INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
MESTRADO EM ENGENHARIA MECÂNICA




EcoGrip: Developing sustainable gripper solutions for collaborative robotics

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outubro de 2025

POLITÉCNICO
DO PORTO

EcoGrip: Developing sustainable gripper solutions for collaborative robotics

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Dissertation to fulfil the requirements to obtain the Master degree in Mechanical Engineering, with a specialization in Mechanical Constructions

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Porto, september 2025

Acknowledgments

The completion of this dissertation was only possible with the support, guidance, and encouragement of several individuals and institutions, to whom I would like to express my sincere gratitude.

I would like to begin by expressing my gratitude to the host institution, INEGI, for providing me with the opportunity to enrol in a curricular internship within the scope of my dissertation.

I would also like to thank Doctor Raul Campilho for his continuous guidance, expertise, and constructive feedback throughout the development of this work.

I am also grateful to Flávia Barbosa and Teresa Gonçalves from INEGI, for their support, supervision, and significant contributions provided during the course of this work and the development of supporting scientific papers. I would also like to extend my appreciation to José Barbosa for its contributions in regard to gripper model development and ensuring its structural integrity.

My appreciation is further extended to Filipe Pinto, from INEGI, responsible for the printing of components, and to Diana Martins, from INEGI, for her assistance with the control of the collaborative robot. Their contributions were essential for the practical realization of this project.

I wish to also acknowledge my parents for their constant encouragement, support, and trust, which provided the foundation for my academic path.

Finally, I am grateful to my friends, whose understanding and companionship offered motivation and balance throughout this journey.

Abstract

With the intensification of competition across industries, companies are increasingly adopting strategies to secure a competitive advantage. One such approach is the growing integration of robots into factories to optimize operations and enhance efficiency. However, this shift also results in workforce reductions. For that reason, organizations and policy makers are increasingly tasked with balancing technological advancement and the preservation of employment opportunities. This practice has led to the adoption of collaborative robots, and the development of robotic grippers for collaborative applications which are designed with safety in mind. On the other hand, a completely different topic that influences gripper design is the European Union's Ecodesign for Sustainable Products Regulation. This regulation aims to reduce the environmental impact of products during the entirety of its lifecycle. Together, the need to enhance gripper safety for collaborative operations and the imperative to reduce their environmental impact have resulted in the demand for a new approach to the gripper development process. With this goal in mind, the objective of this dissertation is to create a methodology for the development of a collaborative robotic gripper that integrates Ecodesign principles to be employed in a practical use case. This use case proposes the creation of a vacuum based collaborative robotic gripper with four suction cups, capable of handling boxes of up to 10 kg with both 150 and 550 mm edge size. To have this capability, the gripper must be adjustable in the X-axis. In regard to weight, the gripper should weigh less than 1.5 kg and be fabricated using acrylonitrile styrene acrylate or polylactic acid. An important design characteristic was that access to the internal components of the gripper should be simple. Through the study of peer-reviewed scientific papers and also an analysis of existing gripper engineering solutions, the new methodological approach for gripper development was formulated. It encompasses six phases: Product planning, Product concept, Product architecture, Product detail, Product Prototyping, and Product testing and improvement. During the course of this work, a model is conceptualized that responds to the use case, safety, and Ecodesign requirements. The developed design is validated through numerical simulations. After validation, a physical prototype is fabricated and tested using additive manufacturing to assess its functionality and performance. The results of these tests also resulted in the creation of an improved prototype. The developed prototype was validated as a proof-of-concept, which demonstrated that Ecodesign requirements could be fully integrated into the gripper development process without compromising functionality or safety.

KEYWORDS: Collaborative robots, Robotic gripper, Human-robot collaboration, Ecodesign, Mechanical project.

Resumo

Com a intensificação da competição entre indústrias, as empresas têm vindo a adotar estratégias para assegurar uma vantagem competitiva. Uma dessas abordagens é a crescente integração de robôs nas fábricas, de modo a otimizar operações e aumentar a eficiência. No entanto, esta mudança conduz também a reduções na força de trabalho. Por essa razão, as organizações e os decisores políticos são cada vez mais desafiados a equilibrar o avanço tecnológico com a preservação de empregos. Esta prática conduziu à adoção de robôs colaborativos e ao desenvolvimento de garras robóticas para aplicações colaborativas, ambos concebidos com a segurança em mente. Por outro lado, um tema completamente distinto que influencia o design das garras é o regulamento da União Europeia sobre Ecodesign para produtos sustentáveis, que visa reduzir o impacto Ambiental dos produtos ao longo de todo o seu ciclo de vida. Em conjunto, a necessidade de melhorar a segurança das garras para operações colaborativas e o imperativo de reduzir o seu impacto Ambiental geraram a necessidade de uma nova abordagem no processo de desenvolvimento de garras. Considerando esta necessidade, a presente dissertação tem como objetivo criar uma metodologia para o desenvolvimento uma garra robótica que integre os princípios de Ecodesign, a ser aplicada e testada em um caso de estudo prático. Este caso de estudo propõe a criação de uma garra robótica colaborativa que funcionasse através de vácuo, com quatro ventosas, capaz de manipular caixas de até 10 kg com dimensões laterais de 150 e 550 mm. Para garantir esta capacidade, a garra deverá ser ajustável no eixo X. Relativamente ao peso, a garra deverá pesar menos de 1,5 kg e ser fabricada recorrendo a acrilonitrilo estireno acrilato ou ácido poliláctico. Uma característica importante para o design é que o acesso aos componentes internos da garra deve ser simples. Através do estudo de artigos científicos e da análise de soluções de engenharia aplicadas em garras existentes, foi formulada uma nova abordagem metodológica para o desenvolvimento de garras. Esta metodologia abrange seis fases: Planeamento de produto, Conceito de produto, arquitetura do produto, detalhe do produto, prototipagem do produto, e testagem e melhoramento do produto. No decorrer deste trabalho, foi conceptualizado um modelo que responde ao caso de estudo, aos requisitos de segurança, e aos princípios de Ecodesign. O design desenvolvido foi validado através de simulações numéricas. Após validação, foi fabricado um protótipo físico através de fabrico aditivo que foi também testado de forma a avaliar a sua funcionalidade e desempenho. Os resultados destes testes conduziram também à criação de um protótipo aprimorado. O protótipo que foi desenvolvido e testado foi validado como prova de conceito, já que demonstrou que os requisitos de Ecodesign podem ser totalmente integrados no processo de desenvolvimento de garras sem comprometer a funcionalidade ou a segurança.

PALAVRAS-CHAVE: Robô colaborativo, garras robóticas, colaboração robô-humano, conceção ecológica, projeto mecânico.

Index

Figures Index

Tables Index

Acronyms and Symbols

Acronyms

AM	Additive manufacturing
ABS	Acrylonitrile butadiene styrene
ASA	Acrylonitrile Styrene Acrylate
BESO	Bi-directional evolutionary structural optimization
CAD	Computer aided design
CAE	Computer aided engineering
CEAP	Circular economy action plan
CR	Collaborative robotics
DfX	Design-for-eXcellence
EGD	European green deal
ESPR	Ecodesign for sustainable products regulation
FDM	Fused deposition modelling
FEM	Finite element method
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
LCA	Life cycle assessment
MAM	Metal additive manufacturing
MOCA's	Mobile collaborative assistants
MSM	Multi-layer stream mapping
PD	Product development
PCL	Polycaprolactone
PET	Polyethylene terephthalate
PLA	Polylactic acid
TPU	Polyurethane
TO	Topology optimization
X-FEM	Extended finite element method

Symbols

a	Acceleration	$\mathrm{m/s^2}$
μ	Coefficient of friction	-
g	Gravitational acceleration	$\mathrm{m/s^2}$
m	Mass	kg
S	Safety factor	-

1. Introduction

1.1. Contextualization

Since the early days of the robotics industry, the goal has been to improve process efficiency in factories. For that reason, when robots first began to be deployed, they were primarily designed to replace workers in repetitive and/or hazardous tasks, such as box palletization (Dmytriyev et al., 2024). Thus, this technological change often led to workforce reduction, as employees were fired due to automation taking over their roles.

The introduction of the Industry 5.0 framework marked a paradigm shift, as robots are now expected to be deployed in factories alongside humans, instead of replacing them (Al Mubarak, 2023). To support this shift, collaborative robots (cobots) are instead developed to enable a safe human-robot collaboration in factories (IFR, 2023). However, ensuring worker safety extends beyond just the robot in itself, as robotic grippers, which allow object manipulation, also pose a safety risk. For that reason, there has been a continuous effort to develop grippers that are specially designed to be paired with cobots. These grippers are characterized by the use of rounded edges, which is a method proposed by the ISO/TS 15066 which regulates the safety of cobots (ISO, 2016).

Currently, when developing a product, including a robotic gripper, it is also very important to consider its environmental impact. For years, this factor has been a focal point of discussion in the European Union (EU). The recent commitment made by the member states to turn the union climate neutral in 2050 has led to an introduction of new regulations that focus on the creation of a circular economy. One of these, the Regulation 2024/1781, is known as Ecodesign for sustainable Products Regulation (ESPR), and aims to diminish the environmental impact of products during their lifecycle (Regulation 2024/1781, 2024).With the recent release of Ecodesign regulations, only a limited number of collaborative robotic grippers, that can be used for palletization processes, are available on the market. Additionally, they do not fully embrace Ecodesign considerations. For example, the modular gripper system PXT (Schmalz, 2024f) sold by Schmalz achieves certain Ecodesign goals through its modularity but does not use sustainable manufacturing processes and materials. The Schmalz area gripping systems FMCB (Schmalz, 2024a) is rated for collaborative applications, yet it lacks any Ecodesign features. The Schmalz lightweight gripping systems SLG (Schmalz, 2024e) embraces Ecodesign by being additively manufactured and using a recyclable material but , it is not modular.

In this context, the work to be presented in this dissertation is significant as it will address the dual challenge of ensuring functionality and safe human-robot collaboration, while incorporating the highest possible number of Ecodesign principles, which remains a relatively recent approach that has not yet been fully applied in market solutions for robotic grippers. This makes its study particularly relevant within the broader transition to a more environmentally responsible robotics industry.

1.2. Objectives

This dissertation seeks to present the structured development process of a sustainable robotic gripper designed for integration with a cobot used in cardboard box palletization tasks. To achieve the main goal, this dissertation will pursue specific objectives:

a) The development of a methodology for the development of robotic grippers based on Ecodesign principles;

b) The conceptualization of a model that responds to the requirements of the use case company, Ecodesign, and safety standards;

c) The design of a lightweight solution validated by numerical simulations;

d) The construction of the prototype using additive manufacturing (AM);

e) Experimental validation in laboratory environment.

Following this approach, the proposed work intends to provide a scientifically based response to the following research question: How can Ecodesign principles be integrated into the development of robotic grippers for collaborative robots to minimize environmental impact while maintaining functional performance?

1.3. Structure

Introduction - In this section, the work was contextualized, the main goals of the work were mentioned, the structure of the work was explained, and the host company presented.

Literature review - This section was divided into three sub-sections. In the first sub-section, entitled “*Industrial robotics*”, the goal was to assess the major differences between traditional industrial robots and cobots, to understand the various levels of collaboration between robot and humans in factories, and to analyse relevant standards to cobot safety. Various solutions were also analysed for collaborative palletization in factories. The goal of the second sub-section was to analyse the various types of grippers on the market, identify their key attributes, determine which are most suitable for box palletization, and also analyse recent developments. Furthermore, it was essential to examine relevant standards, explore design considerations that enhance their safety for use in collaborative applications, and also to study methods to increase their sustainability. In the third sub-section, the goal was to define the most important phases of product development (PD) regarding robotic grippers, to examine the LeanDfX tool’s usefulness in design optimization and also how to interpret its results, to study the Ecodesign directive and assess its importance in the development of more sustainable products, to assess the importance of engaging in structural simulation and topological optimization, and to examine recent developments.

Collaborative robotic gripper development methodology - This section presents the methodological approach developed to create a collaborative robotic gripper that achieves the highest possible number of Ecodesign goals. The developed methodology has six phases: Product planning, Product concept, Product architecture, Product detail, Product prototyping, and Product testing and improvement. The work to be developed in each phase is also presented in this section.

Results and discussion - This section encompasses the application of the methodological approaches to obtain the final collaborative robotic gripper. It starts with the presentation of various concepts developed using the SolidWorks® software, selection of the ideal concept using a concept selection decision matrix, and evaluation using the LeanDfX software. Next, all the components of the concept were optimized, and the pneumatical material introduced to create a final functional computer aided design (CAD) model to be tested using the SolidWorks® software. With the final model created, the material to be used was selected, and the gripper structural integrity assured. This process allowed the fabrication of all components, and the consequent assembly of the collaborative robotic gripper. The physical prototype was tested in regard to functionality and performance, which allowed the identification of improvement possibilities to the design. With this information, a revised CAD model was created.

Conclusions and future work - This section explains all the conclusions retrieved from the collaborative robotic gripper development, and future works important for gripper optimization and preparation for full deployment in collaborative applications.

1.4. Scientific outputs

The work produced during the course of this dissertation as resulted in the development of three scientific papers, two conference papers and one journal paper, and one presentation in an international conference SUSTECH2025 (Sustech, 2025):

a) Optimizing product design and development through PLM tools enhanced with LeanDfX integration (T. Gonçalves et al., 2025b);

b) Integrating LeanDfX into PLM Tools to Enhance Efficiency and Effectiveness in Product Development (T. Gonçalves et al., 2025a);

c) Sustainable Product Design Strategies for Collaborative Robotics: Balancing Circularity and Functionality (Sousa et al., 2025).

1.5. Host company

The entirety of the development process of the collaborative robotic gripper presented in this dissertation was developed on a curricular internship at the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), which is a leading research and technology organization based in Porto, Portugal. Founded in 1986 as an interface institution of the

University of Porto, INEGI operates at the intersection between universities and the industry, with a strong focus on applied research, technological development, and innovation. Its areas of expertise span a wide range of sectors such as:

- Transportation;
- Automation;
- Robotics;
- Space;
- Defence;
- Infrastructure development;
- Renewable energy;
- Aeronautics;
- Health and sports;
- Additive manufacturing.

INEGI has over 350 workers, and over 120 investigators which work on a building with over 9400 m^2. Nowadays INEGI has an annual business volume in excess of 20 million euros, which derive from a client base of over 700 organizations, including over 400 international partners. Owing to its strong academic orientation, INEGI records an average of 3.2 scientific articles per researcher, as well as 1.8 PhD supervised theses per researcher. INEGI's strong culture of innovation and applied research has also led to the creation of 6 spin-off companies. These ventures embody the institute's ability to transform scientific knowledge into market-ready solutions. INEGI's mission is to contribute to the advancement of industrial competitiveness and the economy while also contributing to the personal and professional development of its workers. As for its vision, they aim to grow and become the best converter of knowledge into value for companies and therefore confirm its strong institutional identity as a technological partner. In regard to its values, they are as follow:

- Costumer orientation;
- Responsibility;
- Passion for innovation;
- Cooperation;
- Ambition.

As for INEGI's organizational structure, it rests on three main pillars, which are:

- Research and development;
- Innovation and technology transfer;
- Consulting and technical services.

To finish, it is also important to mention that INEGI is part of LAETA (*Laboratório Associado de Energia, Transportes e Aeroespacial*), which incorporates several research groups that address societal challenges and research and development priorities.

2. Literature review

2.1. Industrial robotics

In this section, an introduction to robotics is presented starting from the first robot to the industrial application of collaborative robots (cobots). Next, the field of CR and respective standards is introduced. To finish, the influence of robots in the palletization process is discussed and some collaborative palletization solutions described.

2.1.1. Introduction to robotics

After the introduction of assembly line automation in the 1940s, reducing assembly times became a focal point of attention. This situation led to the creation of the first industrial robot, the *Unimate*, developed by George Devol and Joseph Engelberger in 1961 (Detesan & Moholea, 2024). The *Unimate* was first used to grab castings in a General Motors assembly plant (Marsh, 2022), and sparked a revolution that led to the employment of automation and robotics in various industrial applications (Detesan & Moholea, 2024). According to the ISO 8373:2021 standard, entitled "*Robotics-Vocabulary*", an industrial robot is an "*automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or fixed to a mobile platform for use in automation applications in an industrial environment*" (ISO,2021). The industrial implementation of these robots promotes cost reduction, quality improvement, easier adaptation to demand changes, and improvement of resource and energy efficiency (IFR, 2023). Figure 1 illustrates the evolution of industrial robot presence in factories, from about one million in 2013 to a record of over four million in 2023.

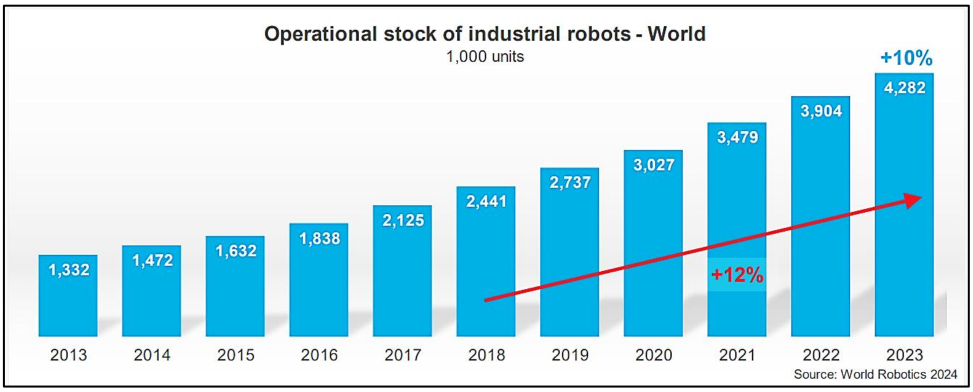


Figure 1 - Evolution of robot presence in factories worldwide (IFR, 2024)

With the implementation of the Industry 4.0 framework, which focusses on the technological evolution of manufacturing, the use of traditional industrial robots has increased. However, this paradigm shift led to the issue of technology replacing humans instead of assisting them. The Industry 5.0 framework tries to fix this limitation by focussing on technology helping humans (Al Mubarak, 2023). One technology that is used to help humans instead of replacing them are collaborative robots (cobots), which are able to work alongside humans (IFR, 2023), and perpetuate the combination of robot precision, repeatability, and resistance with human mental capacity and expertise (Hameed et al., 2023; Othman & Yang, 2023). Figure 2 is a representation of two palletization robots. The first image depicts a KR QUANTEC PA traditional industrial robot (a), and the second image is a representation of a LBR iisy cobot (b).

a) 

b) 

Figure 2 - Palletization robots: KR QUANTEC PA traditional industrial robot (a), and LBR iisy cobot (b) (KUKA, 2024)

The cobot market has steadily increased over the years, but it still represents a fraction of the total number of industrial robot installations. Actually, in 2023, the proportion between cobots and traditional industrial robot installations has decreased. Figure 3 represents the proportion between cobots and traditional industrial robot installations, between 2017 and 2023.

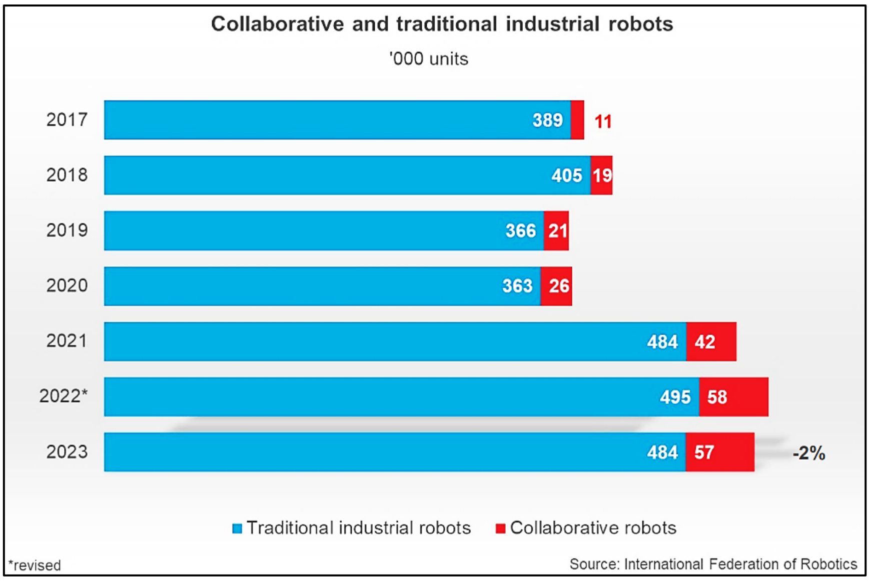


Figure 3 - Proportion of collaborative and traditional robot installations over the years (IFR, 2024)

2.1.2. Collaborative robotics and standards

Collaborative robotics (CR) is a field that plays a major role in the implementation of the Industry 5.0 framework in factories, and it focusses on the idea of humans and robots working safely together, without safety fences and in the same workspace, aiming to improve productivity by reducing production times (Othman & Yang, 2023; Zafar et al., 2024). CR implies the use of cobots, which differ significantly from traditional industrial robots. Table 1 summarizes the major differences between these two types of robots.

Table 1 - Differences between traditional industrial robots and collaborative robots (adapted from Kumar et al., 2024)

Characteristic	Traditional industrial robot	Collaborative robot
Human proximity	Prohibited	Allowed with application of safety procedures
Workspace	Isolated	Shared
Safety barrier	Physical fence	Sensorial safety mechanisms
Robot footprint	Large due to protections	Small to facilitate collaboration
Structure	Heavy and stiff	Light and easy to move
Payload	Medium to high	Low to medium
Programming	Before task	Before and during task

Cobots can be utilized to perform a wide range of tasks across various industries, as depicted in Figure 4.

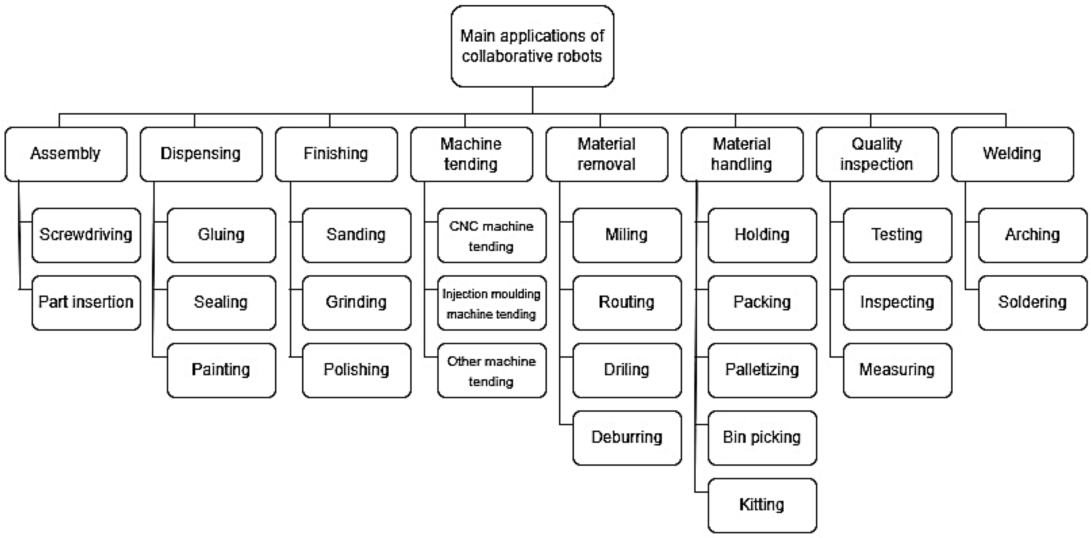


Figure 4 - Tasks performed by collaborative robots (adapted from Montini et al., 2024)

Due to the continuous evolution of the cobot market, in 2016, the standard ISO/TS 15066, entitled *"Robots and robotic devices - Collaborative robots"*, was created as a supplement to the ISO 10218 standard, "*Robots and robotic devices-Safety requirements for industrial robots*" (ISO, 2016). Nowadays, the ISO/TS 15066 standard is the reference for cobots, as it specifies guidelines for the introduction of passive and active safety procedures (Chemweno et al., 2020;

Mariscal et al., 2024). Cobots are characterized by their smooth round edges, and the absence of sharp edges, which facilitate their safe use in a collaborative workspace (Faccio et al., 2023). According to the ISO/TS 15066 standard, the collaborative workspace is a “*space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation*” (ISO, 2016). Figure 5 illustrates the robot workspace, the human workspace, and their overlapping which is known as shared workspace or collaborative workspace.

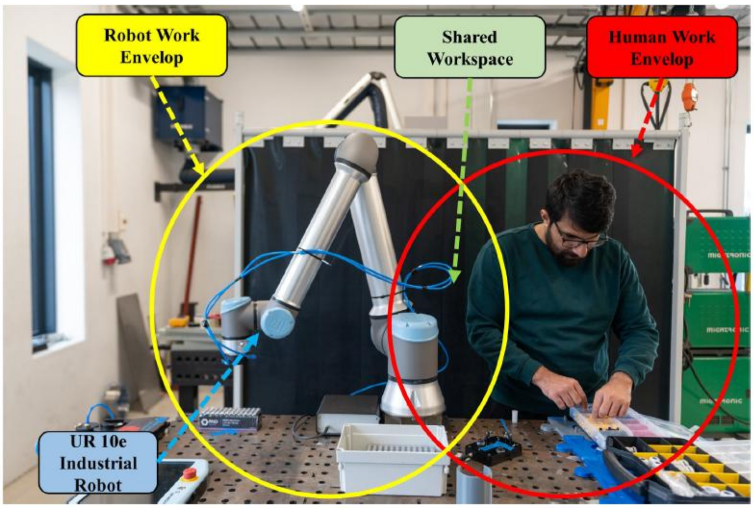


Figure 5 - Representation of a collaborative workspace (Zafar et al., 2024)

However, using a cobot to complete tasks and not considering a safety barrier, or even the existence of a collaborative workspace, are not sufficient to guarantee a full collaboration between human and robot (Montini et al., 2024). Figure 6 specifies the five different possibilities of human-robot interaction in the workspace, and the differences between them.

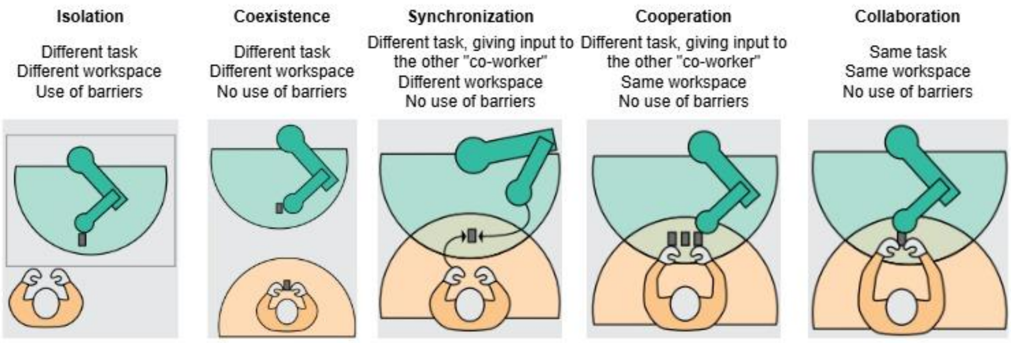


Figure 6 - Human robot interaction in the workspace (adapted from Bauer et al., 2016; Benos et al., 2022)

A problem created by the increased level of collaboration between the human and robot is the augmentation of the safety risks that workers are exposed to. For this reason, to guarantee that there is a safe interaction between the human and robot, the ISO/TS 15066 standard defined four methodologies that may be implemented individually or as a combined approach to increase the workplace safety for workers. These methodologies are presented and described in Table 2.

Table 2 - Methods for the safe implementation of a collaborative operation (Benos et al., 2020;ISO, 2016; Zafar et al., 2024)

Methodology	Description
Safety-rated monitored stop	The collaborative robot is in motion until an operator enters the collaborative workspace, which allows a software to trigger a safety-rated monitored stop that forces the robot to stop. Next, the operator completes the robot's work in the collaborative workspace. When the operator exits this space, the safety-rated monitored stop is deactivated, and the robot resumes its motion without worker intervention. If this methodology is applied, most of the time, the robot and the human end up working non-collaboratively.
Hand guiding	The worker physically guides the robot arm to complete tasks. To accomplish this task, the worker performs a safety-rated monitored stop that allows him to enter the collaborative workspace. Then, the safety-rated monitored stop is deactivated, and the hand guiding of the robotic arm, by the worker, begins. When the collaboration is finished, the safety-rated monitored stop is activated allowing the worker to leave the collaborative workspace, and the robot to resume its motion.
Speed and separation monitoring	This method relies on the use of sensors and cameras that control the distance between the worker and the robot while also measuring their speeds. When a safety risk is present, the robot system stops, and only restarts when the worker safety is guaranteed. The safe distance between the worker and the robot varies depending on robot speed.
Power and force limiting	The power and force limiting method also relies in the use of sensors. However, these monitor the physical interaction between the worker and robot. An algorithm analyses the workers input and controls the robot's power accordingly. For the effective implementation of this methodology, it is important for the algorithm to know what normal and not normal contact between worker and robot is.

Even though the usage of cobots has increased over the years, there are still a handful of challenges that block the mainstream application of CR in factories. In their work, Montini et al., (2024) identified, as implementation blockers, the high acquisition prices, the need for even higher flexibility to adapt to various working conditions, the safety concerns, the cost of retrofitting factories, the unproven impact of cobots, the cobots low dexterity and their rigid behaviour. Additionally, for companies, it is much easier for robots and humans to be separated by safety fences, as it avoids the occurrence of human and robot collisions that may cause injuries and create legal issues (Cairnes et al., 2023). All the aforementioned reasons that still hinder the widespread adoption of cobots in factories reinforce the need to develop increasingly safer and more adaptable cobots that can be seamlessly integrated in various industrial environments. To achieve these goals, Montini et al., (2024) suggests that there is a need to develop more technically advanced cobots capable of accurately assessing worker behaviour and act accordingly to avoid collisions, therefore, enhancing the collaboration between human and robot. Additionally, the authors emphasize that more research must be conducted on the creation of collaborative solutions for key areas of industrial interest, such as material handling.

2.1.3. Collaborative palletization solutions

According to Dmytriyev et al., (2024), palletizing can be defined as "*the process of arranging products onto pallets for efficient storage and transportation*". This task is considered as an end-of-line manufacturing process, and it has upmost importance in the implementation of the Industry 5.0 framework. However, palletizing is usually carried out by traditional robots (Dmytriyev et al., 2024). For that reason, it is important to develop collaborative solutions that increase versatility, and can reduce costs and minimize the palletization footprint in factories (Dmytriyev et al., 2024).

The palletization process is very repetitive. Additionally, the palletized products are usually the same. Although traditional robots are ideal in this scenario, often the palettized products are different, which augments the process complexity, perpetuating the need for cobots, in an attempt to simplify the process. The idea of using cobots in palletization tasks is very recent, which means that there are only few studies on its application (Pantoja-Benavides et al., 2024). One example of the use of cobots in palletization was developed by Lamon et al., (2020). These authors proposed the concept of Mobile Collaborative Assistants (MOCAs), which were able to move freely in the factory floor, while helping workers in the palletization process. MOCAs work in three different modes. As depicted in Figure 7, in mode A, they work non collaboratively, in mode B the MOCA picks a box and hands it to a worker to place it in a pallet, and in mode C there is full collaboration between MOCAs and human as they both grab the box simultaneously and place it in a pallet. This mode is necessary for picking heavy loads.

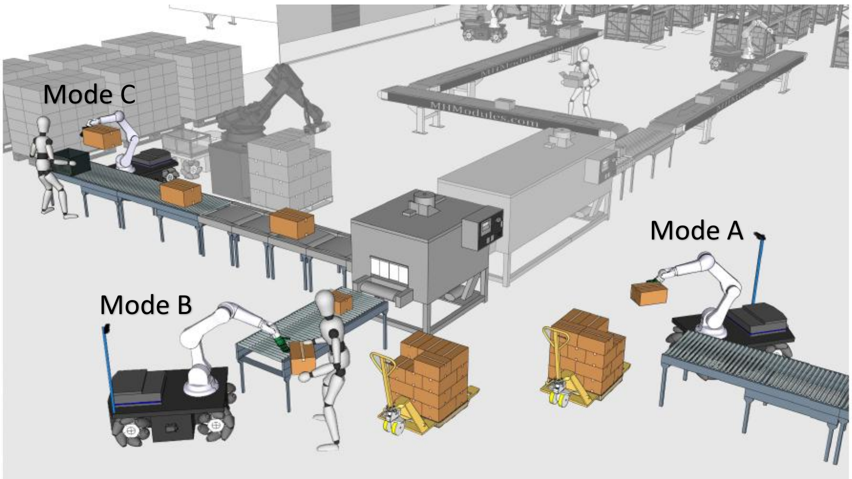


Figure 7 - MOCAs and humans working together in a factory (adapted from Lamon et al., 2020)

Baptista et al., (2024) used a different approach. The authors developed a solution using a stationary cobot inside a cell. This cell, pictured in Figure 8, still allows workers to engage with the cobot easily. However, additionally cameras and sensors can be mounted to the cell. In the authors' work, the cameras and sensors were used to enable gesture recognition. Thereby, in this solution, the worker was able to utilize gestures to instruct the cobot about the operations to carry out while the worker is in the collaborative workspace. However, a disadvantage of this work was the low level of human-robot interaction, as the worker would only engage with the cobot to grab the product from him and inspect it. After inspecting the product, the worker would place it in a prespecified spot and order the robot to grasp it again while continuing his job non collaboratively.

