows to quickly prepare different simulations that use the same information as geometry or physical properties, but also make several simple simulations and obtain a result that could be performed with a special simulation, which can be more complicated to prepare and can take more processing time.

The mesh process in ANSYS allows to create a mesh that is more suitable for geometry and for which you do not want to obtain results, thanks to its meshing tools, where with the other software very limited mesh sizes.

It has the advantage of being able to obtain different results, processing is faster, if you need fast simulations, but can also get a more complete simulation with all results.

So, of the 3 simulation tools, Ansys is the most appropriate tool since it allows obtaining results closer to reality since it is the most complete, quickest and with easiest data analysis of the simulation.

7.3 Conclusions

The 3D design of elements of the assembly cell was created. The conveyor was created in aluminum profile, with a system that allows a correct assembly of the automotive glass.

The systems for the cell loading process allow to load the glass with constant position for the assembly process and the system of rotation of the cart allows the application task of the primer, besides allowing to perform the inspection task.

The implementation of the assembly cell was achieved using a tool for the assembly of the bracket. The cell allowed to reduce the space used in the process of assembly of automotive glass, in addition the cycle times of the manual assembly process were maintained.

The tool for the assembly of the proposed elements was designed.

Three tools with different profiles were created, which complied with the mass restrictions and the center of gravity of the robot. The results of the analyzes indicated that the 3 tools would resist the assembly task. The tool of economic profile was selected as the tool to be used in the cell, this election achieved the required savings in the costs of the materials.

In the software benchmarking for FEA, ANSYS turned out to be the best performance and easier to work with. Allowing quick and easy analysis to configure and with shorter processing times.

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