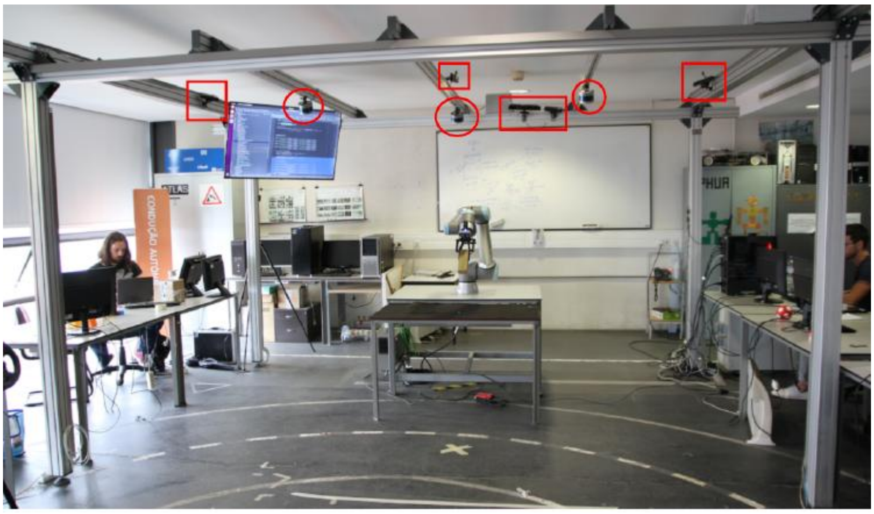


Figure 8 - Cobot inside the cell (Baptista et al., 2024)

Both mentioned solutions were never tested in a factory floor. However, there are some robotics companies that produce collaborative palletization solutions to be implemented in industrial environments. One example of a collaborative palletization solution ,which was implemented by Universal Robots, took place in the Unilever factory in Poland (UR, 2024a), where six cobots were deployed to help in tea packaging and palletization. After testing, it was concluded that cobots allowed a 30 % reduction of the workers tasks and liberated them from cumbersome movements such as bending to place boxes. Universal Robots has also developed a collaborative palletization solution for Nortura (UR, 2024b), which is a meat production company. In this case, due to the small space available, a camera was mounted in the ceiling above the cobot. This camera was able to recognize when an empty pallet was placed near the robot, and also to detect when a box was ready to be palletized, which allowed the cobot to start palletizing automatically. The major advantage of this solution was that, when there was no palletization occurring, it only required 0,5 m^2 of space, which liberated the space to be used for other tasks. The solutions deployed by Universal Robots are characterized by the low level of collaboration between worker and cobot, as the palletization process is automatic and does not require the workers help. Additionally, in both the Unilever and the Nortura solutions, the workers were reallocated to accomplish other tasks, instead of them still taking part in the palletization process (UR, 2024a, 2024b). A different company that also sells collaborative palletization solutions is Warsonco, which is based in China, but has developed solutions for companies such as Pepsico and Nestlé (WARSONCO, 2024). Their solutions are capable of handling boxes of up to 55 kg and offer easy reconfigurability. This capability gives workers the possibility to inform the system about pallet size, the different sizes of boxes to be handled, and box positioning in each layer of the pallet. However, similarly to the Universal Robots solutions, these systems can perform the palletization process without the need for worker assistance. Another company which produces systems for collaborative palletization is OnRobot. Their system, D:PLOY, stands out for its ease of implementation, with setup times up to 90 % faster than other solutions, mainly due to not requiring any programming (OnRobot, 2024a).

2.2. Robot handling solutions

This section introduces and compares various types of grippers based on the methods used to grasp objects and the driving forces that allow the gripper system to function. Next, the standards regarding gripper safety and development are mentioned, followed by an explanation about project decisions that improve gripper safety and sustainability. To conclude, relevant works in the gripper development field are described.

2.2.1. Industrial grippers and applications

A robotic gripper is a manipulator mounted at the end of the robotic arm, which enables robots to mimic human tasks, such as picking and moving objects (Arulkirubakaran et al., 2022). With the increasing levels of automation in industries, gripper's research and development has faced a continuous evolution over the last ten years, which in turn has allowed the robotic grasping field to become a billion-dollar industry (Cortinovis et al., 2023; Cramer et al., 2024). In factories, robots can be deployed to accomplish a wide range of tasks. For that reason, it is of upmost importance to choose the ideal gripper for a specific application. However, due to the enormous gripper solutions available on the market, the selection process becomes highly challenging. The first consideration to make when choosing a gripper is to study the object to be manipulated, and the task to be accomplished, while also focussing on avoiding the over-dimensioning of the gripping system (Cramer et al., 2024). Factors such as the shape, weight, stiffness, and material of the manipulated object, have great influence on gripper selection (Engelen et al., 2024; Samadikhoshkho et al., 2019). For that reason, it is very important to categorize grippers based on the method used to grasp objects. In this regard, grippers can be broadly categorized into four families, as depicted in Table 3.

Table 3- Gripper families and characteristics (Cramer et al., 2024; Sithiwichankit & Chanchareon, 2023; Zhou et al., 2021)

Gripping method	Description
Impactive	Impactive grippers use pinch mechanisms that apply contact forces to grasp objects, and function in a way that mimics the human hand.
Astrictive	Astrictive grippers make use of a force field that enables object manipulation.
Ingressive	Ingressive grippers grasp objects by physically perforating them, essentially working as hooks.
Contigutive	Contigutive grippers perform object manipulation by using adhesion.

In the industry, the most commonly used grippers are impactive or astrictive grippers (Sithiwichankit & Chanchareon, 2023). In Figure 9, a three-finger gripper (a) and a two-finger gripper (b), both impactive grippers, are shown alongside a vacuum gripper (c) and a magnetic gripper (d), which are categorized as astrictive grippers.

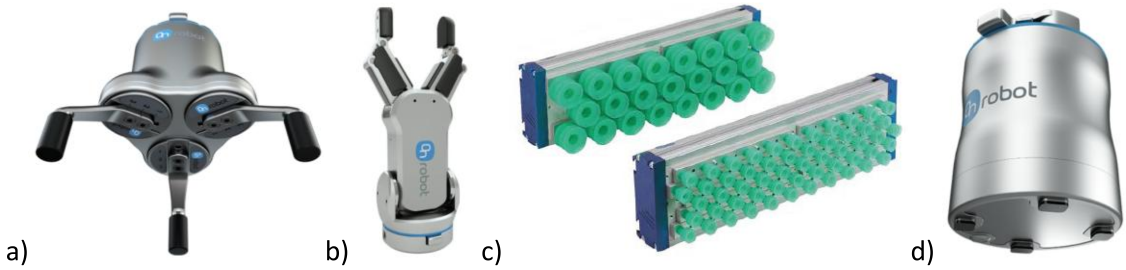


Figure 9 - Examples of impactive and astrictive grippers: three-finger gripper (OnRobot, 2024b) (a), two finger gripper (OnRobot, 2024c) (b), vacuum gripper (Schmalz, 2015) (c), and magnetic gripper (OnRobot, 2024d) (d)

Two finger impactive grippers are the simplest type of gripper available on the market due to its low price and versatility. However, sometimes, there is a need to execute tasks that demand higher accuracy and precision from robots. In this situation, three fingered impactive grippers are used as they diminish the risk of damaging the grasped object and, additionally, can adjust to more complex shapes (Aoyagi et al., 2020; Samadikhoshkho et al., 2019). Impactive grippers may rely on electrical, pneumatic, or hydraulic power to open and close their grips, and handle objects (Ivanov et al., 2024). However, in the industry, the most common drive forces are electrical and pneumatic (Zhang et al., 2020). Table 4 summarizes the drive methods used for impactive grippers, and their main advantages.

Table 4 - Drive force methods for impactive grippers and their main advantages (Ivanov et al., 2024)

Drive method	Main characteristics
Electrical power	• Efficiency • Movement accuracy • Controllability
Pneumatical power	• Resistance to dirt • Cost • Resistance to hazardous environments
Hydraulic power	• Force-to-weight ratio • Resistance to dirt

In regard to astrictive grippers, such as vacuum grippers and magnetic grippers, these are both characterized by their ability to handle objects with smooth or minimally undulated surfaces, such as boxes (Aoyagi et al., 2020). They also rely on larger contact areas and only come into contact with one face of the object, which differentiates them from impactive grippers. These characteristics not only reduce the risk of damaging the grasped object but also diminish the possibility of collisions occurring during the manipulation (Zhou et al., 2021; Zhu et al., 2024). Magnetic grippers, as the name suggests, are used to grasp ferromagnetic objects. Vacuum grippers, alternatively, are adequate for non-ferrous, and nonporous objects (Caldwell, 2023; Chitroda & Patle, 2023). Moreover, vacuum grippers offer robust and easy to implement handling solutions, which in turn has made them a popular option for the palletization of cardboard boxes (Caldwell, 2023; Stegmaier et al., 2023). Figure 10 is a representation of a vacuum gripper grasping cardboard boxes.

Figure 10 - Vacuum gripper grasping cardboard boxes (Schmalz, 2015)

The working principle of vacuum grippers is the difference between air pressure inside the gripper, which can be created using vacuum pumps or pistons, and the atmospheric pressure outside the gripper, which generates a force that allows object handling (UR, 2019; Wang et al., 2023). An essential component of vacuum grippers are the suction cups, which serve as the interface with the grasped object. Depending on their shape, suction cups can be defined as flat suction cups, bellows suction cups or bell shaped suction cups (Ivanov et al., 2024). Figure 11 is a representation of a flat suction cup (a), a bellows suction cup (b), and a bell-shaped suction cup (c).

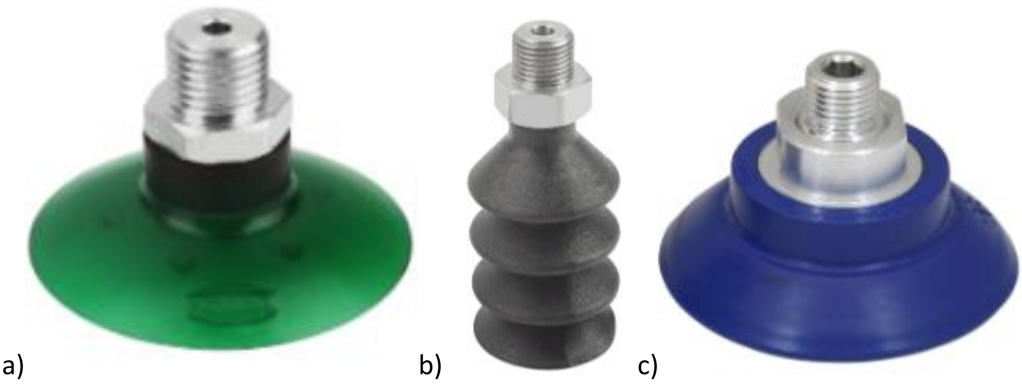
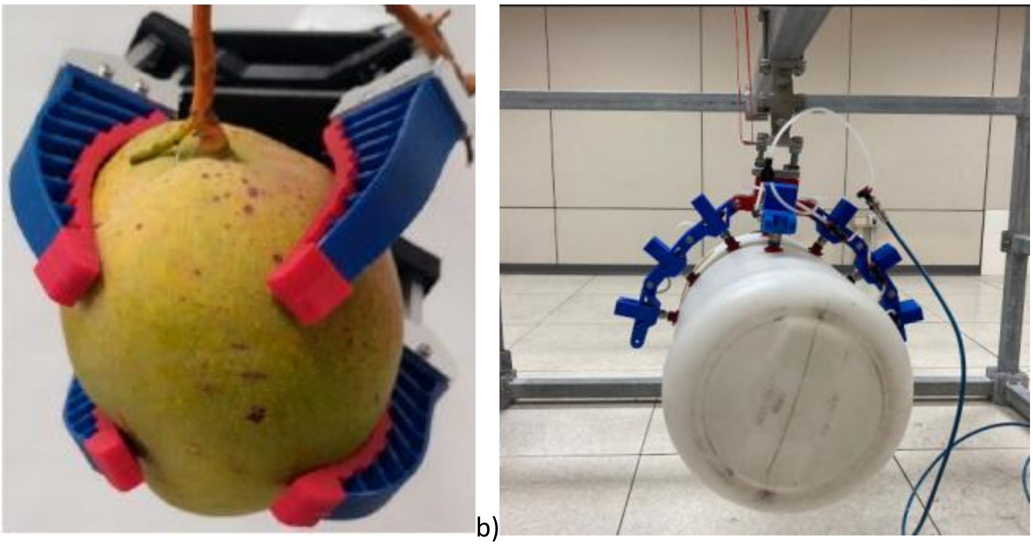


Figure 11 - Vacuum suction cups: flat suction cup (Schmalz, 2024d) (a), bellows suction cup (Schmalz, 2024c) (b), and bell-shaped suction cup (Schmalz, 2024b) (c)

Flat suction cups are most typically used to grasp flat objects such as cardboard boxes and sheet metal. Additionally they allow lower cycle times and optimal gripping forces (Ivanov et al., 2024; Schmalz, 2024d). Bellows suction cups are ideal to grasp pieces with irregular or highly curved surfaces and they also excel in the process of handling fragile objects (Schmalz, 2024c). Bell shaped suction cups are characterized by their capability to support lateral forces, which compromise the manipulation process (Schmalz, 2024b). A drawback of vacuum grippers that use vacuum pumps to compress air is their inefficiency, as only approximately 10 % of the required energy for the process is transformed in to vacuum suction that can be used to effectively grasp objects (Gabriel et al., 2020). For that reason, there have been studies on the usage of passive suction cups which function on the basis of shape alteration. In this approach, when the object touches the suction cup, air is expelled, which forms a suction force that grasps the object. This methodology is much more efficient as it does not require the use of pumps. However, it does create safety risks, as the lack of pumps means that a pressure increase, which can happen due to leaks, cannot be compensated (Wang et al., 2023). However, Kuolt et al., (2021) developed a passive suction cup that was designed to also function with the help of a vacuum pump, which would only be activated when there were leakages or when there was a need to grasp heavier objects that could not be handled passively. According to the authors, this solution would allow energy consumption to be reduced by 20 %.

Recent developments in the robotic gripper field have led to the introduction of soft grippers which, due to their soft characteristics and lack of sharp edges, can improve the safety of human-robot collaboration in factory environments (AboZaid et al., 2024; Xie et al., 2023). The soft materials utilized for instance in the fingers of this type of gripper allow the component to possess an unlimited amount of degrees of freedom (AboZaid et al., 2024). Additionally, soft grippers do not require the same number of joints and actuators when compared with rigid grippers. For this reason, soft grippers have also been classified as underactuated grippers (Zappatore et al., 2017). Moreover, when compared to rigid grippers, soft grippers are lighter, more compact, more energy efficient, and can easily adapt to various shapes without damaging the grasped object (Xu et al., 2024). The soft properties that characterize this type of gripper have been mostly utilized in impactive grippers. However, Maggi et al., (2022) has developed an astrictive gripper that does not fall under the soft gripper category, but it possesses the same levels of adaptability to various shapes, and is also underactuated. In Figure 12 it is possible to observe an impactive soft gripper handling a mango fruit, which is very fragile, and also the astrictive gripper developed by Maggi et al., (2022) conforming to the shape of a bin.



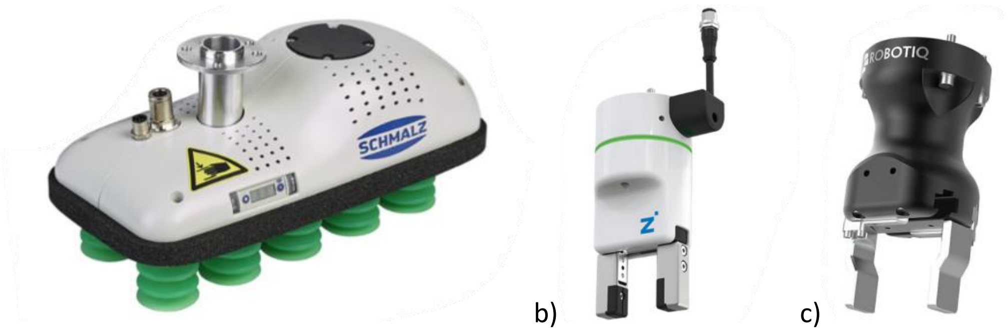
a) b)

Figure 12 - Soft gripper manipulating a mango fruit (Goulart et al., 2023) (a), and an adaptive gripper grasping a bin (Maggi et al., 2023) (b)

In regard to the methods used in soft impactive grippers to enable finger motion, there have been studies on the use of pneumatic actuation, cable actuation, mechanical gears activated by motors, shape memory polymers (which change their shape when exposed to temperature variations), and even magnetic materials who respond to changes in magnetic fields (Blanco et al., 2024).

2.2.2. Global standards and safety requirements

As previously mentioned in this work, the use of cobots in factories augments the safety risks that workers are exposed to. These risks can arise not only from the robotic arm but also from the gripper. Therefore, it is crucial to study the standards that refer to the safety of robotic systems, as these can be also applied to robotic grippers (Cairnes et al., 2023). The ISO/TS 15066 standard (ISO, 2016) recommends some passive safety measures that can be applied to collaborative robotic systems, including robotic grippers, to improve worker safety. One approach involves increasing the surface area of components through the design of rounded and smooth surfaces. Figure 13 shows an astrictive vacuum gripper (a), and two impactive grippers (b and c), with rounded and smooth surfaces due to having been designed in accordance with the recommendations mentioned in the ISO/TS 15066 standard (ISO, 2016).



a) b) c)

Figure 13 - Grippers designed according to the ISO/TS 15066 standard: area gripping concept (Schmalz, 2024a) (a), jaw parallel gripper (Zimmer, 2024) (b), and Hand-E gripper (UR, 2024b) (c)

Additionally, the standard also suggests the option of improving the components' capability to absorb energy that stems from impacts. This goal can be accomplished by equipping grippers with padding, or by using materials that can deform when impacted (ISO, 2016). Other standards can be followed when developing grippers, which are not only related to robotic system safety, but also to consider design aspects. Table 5 summarizes these standards and scope.

Table 5 - Important standards to be considered when developing grippers

Standard	Scope
ISO 10218:2011	The ISO 10218:2011 entitled "*Robots and robotic devices — Safety requirements for industrial robots"* has two parts. Part one refers safety risks associated with the usage of industrial robots in factories and identifies methods that can be used to reduce or eliminate them (ISO, 2011a). Part two mentions important safety requirements that must be considered when designing, manufacturing, installing, operating, and maintaining the components of a robotic cell (ISO, 2011b).
ISO 12100:2010	This standard refers to the "*Safety of machinery-general principles for design-risk assessment and risk reduction*" mentions strategies that can be used to assess risks and how to reduce them, and also refers measures that can be applied to design safe machines (ISO, 2010).

Table 5 - Important standards to be considered when developing grippers (continued)

ISO/TR 20218-1:2018	The ISO/TR 20218-1:2018 technical report entitled "*Robotics-safety design for industrial robot systems-part 1: end effectors*" mentions safety measures to be considered during manufacturing, design, and integration of end effectors, such as grippers. Serving as a complement to the ISO 10218-2:2011 standard (ISO, 2018).
ISO 14539:2000	The ISO 14539:2000 entitled "*Manipulating industrial robots-object handling with grasp-type grippers-vocabulary and presentation of characteristics*" presents and explains a number of important nomenclatures for grasp-type grippers (ISO, 2000).
ISO 9409-1:2004	The ISO 9409-1:2004 entitled "*Manipulating industrial robots-mechanical interfaces-part 1: plates*" defines the main dimensions of the base plate that serves as the connection between the gripper and the robotic arm (ISO, 2004).

2.2.3. Sustainability on gripper design

Sustainable products have been receiving greater market attention, as evidenced by consumers' willingness to pay more for them (Eurobarometer, 2024). However, due to their increasing complexity, developing and manufacturing these products has become challenging (Omidzadeh et al., 2024). For that reason, it is important to study approaches in gripper design that enhance their sustainability, such as the selection of bio-based and biodegradable materials (Achilli et al., 2023), and the usage of efficient manufacturing processes (Devito et al., 2024).

A process that has been gaining traction in the aerospace, automotive, healthcare, textile, electronics, and robotics fields is AM (Blanco et al., 2024; Devito et al., 2024; Islam et al., 2024). AM is an operation that creates products by adding consecutive layers of material, until the final shape for the product is obtained. Due to the aforementioned additive nature of AM, material waste is essentially eliminated. Additionally, the process also allows the reduction of development times, is energy efficient, can use biodegradable and recycled materials, and enables the creation of lighter products with complex geometries. All factors that contribute to its sustainable nature (Bigliardi et al., 2024; Islam et al., 2024; Kellens et al., 2017). In the production of low volume products, such as grippers, AM becomes an even more attractive solution when compared to traditional manufacturing processes (Bigliardi et al., 2024). Between the various types of AM processes that can be used, Schuh et al., (2022) found fused filament fabrication to be very efficient in the processing of recycled materials to create new products. Figure 14 represents a commercially available 3D printed vacuum gripper, characterized by its complex geometry.

Figure 14 - 3D printed vacuum gripper (Schmalz, 2024e)

In gripper design, AM has also gained increased traction due to its capability to produce various components together, as one piece, which mitigates the need to resort to subsequent joining processes, such has welding. The process of reducing the number of individual parts required to build a gripper, by joining them in building blocks (modules), is called modularization (Wei Lun Lee et al., 2023). If the number of modules is low, in addition to the reduction of assembly and disassembly times, there is also an improvement in the potential to create more cost effective solutions, with higher quality (Braileanu et al., 2023; Devito et al., 2024; Wei Lun Lee et al., 2023). Modularity also contributes to the creation of products that can be easily adapted, redesigned, customized, and reused, which in turn increases their expected operation period (Habib et al., 2023; Wei Lun Lee et al., 2023). In their work, Achilli et al., (2023) took advantage of the modularity of their gripper design to simplify the replacement of the fingers when they were damaged, which eliminates the need to replace the entire gripper. In the market, there are also modular grippers available, such as the modular gripper system PXT sold by Schmalz, which is fully customizable. This capability allows customers to choose the different modules required to build the ideal gripper for their needs. Additionally, when the gripper is no longer needed for its original intended purpose, by changing and buying new modules, customers can adapt the original gripper for a new application. Figure 15 is a representation of three different configurations of the same vacuum gripper.

Figure 15 - Three different configurations of the same vacuum gripper: configuration for profiles and pipes manipulation (a), configuration for assembly processes (b), configuration for loading and unloading pieces (c) (Schmalz, 2024f)

Another relevant factor in the development of grippers is the selection of sustainable materials. Plastics have become a common employed material for gripper manufacturing due to their low friction coefficient and wear resistance (Braileanu et al., 2023). However, the most commonly used plastics derive from fossil fuels and are not biodegradable (Achilli et al., 2023; Braileanu et al., 2023), which compromises gripper sustainability. This situation has prompted the adoption of biodegradable plastics as a material to manufacture grippers. In this regard, one biodegradable plastic that is widely employed in the robotic gripper industry is polylactic acid (PLA). PLA is a biodegradable polyester polymer that derives from natural sources such as corn starch, and it is characterized by its reduced impact on the environment when compared with more traditional plastics such as acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PET) (Braileanu et al., 2023; Natarajan et al., 2020). Additionally, PLA enables fast and high-quality 3D printing. For that reason, it has become the material of choice when manufacturing products resorting to AM (Pereira et al., 2023). Both Achilli et al., (2023) and Pereira et al., (2023) opted to use PLA for the rigid components of their grippers. In addition to PLA, other biodegradable materials have been employed in the construction of robotic grippers. Achilli et al., (2023) used polycaprolactone (PCL) as a material for the flexible joints of the gripper finger. Although PCL derives from fossil fuels, it is biodegradable, and it exerts less impact on the environment when compared with polyurethane (TPU), which is biobased and biodegradable (Achilli et al., 2023; Chambers et al., 2024). However, for instance, Pereira et al., (2023) opted to use TPU in the fingers of his gripper due to its high deformation at failure. Another possibility in gripper manufacturing is the usage of metals. A manufacturing process that can be used to produce highly complex metallic components with minimal material waste is metal additive manufacturing (MAM) (Kahhal et al., 2024). As an example, Gonçalves et al., (2023) found that using MAM to produce an industrial component reduced environmental impact by 60.5 % when compared with traditional manufacturing methods. The authors attributed this significant reduction to MAM’s ability to produce topology optimized components without resource waste.

2.2.4. State-of-the-art

Table 6 represents recent works that have contributed with important solutions to the development of the robotic gripper field.

Table 6 - State-of-the-art in gripper development

Article	Description
Achilli et al., 2023	In this work, a sustainable soft gripper was developed in accordance with the United Nations sustainable development goals, to be employed in a waste sorting facility. To achieve these goals, the authors used eco-friendly materials such as PCL for flexible joints, and PLA for rigid parts, improved the gripper modularity to ensure the easy recycling of parts, and resorted to AM. After finishing the design, the authors concluded that the developed gripper’s main attributes are its recyclability, sustainability, versatility, and cost-effectiveness.

Table 6 - State-of-the-art in gripper development (continued)

Koch et al., 2024	This study introduced DW-flex, a fully biobased and biodegradable composite which combines a gelatin-glycerol matrix with wood, creating a compliant material with relevant mechanical attributes for soft robotic grippers. In their work, the authors found that this material only took sixty days to decompose when buried in the soil, and also demonstrated that the material was capable to be used in gripper fingers, to grasp soft and complex shaped objects.
Maggi et al., 2024	In this paper, an underactuated vacuum gripper concept was developed. The underactuation allowed the gripper to conform to complex shapes, and vacuum suction cups were used to improve grasping stability. Due to the gripper possessing both fingers and vacuum suction cups, in case of vacuum failure the safety of the grasped object was always guaranteed. The authors found that this gripper solution was much more stable when compared with normal underactuated grippers.
Maggi et al., 2023	This article presented POLYPUS, an underactuated modular vacuum gripper, capable of handling various materials such as cardboard, sheet metal, and plastic. The most important characteristic of this gripper was its modularity, which enabled it to be easily reconfigured to grasp different shaped objects. After testing the gripper in various grasping conditions, the authors concluded that, to their knowledge, this was the only underactuated gripper with suction cups that was able to grasp loads of up to 2.1 kg.
Carloni et al., 2025	This paper proposed a soft gripper that combined the usage of urethane rubber for the finger structure, with custom electro-adhesion pads. After testing, the authors found that this gripper achieved holding forces similar to the ones created by a commercially available more rigid gripper, while exerting 77 % less pressure on the grasped object. Moreover, the compliance of the material used in the fingers promoted a 71 % reduction of the actuation force needed to create that same holding force, which enhanced its cost effectiveness and sustainability.
Pyo & Park, 2024	This article introduced a passive suction gripper equipped with a trigger release mechanism designed to function without the need of external power sources. This trigger mechanism was activated by the introduction of negative pressure in the system, which forced the suction cups to deform. After testing, the authors found that when the trigger was activated, it only took the gripper 0.6 seconds to release the grasped object.

2.3. Gripper design and development

In this section, various methodologies important to gripper development are presented and explained. First, the phases of PD relevant to gripper design are introduced and summarised. Next, an introduction is made on the Ecodesign framework and the requirements it proposes to increase product sustainability. Additionally, the importance of the LeanDfX tool for design evaluation and its implementation process are mentioned. Afterwards, the Finite Element Method (FEM) is delineated due to its relevance in the structural simulation field, and topology optimization (TO) is presented due to its importance in design optimization. To complete this section, recent works in the field of PD, Design-for-eXcellence (DfX) methodology, and TO in gripper development are presented.

2.3.1. Methodological design and development process

PD can be defined as "*the complete process needed to take a product from concept to market availability*" and it comprises the identification of market needs, creation of a concept for the solution, development of the product itself, presentation of the product, and evaluation of customer feedback (Lourenço et al., 2024). Given that only 30 % of developed products achieve commercial success in the market (Cooper & McCausland, 2024), effective PD becomes crucial to increase profits and to offer companies a competitive advantage in today's highly competitive markets (Lyu et al., 2024). PD is normally carried out by three different teams who work together to obtain a final product: marketing, design, and manufacturing (Ulrich & Eppinger, 2020). The major responsibility of the design team is to research and develop solutions that can be implemented to achieve a product´s defined specifications (Pahl et al., 2007). As a result, 80 % of the product's final cost stems directly from decisions made during the design process (Cukor Kirinić & Hegedić, 2023) and, furthermore, about 80 % of a product's effect on sustainability results from decisions made on this phase (Delaney et al., 2022). These aspects emphasize the need to develop new PD frameworks that focus not only on the profitability of products, but also on their sustainability and the perceived value they add to consumers. These factors were the base for the PD process developed by Gonçalves et al., (2025), as the authors focussed on functionality, circularity, and user friendliness, with the final goal of obtaining a profitable product. Gonçalves et al., (2025) additionally proposed the PD phases present in Table 7.

Table 7 - Phases of PD (Gonçalves et al., 2025)

1st	Product planning
2nd	Product concept
3rd	Product architecture
4th	Product detail
5th	Product prototyping
6th	Product testing and improvement

Product planning (Phase 1) is the phase of the project that defines the various requirements for a product. To successfully obtain these parameters, it is important to consider applicable EU standards and customer specifications. Additionally, with the increasing concern with product circularity and sustainability, these factors have also been steadily introduced and considered in this phase (Gonçalves et al., 2025). Identifying costumer needs and defining the most important requirements to be considered during PD is of upmost importance to define product requirements, develop concepts, and ultimately help choosing the concept that addresses those needs the best (Ulrich & Eppinger, 2020). When the final requirements for the product are defined, it is possible to start the product concept phase (Phase 2). In this phase, various solutions for the final product are developed considering costumer needs defined during product planning. A method used to generate ideas for concepts is brainstorming. This methodology, in an attempt to obtain more creative solutions, encourages designers to search and present new ideas freely and discourages them to criticize others (Filippi, 2023). After the creation of the various concepts, a decision matrix is used that enables engineers the possibility to choose the one that best suits costumer needs. With the ideal concept selected, engineers enter in the next phase of PD, product architecture (Phase 3). In this phase, the modularity of the product and the interaction between each assembly is determined (Ulrich & Eppinger, 2020). For that reason, important factors for the final product, such as the ease of maintenance, structural integrity, and the operating life, are affected by the decisions made in this phase (Gonçalves et al., 2025). Phase 4 of PD is product detail, and during this phase engineers engage in structural simulation and TO (Gonçalves et al., 2025). Due to the mainstream use of CAD and Computer Aided Engineering (CAE) software, this phase has evolved over the years as these software allow faster design iteration cycles, and easier optimal design evaluation (Mustapha, 2022). With the product detail phase finished, it is possible to start prototyping (Phase 5). Prototyping is the resource intensive experimental phase of the project leading to the final concept production and testing, and is used to guarantee that the technology performs as it was intended to (Bourgeois et al., 2024; Rehberg & Brem, 2024). However, with the mainstream use of AM, prototyping has become a simpler task, as AM allows the creation of complex geometries while also reducing waste (Wolf et al., 2024). Prototyping is also crucial to guarantee that the customer requirements are met and, that if needed, it is possible to improve the concept by refining and optimizing it. Actually, the effective implementation of prototypes during PD enables engineers to prematurely recognize risks associated with their design, thus preventing project modifications at a later stage (Rehberg & Brem, 2024). Product testing and improvement (Phase 6), is used to test the final prototype that should be production ready, to ensure that it complies with established standards and to assess its profitability (Gonçalves et al., 2025).

2.3.2. Ecodesign requirements and standards

Nowadays, the emphasis on the creation of more sustainable products has never been greater. However, for companies to develop more sustainable products they need to consider sustainability from the beginning of the development process. Therefore, it is important to explore strategies that can be used to achieve this goal. Ecodesign can be described as the consideration and integration of sustainability during PD with the final goal of producing a product with a reduced impact on the environment during its full life cycle (Timm et al., 2023; Wei Lun Lee et al., 2023). The process of evaluating a product's life cycle, known has Life Cycle Assessment (LCA), is key to obtain data on its environmental impact. The LCA methodology not only analyses early factors such as the harvesting of raw materials and manufacturing, but also the products usage and its disposal (Fonseca et al., 2023). To aid in the implementation of Ecodesign during PD, the ISO 14006:2020 standard (ISO, 2020), entitled *"Environmental management systems - Guidelines for incorporating ecodesign*" proposes six steps, which are represented in Table 8.

Table 8 - Ecodesign implementation steps (adapted from Boix Rodríguez et al., 2023)

1st	Define product functions
2nd	Environmental analysis
3rd	Environmental improvement strategies
4th	Develop environmental objectives
5th	Environmental product specification
6th	Develop technical solutions

In the specific case of the EU, the idea of Ecodesign has been discussed for the last 40 years primarily because the EU has made energy efficiency one of the its greatest concerns due to its role in achieving climate goals (Gonzalez-Torres et al., 2023). Figure 16 represents the evolution of EU product policies and it includes the Minimum Energy Performance Standards (MEPS), Energy Labelling, and Ecodesign directives.

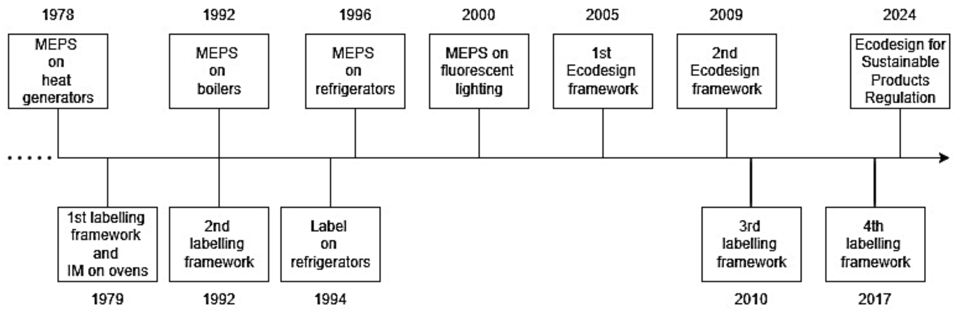


Figure 16 - Evolution of product policies in the EU (adapted from Gonzalez-Torres et al., 2023)

The first Ecodesign Directive was released in 2005 with the goal of setting Ecodesign requirements for energy-related products. However, after some studies on its effects, it was quickly realized that this directive only influenced the environmental impacts of 31-36 % of products under its sphere (Gonzalez-Torres et al., 2023). Therefore, the Ecodesign Directive 2009/125/EC was introduced with a focus on energy-related products. According to the European Commission, in 2021 this directive has enabled the save of 120 billion euros in energy consumption and made possible a reduction by 10 % of the annual energy usage by products under its domain (EC, 2022). In 2015 with the signing of the Paris agreement by the EU, a commitment was made to turn the EU climate neutral by 2050, prompting the adoption of the European Green Deal (EGD) in the 11th of December of 2019. This deal reiterated the urgency in shifting to a circular economic model (EU, 2019). As a result, the European Commission designed a program that would help in that shift, called the new Circular Economy Action Plan (CEAP) which seeks to establish sustainable products as the standard in the EU (CEAP, 2020). To achieve the objectives outlined by the CEAP, a set of measures was created, with ESPR being both a key component and a cornerstone (Commission, 2024). ESPR came into effect on the 18th of July of 2024 and its approach is based on the Ecodesign Directive 2009/125/EC but an expansion was made to encompass the product´s full life-cycle while also introducing a new digital product passport, which encapsulates the impact of products during their life-cycle (Regulation 2024/1781, 2024). ESPR's main strive is to diminish the carbon footprint of products during their life cycle while making them the default option in EU's internal market. To accomplish these goals, ESPR mentions various requirements that should be considered during PD that not only affect the design in itself but also the choosing of raw materials, production processes, product usage, and also product disposal. Table 9 represents these requirements, referred in the regulation as "*Product Aspects*".

Table 9 - Ecodesign requirements (Regulation 2024/1781, 2024)

• Durability	• Resource use and resource efficiency
• Reliability	• Recycled content
• Reusability	• The possibility of remanufacturing
• Upgradability	• Recyclability
• Repairability	• The possibility of the recovery of materials
• Energy use and energy efficiency	• Environmental impacts, including carbon footprint and environmental footprint
• Water use and water efficiency	• Expected generation of waste

Although these requirements should be followed during PD it is important to note that ESPR emphasizes the importance of new products keeping the same level of usability as previous models that did not follow the same Ecodesign rules, while also ensuring the product's price remains competitive (Regulation 2024/1781, 2024). The consideration of the aforementioned product aspects during gripper development is fundamental for the creation of more sustainable grippers due to the usage of recyclable and reusable materials, the adoption of more efficient manufacturing processes, and the creation of designs that prioritize ease of repair and maintenance, which in turn will also enhance durability.

2.3.3. Design-for-eXcellence through the LeanDfX methodology

Nowadays, the complexity of products has significantly increased due to costumer's demand for innovation. This situation has prompted companies to seek strategies that help them to optimize PD while also mitigating the risks of developing new products (Lopes et al., 2024). One methodology that companies use is the DfX approach, which is an iterative process that incorporates design from the beginning of PD, with the final goal of refining it to meet customer demands (Weiss et al., 2023). The X domain represents key requirements to be considered during the design of a product (Copriva et al., 2024). In Table 10 it is possible to observe some examples of X domains that are used to improve the effectiveness of PD, to reduce costs and PD time, and to enhance product sustainability.

Table 10 - Examples of X domains used in the DfX methodology (Benabdellah et al., 2024)

Design for Assembly (DFA)	Design for Cost (DFC)
Design for Quality (DFQ)	Design for Recycling (DFRcy)
Design for Maintenance (DFMt)	Design for Remanufacture (DFRem)
Design for Supply chain (DFSC)	Design for Reuse (DFRu)
Design for Manufacture (DFM)	Design for Environment (DFE)

The vast range of X domains make it challenging for companies to determine which ones are the best for their specific needs (Copriva et al., 2024). Product complexity can also cause different domains to interact, making it essential to identify the linkages between design variables (Lopes et al., 2024). These difficulties created the need for a tool that would enable the quantitively evaluation of "X" domains as a way to facilitate analysis and comparisons between designs (Baptista et al., 2018). Since 2015, the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI) has been developing the Lean Design for eXcellence (LeanDfX) framework (Carneiro et al., 2022). LeanDfX traces its roots to the Multi-layer Stream Mapping (MSM) framework but with a renewed focus on products and recurring to "*lean thinking*" as form of evaluating design variables (Baptista et al., 2018).

By applying the Lean thinking approach, LeanDfX reassures that resource waste is considered through the life cycle of the product and consequently on all X domains (Atilano et al., 2019). Additionally, LeanDfX's holistic approach allows the study of systems as being interconnected and not isolated parts (Lopes et al., 2024). The underlying principles of the LeanDfX tool can be organized in four pillars, which are represented in Table 11.

Table 11 - Four pillars of the LeanDfX framework (adapted from Atilano et al., 2019; Lopes et al., 2024)

Pillar 1	Product breakdown in modules
Pillar 2	Definition of X domains and design variables
Pillar 3	Simple to interpret visualization system
Pillar 4	Aggregation of data in a bottom-up logic until obtaining full product evaluation

In most companies, resistance to change is one of the barriers that prevent new methodologies from succeeding. As an example, Olayiwola et al. (2024) found that one of the biggest obstacle to applying Total Quality management in a cleaning company was the resistance to change. For that reason, it is important for new tools and methodologies to incorporate clear steps to help users (Atilano et al., 2019). In the specific case of the LeanDfX methodology, it is possible to divide its implementation in seven steps, as observed in Table 12.

Table 12 - LeanDfX implementation steps (adapted from Atilano et al., 2019; Baptista et al., 2018)

1st	Workshop
2nd	Modularization
3rd	Selection of design domains
4th	Selection of indicators and parameter values
5th	Calculation of the ratios of effectiveness and efficiency
6th	Analysis of the results
7th	Improvement of the design

The workshop is a preliminary phase in which team members are questioned about the LeanDfX framework in an attempt to assess if they are acquainted with the tool. Next, to simplify the evaluation process, it is crucial to divide the product in modules and submodules (Atilano et al., 2019). Figure 17 illustrates an example of the modularization process applied to a palletizing cell and consequently to a gripper.

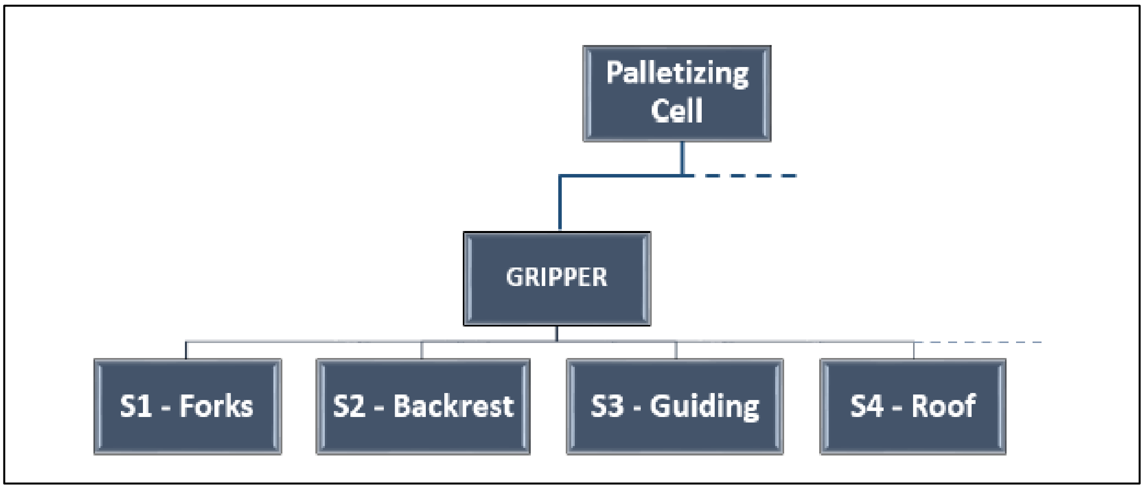


Figure 17 - Modularization of a palletizing cell (Atilano et al., 2019)

After the completion of the modularization procedure, the next step is to define the design domains, typically known as X domains, to be regarded in the analysis. These domains represent the goals the designers of the product should strive for, which are essential to define the design variables that represent them. For the same X domain, it is possible to utilize different design variables depending on the required final characteristics specified for a product. Table 13 specifies two X domains and respective design variables which were chosen by Atilano et al., (2019) due to their relevance in gripper development.

Table 13 - Examples of X domains and respective design variables used in gripper development (Atilano et al., 2019)

Design for structural integrity	• Mass • Fork length • Supported load • Maximum load width • Maximum stress
Design for Maintainability	• Operating life • Mean time between failures (MTBF) • Accessibility • Part change time

With the X domains and respective design variables defined, the next step is to incorporate them in the LeanDfX tool, which automatically assesses their effectiveness and efficiency. The effectiveness of a design indicates whether it meets the key requirements defined for the product or not, thus resulting in an approved/not approved status (Atilano et al., 2019). Efficiency evaluates the existence of over-engineering spots in the design, thus providing insights into areas for potential simplification, which can lead to significant material and energy waste reduction. Additionally, it is important to mention that efficiency is evaluated from 0 to 100 % and only if the effectiveness of the design is approved (Atilano et al., 2019). Figure 18 represents a LeanDfX scorecard, which represents the effectiveness and efficiency values in an easy-to-interpret manner.

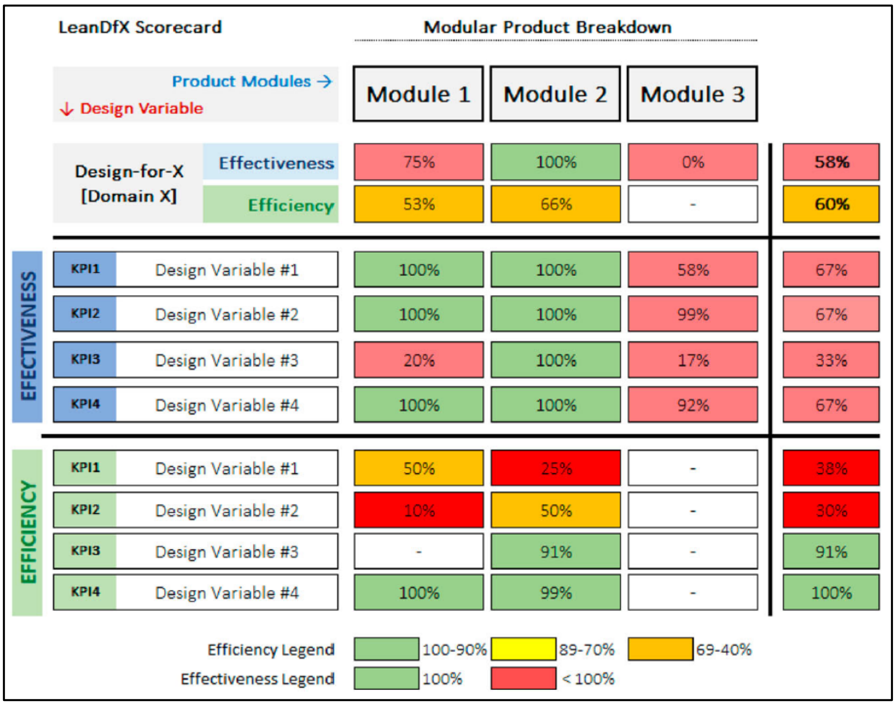


Figure 18 - Example of a LeanDfX scorecard (Lopes et al., 2024)

By analysing the results portrayed by the scorecard in Figure 18, it is possible to conclude that the third module design is not effective. Therefore, it was not approved. On Module 2, the design was considered effective for all variables although not all of them are considered effective. In relation to the X domain itself, considering the 58 % effectiveness it is possible to conclude that the design did not meet the specified requirements resulting in a non-approved status. However, the analysed scorecard only evaluates the implementation of an X domain in one system formed by three modules. On a full evaluation, there are more X domains to be analysed for each module, submodule and final product. Thereby, to simplify the analysis, it is important to aggregate these data with the intention of obtaining a global assessment (Baptista et al., 2018). Additionally, the final product effectiveness and efficiency is affected by the data from the modules and submodules (Atilano et al., 2019). Thus, it is necessary to proceed the analysis from the bottom to the top in a bottom-up logic (Lopes et al., 2024). As a final step, if the final results are not satisfactory, the user should improve the design and engage in an iteration loop until product requirements are met, or the desired efficiency is obtained. The best way to accomplish this goal is to start the improvement procedure by the most critical modules (Atilano et al., 2019).

2.3.4. Structural simulation and topological optimization

As mentioned during this work, during the product detail phase, it is crucial to validate if the developed gripper design can effectively perform the task it was developed for. To assess this, engineers engage in structural simulation using CAE software. Additionally, in an attempt to identify areas in the design that can be optimized, engineers use topological optimization.

Structural analysis is the process of evaluating a structure's internal forces and deflections under different loads (Leet et al., 2020). These data can be calculated using analytical models based on methodologies like the Theory of Elasticity, or numerical models such as the FEM (Yaylacı et al., 2024).The FEM discretizes a domain into a finite number of elements and nodes where stress and displacement calculation is possible. Additionally with the aid of interpolation functions, also known as shape functions, it is possible to predict the stress and displacement conditions in each element (Oleszek et al., 2024). When all elements are analysed the behaviour of the entire model is known (Yaylacı et al., 2024). The FEM can be used to analyse structural and non-structural problems. The most common structural problems that can be analysed are stress, displacement, buckling, vibration, and impact (Logan, 2022). To evaluate models using FEM, the most important part is the creation of the finite element mesh, as the final results directly depend on its correct implementation (Bourgeois et al., 2024). The finite element mesh is formed by all elements and nodes and, to define the mesh, it is first necessary to choose the elements shape and dimensional characterization. Elements are bars/beams, triangles, quadrilaterals, tetrahedrals, or hexahedrals. Dimensionally, elements can be one-dimensional, two-dimensional, three-dimensional and axisymmetric (Logan, 2022). If all elements are exactly the same size, then the mesh is a linear mesh, although it is recommended for the element size to vary with model geometry (Whiteley, 2018). In certain areas, smaller elements are needed to obtain satisfactory results. However, in areas where the model is characterized by constant geometries, larger elements can be used to reduce calculation times. The variation in element sizes is called aspect ratio, and it represents the ratio between the longest and shortest element edges. Furthermore, it is important to note that the accuracy of the study is affected by the application of a high aspect ratio (Logan, 2022). Figure 19 represents three different meshes applied to the same gripper, where the first mesh has an aspect ratio of 1.1 (a), of 2 (b), and of 3 (c).

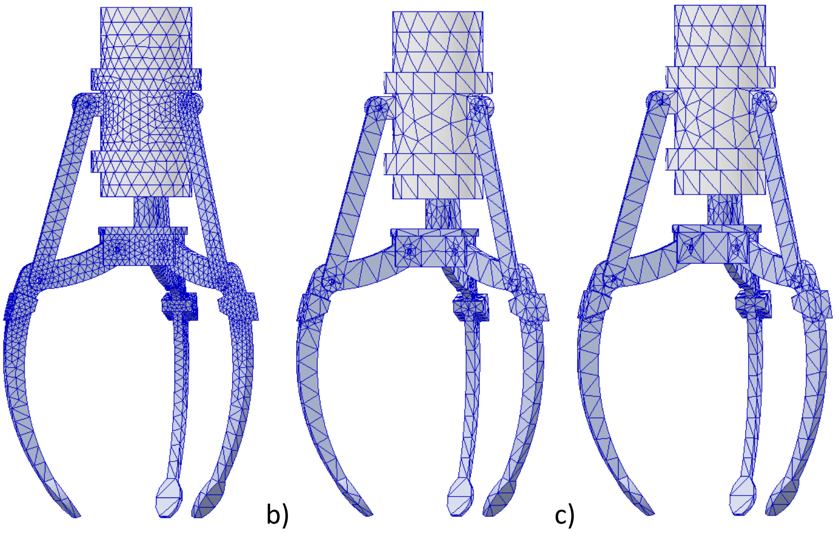


Figure 19 - Three different mesh geometries: aspect ratio of 1.1 (a), of 2 (b), and of 3 (c)

CAE software like SolidWorks® and ANSYS use FEM as a basis for their calculations. To use these software, users must not only create the mesh but also specify material properties, apply loads and boundary conditions, and, for assembly simulations, also define the connections between parts (Mustapha, 2022). Figure 20 represents a simulation result where the measured maximum stress is higher than the material yield strength.

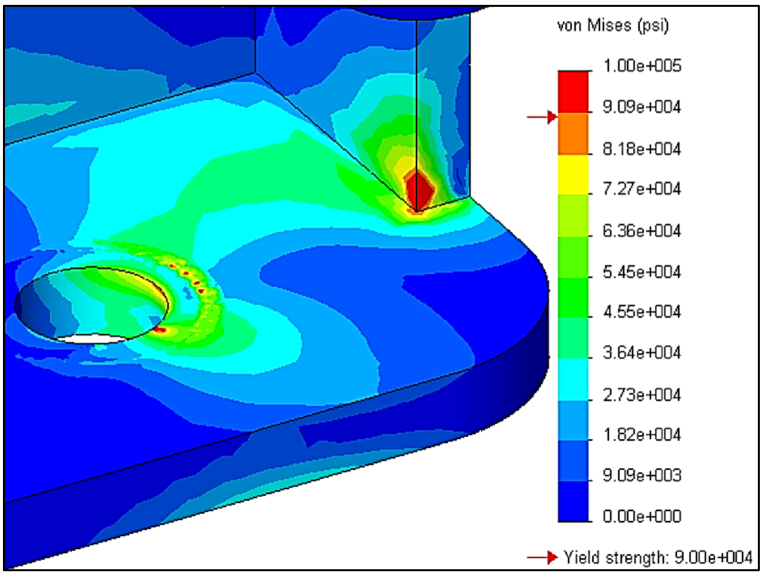


Figure 20 - Stress distribution representation in CAE software (Akin, 2010)

After completing a simulation analysis using CAE software, normally regions are identified that can benefit from design improvement. A mathematical way to improve these areas is using TO (Lee et al., 2023). TO allows engineers to optimize the allocation of material in a model while also improving stiffness. If correctly applied, TO can help in the creation of lighter structures that are characterized by improved structural integrity (Dib et al., 2024). One software that was developed by Siemens and that is used to engage in TO is called NX Topology Optimization. Table 14 represents the various phases needed to optimize the topology of a model using this software.

Table 14 - Implementation of the NX CAE software (NX, 2011)

1st	Create 3D model
2nd	Define loads and boundary conditions to create finite element model
3rd	Choose elements that can be modified
4th	Define the targets of the optimization (stiffness, volume and node displacement)
5th	Define design and manufacturing constraints (volume, displacement, symmetry constraints, element constraints, cast conditions)

After defining all the constraints, the software will create a new optimized model that cannot be manufactured. For this reason, the software has a smoothing tool that reconstructs the optimized model. The new model presents a shape that can be used as a base for the creation of the final design. Figure 21 represents an evolution of a model, from the finite element model to the final ready to be manufactured model.

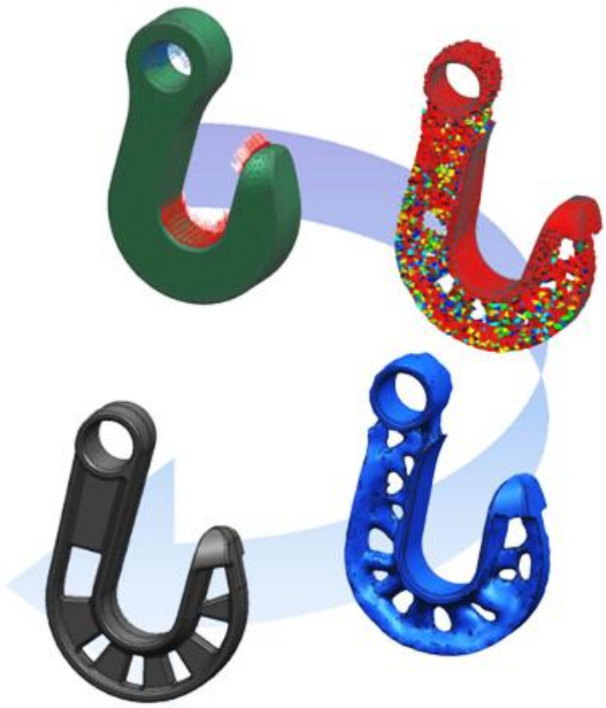


Figure 21 - Evolution of a model using NX CAE software (NX, 2011)

One important factor that must be always considered in FEM and TO, is that the usage of computational software does not replace engineering judgment (Harries et al., 2024). This affirmation is particularly evident in the mesh creation process during the application of the FEM, as it is up to engineers to select the element type to be used in each component of an assembly, and also to define their size variation (Logan, 2022).

2.3.5. State-of-the-art

Table 15 describes recent and innovative articles that contributed with advancements to the fields of PD, DfX methodology, LeanDfX framework, and TO.

Table 15 - State-of-the-art in design and product development

Article	Description
Gonçalves et al., 2025	This article introduced a new PD framework that comprises various steps to be followed by companies, to develop more sustainable products that comply with the ecodesign directive created by the EU. This methodology focussed on four DfX domains, profitability, circularity, functionality, and user needs, that should be considered in every phase of PD.
Gallegos-Nieto et al., 2024	This paper introduced a haptic-enabled virtual reality design for assembly software (HVR-DFA) which, from a virtual CAD assembly, can evaluate the proposed assembly process. The software analysed the time and number of tasks required to complete the assembly process, as well as the energy efficiency of the process. After applying HVR-DFA in a case study, the authors concluded that this software allowed the optimization of assembly planning, and also that it can reduce PD time in the industry.
Lopes et al., 2024	In this article, the goal of the authors was to improve the structure of a coach bus while also enhancing its sustainability. To achieve this goal, the authors created a new technique called *"Automotive Eco-Safe by LeanDesignX"*. This methodology enabled the cross-assessment of structural integrity and sustainability, which allowed the authors to develop a more sustainable and lighter structure.
Hartomacıoğlu et al., 2024	In their work, the authors created a carbon fibre-reinforced industrial robotic gripper. To optimize one of the components of the gripper, the authors employed the Autodesk fusion 360 software, enhanced with an artificial intelligence generative design module. After analysing and testing the eight possible designs provided by the software, the authors discarded some of the possibilities and found that the optimal design allowed them to reduce the weight of the part from 14 g to 4 g, the production time of the part from 58 to 28 min, and the cost of the part by 71 %.
Habashneh & Movahedi Rad, 2024	In this article, the authors aimed at improving the TO methodology by considering the fatigue resistance of a design, as the propagation of cracks negatively affects structural performance. To achieve this goal, the Bi-directional Evolutionary Structural Optimization (BESO) algorithm was combined with the Extended Finite Element Method (X-FEM), The authors applied this new methodology in various geometries and discovered that the optimized structures exhibited greater stiffness in crack-prone areas, which allowed the improvement of the structure's resistance to fatigue.

3. Collaborative robotic gripper development methodology

The present section presents all the stages involved in the development process of the collaborative robotic gripper. It begins with a brief overview of the agenda that serves as the foundation for the project presented in this work. Following this stage, the development process is introduced through a structured methodology that outlines the various stages of the project. Once the methodological framework is established, each stage of the process is described in detail, including the assessment of stakeholder’s requirements, the analysis of applicable standards and regulations, the generation of design concepts, structural simulation, and finally, the creation and testing of a functional prototype.

3.1. Use case presentation

One of INEGI’s strategic collaborations is with PRODUTECH, which is a Portuguese production technologies cluster, particularly through its involvement in the PRODUTECH R3 - Recovery, Resilience, and Reindustrialization agenda. The PRODUTECH R3 agenda is a national initiative aligned with Portugal’s recovery and resilience plan, which aims to strengthen the competitiveness, digital transformation, and environmental sustainability of the Portuguese industrial fabric. It is made of a national consortium of 108 companies, led by COLEP PACKAGING. From these 108 companies, 45 are suppliers of production technologies, 37 are the users of the production technologies, and 26 are ENESIIs (*Entidades Não Empresariais do Sistema de Investigação e Inovação*), entities from the scientific and technological system, and technology centres, where INEGI is included. JPM industry is one of the companies that takes part in this agenda, and it is an intralogistics company based in Portugal. More specifically, JPM industry was founded in 1994 in Vale de Cambra with the mission to supply electrification and automation services to industries. Over time, the company has grown to become a global benchmark in the intralogistics and robotics market. Within the scope of this agenda, JPM industry proposed the development of a collaborative robotic gripper to be employed in cardboard box palletization. This work is integrated into the WorkPackage 2 - Design2Transform.

3.2. Methodological approach

To develop the collaborative robotic gripper, it was essential to establish a clear methodology that could be used to guide the development process through its multiple stages. Additionally, the systematization of the entire development process is crucial to identify opportunities where it is possible to balance gripper functionality with Ecodesign and circularity principles.

Considering these factors, the methodology depicted in Figure 22 was created, and it was not based on any pre-exiting model. Instead, its stages were defined considering the information retrieved during literature review that could be used to address the specific goals of this project.

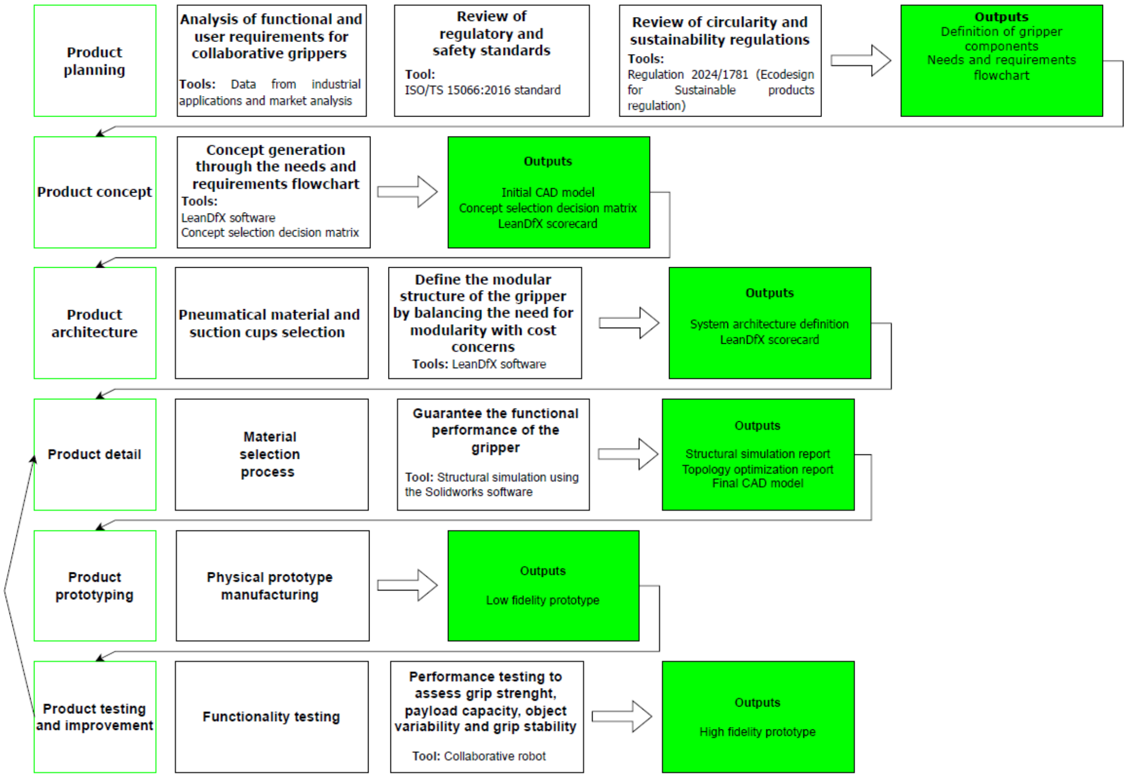


Figure 22 - Collaborative robotic gripper development methodology

The aforementioned methodology is composed by six distinct phases: Product planning, Product concept, Product architecture, Product detail, Product prototyping, and Product testing and improvement. Each phase involves the completion of a set of tasks as part of the gripper development process, which will ultimately generate outputs that will serve as inputs for the initiation of the next phase. Additionally, it is important to mention that the last three phases of the development process may require iterative feedback loops, meaning it might be necessary to revisit and refine the gripper model in previous phases before progressing further with the development process. The steps taken during each phase will be presented and explained in detail in the next sections.

3.3. Product planning

Product planning represents the initial phase of the PD process. During this phase, a thorough market analysis is conducted to identify important functional requirements present on existing collaborative robotic grippers that could be incorporated in the gripper being designed. In parallel, input is gathered from stakeholders to compile a list of the most critical user requirements. Furthermore, relevant regulatory and safety standards, namely the ISO/TS 15066 standard and the ESPR is reviewed to ensure that the gripper design would meet both safety and sustainability criteria. To finish, a needs and requirements flowchart is created to correlate each component of the collaborative robotic gripper with the specific requirements that guide their development and selection. These considerations help define a clear set of objectives to be followed in the product concept, product architecture, and product detail phases.

3.3.1. Functional and user requirements

The first task to be accomplished in the product planning phase is to identify the major components required for the creation of a functional gripper and also to assess the functional requirements common to all robotic grippers. A market analysis of vacuum-based robotic grippers revealed that these systems typically consist of three main components: the gripper structure, the pneumatical material, and the suction cups. Among these three, the most important component is the gripper structure, as it provides the structural integrity of the entire system and it is the only one that can be fully engineered and tailored to a specific application. The pneumatical material encapsulates all the components required to guide compressed air from the main supply line to the suction cups. These include valves, vacuum generators, and tubing. To finish, the suction cups are responsible for the grippers' grasping capability. Both the pneumatic material and the suction cups are sourced from manufacturer catalogues. These three major components are displayed in Figure 23.

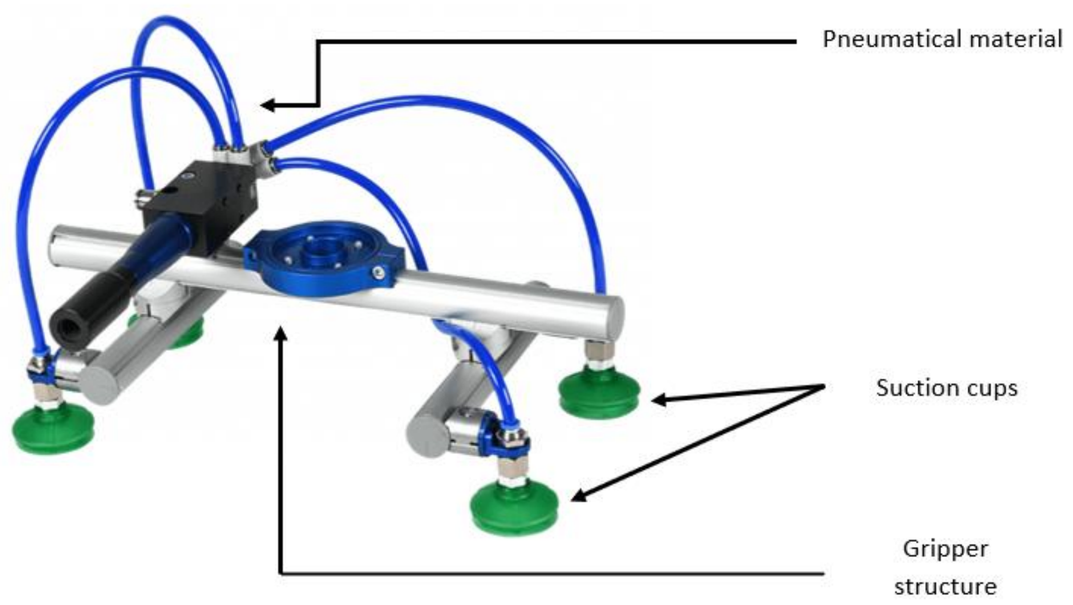


Figure 23 - Three major components of a vacuum gripper - Adapted from (Direct, 2025)

The study of the various vacuum-based robotic grippers available on the market revealed that they are expected to grasp, secure, and position objects in a precise and controlled way without compromising the safety of workers, to possess enough structural integrity to avoid its unexpected failure, to not damage the handled objects, and finally to have the capacity to resist climatic conditions such as temperature and humidity. In this phase, the use case company JPM

Industry was questioned about their needs for the final product. This information is displayed in Table 16.

Table 16 - Stakeholders requirements

- Vacuum based gripper
- Use four suction cups
- Adjustable in the X-axis
- Handle cardboard boxes ranging between 150 and 550 mm in edge size thar can weigh up to 10 kg
- Resist temperatures from -10 to 50°C and a relative humidity of up to 90 %
- Developed in consideration of the ISO/TS 15066 standard for collaborative robots
- Easy access to internal components to enhance repairability
- Weigh less than 1.5 kg
- Use ASA (Acrylonitrile Styrene Acrylate) or PLA

In addition to identifying all stakeholder requirements, it was also important to rank them according to their priority. This procedure would be important to assess which requirements were deemed essential for the final product and which could be sacrificed to reduce costs. However, in this work, the stakeholders ranked all requirements, except the one related to weight, as very important. The functional requirements of the gripper highly depend on the cobot specification, therefore it was selected at the preliminary stage of this work. The cobot is a KUKA LBR iiwa 14 R820, which as a maximum payload of 14 kg, a maximum reach of 820 mm, and seven axes (KUKA, 2025). This cobot, that is within INEGI's facilities, is depicted in Figure 24.

Figure 24 - KUKA LBR iiwa 14 R820 cobot (KUKA, 2025)

The information obtained from the cobot datasheet allow to determine the positioning of the holes used to mount the gripper in the cobot flange. This information was important, as the hole positioning (Figure 25) will be replicated in the gripper design. With this information retrieved it was possible to proceed with the product planning phase.

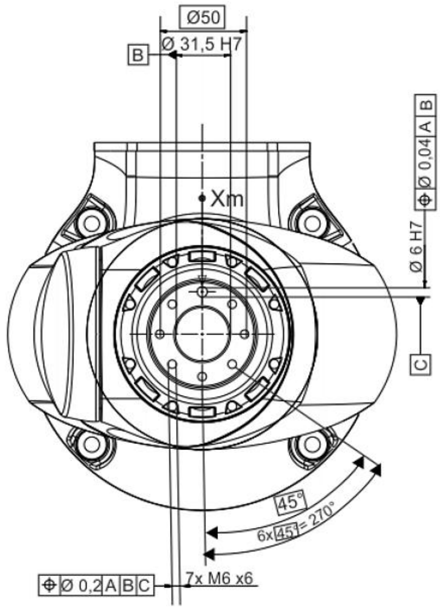


Figure 25 - Hole positioning in cobot flange (KUKA, 2016)

3.3.2. Safety and sustainability standards and regulations

During the product planning phase, it was also crucial to evaluate safety and sustainability standards, regulations thar are considered relevant for gripper development. Previously in this work, the ISO/TS 15066 standard for collaborative robot safety and the ESPR have been identified as the main regulations for both safety and sustainability improvement. In regard to gripper safety, the aforementioned ISO standard, mentions design possibilities that can be introduced in the models, such as the use of smooth and round edges, and the use of proximity sensors that can stop cobot motion in case of impact. Additionally, although it is not mentioned in the ISO/TS 15066 standard, it is also important to integrate the pneumatical material inside the gripper structure.

In regard to the ESPR, due to its recent introduction, its requirements are still being interpreted and integrated into industry spaces. For that reason, during product planning it was important to assess how each sustainability solution for gripper design could be used to achieve Ecodesign goals. During the literature review process, it was identified that gripper sustainability could be improved through higher modularity, and during the material and manufacturing process selection. Modularity can be integrated into gripper design through interchangeable components that adapt to different tasks and products, while the selection of materials that ensure the gripper’s structural integrity with low environmental impact is crucial to achieve Ecodesign requirements. Higher modularity mainly increases repair possibilities since, when a component fails it can be replaced, therefore avoiding the possibility of this failure making the gripper unusable and obsolete. Moreover, this factor also will help the gripper being aligned with circularity principles. Actually, when the gripper is no longer needed for its first intended purpose, by replacing some components it can be deployed in new tasks, therefore extending its service life. Modularity will also improve the efficiency of the repair process, as most of the components can be easily accessed and replaced.

Focusing on the manufacturing process, AM offers a promising approach to achieve Ecodesign goals, as it enables material efficiency, design flexibility, and the production of lightweight structures that reduce environmental impact across the product's lifecycle. Due to its additive nature, this process generates almost zero waste. Therefore, resource use is also extremely efficient when compared with other solutions. Energy efficiency is another attribute of AM that is mentioned in the Ecodesign directive.

In respect to functionality, the aforementioned manufacturing process offers almost endless design possibilities, therefore allowing the collaborative gripper to be not only extremely safe for workers through the creation of smooth round edges, but also highly modular and tailor made to the specific needs of the stakeholders. The last solution to achieve Ecodesign goals is to use a recyclable material with a high recycled content that enables the possibility of remanufacturing. Considering the previously discussed solutions and the Ecodesign requirements, the flowchart depicted in Figure 26 was created. It highlights the Ecodesign requirements (painted in green) and the corresponding solutions that support them (painted in white).

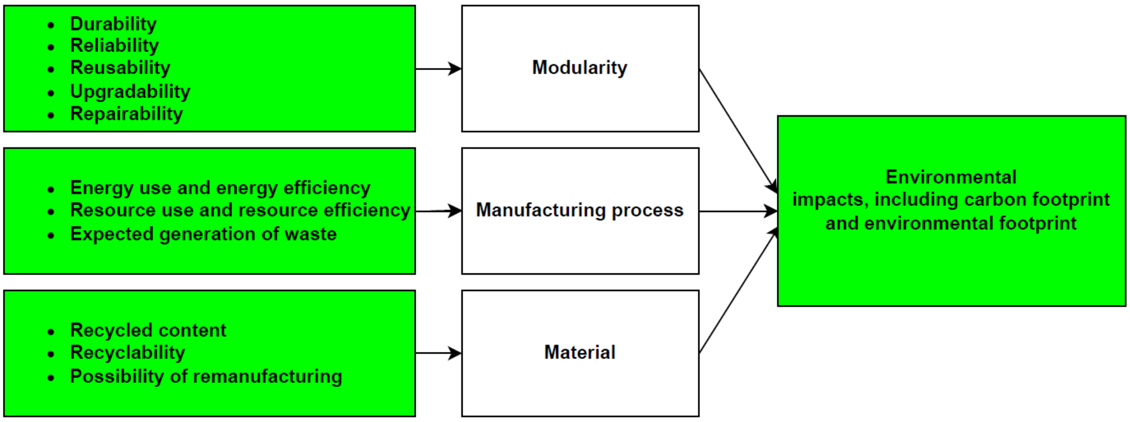


Figure 26 - Ecodesign requirements and respective design strategies flowchart

The creation of this flowchart was critical to integrate Ecodesign from the early stages of the gripper development process and to also ensure that Ecodesign is considered in the product architecture and product detail phase.

3.3.3. Needs and requirements flowchart

Based on the collected data in regard to JPM industry requirements, functional requirements, safety considerations, and Ecodesign goals, it was essential, at the conclusion of the product planning phase, to develop a flowchart that clearly linked these inputs to the to the three major components of a collaborative gripper: the gripper structure, the pneumatical material, and the suction cups. The systematization of this information in an easy to interpret flowchart will ensure that all the requirements will be considered throughout the subsequent stages of the PD process. This flowchart is depicted in Figure 27.

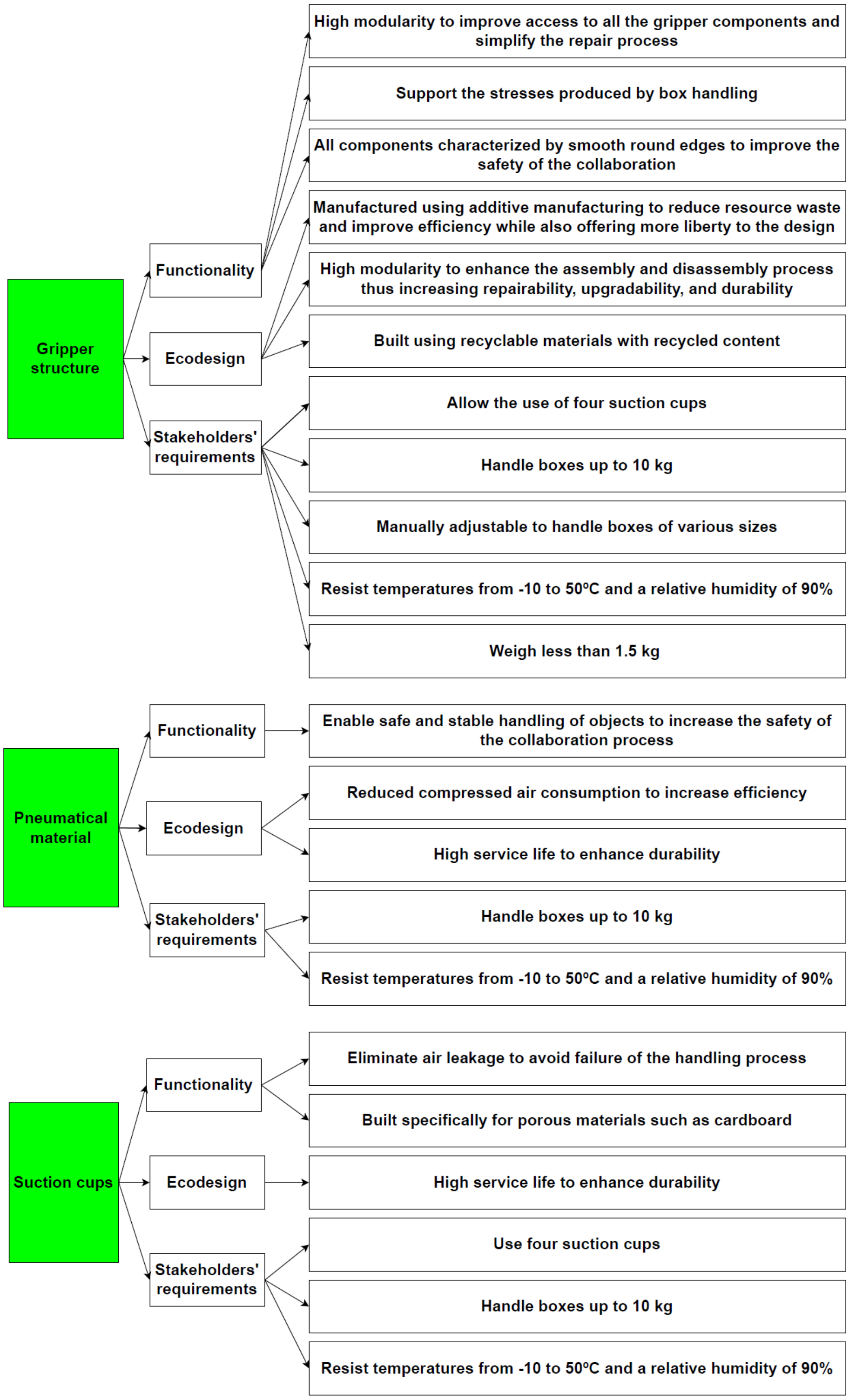


Figure 27 - Collaborative robotic gripper major components and respective requirements flowchart

This flowchart will serve as the base for the following phases of the collaborative robotic gripper design and development process.

3.4. Product concept

The Product concept phase represents the second phase of the collaborative robotic gripper development methodology, during which initial design ideas begin to take shape. In this phase, multiple concepts are developed using the SolidWorks® 2024 student edition software. The most suitable concept is selected through a decision matrix, which ensures an objective evaluation. Additionally, the chosen concept is evaluated using the LeanDfX tool to identify areas of the design that require improvement and to establish a reference point for future design enhancements. These steps are summarized in the flowchart depicted in Figure 28.

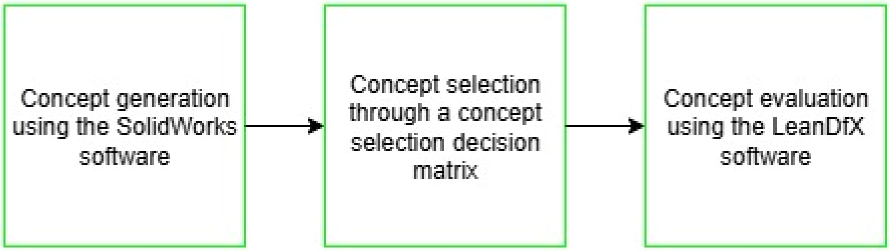


Figure 28 - Product concept phase flowchart

The use of the SolidWorks® software provides an efficient and rapid method for creating various 3D concepts for the collaborative robotic gripper design. This software offers a new approach to concept creation, as it allows a preliminary evaluation of functionality, weight, and gripper adaptability to the different sixed boxes, even before possessing a final model of the physical prototype.

This information is also valuable for the creation of a concept selection decision matrix in collaboration with the stakeholders. It was determined that functionality would serve as the most important criteria for evaluation, followed by cost. Ecodesign and user safety were assigned equal levels of importance. Functionality was measured based on component accessibility, which is important to simplify the assembly and disassembly process, as well as the degree of adjustability offered by the design. User safety was evaluated based on two primary factors: the overall weight of the gripper solution, which should be minimized to reduce the risk of injury in case of impact, and the components roundness. Ecodesign was also evaluated through weight, although in this case due to the need to decrease resource usage, and also modularity. In regard to cost, the volume of each concept was assessed, as a higher volume leads to a higher usage of raw materials. Additionally, the number of fixing elements was also considered in the cost criteria, given its impact on assembly costs.

Each criterion was evaluated for each concept using a scale from 1 to 5, where a rating of 1 indicated significantly worse performance when compared to the reference, 3 represented parity with the reference, and 5 denoted significantly better performance than the reference. To determine the total score for each concept, a weighted evaluation method was applied. An importance level was assigned to each of the four parameters defined by the stakeholders, so that their sum equalled 100. This procedure ensured that the relative influence of each criterion was properly accounted for in the evaluation. The rating of each concept in a given parameter was then multiplied by their respective assigned weight, and the resulting weighted values (score) were summed across all parameters to obtain a total score for each concept. After the selection process is complete, it is important to further evaluate the chosen concept using the LeanDfX tool (described in section 2.3.3).

While LeanDfX was conceptually developed by INEGI (Atilano et al., 2019), its implementation as a software was carried out by SisTrade, a specialized software development company. Concept evaluation was important to create a benchmark for future product optimization, and also to assess the parts of the design that needed improvement. More specifically, in this work, LeanDfX was used to compare weight, modularity, and the gripping area that the gripper should cover to handle the smallest and biggest boxes. The ideal weight is a stakeholder requirement. The target values for both modularity and gripping area are defined by analysing other grippers available on the market and by using some engineering judgment. T. Gonçalves et al. (2025) explains in detail the entire process that must be completed to obtain the LeanDfX scorecard.

3.5. Product architecture phase

Following the selection of the concept, the next stage in the collaborative gripper development process is the product architecture phase. During this phase, the pneumatical material must be selected and integrated in the concept to produce a fully functional final model, which can be tested and refined in the product detail phase. Additionally, the modularity of the final concept is evaluated to determine whether further improvements are required.

The task of selecting of the pneumatical material required for the gripper's operation, is important as it directly influences the design of the gripper structure. Furthermore, the selection of highly efficient pneumatical material can enhance the grippers' Ecodesign credentials, mainly by reducing compressed air consumption. However, in this work, due to project constraints only FESTO material was considered, which limited the range of possible solutions.

To start the selection process, it was first necessary to analyse the gripper implementation space. This analysis revealed that the space had an easily accessible compressed air line, which could be used to power the gripper. This information revealed that it was not necessary to use an air compressor. Nonetheless, other components were also needed for the gripper to function, mainly valves to control airflow, vacuum generators to create vacuum, suction cups, tubing to direct airflow, and various fittings. Among all the components, the suction cups require the most detailed analysis to ensure the gripper's safety and optimal performance. In particular, it is essential to determine their diameter based on the weight of the items to be handled and the level of acceleration produced by the cobot, as it is important to ensure sufficient gripping force to maintain stability and prevent slippage during operation. Moreover, it is also important to consider the material composition of the packages to handle, particularly when dealing with highly porous materials such as cardboard. The high porosity can cause air leakage, which is a critical factor that may reduce the systems' efficiency and compromise operational safety.

To calculate the suction cups holding force, the load case should be assessed. In a palletization process, the suction cups remain in a horizontal orientation. However, they are also subjected to vertical movement when the boxes are picked, and horizontal movement during placement on the pallet. For this load case Schmalz (2025b) proposes the use of equation (1) to calculate the suction cups total holding force.

$$F_{TH} = m \times \left(g + \frac{a}{\mu}\right) \times S \quad (1)$$

where m denotes the mass of the object to be handled in kilograms (kg), g represents the gravitational acceleration (m/s^2), a is the cobots' acceleration during operation (m/s^2), μ corresponds to the coefficient of friction between the gripper and the object's surface, and S denotes the safety factor. In this work, beyond the requirements specified by the stakeholders, the cobots operational acceleration was defined to be 3 m/s^2, the coefficient of friction between the suction cups and cardboard was 0.6 (Schmalz, 2025b), and a safety factor of 2 was adopted for the design calculations. By replacing the previously mentioned values in equation (1), it was revealed that each suction cup should offer a theoretical holding force of 74.05 N. This information was essential to select the suction cup according to its diameter. The first stage of the process suction cup selection process was to decide between flat suction cups and bellows suction cups. Theoretically, for the application presented in this work, a flat suction cup would be sufficient to handle the boxes. However, due to cardboards high porosity and roughness, it was decided for safety reasons that the best solution would be to use bellows suction cups.

After an analysis of the available options on the FESTO website, the suction cup with OGVN connection (FESTO designation) was selected due to its suitability to handle porous materials with irregular surfaces. In regard to the required diameter, the datasheet indicates that, to achieve the calculated theoretical holding force of 74.05 N, a suction cup with a diameter of 52 mm is necessary. This specific size provides a holding force of 85 N at a nominal operating pressure of -700 bar (FESTO, 2025b). Additionally, this suction cup contributes to Ecodesign objectives, as it is manufactured using a wear-resistant polyurethane that extends its service life. As a result, the frequency of replacement is reduced, which leads to less maintenance demands, reduced suction cup consumption, and improved operational efficiency. Figure 29 depicts a suction cup with OGVN connection.

Figure 29 - Suction cup with OGVN connection (FESTO, 2025b)

With the suction cup selected, the next component to be selected was the vacuum generator, which is a component that typically functions based on the venturi principle and creates vacuum through the use of compressed air. Its most relevant feature is the suction rate, which controls the safety of the operation and the time needed to create the desired vacuum level. According to Schmalz (2025a), the minimum necessary suction rate that must be created by a vacuum generator to ensure a safe handling operation is dependent on the suction cup diameter, as shown in Table 17.

Table 17 - Typical values for suction rate (with smooth, airtight surfaces) depending on the diameter of a suction cup (adapted from (Schmalz, 2025a))

Suction cup Ø	Suction area (cm^2)	Suction rate (m^3/h)	Suction rate (l/min)
Up to 60 mm	25	0.5	8.3
Up to 120 mm	113	1.0	16.6
Up to 215 mm	363	2.0	33.3
Up to 450 mm	1540	4.0	66.6

Therefore, for a 52 mm diameter suction cup, the minimal suction rate must be of 8.3 l/min. However, Schmalz (2025a) notes that this value applies to smooth, airtight surfaces, unlike cardboard. Considering this information, the VN vacuum generator was selected, as it offers a suction rate of 15.7 l/min through the use of a 0.45 mm diameter laval nozzle. This increased suction rate will enhance the safety of the handling operation. Moreover, this product is compact and lightweight, operates without wear or the need for maintenance, offers excellent energy efficiency, which is an important factor to achieve Ecodesign goals, and it is particularly suited to handle cardboard boxes due to its high suction volume flow (FESTO, 2025c). A VN vacuum generator is displayed in Figure 30.

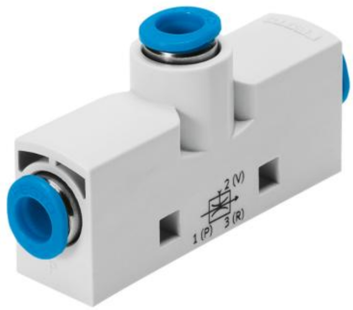


Figure 30 - Vacuum VN generator (FESTO, 2025c)

Although the collaborative robotic gripper will use four suction cups, this does not necessarily mean that four vacuum generators are required. However, in order to reduce vacuum generation time, to avoid the use of shared pressure lines, and to compensate for pressure losses resulting from longer tubing length, it was decided that the best solution would be to use four suction cups in direct contact with the vacuum generators. This ensured that there load losses would be close to zero. As for the valves, they are needed to control the feed of airflow to the suction cups. In this work, the VMEF valve (FESTO designation) was selected due to its durability. For the gripper to function, as with the vacuum generators, it would have been sufficient to use a single valve to supply air to the suction cups. However, to enhance safety, the decision was made to use individual valves for each suction cups. This approach ensured that in the event of a valve failure, the others would still continue supplying air to the other suction cups, therefore reducing the risk of dropping the handled box. Figure 31 is a representation of the selected valve.

Figure 31 - VMEF valve (FESTO, 2025a)

To ensure the compatibility between the previously mentioned components, and to guarantee the creation of a working pneumatical system that could feed air from the air line to the suction cups, it was also necessary to use a number of fittings and to select the tubing elements. A threaded adapter was used to connect the female thread of the suction cup to the male thread of the vacuum generator. Additionally, push-in fittings were employed to facilitate a quick and secure connection between the tubing, vacuum generator, and valve. This component uses small internal teeth to grip and hold the tubing firmly in place, which ensures a reliable seal without the need for additional tools. In this work, polyamide tubing with 4 mm diameter was used. Figure 32 depicts the threaded adapter (a), the push in fitting (b), and PAN tubing (FESTO designation) (c).

Figure 32 - Fittings and tubing: NPFC-D-2G18-M threaded insert (a), QS-G1/8-4 push-in fitting (b), and PAN tubing (c)

With all these components selected it was important to verify if they could be assembled without interference, mainly in regard to the vacuum generator and suction cup assembly. However, this assessment had to be carried out before placing the orders to avoid potential incompatibilities or costly design revisions. Fortunately, the FESTO website provided CAD models of these components, which could be integrated and assembled using the SolidWorks® software. This capability was also crucial for the subsequent steps of the product architecture phase, as it enabled the incorporation of the pneumatic components directly into the gripper's CAD model. Consequently, a fully functional CAD model of the gripper could be developed, allowing for precise design of the components necessary to accommodate and assemble the pneumatic system. Figure 33 illustrates the assembly of the vacuum generator and the suction cups through the use of the various fittings.

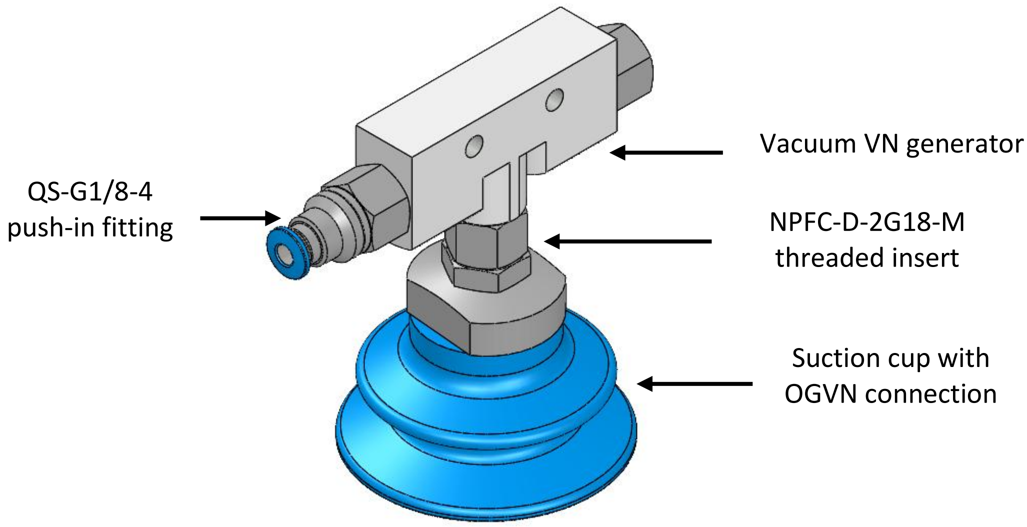


Figure 33 - Suction cup and vacuum generator assembly

With the pneumatical components selected, and their assembly ensured, it was possible to optimize and refine the selected concept to assess how the components could be effectively integrated in the design.

3.6. Product detail phase

The product detail phase is used to guarantee the structural integrity of the developed collaborative robotic gripper before the creation of a physical prototype. This phase initiates with the material section process, as this decision is necessary to engage in structural simulation using the SolidWorks® software. The stakeholders defined that only two materials could be considered for the production of the developed collaborative robotic gripper, ASA and PLA. Additionally, for this work both filaments will be supplied by Bambu Lab, a company specializing in desktop 3D printers, and related materials in filament form. According to the respective datasheets, ASA is characterized by its exceptional durability, provided by its high resistance to adverse weather conditions and UV radiation, as well as a high mechanical and thermal resistance (Bambu Lab, 2025d). These properties contribute to its suitability for achieving Ecodesign goals, particularly in regard to durability. However, since the collaborative robotic gripper to be developed in this work will be operated indoors under controlled environmental conditions, such characteristics may not be strictly necessary. PLA, on the other hand, is one of the most widely used materials in AM, primarily due to its lower printing temperature, which facilitates processing (Bambu Lab, 2025d). Furthermore, as highlighted in the literature review phase of this work, PLA is biodegradable, thereby aligning it well with Ecodesign principles. In regard to cost, PLA is cheaper than ASA (Bambu Lab, 2025a). To further compare these two materials, Table 18 was created. It is also important to mention that these properties were measured using specimens with 100 % infill density.

Table 18 - ASA and PLA mechanical and physical properties - (Bambu Lab, 2025b, 2025d)

	ASA	PLA
Printing speed (mm/s)	≤ 250	≤ 300
Nozzle temperature (°C)	240 - 270	190 - 230
Melting temperature (°C)	210	160
Density (g/cm^3)	1.05	1.24
Young's modulus (X-Y) (MPa)	2450 ± 270	2580 ± 220
Young's modulus (Z) (MPa)	2120 ± 260	2060 ± 170
Tensile strength (X-Y) (MPa)	37 ± 3	35 ± 4
Tensile strength (Z) (MPa)	31 ± 4	31 ± 3
Bending strength (X-Y) (MPa)	65 ± 5	76 ± 5
Bending strength (Z) (MPa)	40 ± 3	59 ± 6
Impact strength (X-Y) (kJ/m^2)	41 ± 2.3	26.6 ± 2.8
Impact strength (Z) (kJ/m^2)	4.9 ± 0.6	13.8 ± 0.9

The table provides some important data for the material selection process. As discussed earlier, PLA allows for higher printing speeds, which will reduce the time required for component fabrication. Additionally, it requires lower processing temperatures, which will increase efficiency and contribute to the achievement of Ecodesign goals. In regard to the mechanical properties, ASA as the edge. It offers improved tensile and impact strengths. However, for this use case, bending strength is the most important, because when a robotic gripper is handling a box, the tubes are subjected to bending forces, and in this parameter PLA is superior. With regard to impact strength, ASA demonstrates superior performance. However, this property may not be critical in the present application, as the gripper is not expected to experience significant impacts from falling onto hard surfaces, such as the factory floor. Potential collisions are more likely to occur with human operators, but given the low operating speeds of cobot, such impacts would be more detrimental to the worker than to the gripper itself. Considering all the analysed information, PLA was selected as the to manufacture the collaborative robotic gripper components. Its use supports the achievement of Ecodesign goals, which represent a key requirement of this work. Additionally, it is characterized by a superior bending strength, which is a very important factor for this application. With the material selected, it was possible to engage in structural simulation using the SolidWorks® software. To obtain meaningful results from the numerical simulations, it is important to engage in a mesh convergence study, Figure depicts a flowchart that summarizes all the steps needed to retrieve meaningful values from numerical simulations. This process is carried out by progressively refining the finite element mesh until the solution reaches a stable and reliable level of accuracy (Logan, 2022). Figure 34 depicts a flowchart of all the steps needed to engage in a mesh convergence study. The mesh convergence study is done with the same pre-processing conditions as the final models.

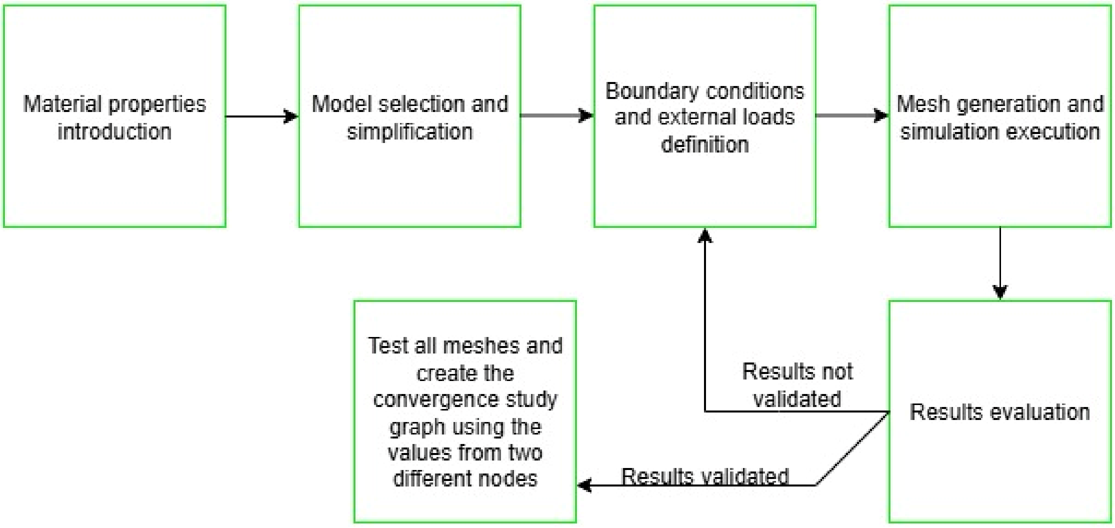


Figure 34 - Mesh convergence study flowchart

3.7. Product prototyping

After the structural integrity of the final CAD model is validated, it is possible to start the fabrication process of the physical prototype for the collaborative robotic gripper. The product prototyping phase encompasses the steps shown in the flowchart (Figure 35).

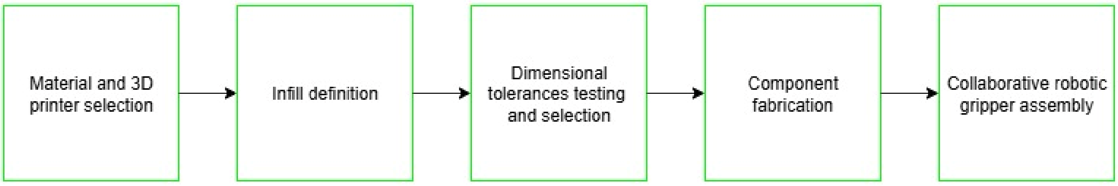


Figure 35 - Product prototyping flowchart

AM has been widely adopted in the industry for prototype development, even when the final product is intended to be manufactured through conventional processes such as machining or injection moulding. In this project, the role of AM is even more significant, as the final product itself is intended to be manufactured using this technology. For that reason, this prototype is not only valuable to validate the structural integrity of the design but also to serve as a means to identify potential failure zones within the components.

For the fabrication of the prototype, black PLA basic filament supplied by Bambu Lab was employed. This material had been selected during the product detail phase due to its reduced cost, widespread availability, ease of printing, and adequate mechanical properties. Figure 36 depicts a representative component fabricated using black PLA basic. The surface quality and overall finish observed in this example are indicative of the expected manufacturing outcome for the collaborative robotic gripper components.

Figure 36 - Representative component fabricated using Bambu Lab PLA basic (Bambu Lab, 2025d)

Regarding the equipment used for fabrication, the Bambu Lab X1E 3D printer (Figure 37) was employed. This machine manufactures components using the Fused deposition modelling (FDM) process, a common AM technique in which polymeric filament is heated until it reaches a semiliquid state and subsequently extruded through a nozzle. The material is deposited in successive layers, which solidify and bond to form the final component. (Kristiawan et al., 2021). In regard to the level of infill, it will be selected considering the thickness of the various components of the collaborative robotic gripper.

Figure 37 - Bambu Lab X1E 3D printer (Bambu Lab, 2025c)

3.8. Product testing and improvement

With the physical prototype fabricated, in this phase, tests are carried out to evaluate its functionality and overall performance. During this phase, the behaviour of the gripper is analysed, to identify operational issues and design shortcomings. Based on these observations, specific components are optimized to guide the development of a revised prototype. The flowchart depicted in Figure 38 illustrates the testing steps.

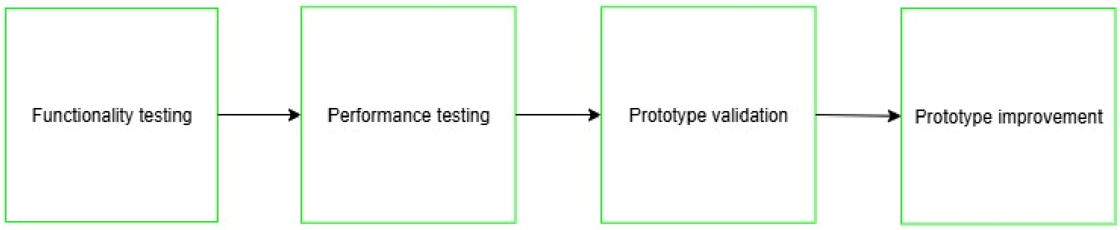


Figure 38 - Product testing and improvement steps

The first step of the product testing and improvement phase is functionality testing. This step will evaluate the behaviour of the prototype when adjusted and adapted to handle both the 150 and 550 mm edge size boxes, assess the quality of additively manufactured components, and examine the integration of the pneumatic tubing.

The tests to be performed during performance testing are depicted in Table 19.

Table 19 - Performance tests

Test	Box weight	Box dimension
Test 1	3.5 kg	150 mm edge size
Test 2	3.5 kg	550 mm edge size
Test 3	5.5 kg	150 mm edge size
Test 4	5.5 kg	550 mm edge size
Test 5	7.5 kg	150 mm edge size
Test 6	7.5 kg	550 mm edge size
Test 7	10 kg	150 mm edge size
Test 8	10 kg	550 mm edge size

For performance testing, the prototype of the collaborative robotic gripper will be tested on both retracted and extended configurations for the 150 mm and 550 mm edge size boxes, respectively, with increasingly higher weights up to the target maximum payload of 10 kg. In these tests, the KUKA LBR iiwa R820 cobot will be programmed to execute a standard pick-and-place operation, whereby the gripper is lowered to engage with the box, vacuum will be generated to secure the load, and the cobot subsequently transfers the box horizontally to its designated final position before releasing it. Both the functionality and the performance testing is crucial to assess the points of improvement for the gripper. The various conclusions retrieved from testing will also result in the creation of a prototype validation table. Finally, a revised prototype is presented, which addresses the issues identified during the testing of the previous version.

4. Results and discussion

4.1. Concept generation, selection, and evaluation

Considering the needs and requirements flowchart displayed in Figure 27, it was clear that the initial design of the gripper structure, along with the future integration of the pneumatical material, should be addressed during the product concept phase. Therefore, the concepts developed at this stage should be compatible with the pneumatic material and also be characterized by a degree of modularity and adjustability to guarantee that resulting designs are better aligned with the project's overall objectives and ready for improvement during the subsequent development stages. However, due to the endless design possibilities for robotic grippers, as it became evident during the market analysis, the first generated concepts were still far from being viable solutions. The generated concepts are depicted in Figure 39.

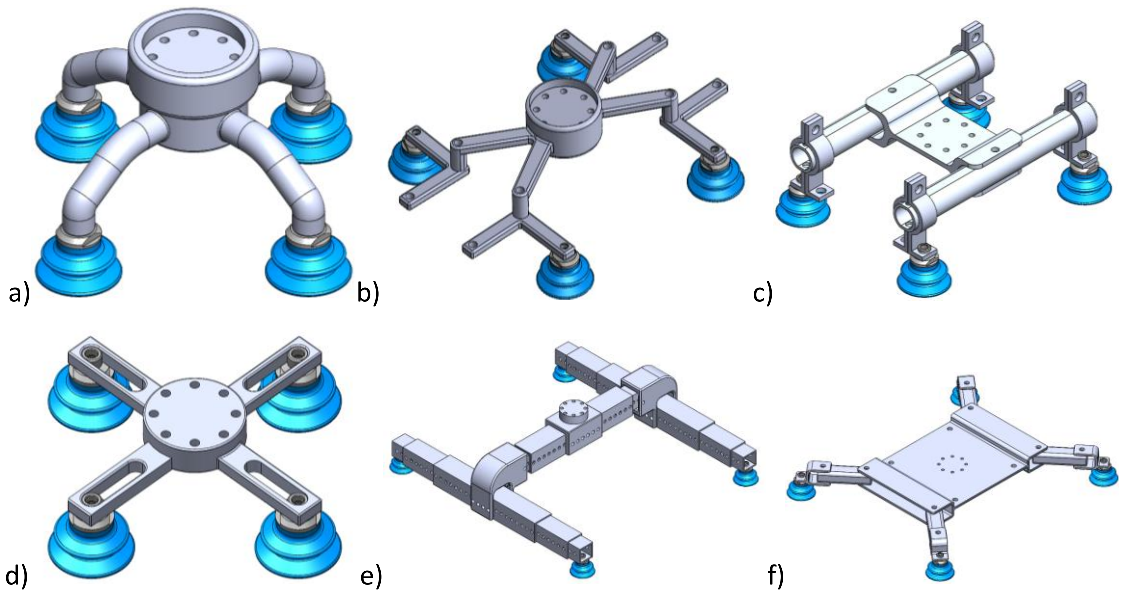


Figure 39 - Initial design concepts for the collaborative robotic gripper: concept A (a), concept B (b), concept C (c), concept D (d), concept E (e), and concept F (f)

As expected, these first concepts were discarded as solutions for the final product, as they failed to meet most of the previously mentioned requirements. Notably, these exhibited insufficient modularity and limited adjustability, and also posed constraints to the safe introduction of the pneumatical material. However, these concepts did display certain characteristics that were helpful to create a new batch of higher quality concepts that could more closely resemble the model to be used in the product architecture phase. Concepts B, C, and D were characterized by higher levels of modularity and offered adjustment possibilities by repositioning the suction cups within the gripper structure. Concept E was also adjustable, although this feature was achieved through the use of a telescopic structure, therefore eliminating the need to disassemble the suction cups. Lastly, concept F, offered suction cup adjustment through the rotational movement of the gripper arms. The distinguishing features of each concept were subsequently integrated into the development of new, more refined design alternatives. However, the incorporation of all these features into a single solution was deemed potentially unfeasible due to cost constraints and mechanical limitations. For that reason, the new concepts were evaluated with the help of a selection matrix to identify the most suitable solution. The new concepts are depicted in Figure 40.

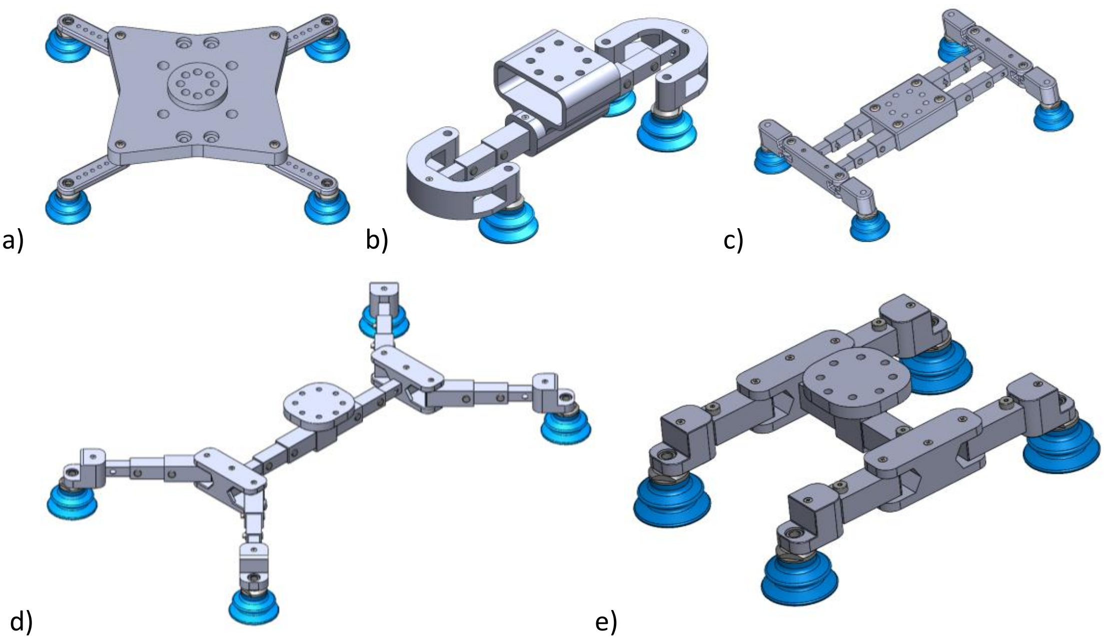


Figure 40 - Improved design concepts for the collaborative robotic gripper: concept 1 (a), concept 2 (b), concept 3 (c), concept 4 (d), and concept 5 (e)

Concept 1 was the one which was least aligned with the features identified as important in the original concepts. In particular, adjusting the suction cups required the disassembly of components, and the integration of the pneumatical material inside the gripper structure was not possible. Nevertheless, this design idea was kept in the analysis to serve as a baseline reference for comparative evaluation. In contrast, the other developed concepts successfully incorporated some of the main characteristics identified in the original designs. Concept 2 was designed with user safety in mind, as it is mainly characterized by round surfaces. It is also adjustable through the use of telescopic structures, i.e., disassembly is not required. Its main disadvantage is the limited gripping area, which may reduce the stability of the handling process. To fix this issue, in concept 3, two additional telescopic structures, and four rotating arms were introduced. For concept 4, the rotating arms were redesigned to become telescopic structures, which improved adjustment possibilities and modularity. However, these enhancements also contributed to an increase in overall system complexity. Concept 5 closely resembled Concept 4, although, it used slotted holes to increase the number of positions of the telescopic structure. This solution enhanced adjustment possibilities but compromised the maximum extension of the telescopic structure. By filling the concept selection decision matrix, it was revealed that the winning concept was concept 4, as it can be seen in Figure 41.

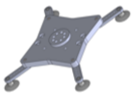
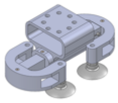
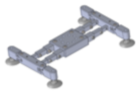
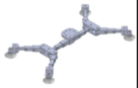
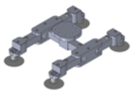
Concept selection matrix		1 		2 		3 		4 		5 	
Selection criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Worker safety	**20**										
Weight	10	3	30	5	50	4	40	5	50	5	50
Rounded edges	10	3	30	5	50	3	30	3	30	3	30
Ecodesign	**20**										
Weight	10	1	10	5	50	4	40	5	50	5	50
Modularity	10	1	10	2	20	4	40	5	50	4	40
Functionality	**30**										
Accessability	10	5	50	2	20	3	30	5	50	5	50
Adjustability	20	2	40	3	60	4	80	5	100	4	80
Cost	**30**										
Volume	20	1	20	4	80	3	60	4	80	4	80
Fixing elements	10	3	30	5	50	4	40	3	30	2	20
Total score	_	_	220	_	380	_	360	_	**440**	_	400
Rank	_	_	5	_	3	_	4	_	**1**	_	2

Figure 41 - Concept selection decision matrix

Concept 4 emerged as the solution that most effectively balanced Ecodesign with functionality, while also ensuring a satisfactory level of worker safety at a satisfying cost. Additionally, this concept incorporated the features that were identified in the concepts presented in Figure 40, including the high level of adjustability, the high modularity, the use of telescopic structures, the introduction of rotating arms, and the possibility of hiding the pneumatical material inside the gripper structure. To evaluate the winning concept using LeanDfX, it was necessary to introduce in the software the admissible value, and the ideal value for the final gripper model to be compared with the measured values observed in the concept. The exact values defined for the creation of the LeanDfX scorecard can be observed in Table 20.

Table 20 - Values introduced for the creation of the concepts LeanDfX scorecard

		Gripper structure
Gripping area for the 150 mm box (mm^2)	Admissible value	8000
	Ideal value	8500
	Measured value	7280
	Objective	Maximize
Gripping area for the 550 mm box (mm^2)	Admissible value	120000
	Ideal value	175000
	Measured value	125882
	Objective	Maximize

Table 20 - Values introduced for the creation of the concepts LeanDfX scorecard (continued)

Modularity	Admissible value	10
	Ideal value	13
	Measured value	13
	Objective	Maximize
Weight (kg)	Admissible value	1.5
	Ideal value	1.3
	Measured value	0.39
	Objective	Minimize

This information supported the creation of the scorecard using the LeanDfX module of the SISTRADE SW shown in Figure 42.

1110: Collaborative gripper		**Gripper structure**
Average	Effectiveness	75.00 %
	Efficiency	67.31 %
Effectiveness	Gripping area for the 150 mm box (mm^2)	91.00 %
	Gripping area for the 550 mm box (mm^2)	100.00 %
	Modularity	100.00 %
	Weight (kg)	100.00 %
Efficiency	Gripping area for the 150 mm box (mm^2)	-
	Gripping area for the 550 mm box (mm^2)	71.93 %
	Modularity	100.00 %
	Weight (kg)	30.00 %

Figure 42 - Concept 4 LeanDfX scorecard

The scorecard indicated that concept four was effective in achieving all the parameters, apart from the gripping area for the smallest box, with a 91 % effectiveness in Figure 42, reason why the respective efficiency was not tested. Therefore, the design still needs some improvement to achieve the goal of safe and stable handling of all boxes. In terms of efficiency, besides modularity, all parameters could be improved. Regarding weight, the LeanDfX scorecard results showed that, despite the future introduction of the pneumatical material and suction cups, there was still allowable weight capacity that could be utilized to improve structural integrity.

Following this evaluation, it is also essential to provide a comprehensive review of the selected concept and its components. As a first step, it is important to present the gripper configurations that will be used to handle the biggest and smallest boxes. In Figure 43, it is possible to observe a representation of the boxes (line in blue), and the gripper configuration to handle the 550 mm edge size boxes (a), and the configuration to handle the 150 mm edge size boxes (b).

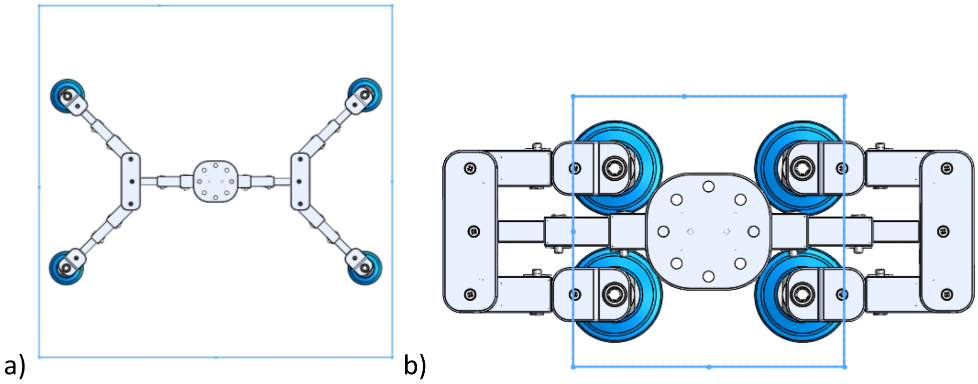


Figure 43 - Concept four box handling configurations: 550 mm edge size box (a), and 150 mm edge size box (b)

Regarding the structure of the selected concept, the gripper is characterized by thirteen modules, including six telescopic structures, two that only adjust in one direction, and four that also rotate, one gripper mount, two telescopic structure coupler, and four suction cup mounts. Table 21 presents the major components of concept four and respective description.

Table 21 - Concept four component list

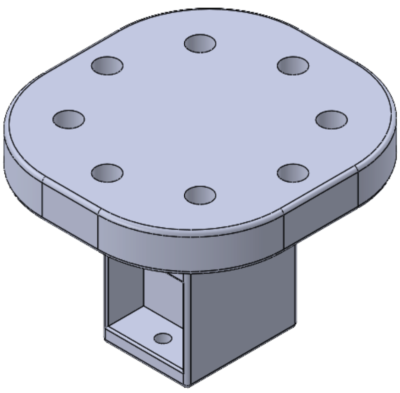
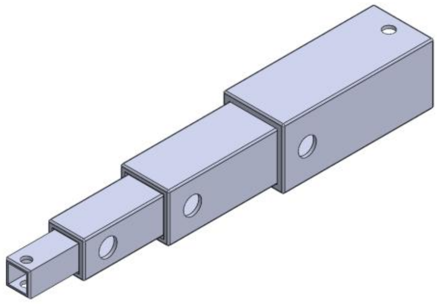
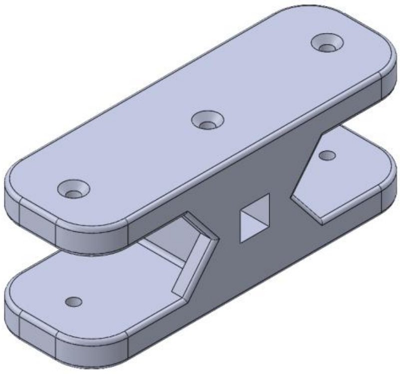
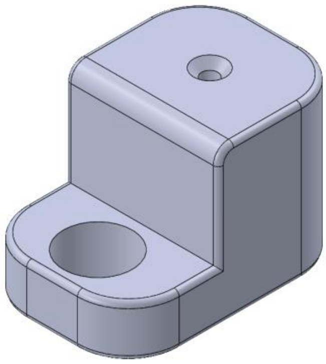
Component		Description
Gripper mount		This is the largest component of the gripper, and it serves as the interface between the gripper and the cobot. It features six precisely modelled holes designed to match those of the cobot's mounting plate, which is used to attach end-effectors. Additionally, this component provides the mounting points for two telescopic structures.

Table 21 - Concept four component list (continued)

Telescopic structure		The telescopic structures provide the collaborative robotic gripper its adjustment capabilities. In this concept, the structure is fixed in the desired position using screws. However, this approach does limit the overall adjustability of the gripper. Each segment of the structure uses a small notch that mechanically interlocks the components and prevents them from falling out or disengaging during adjustment.
Telescopic structure coupler		This part is very important as it will serve as the coupler for three telescopic structures, both the ones with linear adjustment and those capable of rotational movement. It will be used on both sides of the gripper.
Suction cup mount		This component functions as a mounting bracket for the suction cups, and it will be placed at the edges of each rotational telescopic structure. It incorporates two distinct holes, the smallest was designed for the attachment of the telescopic structure, and the other for securing the suction cups.

4.2. Gripper structure development

Although the previously selected concept design through a decision matrix was developed with production feasibility in mind, it remained far from fully functional. In particular, enhancements were necessary to enable the correct integration of the pneumatical material within the gripper structure. This is an important factor to increase the safety of the gripper during collaboration with workers. Additionally, the design in itself required further modifications not only to enhance safety but also to improve overall functionality. However, before implementing these design changes it was important to evaluate the desired level of modularity. As shown by the LeanDfX scorecard in Figure 42, the level of modularity present in the concept was already satisfactory, however, that scorecard did not consider cost. For that reason, it would be important to create another scorecard to balance modularity with cost concerns as, theoretically, a higher degree of modularity may lead to increased costs. Nevertheless, in this work, certain fabrication decisions identified as essential for achieving Ecodesign goals have rendered the previously mentioned trade-off largely irrelevant. Specifically, the use of AM for component production results in similar costs regardless of the number of components produced, as the consumption of raw materials will remain unchanged, while also resulting in similar production times. Additionally, this manufacturing process does not require the use of specialized tooling. The modularity consideration would have been much more critical if machining was used, as in that case the number and complexity of individual components would directly influence material waste, manufacturing time, and overall production costs.

4.2.1. Pneumatical tubing routing path

With the level of modularity defined, it was possible to advance in the development process. By the conclusion of the product architecture phase, the gripper is expected to be fully functional and ready for structural integrity simulation testing using the SolidWorks® software. To meet this objective, the gripper structure must be redesigned to accommodate the integration of the pneumatical material and the suction cups previously selected, to ensure proper functionality and to allow the integration of this material within the gripper structure. Moreover, the design of most of the gripper structure components could be further optimized to enhance safety during collaborative operations. Before initiating the optimization of the gripper components, it was necessary to determine the routing path of the tubing within the gripper structure to supply the suction cups. After evaluating several hypotheses, it was decided that the tubing would originate from the valves and enter the gripper structure through the gripper mount. This configuration ensured secure routing of the tubing within the gripper structure, minimized the risk of interference during operation, and also allowed gripper adjustment without tubing removal or entrapment. Additionally, as the gripper mount is the component positioned closest to the cobot, this arrangement enabled the tubing to be fastened along the cobot structure rather than being left hanging, which could result in injuries for workers and also potential entanglement during operation. Figure 44 depicts the path (painted in blue) to be followed by the tubing inside the gripper structure.

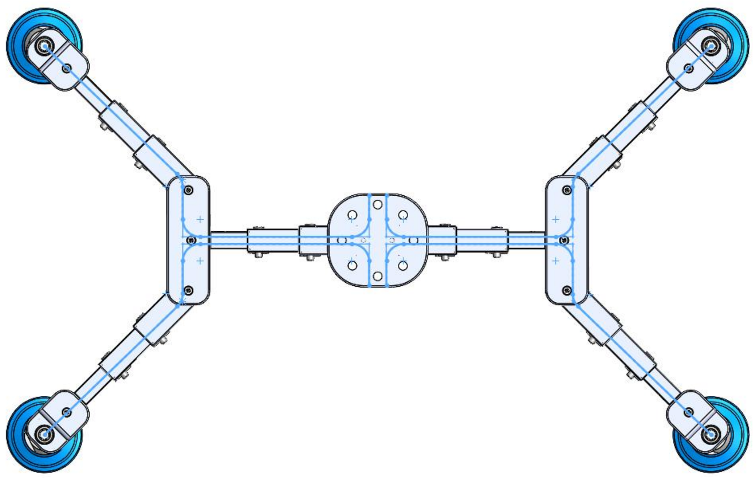
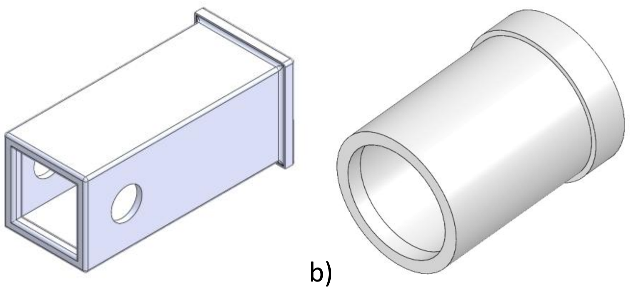


Figure 44 - Tubing path inside the gripper structure from the gripper mount the suction cups

It is also important to note that the selected tubing has a minimum bend radius of 12 mm, which must be considered during component design to create the routing channels. This constraint influences the way the tubing is introduced in the gripper structure, as it will require smooth curvatures and carefully positioned entry points to avoid excessive bending.

4.2.2. Telescopic structure development and movement blockage

Considering all the previously mentioned information, the first component to have its design optimized was the telescopic structure as its design can influence the design of the gripper mount and the telescopic structure couplers. To start, aiming to increase worker safety in case of impact, it was decided that the telescopic structure original rectangular shape should become rounded. Figure 45 represents the original tubing used in concept four (a), and its evolution (b), which will be used in the final model obtained in the end of the product architecture phase



a) b)

Figure 45 - Optimization of the tubing design: concept four rectangular shape tubing (a), and new rounded tubing (b)

The tubing length was also increased to ensure that the final model, obtained after the product architecture phase, achieved a higher level of efficiency according to the LeanDfX scorecard. By extending the telescopic structures tubing, the design reached 100 % effectiveness in the goal of meeting the requirement of gripping the boxes with a 150 mm edge size, as shown in Figure 46. Additionally, the model also achieved 100 % efficiency when handling 550 mm edge size boxes. In regard to weight, this parameter will be reevaluated at the end of the product architecture phase, when the model will be ready for prototyping.

It also decided, early in the design process, to eliminate fastened connections to secure the structure in position, as the reliance on screws not only prolonged the adjustment process, which increased downtime, but also introduced the risk of loosening over time. However, this decision also created the need to develop an alternative solution. To address the previously mentioned challenges, and after research being made on commonly used mechanisms, the proposed idea involved using quick release mechanisms such as the one displayed in Figure 47 which is designed to allow easy adjustment of a bicycle seat. It functions by clamping the seat post, which is the inner tube, to the bicycle frames seat tube, which is the outer tube. Interestingly, this clamping principle is analogous to the one required to secure telescopic structures as, in both cases, a friction-based clamping force is applied to lock a smaller tube within a larger one. In Figure 47 it is also possible to observe the major components of a quick release mechanism.

1110: Collaborative gripper		Gripper structure
Average	Effectiveness	100.00 %
	Efficiency	82.02 %
Effectiveness	Gripping area for the 150 mm box (mm^2)	100.00 %
	Gripping area for the 550 mm box (mm^2)	100.00 %
	Modularity	100.00 %
	Weight (kg)	100.00 %
Efficiency	Gripping area for the 150 mm box (mm^2)	98.84 %
	Gripping area for the 550 mm box (mm^2)	99.25 %
	Modularity	100.00 %
	Weight (kg)	30.00 %

Figure 46 - LeanDfX scorecard of the model obtained after the product architecture phase

Figure 47 - Bicycle seat quick release mechanism - (Adapted from Decathlon, 2025)

Mechanically, a quick release mechanism's working principle is based on a cam and lever system. When the lever is rotated, it engages a cam that pulls the rod that runs through the quick release mechanism. This motion creates a powerful clamping force that compresses the clamping body, which in turn compresses both the outer and inner tube, and secures them in place.

Before initiating the development of the quick release mechanism for the collaborative robotic gripper, it was defined that the rod would be created using a normalized screw and nut combination. Consistent with the gripper structure, AM would be used for the clamping body and lever to achieve Ecodesign goals and to enhance design freedom.

The first component to be developed was the clamping body. To facilitate the adjustment of the telescopic structures and consequently improve the grippers' adjustability, the quick release mechanism should be able to be easily disassembled. For that reason, the clamping body was designed to have two components, contrarily to the one depicted in Figure 47, which is a single integrated part. This decision allows the clamping body to open and close on a common pivot point. These two parts would be secured by an additive manufactured pin. Figure 48 shows the assembly of these three components.

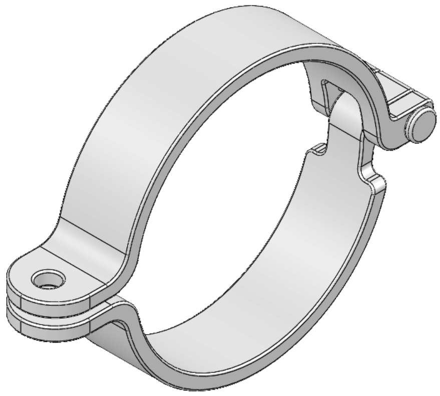


Figure 48 - Assembly of the clamping body

The next step on the design process was the lever, including the zone where the cam will be introduced and its external rounded shape. This zone is the most critical part of the lever's design as it will dictate the separation between the two faces of the clamping body when the lever is closed. The precise level of displacement needed to not only secure the tubing but also maintain structural integrity will be assessed during the product detail phase through structural simulation. To improve safety, and also to enhance the aesthetics of the gripper, the lever was developed to be coincident with the telescopic structure's tubing when in the closed position. Figure 49 is a representation of the developed lever. In the figure it is also possible to observe the hole where the cam will be assembled.

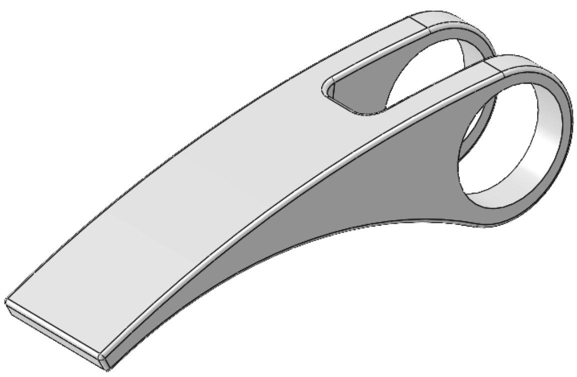
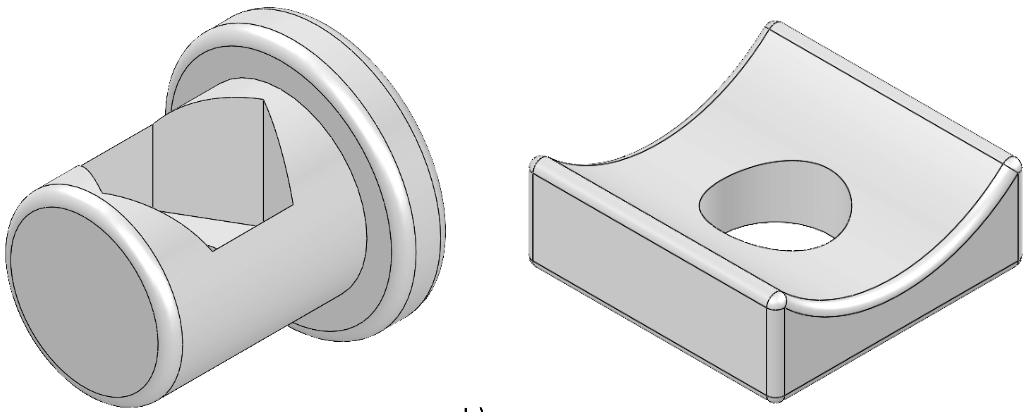


Figure 49 - Quick release mechanism lever

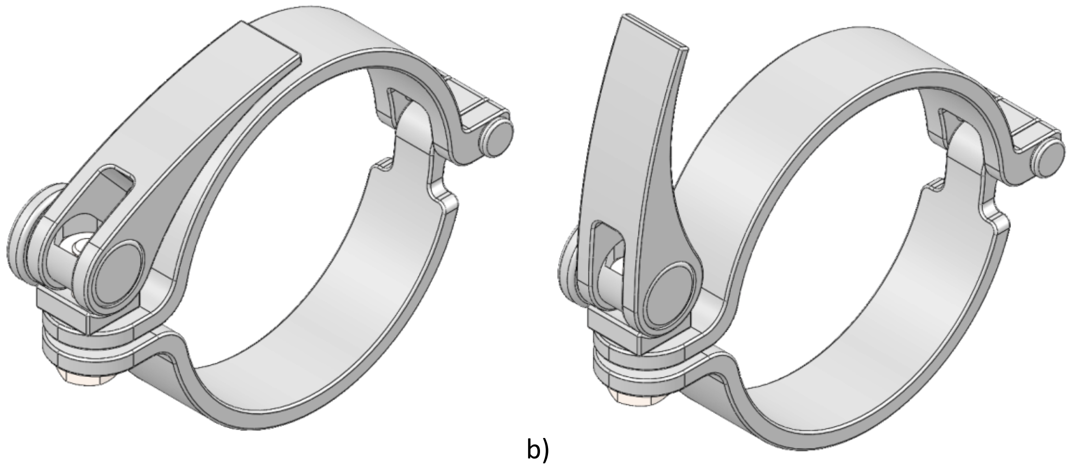
To complete the lever system, the cam and cam seat were developed. The cam (Figure 50 a) has a dual function, which is to provide the pivot point for the lever, and also secure the rod's nut. AM made it possible to combine these roles in a single part. The component was designed with an external circular surface for proper placement within the lever and an internal recess to accommodate the nut. On the other hand, the cam seat (Figure 50 b) has a rounded surface to serve as a contact point for the lever to rotate against.



a) b)

Figure 50 - Quick release mechanism's cam components: cam (a), and cam seat (b)

With all the parts of the quick release mechanism developed, the assembly of the final design was completed, and will undergo testing during the product detail phase. Furthermore, it is important to mention that, during the design process, different variants of the mechanism were developed to accommodate different tube diameters. Figure 51 depicts the final assembly of the developed quick release mechanism in closed position (a), and open position (b).



a) b)

Figure 51 - Assembly of the developed quick release mechanism: closed position (a), and open position (b)

The implementation of a quick release mechanism to secure telescopic tubing introduced a new challenge that required resolution. For proper functionality, the outer tube must undergo a slight deformation to generate sufficient friction against the inner tube. However, even with the use of additively manufactured components, the inherent stiffness of the tubes prevented the necessary deformation from occurring. To overcome this issue, small notches were introduced in the tube design, which promote the tubes' deformation and secure the telescopic structure in the required position. The original tube (a), and optimized version with notches (b) are represented in Figure 52.

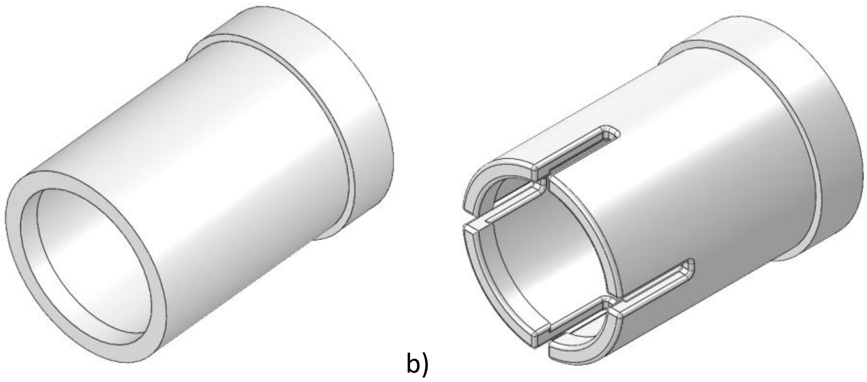

a) b)

Figure 52 - Evolution of tube design: original rounded tube (a), and rounded tube with notches (b)

4.2.3. Gripper mount

With the telescopic structure's functionality ensured, the next step was to design its coupling with the gripper mount and telescopic structure coupler. To achieve this goal, both these components suffered major changes. The first component to be optimized was the gripper mount. Figure 53 depicts the gripper mount used in concept four (a), and its optimization for the final model (b).

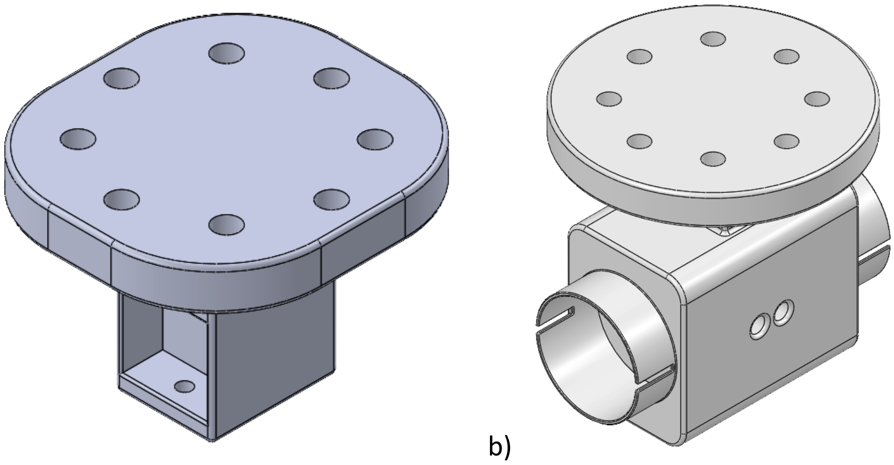

a) b)

Figure 53 - Evolution of the gripper mount design: concept four gripper mount (a), and final model gripper mount (b)

The first major modification to the gripper mount involved adapting it to accommodate rounded tubes instead of rectangular ones. Although this adjustment was relatively straightforward, it introduced a new challenge. In the initial concept, the gripper mount was secured to the telescopic structure using a screw, but the transition to rounded tubes rendered this approach unfeasible. To address this change and drawing on the knowledge gained from the development of quick release mechanisms, it was determined that the most effective solution would be to integrate such a mechanism. This choice led to the introduction of the rounded extensions visible in the optimized component (Figure 53 b). These extensions, like the tubes themselves, incorporated notches that enabled the quick release system to securely clamp the tube. Figure 54 depicts the assembly of the gripper mount and the tubing of the telescopic structures using the developed quick release mechanisms.

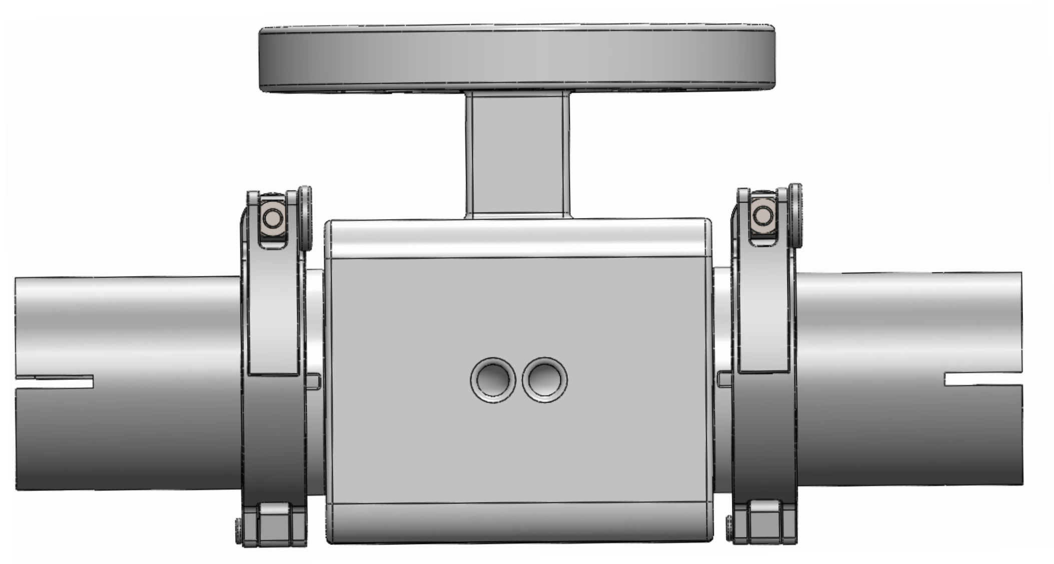


Figure 54 - Assembly of the gripper mount to the telescopic structures

Another change in the gripper mount was the development of the routing path for the pneumatical material tubing to pass inside it. As previously noted, the pneumatical material tubing has a minimum bend radius of 12 mm thus, a 15 mm radius was used in the path design to ensure safe flexing and prevent damage. The designed paths can be observed in Figure 55.

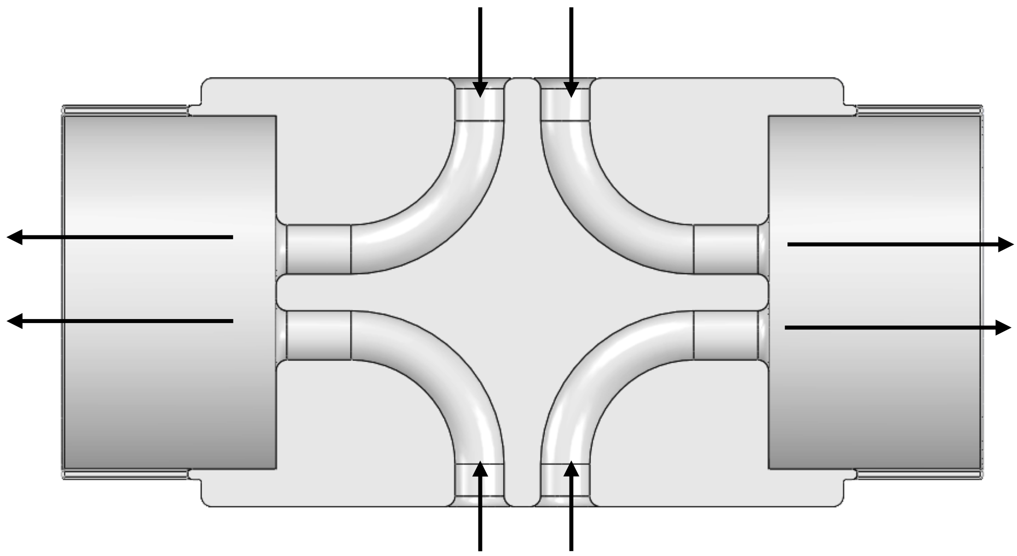
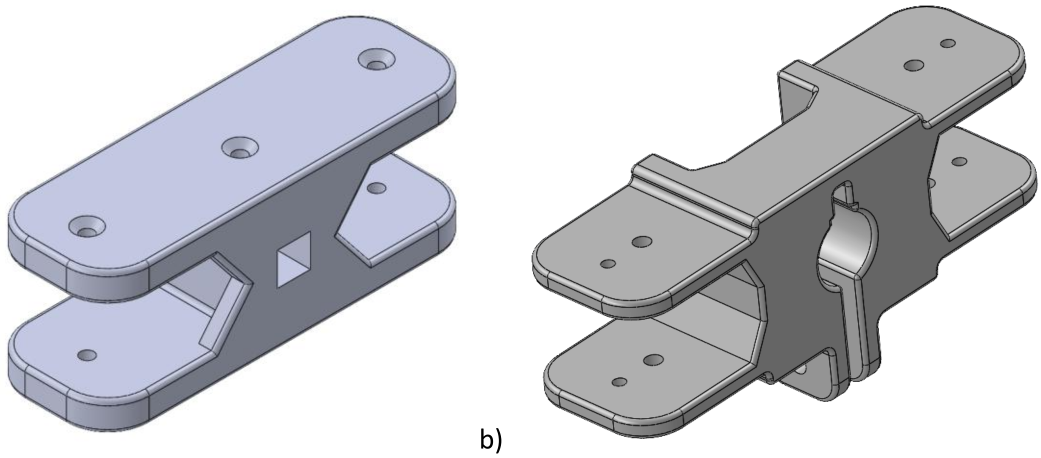


Figure 55 - Routing path for the pneumatical material tubing inside the gripper mount

To finish, it is important to mention that the changes made to the gripper mount involved introducing additional rounded edges in the design, which will enhance the safety of the component in collaborative operations.

4.2.4. Telescopic structure coupler

The next component to be optimized in the product architecture phase was the telescopic structure coupler. As the name suggests, this component is critical for the functionality of the gripper as it holds three telescopic structures together. For that reason, it suffered a big transformation, from the original solution used in the concept (a) to the newly optimized one (b) (Figure 56).



a) b)

Figure 56 - Evolution of the telescopic structure coupler: concept four telescopic structure coupler (a), and final model of the telescopic structure coupler (b)

The first alteration to the component was its geometrical optimization to enable the coupling of the telescopic structure that connects to the gripper mount. The initial change involved adapting the design to accommodate rounded tubes, which was a simple modification. The greater challenge, however, was to assess an effective method to assemble the tube to the coupler as, originally, screws were used, which was now not possible. The first approach involved the integration of a quick release mechanism, similar to those previously developed. While technically possible, this solution proved difficult to implement due to the coupler's geometry and limited dimensions. Consequently, an alternative approach was adopted, which involved the introduction of a large slot in the coupler (Figure 57 a) that could be tightened using a screw and nut combination (Figure 57 b). When fastened, enough friction was generated between the components that were forced to contact to hold them securely in place. During the slot shape design, although the tube should already be fixed securely, it was deemed essential to prevent the rotation of the tubing within the coupler. To achieve this goal, a small notch was introduced in both the tube and the corresponding slot to ensure that the tube could not rotate, and also that it could only be inserted in a specific orientation.

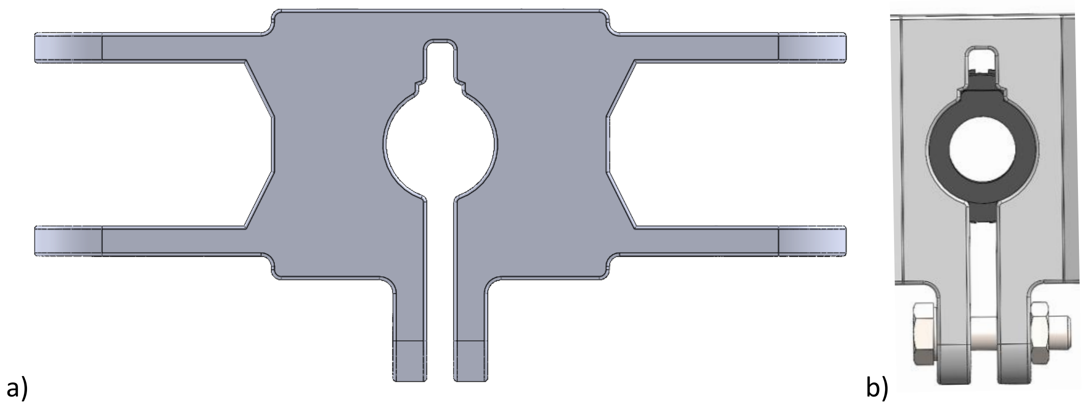


Figure 57 - Coupler and smallest tube assembly: slot geometry (a), and complete assembly (b)

As for the tubing, in addition to the previously mentioned slot, an indentation was incorporated into the design of the smallest diameter tube to ensure its proper seating against the coupler. Figure 58 depicts the indentation created in the tube.

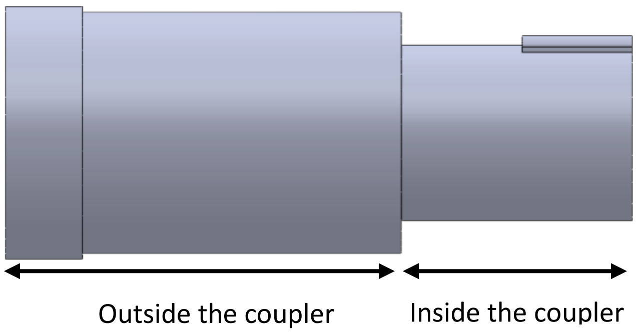


Figure 58 - Smallest diameter tube indentation and positioning in relation to the coupler

After securing the first telescopic structure, it was also important to guarantee that the pneumatical material tubing could continue its path inside the coupler, and into the rotating telescopic structures. Thus, two small 6 mm holes were introduced in the coupler. Figure 59 depicts the developed holes circled in red.

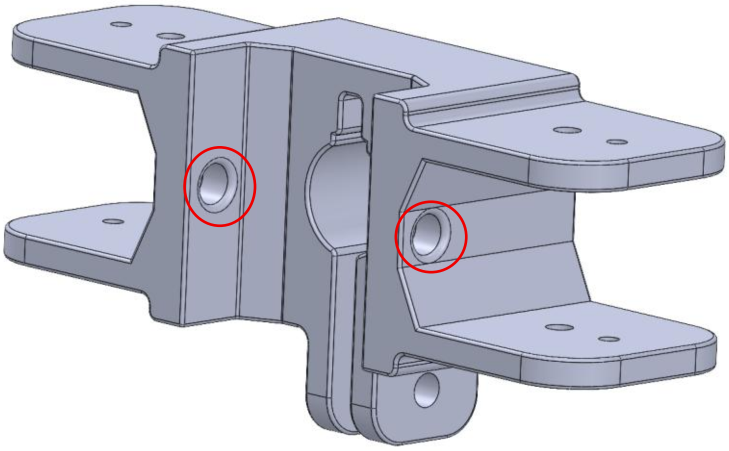
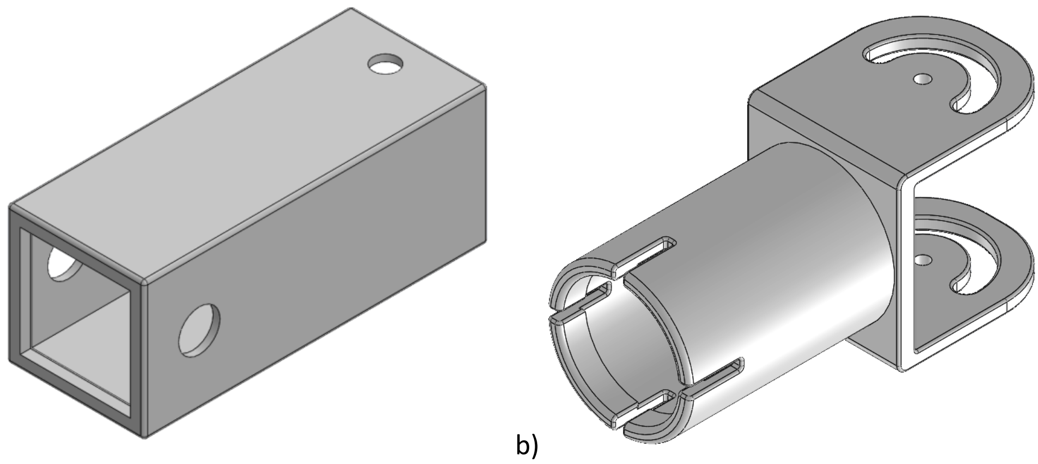


Figure 59 - Pneumatical material routing path holes

Another change made to the design of the coupler was the assembly of the rotating telescopic structures. Initially, the idea was for the large diameter tube to be mounted inside the two extensions of the coupler. However, although this approach was feasible, it was concluded that allowing the tube to enclose the coupler would be preferable, as this configuration enhanced structural stiffness and facilitated the alignment of the components during assembly. This decision made it necessary to perform extensive changes to the large diameter tube to be used in the rotating telescopic structures. Figure 60 represents the original tube used in concept four (a), and the optimized version (b).



a) b)

Figure 60 - Rotating telescopic structure large tube: concept four tube (a), and optimized version (b)

The pivoting hole and the slotted hole present in the optimized tube will be aligned with the two small holes which are present in the coupler. The smaller hole slot is intended for a screw and nut combination, serving as a pivot point for the rotation of the telescopic structure, while the slotted hole will be used to fix the structure in place. Due to its shape, it will offer the rotating telescopic structure almost limitless adjustment possibilities. Figure 61 illustrates the assembly of the tube and the coupler.

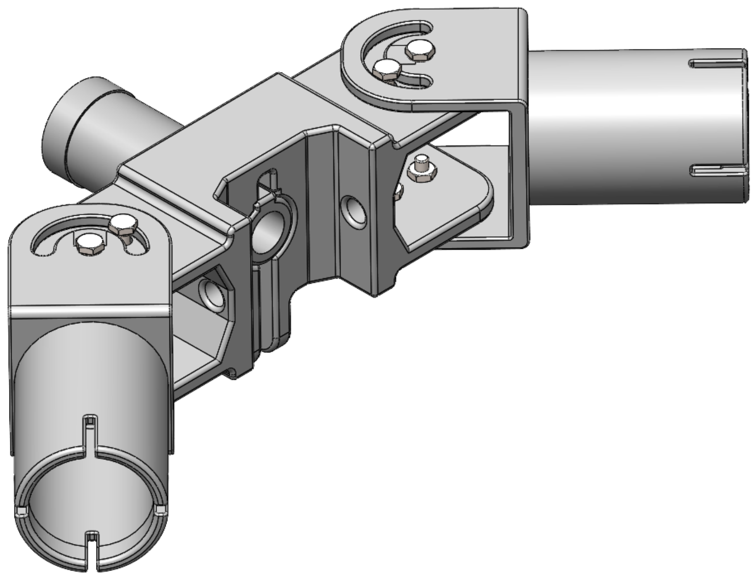
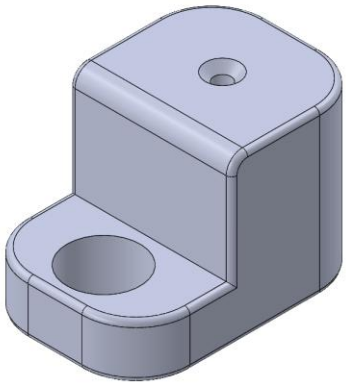


Figure 61 - Coupler and telescopic structures assembly

4.2.5. Suction cup mount and final CAD model assembly

The last component to undergo major modifications was the suction cup mount, which required changing the design of the smallest tube of the rotating telescopic structure. The final design for the suction cup mount, which was used in the concept, prevented the pneumatical material tubing to reach the suction cups internally. During that stage of development, that characteristic was accepted, due to the pneumatical material having not yet been selected, and the only certainty was the use of suction cups. However, after defining all the pneumatical material needed for the gripper to operate and also deciding that the vacuum generators would be in direct contact with the suction cups, it was clear that the suction cup mount needed a thorough redesign. This improvement included changing its shape to make possible the assembly of the vacuum generators within the structure to enhance the overall safety of the gripper. The differences between the initial version (a), and the optimized version (b) can be observed in Figure 62.


a)

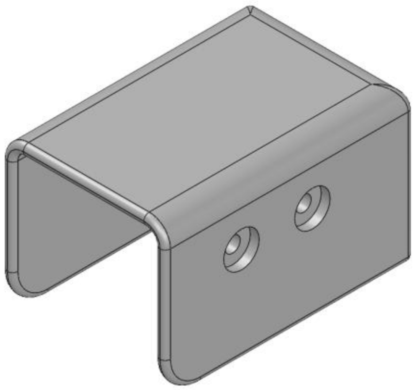

b)

Figure 62 - Evolution of the suction cup mount design: original concept (a), and optimized version (b)

The first important decision to be made on the suction cup mount concerned its attachment to the smaller diameter tube of the rotating telescopic structure. Originally, a solution similar to the one used in the coupler, which was a slot-based connection, was considered. However, this approach required the use of a screw and nut combination at the edges of the gripper, which was deemed as a potential safety risk. For that reason, the design was revised to incorporate a quick-release mechanism solution similar to the ones previously mentioned in this work. This solution eliminated the safety concern and allowed the mechanism to be concealed within the suction cup mount, thereby improving functionality, overall safety of the gripper, and aesthetics. It is though important to mention that, for the previously designed mechanism to be concealed inside the suction cup mount, it was necessary to redesign the lever. For the quick release mechanism solution to be viable, notches were introduced in the section of the suction cup mount where the smaller diameter tube was inserted. As previously mentioned in this work, these notches allow the wall of the suction cup mount to deform elastically, therefore creating sufficient friction to securely hold the tube in place. The zone where the tube was inserted was designed to replicate the circular shape of the tube, while, contrarily to the telescopic structure coupler, a notch was not introduced in the tube design. This decision is based on the small distance between the suction cup, which had limited movement when handling boxes, and restricted rotational movement being anticipated. Figure 63 depicts the assembly of the smallest tube of the telescopic structure (painted in black) within the suction cup mount (painted in dark grey). In the figure it as also possible to observe the use of the quick release mechanism and the newly redesigned lever (painted in light grey).

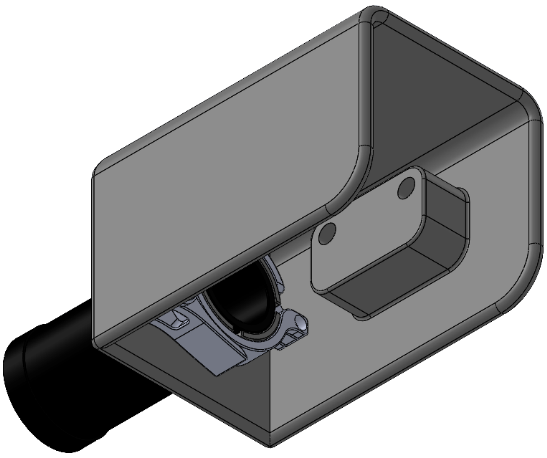


Figure 63 - Suction cup mount and rotating telescopic structure assembly

With the component assembly now introduced and explained, the next step is to present the feature integrated into the suction cup mount that ensured proper fixation of the vacuum generator. As shown in Figure 63, this feature is an extrusion specifically designed for the body of the vacuum generator to seat against the smaller diameter tube edge, while simultaneously concealing the required fitting within the gripper structure. Additionally, two holes were incorporated into the extruded section of the suction cup mount, which were precisely aligned with mounting holes present in the body of the vacuum generator. Figure 64 illustrates the assembly of the vacuum generator in the suction cup mount (painted in black) (a), and also a section view of the fittings concealed inside the telescopic structure smallest tube (b).

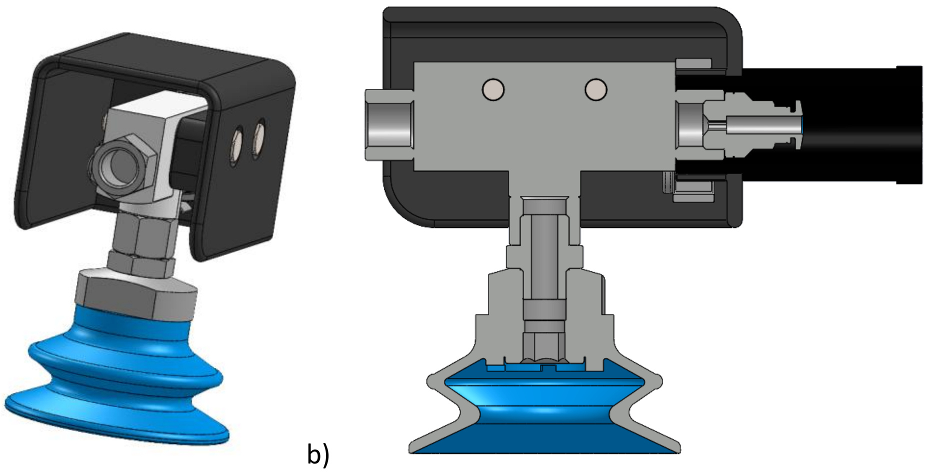


Figure 64 - Suction cup mount and vacuum generator assembly: vacuum generator seated against the gripper mount (a), and section view of the concealed fittings (b)

A screw and nut fastening system was then employed to securely attach the vacuum generator to the mount. The precision which was employed in the introduction of the vacuum generator was crucial to ensure that when the gripper was configured to handle the 150 mm edge size boxes, the suction cups maintained full contact with the box surface.

With this final assembly described, it is now possible to introduce the final CAD model of the developed collaborative gripper, which can be observed in Figure 65.

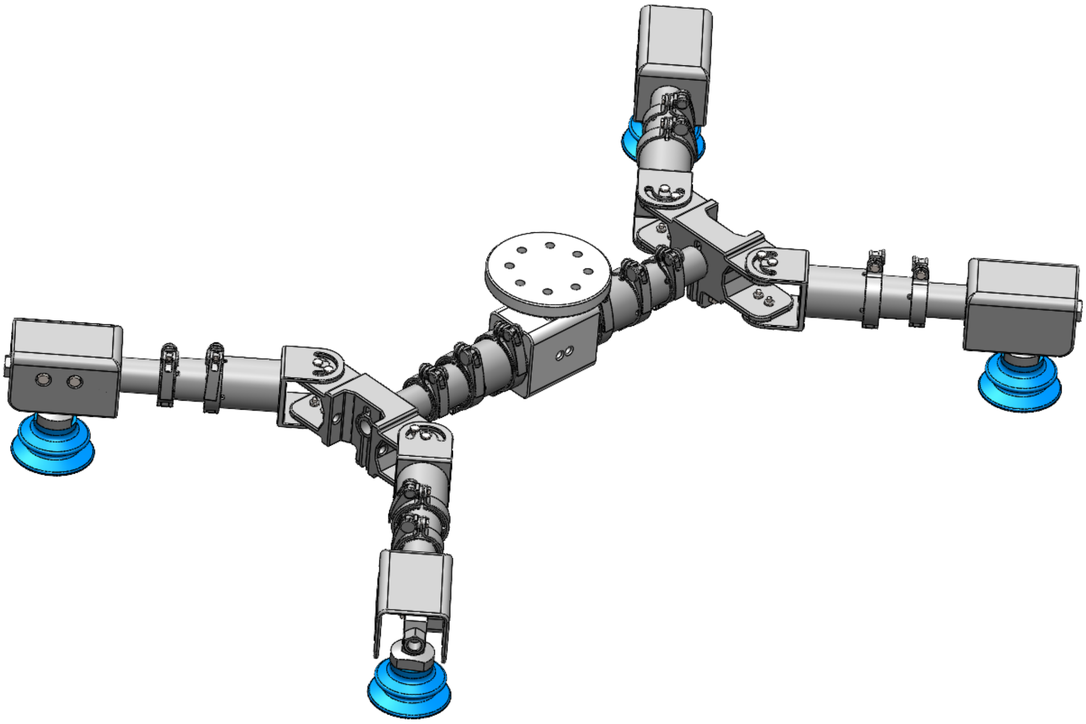


Figure 65 - Final CAD model of the collaborative robotic gripper obtained after the product architecture phase

Table A. 1, which is depicted in appendix A, presents all the manufactured components, the fastening elements, and the pneumatical material, all of which contribute to the gripper's overall weight. With the final CAD model developed it was possible to proceed with the development process, more specifically to enter in the product detail phase and engage in structural simulation.

4.3. Structural simulation

At the beginning of structural simulation procedure, particularly when the model requires a large number of tests on multiple component assemblies, it is essential to perform a mesh convergence study. To start this process, it was first necessary to select a sub-assembly of the gripper that could be used in this procedure, since the simulation of the entire gripper structure multiple times would consume an enormous amount of computational time. Following a preliminary analysis of the sub-assemblies which will be presented and simulated in this section, the configuration selected for testing was the one comprising of two tubes of the telescopic structure, joined by one of the developed quick release mechanisms. This selection was made primarily because it represents one of the most recurrent mechanisms in the gripper. The sub-assembly to be used in the mesh convergence study can be observed in Figure 66.

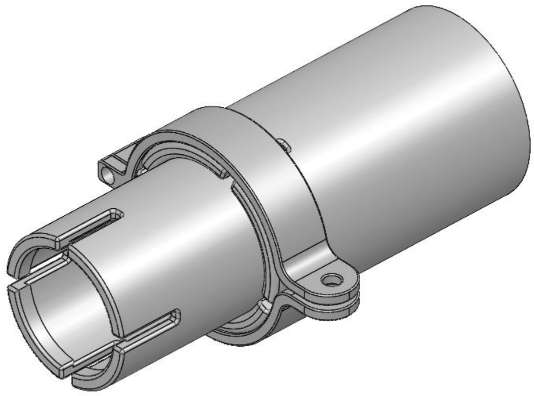


Figure 66 - Two tube sub-assembly used in the mesh convergence study

As it can be seen in Figure 66, the quick release mechanism within the assembly was simplified by removing all components except for the clamping body. This simplification was carried out to reduce computation time, which is a common goal in structural simulation. Regarding the objective of the simulation, in addition to performing the mesh convergence study, it aimed to determine the displacement of the clamping body required for it to secure the inner tube, thereby ensuring that the two tubes are securely fixed together. Understanding the objective of the simulation is essential to define the appropriate boundary conditions during the pre-processing phase, and to draw meaningful conclusions from the simulation results. The first step in the pre-processing phase was to define the type of analysis to be made. In this case, the decision was to perform a static small displacement analysis since the loads do not change with time, and the gripper is not subjected to large deformations. The second step in the pre-processing phase was the introduction of PLA, the material to be used in these components, into the SolidWorks® material library. The majority of the values were previously presented in this work during the material selection process. However, the Poisson ratio was not mentioned, mainly because that value is dependent on the level of infill and also can vary depending on the quality of the printing. For that reason, 0.35 was used, which is a common value for PLA (Aldosari et al., 2023). In this context, the tensile strength was considered as the representative yield strength, because for 3D printed PLA, which is a polymeric material, the yield strength is often comparable to its tensile strength due to its brittle behaviour and limited plastic deformation (Ribeiro et al., 2024).The properties assigned to PLA within SolidWorks® are presented in Table 22, and this properties were used in all of the sub-assembly simulations.

Table 22 - PLA properties introduced in the SolidWorks® material library

Property	Value	Units
Elastic modulus	2580	N/mm^2
Poisson ratio	0.35	N/A
Shear modulus	318.9	N/mm^2
Mass density	1240	kg/m^3
Yield strength	35	N/mm^2

Following this step, the boundary conditions were defined. The first boundary condition applied was the fixed geometry constraint. Based on an analysis of the assembly's mechanical motion, it was determined that, during gripper operation, the outer tube edges exhibited negligible displacement. Therefore, these region was considered fixed in the simulation. The specific geometrical place where this boundary condition was applied is shown in Figure 67.

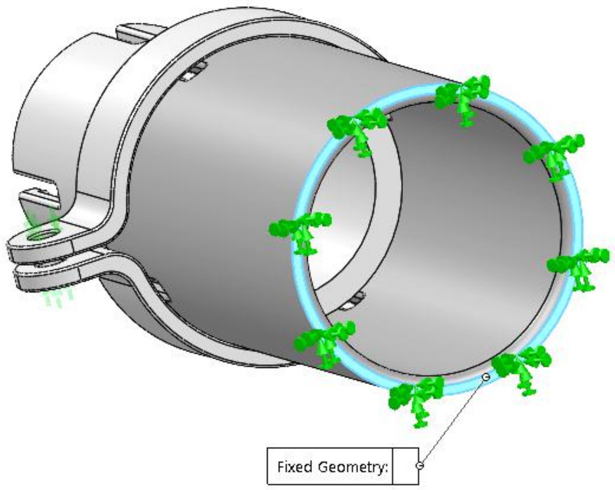


Figure 67 - Fixed geometry boundary condition in the two tube sub-assembly

To further reduce computation times and accurately simulate the motion of the clamping body, a virtual pin with rotation but no translation possibility was introduced in the axis connecting the two components of the clamping body. The location of this pivot axis and respective virtual pin (painted in blue) is displayed in Figure 68.

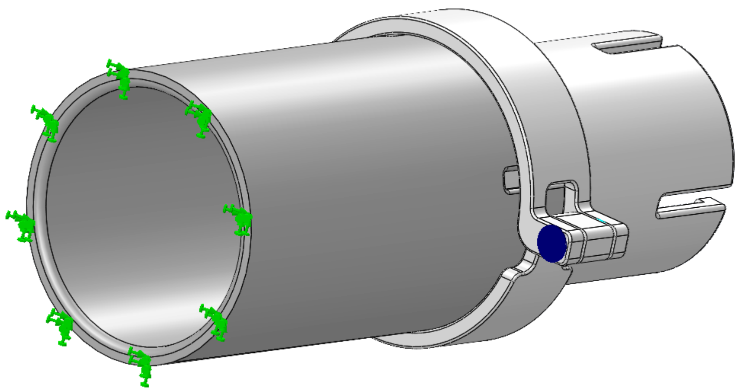


Figure 68 - Virtual pin location in the two tube sub-assembly

The most challenging aspect of this particular simulation was modelling the motion of the clamping body when the lever was closed. After evaluating several approaches, it was determined that the most effective method to replicate this motion was to apply a reference geometry condition at the holes through which the rod is mounted. In this case, it was possible to define that the two components of the clamping body translated 0.2 mm towards their approach, which is what occurs during the actual clamping operation. The 0.2 mm translation corresponds to the value introduced during lever design, which will now be tested to ensure that it can be used. Figure 69 depicts the boundary conditions respective direction. The other boundary condition, which is not visible in this image is equal, but in the opposite direction.

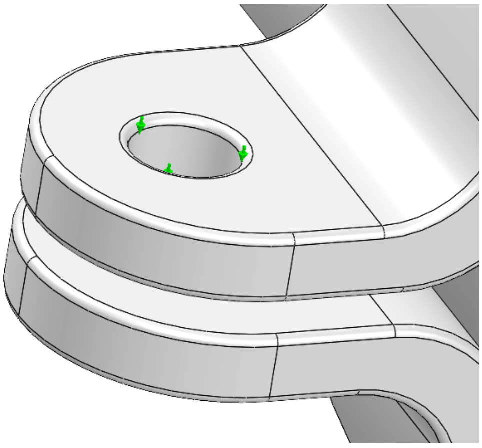
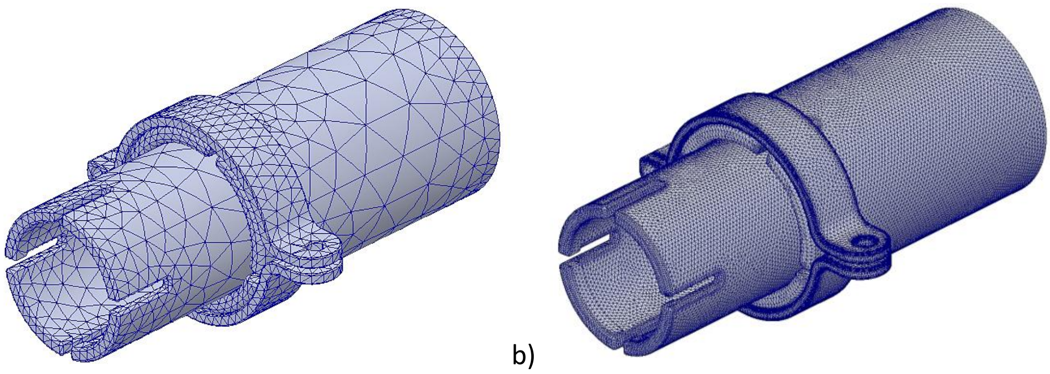


Figure 69 - Reference geometry boundary condition in the two tube sub-assembly

In regard to the interaction between the components, contact local interactions with 0.05 friction coefficient were applied in all surfaces, including the contact zones between the tubes, the largest diameter tube contact with the clamping body, and also the contact between the two components of the clamping body. With all the boundary conditions applied, the mesh generation process could be initiated. At this stage of the work, in light of the mesh convergence study, it was necessary to define the meshes to be tested, beginning with a coarse mesh with a smaller number of larger elements to the most refined mesh with smaller elements. The refinement of the mesh is directly related to the size of the largest and smallest element. For this convergence study, six meshes were tested (dimensions in mm): 20-2, 10-1, 5-0.5, 2.5-0.25, 1.25-0.125, and 0.75- 0.075. Regarding the other characteristics relevant to mesh generation, which were consistent across all meshes, a blended curvature-based mesh was employed with 16 Jacobian points and an element size growth ratio of 1.4. Figure 70 depicts the 20-2 coarsest mesh (a), and the 0.75-0.075 most refined mesh (b).



a) b)

Figure 70 - Differences in mesh refinement: 20-2 coarsest mesh (a), and 0.75-0.075 most refined mesh

Before running the simulations for all mesh configurations, it was first necessary to evaluate and verify the results obtained with the coarsest mesh, which requires the least computational time, to confirm that the stress zones identified in the simulation corresponded to those expected based on the mechanism's motion. After analysing the results, it was concluded that the simulation accurately represented the real-life motion of the mechanism, as the regions with stress values appeared precisely in the expected locations (stress concentration regions in Figure 71. On the other hand, the red zone observed around the rods through holes, in which the highest stress value was recorded, was considered as neglectable, since the resulting stress concentration would, in practice, be absorbed by the rod itself rather than the clamping body, had the rod been used in the simulation. Figure 71 depicts the stress concentration zones previously mentioned.

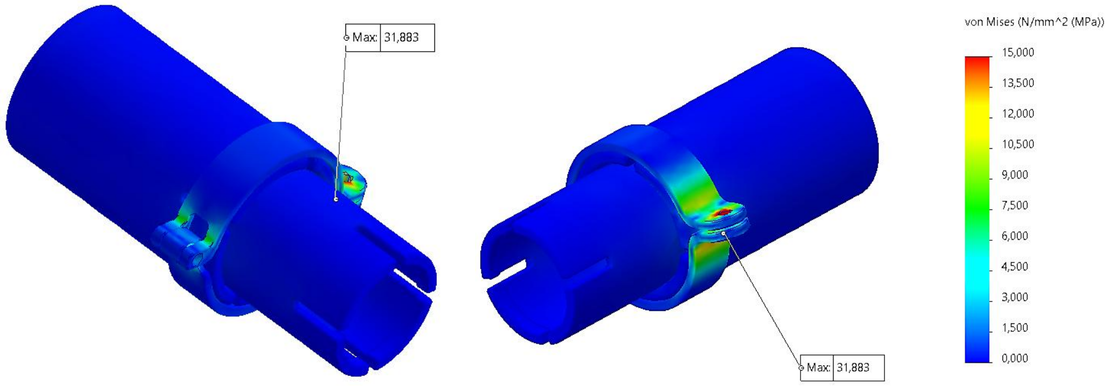


Figure 71 - Stress fields observed in the simulation results for the coarsest mesh of the two tube sub-assembly

After this preliminary evaluation, simulations were performed for all the meshes. As expected, the zones with the most stress fields did not change throughout the various simulations, which is important to validate the reliability of the results. Another important aspect was to verify whether the stresses induced by the closing motion of the clamping body reached the inner tube to secure it in place. This situation was easily verified by changing the measurement scale of the results, which revealed stress existence in the inner tube, as shown in Figure 72. It is also important to mention that these results were obtained from the simulation for the most refined mesh.

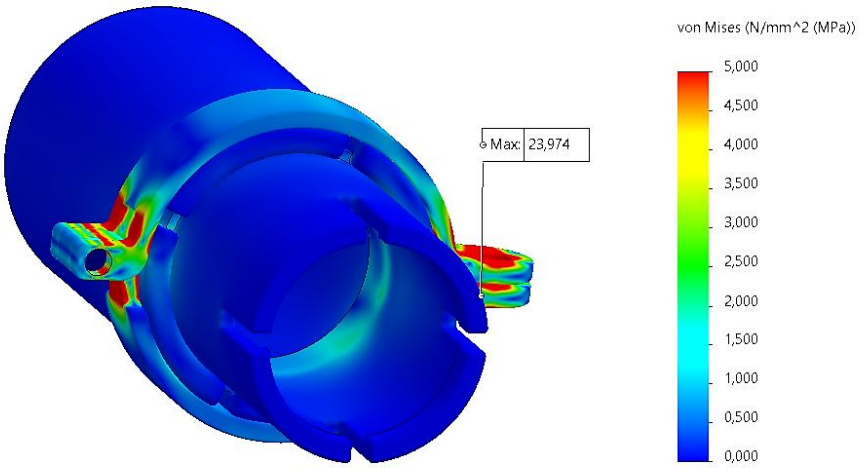


Figure 72 - Inner tube stress concentration in the two tube sub-assembly

In regard to the mesh convergence study, with the simulation results obtained for each mesh, it was possible to proceed with it. To this end, two reference points were defined, at which the stress values were extracted. These reference points (nodes) are depicted in Figure 73.

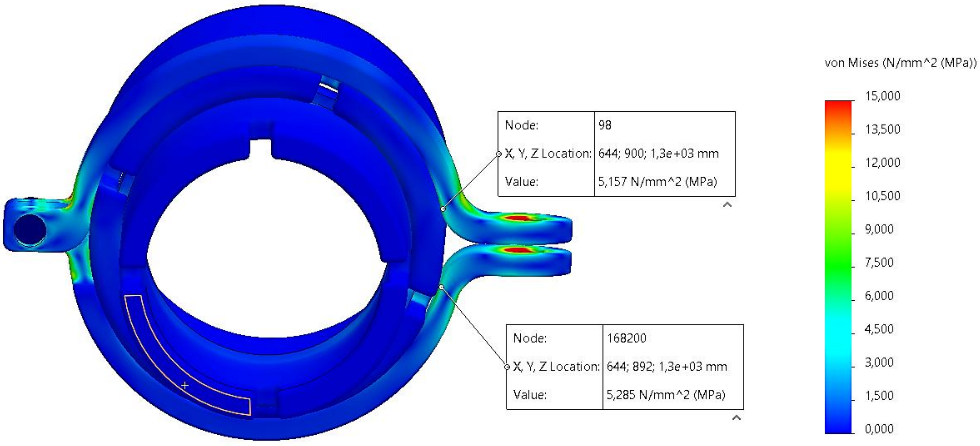


Figure 73 - Reference points used in the mesh convergence study

To facilitate the comparative analysis between meshes, and to illustrate that mesh refinement leads to an increased number of elements and nodes, Table 23 was created. This table also presents the stress values recorded in each reference point, as well as the maximum stress value observed in each simulation.

Table 23 - Simulation results for each mesh

Mesh	20-2	0-1	5-0.5	2.5-0.25	1.25-0.125	0.75-0.075
Number of nodes (MPa)	18483	50731	164180	344787	541003	898966
Number of elements (MPa)	9218	27525	97993	209233	332840	570587
Node 98 Von Mises stress (MPa)	7.142	7.659	7.481	7.313	4.896	5.285
Node 168200 Von Mises stress (MPa)	5.957	6.125	6.314	6.204	4.676	5.157
Maximum Von Mises stress (MPa)	31.883	46.738	29.489	30.404	22.089	23.974

Using the information introduced in the table it was possible to create the mesh convergence graph depicted in Figure 74.

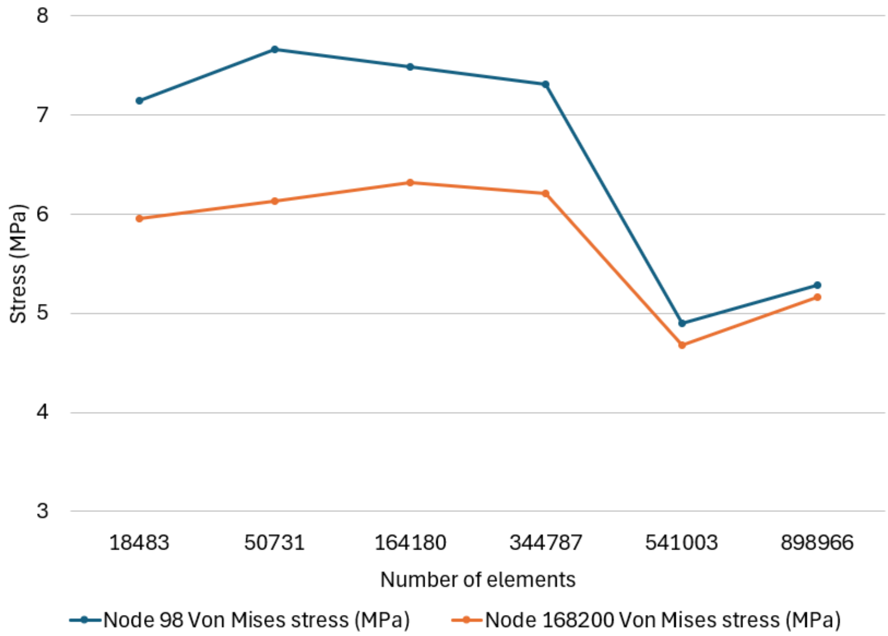


Figure 74 - Mesh convergence study graph

The results indicate two distinct convergence regions in the stress values. The first occurs between the 10-1 mesh and the 2.5-0.25 mesh, while the second is observed between the 1.25-0.125 and the 0.75-0.075 mesh. In the first convergence region, from the 10-1 to the 5-0.5 mesh, a percentile difference of -2.32 % was verified, followed by an even smaller percentile difference of -2.25 % between the 5-0.5 and the 2.5-0.25 mesh. These results indicated that the 10-1 mesh could be used. However, unexpectedly, a percentile difference of -33.05 % was calculated between the 2.5-0.25 and the 1.25-0.125 mesh, which indicated that the results had yet to converge. For that reason, the 0.75-0.075 mesh was also tested. In this case a percentile difference of 7.95 % was calculated between the 1.25-0.125 and the 0.75-0.075 mesh. Based on these results, the 1.25-0.125 mesh was selected for the subsequent simulations.

Considering this information, the selected mesh was used two simulate the same sub-assembly, but with an extra tube inside it, to simulate full retraction of the telescopic structure and to assess if the clamping body 0.2 mm displacement could also secure a third tube. The model used is illustrated in Figure 75.

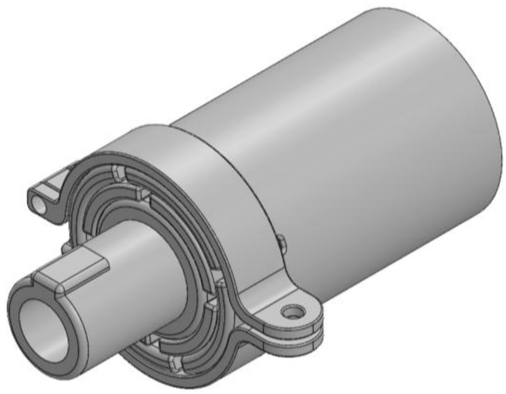


Figure 75 - Three tube sub-assembly

In regard to the boundary conditions, these were identical to the ones used in the convergence study. As for the results depicted in Figure 76, the quick release mechanism was able to secure the assembly. This was proven by the stress concentration present in the inner tube.

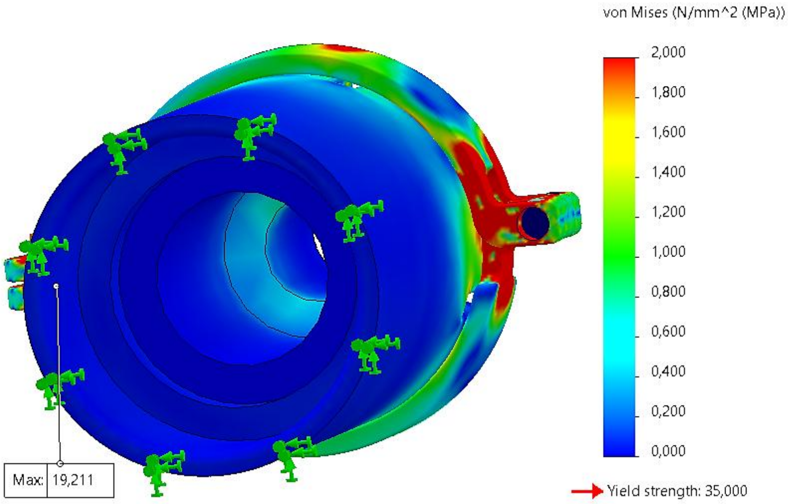


Figure 76 - Stress field inside the inner tube of the three tube sub-assembly

In regard to the other sub-assemblies, which exist in the gripper structure, their simulation was not required because their base principle was similar to the one present in the previously tested sub-assemblies. For that reason, their design was approved. After testing and validating all sub-assemblies, the final step to ensure the structural integrity of the gripper was to simulate the complete gripper structure. The validation of the previously analysed sub-assemblies confirmed that the gripper structure was securely fixed. For the structural simulation, this confirmation allowed the entire gripper structure to be considered as a single component, which enabled the application of a bonded global interaction. This approach significantly simplified the model, as all quick release mechanisms could be removed. The pneumatical material was also excluded from the analysis to reduce computational time. The structural simulation was performed using PLA as the material, consistent with previous analysis. However, as the gripper structure is subjected to bending during operation, the yield strength value originally used in the sub-assembly simulations, was replaced with the bending strength value defined for PLA. As for the configuration to be simulated, the gripper was analysed in its fully open position, which is used to handle the largest boxes. This configuration represents the critical loading condition for the structure as it is the one subjected to higher bending moments. Figure 77 presents the gripper structure model used for the simulations.

The external loads applied in the model were the forces produced by the handling of a 10 kg cardboard. If the suction cups were kept on this analysis, a 25 N load would be applied on the extremity of each suction cup. Since they were excluded, however, the load was instead applied to the through holes of the suction cup mounts, corresponding to the locations where the screws fastening the vacuum generator were installed. The exact zone in one of the suction cup mount where the forces were applies can be observed in Figure 78.

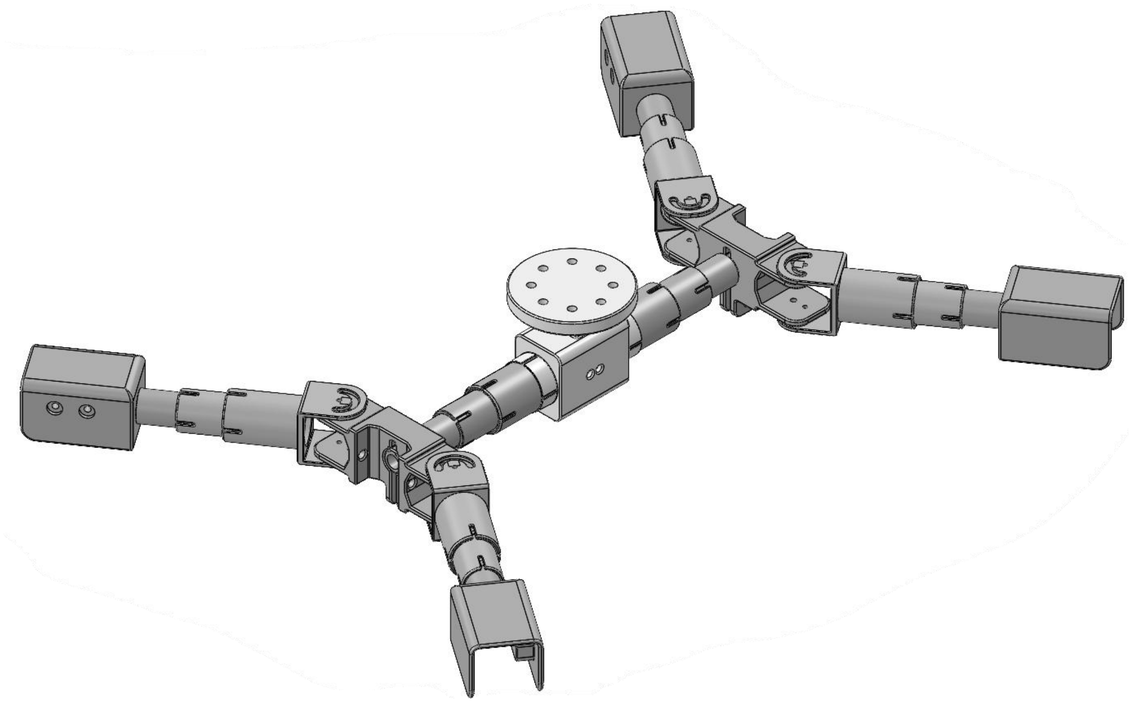


Figure 77 - Gripper structure model used for structural simulation

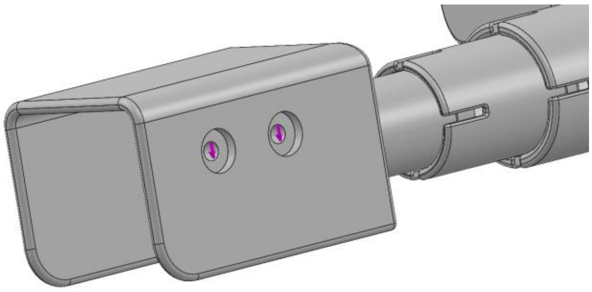


Figure 78 - External load location in the gripper structure simulation

To fix the gripper structure, the gripper mount was clamped, more specifically in the holes used to secure the gripper to the cobot. The introduced fixed geometry condition (painted in green) can be observed in Figure 79.

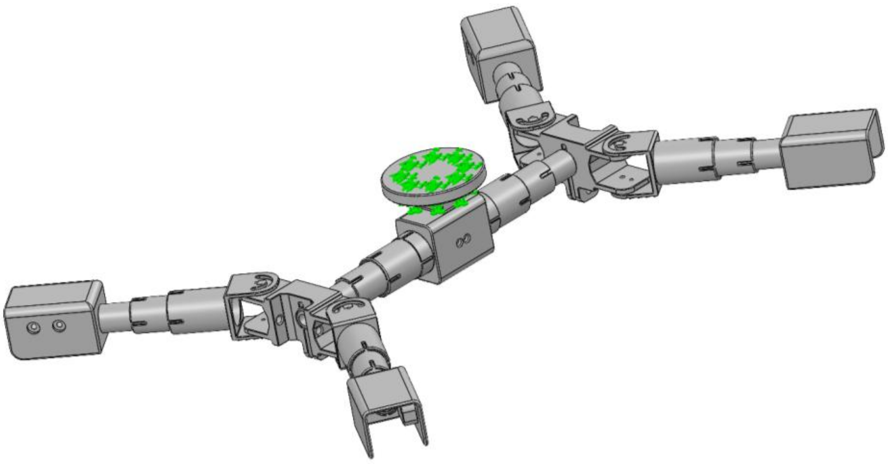


Figure 79 - Fixed geometry condition used in the gripper structure simulation

With the boundary conditions defined it was possible to engage in the mesh generation process. The created mesh was consistent with the one defined during the mesh convergence study, and some of its details around the tubing can be observed in Figure 80.

Figure 80 - Details of the mesh used in the grippers structure simulation

By running the simulation study, the Von Mises stress field illustrated in Figure 81 was obtained.

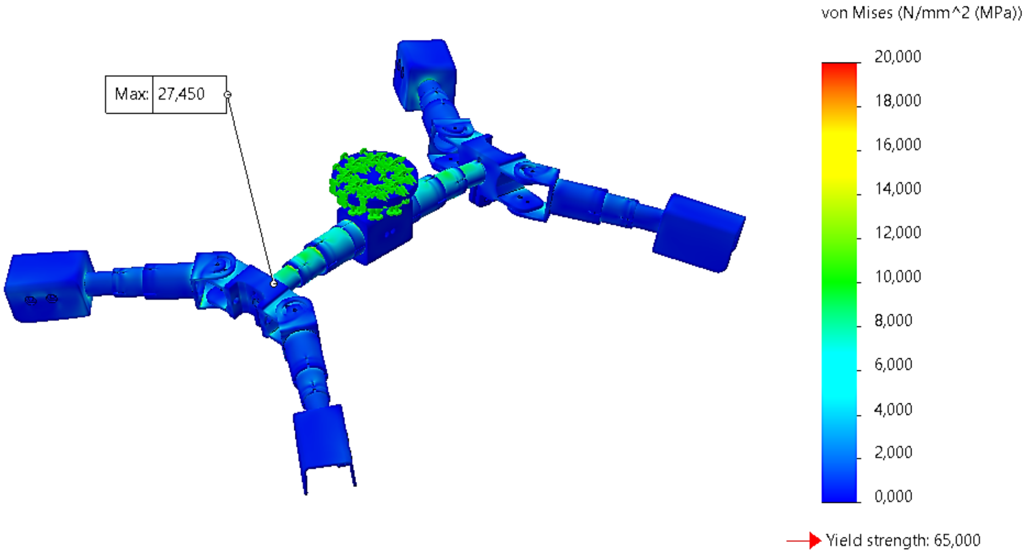


Figure 81 - Stress simulation results for the gripper structure

Regarding the stress concentration zones, the findings aligned with expectations, as most of the stress was observed in the tubes of the interior telescopic structures, which are the ones that do not experience rotation. Importantly, in this zone the stress values were below the tensile strength of PLA, indicating that the material could withstand the applied loads. This assessment was significant, as it confirmed that the simulation accurately represented real life behaviour and could be relied upon for design validation. Unexpectedly, the recorded maximum stress value was present in the contact surface of the telescopic structure coupler with the smaller diameter tube of the interior telescopic structure, as shown in the detail of Figure 82.

A stress field analysis indicated that this peak value originated from a localized stress concentration and did not accurately represent the overall structural behaviour under real operating conditions. Therefore, from a stress perspective, the gripper structure design was approved. Another important information retrieved from the analysis was the maximum resulting displacement (URES) of the gripper structure when handling the box. Although this parameter was not explicitly constrained by stakeholder requirements, it remained critical for safe and efficient operation. Keeping displacements low ensured that the cobot could accurately track the gripper's position at all times, thereby minimizing positioning errors, reducing the risk of unexpected impacts, and improving overall system reliability. The maximum resulting displacement is presented in Figure 83, and it occurred in the expected zones, which are the gripper structure edges.

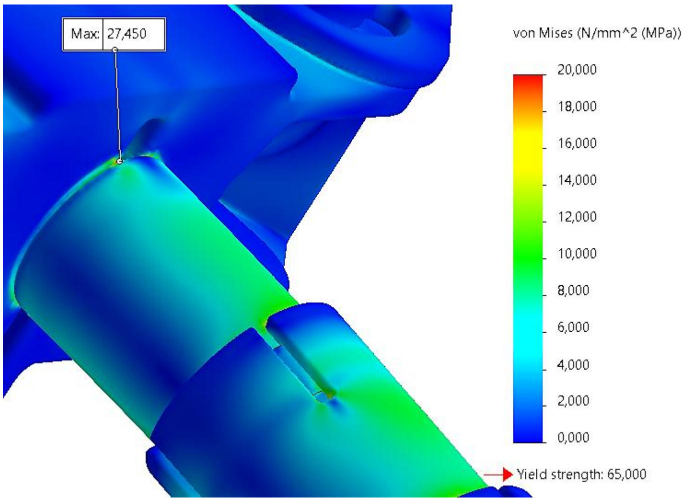


Figure 82 - Location of the maximum recorded stress value in the gripper structure

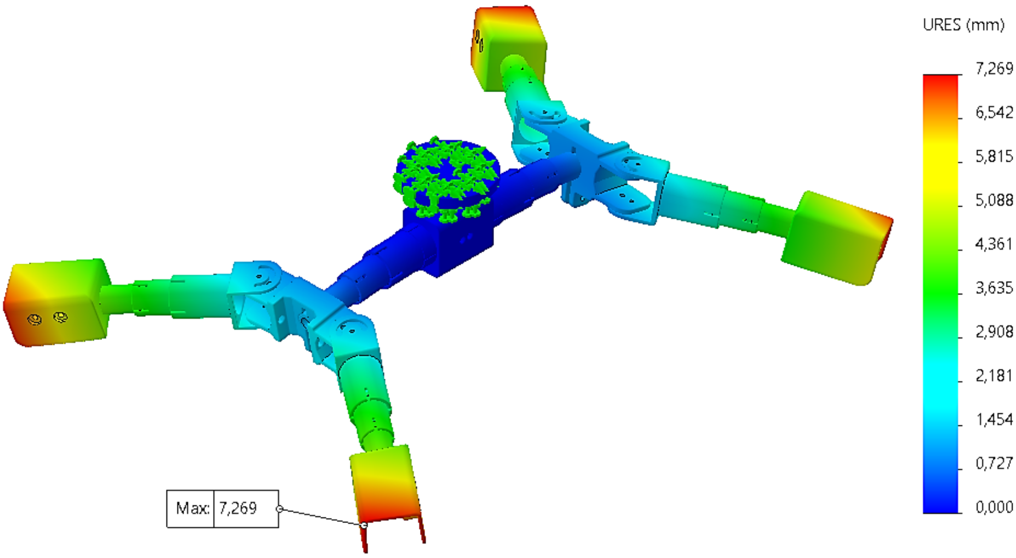


Figure 83 - Resulting displacement results for the gripper structure

Although the resulting displacement could be further reduced by increasing tube thickness, the design was approved since the observed maximum deflection of approximately 7 mm was relatively small and would not interfere with the operation of the cobot. To ensure the gripper's structural integrity, the safety factor was also estimated for all components (Figure 84). The results showed a minimum safety factor of approximately 2.4. As expected, the zones with lower safety factor were in the recorded zone for maximum Von Mises stress, and also the tubes of the internal telescopic structure.

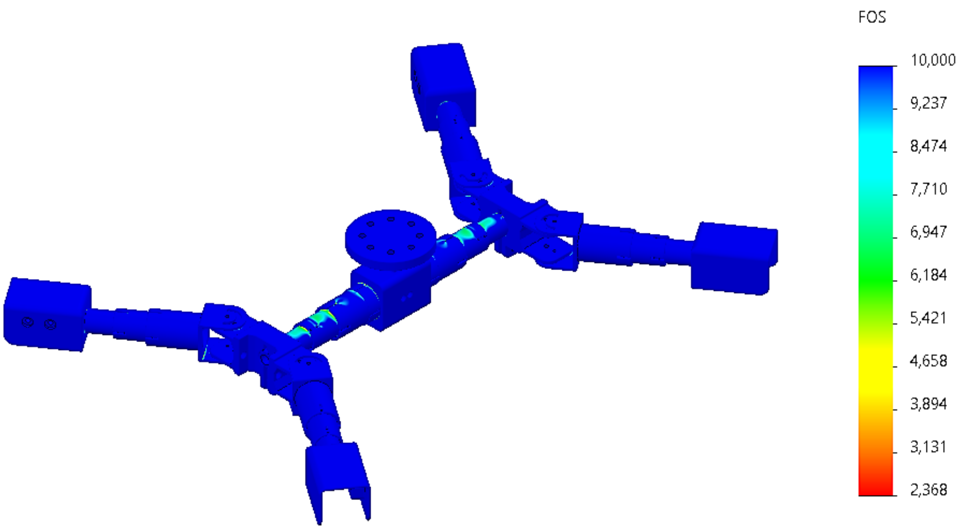


Figure 84 - Factor of safety results for the gripper structure

With structural integrity verified, the subassemblies functionality confirmed, and the material selection finalized, it was also necessary to evaluate the overall weight of the gripper system. The weight was evaluated by utilizing the SolidWorks® mass property setting to analyse the weight of the custom designed components and referencing the datasheet of standardized components. The sum of these contributions showed an estimated total mass for the gripper system of approximately 1.343 kg, which satisfies the stakeholder requirement of remaining below the maximum allowable weight of 1.5 kg. This information allowed the creation of a new scorecard which is depicted Figure 85.

1110: Collaborative gripper		Gripper structure
Average	Effectiveness	100.00 %
	Efficiency	98.78 %
Effectiveness	Gripping area for the 150 mm box (mm^2)	100.00 %
	Gripping area for the 550 mm box (mm^2)	100.00 %
	Modularity	100.00 %
	Weight (kg)	100.00 %
Efficiency	Gripping area for the 150 mm box (mm^2)	98.84 %
	Gripping area for the 550 mm box (mm^2)	99.25 %
	Modularity	100.00 %
	Weight (kg)	97.02 %

Figure 85 - LeanDfX scorecard obtained after the product detail phase

The low weight resulted in a near 100 % efficiency. With these results, it was possible to approve the design and enter in the product prototyping phase.

4.4. Prototype manufacturing and assembly

With the final CAD model approved, it was possible to enter in the product prototyping phase, which encompasses the model preparation for the 3D printing process, the presentation of the manufactured components, and the collaborative robotic gripper assembly process.

4.4.1. Model preparation for printing and fabricated components presentation

As previously discussed in this dissertation, AM was selected as the fabrication method for the components of the collaborative robotic gripper. This decision was primarily driven by the process's capacity to eliminate material waste and the design freedom it offers, which enhances modularity. In regard to the material selection process, PLA was chosen due to its favourable sustainability profile, which aligns with the objectives of Ecodesign, as well as its satisfactory flexural strength and cost-effectiveness when compared to ASA.

For fabrication, an infill density of 100 % was selected in conjunction with a wall thickness of 6 mm. Smaller components such as the tubes, which are characterized by a wall thickness below 6 mm, were manufactured with 100 % infill. However, larger components such as the gripper mount and the telescopic structure coupler were manufactured with an infill density of 35 %, to reduce material consumption and reduce fabrication times. This approach made the prototype not entirely consistent with the FEM analysis. As for other properties, the printing temperature was 220°C, the nozzle diameter was 0.4 mm, each layer had a diameter of 0.2 mm, and the grid pattern was used for the infill.

Despite its advantages, AM requires specific adjustments to the CAD model prior to fabrication. One of the most critical adjustments is the manual definition of dimensional tolerances between mating components. Unlike traditional manufacturing methods, such as machining, where standardized tolerance systems can be applied based on the type of fitting required, AM lacks standardized tolerancing rules. Consequently, tolerances must be manually introduced into the model by altering the nominal dimensions of the components, often requiring multiple iterations to achieve proper assembly. For the collaborative robotic gripper developed in this work, tolerances were particularly important in the design of the telescopic structure tubes, which must slide and fit precisely within each other. In the first attempt, two tubes were designed, the outer tube with an inner diameter of 20 mm, and the inner tube with an outer diameter of 19.8 mm. These tubes were manufactured, and manual assembly showed that the inner tube could not be fully inserted into the outer tube due to insufficient clearance, as illustrated in Figure 86.

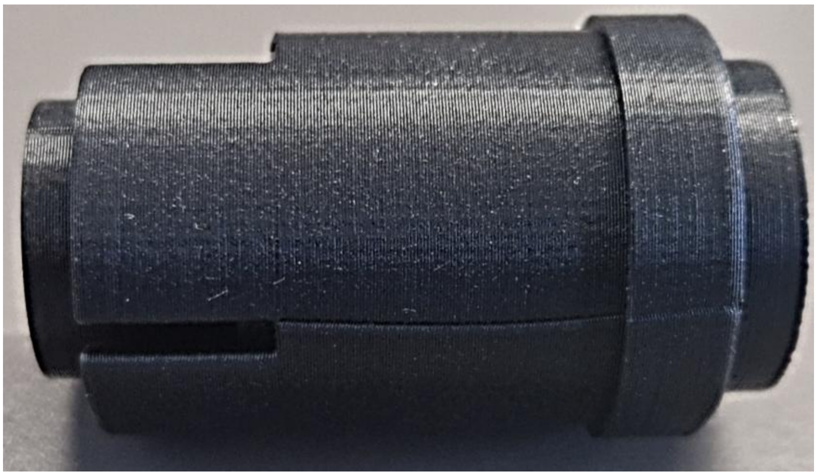


Figure 86 - Maximum insertion of the inner tube using 0.2 mm clearance

Considering the limitations observed during the initial attempt, it was decided to apply a uniform clearance tolerance of 0.3 mm between the gripper's mating components. This value was selected as it allowed the tubes to fit properly inside one another while still enabling movement, albeit with a slight interference fit to ensure positional stability. With this tolerance defined, the printing process could proceed without further geometric adjustments. The fabrication process was relatively time-consuming due to the large number of individual parts required. Nevertheless, this limitation does not undermine one of the advantages of AM, which is that in the event of a component failure, a replacement part can be rapidly reproduced. Once all components were manufactured, it was deemed important to present a comparative illustration between the physical prototype and the corresponding CAD model. To achieve this goal, Table 24 was created, which summarizes the manufactured components alongside their CAD counterparts.

Table 24 - 3D printed components and CAD counterparts

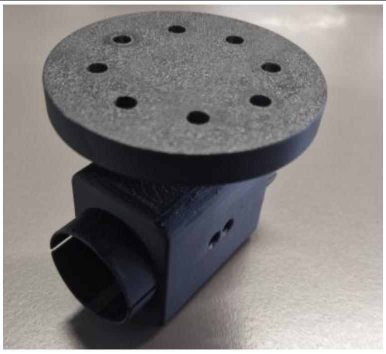
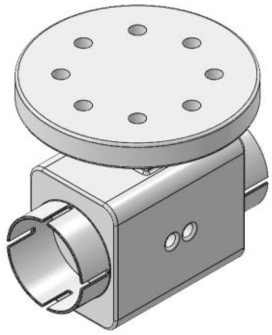
Component name	3D printed model	CAD model
Gripper mount		

Table 24 - 3D printed components and CAD counterparts (continued)

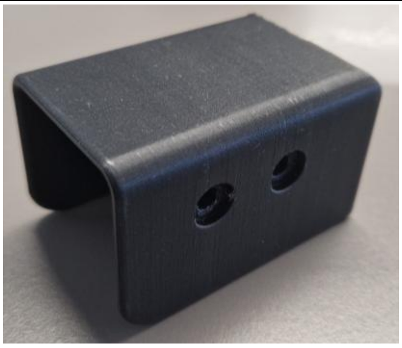
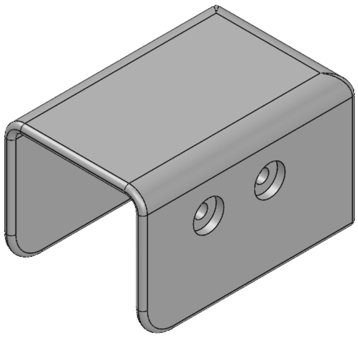
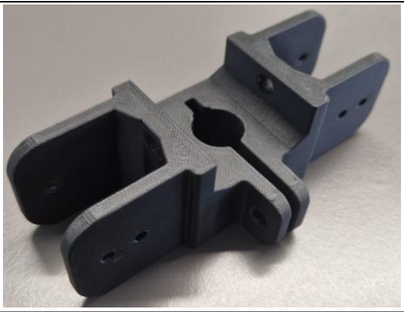
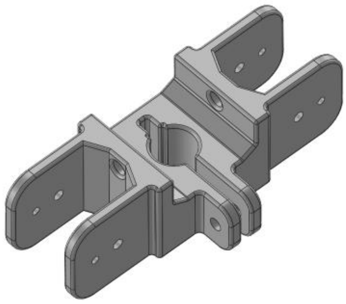
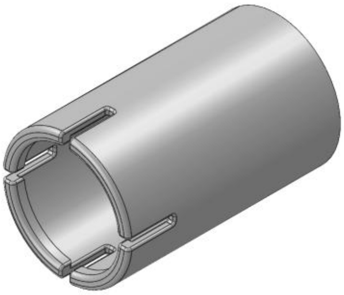
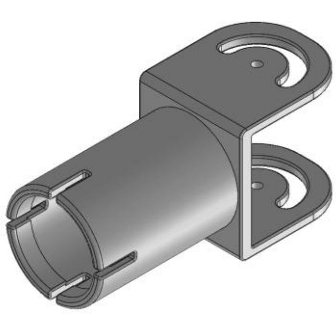
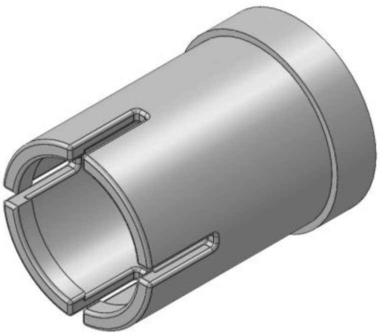
Suction cup mount		
Telescopic structure coupler		
33 mm circular tube_1		
33 mm circular tube_2		
27 mm circular tube_1		

Table 24 - 3D printed components and CAD counterparts (continued)

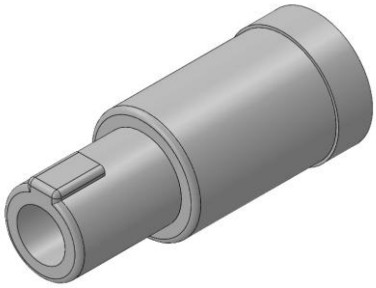
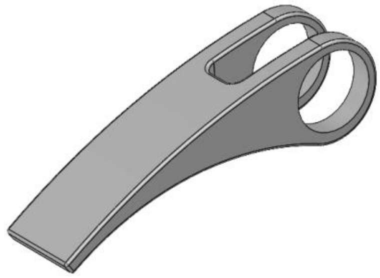
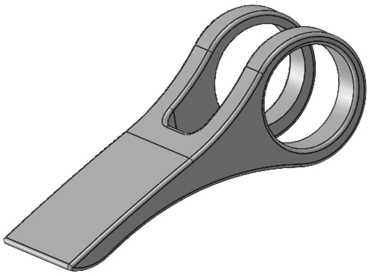
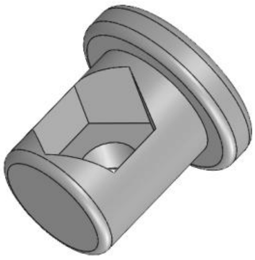
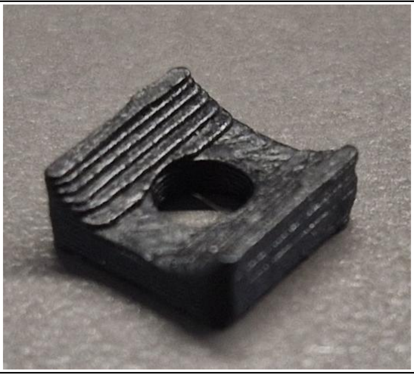
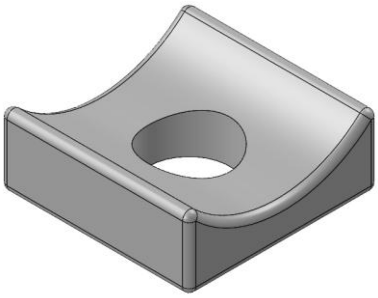
27 mm circular tube_2		
22 mm circular tube_1		
22 mm circular tube_2		
Clamping body_1		
Clamping body_2		

Table 24 - 3D printed components and CAD counterparts (continued)

Lever_1		
Lever_2		
Cam		
Cam seat		
Pivot pin		

4.4.2. Collaborative robotic gripper assembly

Once all components had been manufactured, it was necessary to present the assembly procedure for the complete collaborative robotic gripper. The assembly process included both the main gripper structure and the quick release mechanisms. The assembly of the gripper structure began with the gripper mount, which functions as the coupling element for the internal telescopic structures. These telescopic structures must be pre-assembled prior to their integration with the gripper mount, as each smaller tube must be inserted into the corresponding larger tube in a sequential manner. Figure 87 depicts the gripper mount together with the two assembled telescopic structures.

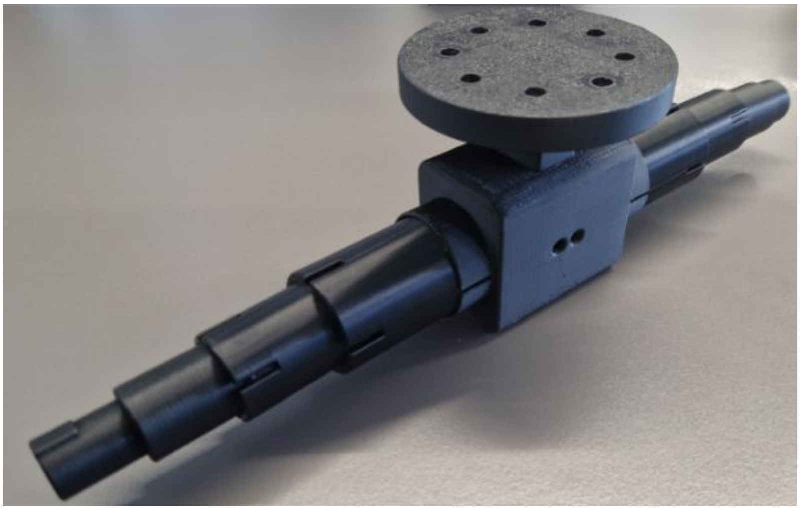


Figure 87 - Assembly of the gripper mount and the internal telescopic structures

The next components to be assembled were the telescopic structure couplers. They were easily fitted to the smaller tube of each telescopic structure, as can be observed in Figure 88, using a screw and nut fastening combination.

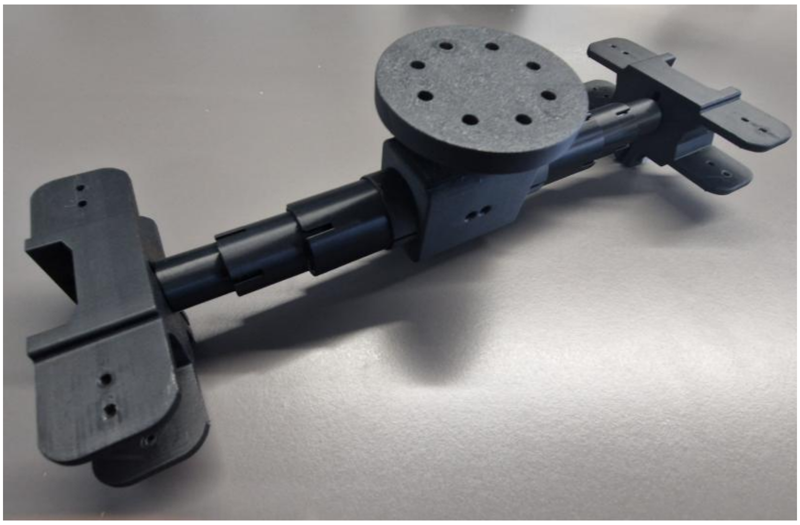


Figure 88 - Gripper mount, internal telescopic structures, and telescopic structure couplers prototype assembly

The last pieces to be fitted to complete the collaborative robotic gripper were the rotating telescopic structures. These structures are composed of the telescopic structure tubes, suction cup mounts, vacuum generators, and suction cups. To simplify the overall assembly of the collaborative robotic gripper, these subassemblies were completed before being mounted onto the telescopic structure couplers. The process began with the assembly of the telescopic tubes which, as previously mentioned, involves the sequential introduction of each smaller tube into the corresponding larger tube. In this case, the smaller diameter tube was then inserted into the suction cup mount. Once this step was completed, the vacuum generator and suction cup assembly could also be attached and mounted onto the suction cup mount (Figure 89).

Figure 89 - Suction cup mount, vacuum generator, and suction cup assembly

With the rotating telescopic structures assembled, these were then secured to the telescopic structure couplers, at which point the collaborative robotic gripper began to take shape. The final step involved the installation of the quick-release mechanisms, which are responsible for locking the telescopic structures in their required positions. The assembly of the quick-release mechanism (Figure 90) is relatively straightforward. First, the pin is inserted to connect the two halves of the clamping body, which is then mounted onto the telescopic structure tube. At this stage, a nut is inserted into the cam, followed by cam positioning inside the lever. The screw is subsequently inserted through the holes of the clamping body, aligned with the cam seat, enabling the lever to be fastened using the nut placed inside the cam. Once the nut was nearly fully tightened, the lever was closed, thereby clamping and securing the telescopic structure.

Figure 90 - Quick release mechanism prototype

With all the quick release mechanisms assembled, the collaborative robotic gripper prototype was assembled, and its configurations will be presented in the next section. This prototype was now ready to be tested during the product testing and improvement phase both in regard to functionality, and performance.

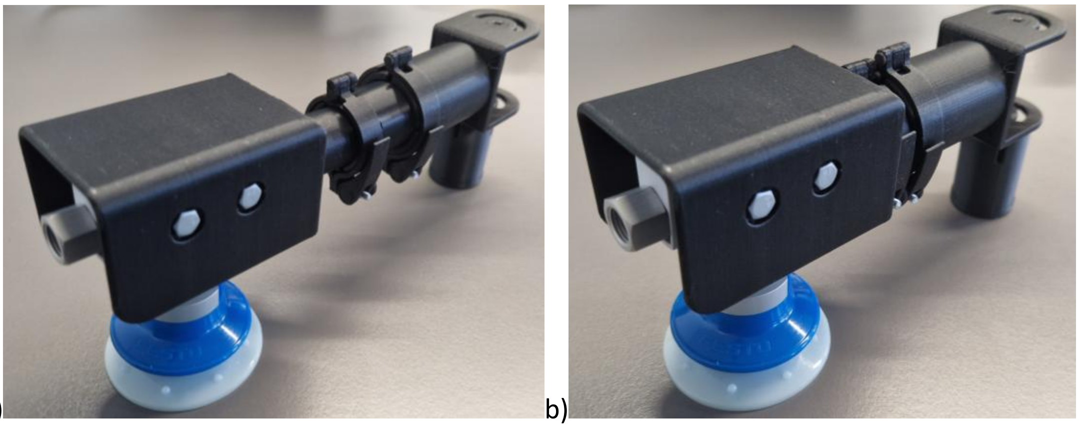
4.5. Prototype testing and validation

After finishing the assembly process of the collaborative robotic gripper, it was possible to start testing the prototype to assess its functionality, performance, and compliance with the defined design requirements.

4.5.1. Functionality testing

Before conducting performance tests, it was necessary to validate the functionality of the concept, particularly regarding ease of assembly, telescopic structure adjustment, possibility of manufacturing components using AM, gripper adaptability to different box sizes, and pneumatical material assembly. During the assembly process, it was confirmed that the gripper could be assembled and disassembled with minimal effort, which is a critical factor to reduce downtime in the event of component failure. Furthermore, the assembly process demonstrated the feasibility of developing a highly modular collaborative robotic gripper using AM since, as expected, the designed components using CAD were reproduced accurately. This situation validated one of the advantages of AM, which is the design freedom it provides.

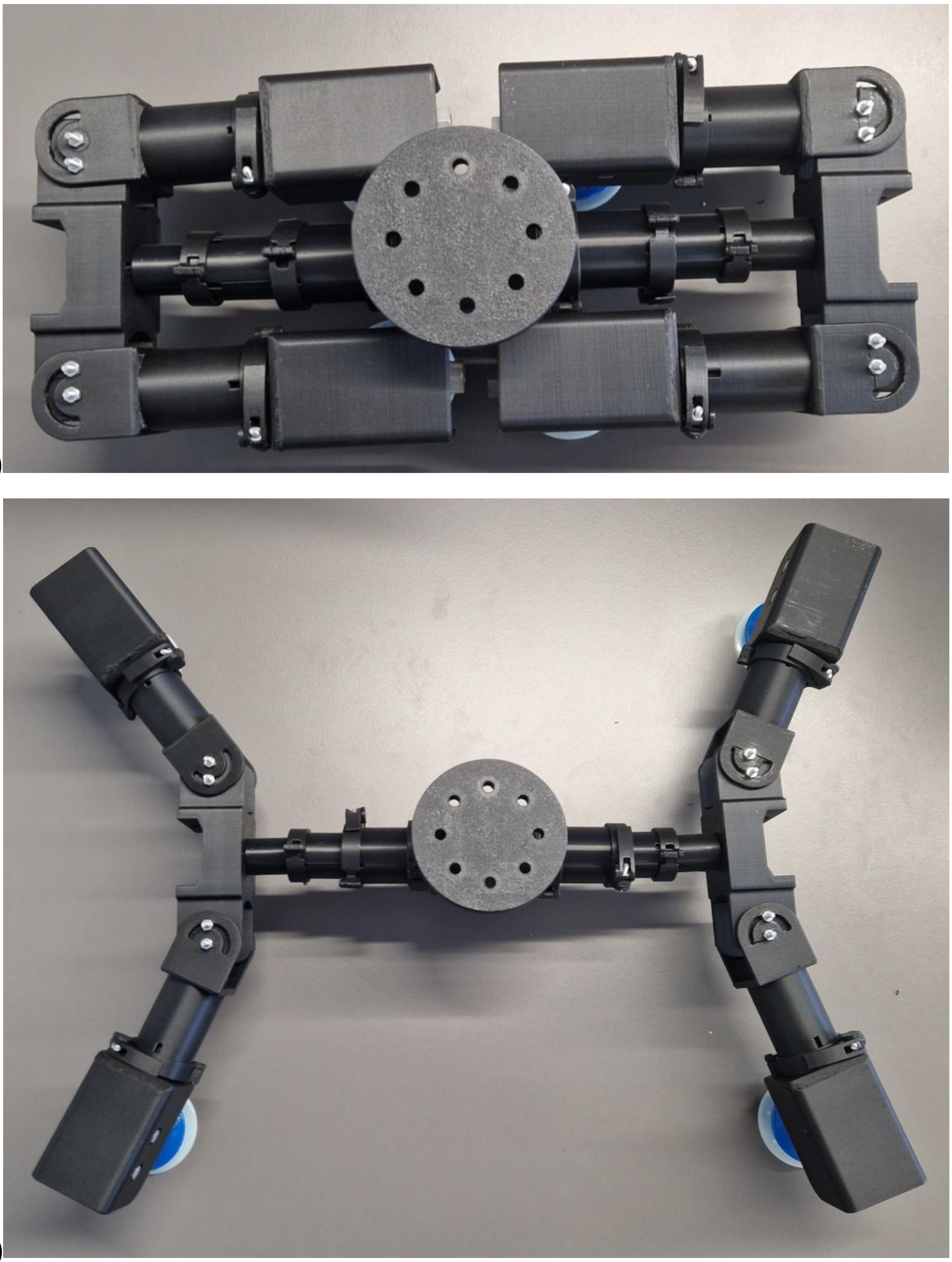
In respect to the adjustment of the telescopic structures and their fixation by means of the quick release mechanisms, it was verified that such adjustment was feasible, as the tubes were able to fit and slide within one another, and the quick release mechanisms provided sufficient fixation between tubes. Figure 91 depicts an extended telescopic structure (a), and a fully retracted telescopic structure (b).



a) b)

Figure 91 - Telescopic structure positions: maximum extension (a), and full retraction (b)

The aforementioned fixation between tubes could be improved primarily by applying tighter dimensional tolerances, as this adjustment would minimize unwanted clearance between components, and thereby allow the quick release mechanisms to function more effectively. The gripper’s adjustability to handle boxes of varying dimensions was also validated. Tests confirmed that the gripper could be adjusted to handle 150 mm edge size boxes (Figure 92 a) and 550 mm edge size boxes (Figure 92 b).



a)

b)

Figure 92 - Gripper prototype configurations: 150 mm edge size box configuration (a), and 550 mm edge size box configuration (b)

This process also revealed that the adjustment process of the rotating telescopic structures was simple, only requiring to loosen the nuts to allow free movement of the arms. Furthermore, it was observed that the slotted hole in the largest diameter tube of the rotating telescopic structure did not require fastening. Rather, it served solely for positioning purposes of the rotating telescopic structures. As for the introduction of the pneumatical material, the installation of the vacuum generators was simple, as the suction cup mount was designed to accommodate the generator directly. Concerning the pneumatic tubing, the holes provided allowed the tubing to pass through and remain concealed within the gripper structure (Figure 93). Although the tubing could be successfully mounted, which enabled the gripper to be used for performance testing, it was verified that this process could be further facilitated by increasing the size of the holes to ease the passage of the tubing. Considering all the information obtained through testing, the functionality of the design was validated, with only minor modifications required to optimize its performance and ensure reliable operation.

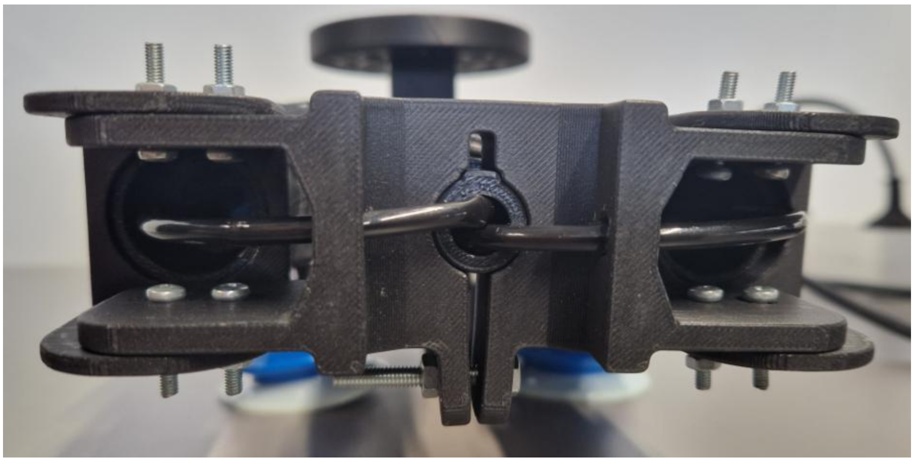


Figure 93 - Pneumatical tubing placement inside the telescopic structure coupler

4.5.2. Performance testing

For performance testing, the gripper was mounted on the cobot, both in the configuration to handle 150 mm edge size boxes (Figure 94 a), and 550 mm edge size boxes (Figure 94 b).

a) b)

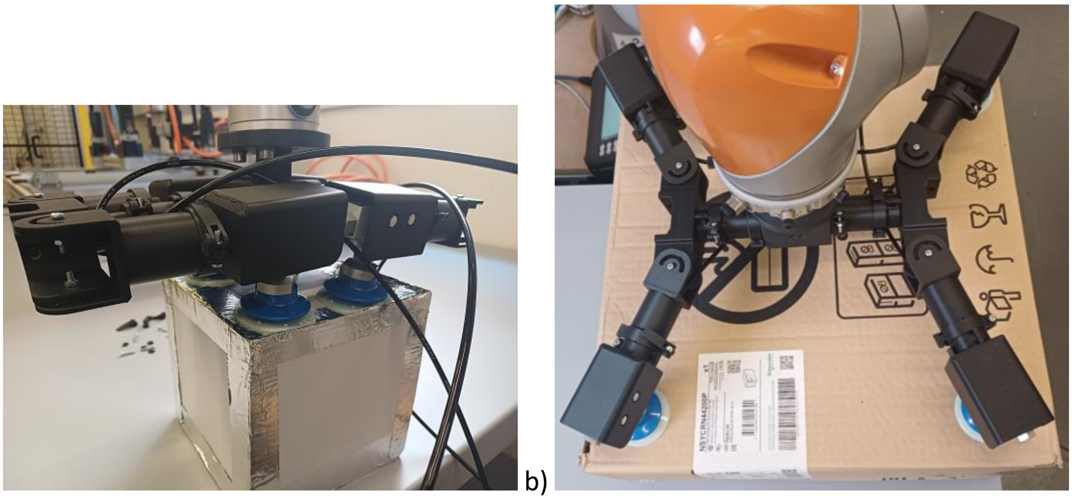


Figure 94 - Gripper prototype configurations in relation to the boxes: 150 mm edge size box configuration (a), and 550 mm edge size box configuration (b)

Gripper mount assembly on the cobot revealed some important optimization possibilities. First, the size of the gripper mount should be reduced to simplify the introduction of the screw and the tooling to fix it. Additionally, during this process, it was verified that the clearance between components allowed rotational movement between the tubes. Although this does not compromise the handling operation, because tube rotation is blocked when the gripper's suction cups are in contact with the box, it was decided that for safety reasons that this movement should not occur. The previously presented configurations were tested separately, following the tests presented in Table 19, at different times to evaluate the gripper's performance under each setup. The results were compiled in Table 25.

Table 25 - Performance testing results

Test	Results
Test 1	Approved
Test 2	Approved
Test 3	Approved
Test 4	Approved
Test 5	Not approved
Test 6	Not approved
Test 7	Not approved
Test 8	Not approved

Based on these results, the developed collaborative robotic gripper was unable to achieve the target of handling boxes weighting 7.5 and 10 kg. The failure occurred in both configurations. To determine the failure cause, the fracture zone was analysed, and it was verified that it occurred in the smallest tube of the internal telescopic structure which, according to simulation results, was the region of maximum stress. However, this failure should not have happened as the recorded highest stress during simulation was much lower than the yield strength of PLA under bending conditions. A closer examination of the failed component showed that the failure occurred due to a defect in the part itself, as indicated by Figure 95, since the components infill was not 100 %, which should be considering that the thickness of the tube was lower than 6 mm. Additionally, the fact that the larger components had an infill of only 35 % also compromised the handling process.

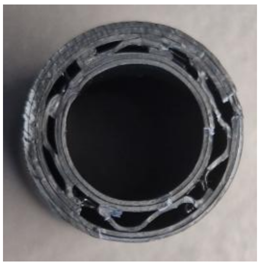


Figure 95 - Defect present on the failing component

Although the gripper did not achieve the target payload of handling 7.5 and 10 kg boxes, successfully handling boxes of 5 kg confirmed the mechanical feasibility of the prototype and validated the overall design approach as a proof-of-concept, indicating that with targeted improvements, the gripper could meet higher payload requirements. Additionally, when holding the 5 kg box, the gripper was stable and showed no signs of vacuum leaks that could compromise the safety of the handling procedure. However, even if the component had not failed it was also observed that for safety reasons the maximum displacement of the gripper should be reduced. This reduction can be achieved by engaging in a general increase of all tube thickness, which will also increase the safety factor of the structure and prevent that defective components lead to a premature failure during the gripping operation.

4.5.3. Prototype validation

After finishing the testing of the collaborative robotic gripper prototype, it was important to compare functional, stakeholders', and Ecodesign requirements with what was assessed through testing (Table 26).

Table 26 - Requirements compliance and prototype results validation

Requirement	Validation	
Vacuum based gripper and use of four suction cups	The prototype collaborative robotic gripper under evaluation is a vacuum- based system equipped with four suction cups. An analysis of palletization solutions implemented in industrial environments confirmed that vacuum base grippers represent the most prevalent end-effector solution. The adoption of a four suction cup configuration was determined to be the most effective approach to ensure the safety and stability of the handling process.	✓
Consideration of the ISO/TS 15066 standard for cobots	All components employed in the prototype were designed with rounded edges to mitigate the risk of injury during unintended contact with human operators. The vacuum generators were integrated within the suction cup mounts, thereby eliminating the possibility of direct impact hazards. Furthermore, the pneumatic tubing was routed internally through the gripper structure, effectively reducing the risk of entanglement during operation. Taking these design measures into account, the prototype was validated as suitable for safe deployment in collaborative robotic applications.	✓
Adjustable in the X-axis	This requirement, defined by the stakeholders, was fully implemented in the prototype design. The incorporation of two internal telescopic structures in combination with four rotating telescoping structures significantly increased the system's adaptability. As a result, the prototype is capable of handling not only boxes but also other objects of varying geometries. This versatility also enhanced the likelihood of the gripper being repurposed for alternative applications in the event that its originally intended function is no longer required.	✓

Table 26 - Requirements compliance and prototype results validation (continued)

Modularity	Modularity was identified as a critical design requirement to align the gripper with Ecodesign and circular economy principles, particularly in terms of durability, maintainability, and resource efficiency. This requirement was implemented in the prototype through the integration of 13 modules. Specifically, each telescopic structure was engineered from three independent tubes, which enhanced modularity and enabled the replacement of only the defective element in the event of a failure. This design strategy reduced the possibility of a single component malfunction rendering the entire gripper obsolete, thereby extending product lifespan and lowering material waste. Additionally, the modular configuration simplifies assembly and disassembly, facilitating repair, upgrades, and end-of-life disassembly for recycling or reuse of parts.	✓
Handle cardboard boxes ranging between 150 and 550 mm edge size	As previously noted, the telescopic structures provided the gripper with a wide range of adjustment capabilities. Functional testing of the collaborative robotic gripper prototype confirmed its ability to reliably handle boxes with edge sizes between 150 mm and 550 mm. The evaluation further demonstrated that the gripper configuration could be readily adapted to accommodate the different boxes, thus reducing the adjustment time.	✓
Easy access to internal components	This requirement was established by the stakeholders as a design feature. The implementation of modularity ensured unobstructed access to all components, which facilitates both assembly and disassembly. This characteristic was particularly significant to minimize downtime in the event of component failure, as it enabled rapid replacement and simpler maintenance operations.	✓
Material selection and handling boxes of up to 10 kg	The material selection process played a critical role in meeting the Ecodesign objectives of the gripper. Based on stakeholder input, two candidate materials were considered, PLA and ASA. PLA was ultimately selected due to its biodegradable nature, which aligned with sustainability requirements. A comparative assessment of the mechanical properties of both materials indicated similar overall performance. However, PLA exhibited superior flexural strength, which corresponds to the primary stress condition experienced by the gripper during operation. In addition, PLA offered cost advantages over ASA, further supporting its selection. Structural simulations demonstrated that PLA could withstand the stresses associated with handling boxes up to 10 kg. However, prototype testing did not confirm this result. The discrepancy was attributed to a manufacturing defect, specifically a component produced with insufficient infill, which compromised structural integrity, and also to the fact that the gripper mount and the telescopic structure couplers had a 35 % infill due to their larger size.	±

Table 26 - Requirements compliance and prototype results validation (continued)

Manufacturing process	AM was employed for the production of all components of the collaborative robotic gripper. This manufacturing method directly contributed to achieving Ecodesign goals by minimizing material waste inherent in subtractive processes. Additionally, the capability to rapidly fabricate replacement parts supports enhanced product durability by facilitating maintenance and extending service life. The high level of modularity achieved in the prototype was made possible through AM, as the process offers extensive design flexibility that would be challenging to replicate with conventional manufacturing techniques. Based on these advantages, AM was validated as the most suitable production method for the collaborative robotic gripper.	✓
Handling stability during operation	Performance testing of the prototype confirmed that the gripper exhibited high operational stability and did not introduce additional risks to human operators during collaborative tasks. Despite this positive outcome, it was determined that rotational movement of the telescopic structure tubes should be eliminated.	✓

4.6. Collaborative robotic gripper improvement

After analysing the assembly procedure of the gripper, and the results obtained through testing, it was clear that some of the components of the gripper needed optimization. With this goal in mind, a second prototype CAD model was created and simulated. The first decision was to increase the thickness of the telescopic structure tubes. The goal of this change was to improve structural integrity, avoid possible failures due to defects, and increase the gripper stiffness which will reduce its displacement during operation. The design of the tubes also changed, as notches were created for them to not rotate in relation to each other (Figure 96).

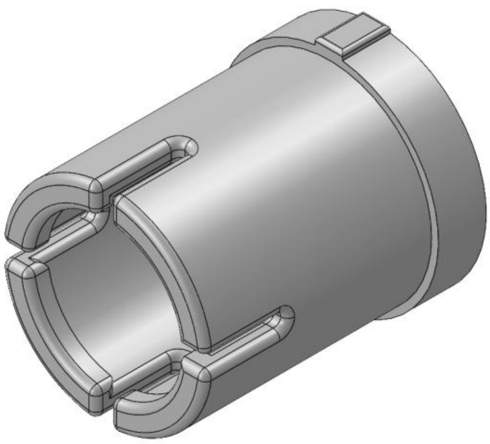


Figure 96 - Second prototype telescopic structure tube

Additionally, the largest diameter tube of the internal telescopic structure was designed with protrusions that engage with the corresponding notches on the gripper mount (Figure 97). These protrusions were incorporated as a safety feature to prevent undesired rotational movement. Furthermore, when the quick release mechanism was installed, it not only secured the two tubes together, as previously described, but also ensured that the clamping body mechanically restricted the tube from disengaging from the gripper mount.

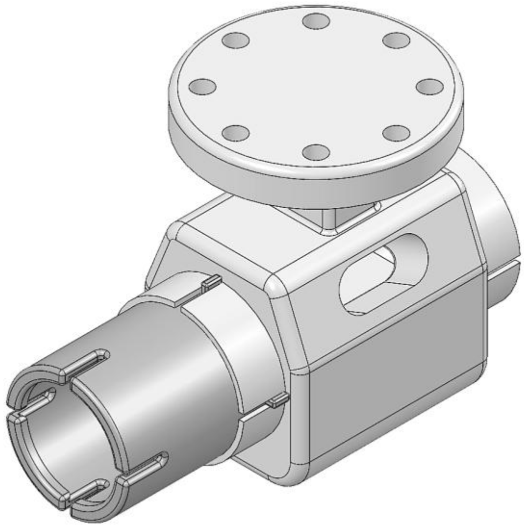


Figure 97 - Second prototype gripper mount and telescopic structure tube assembly

The design of the gripper mount was also optimized to facilitate the fastening of the gripper onto the cobot, addressing a previously identified area for improvement. In addition, the internal channels for routing pneumatic tubing were enlarged, thereby simplifying the integration process (Figure 97). The telescopic structure coupler holes were also enlarged for the same reason (Figure 98).

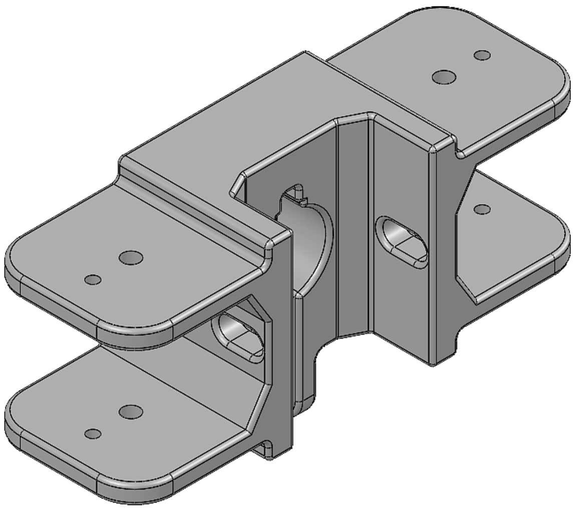


Figure 98 - Second prototype telescopic structure coupler

As for the suction cup mounts, the prototype showed that they allowed the vacuum generators to be easily installed without interferences. However, the assembly process of the telescopic structures to the suction cup mount revealed that the use of a quick release mechanism was difficult due to the small space available. For that reason, it was determined that a more reliable solution would be to adopt the same fastening approach used to secure the internal telescopic structure smallest tube to the telescopic structure coupler, which required fastening using a screw and nut combination. The optimized suction cup is depicted in Figure 99.

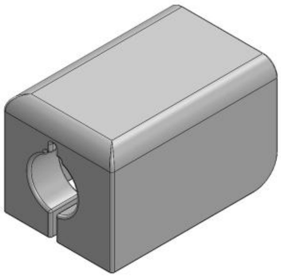


Figure 99 - Second prototype suction cup mount

In regard to the quick release mechanisms, to reduce the number components used, a decision was made to fabricate the clamping body as a single component. This solution does limit the possibility of mounting the quick release mechanisms after the gripper structure is assembled. However, it was considered that it would be more important to simplify the mechanism. Additionally, to obtain higher fixing strength, the majority of the quick release mechanism components thickness were enlarged (Figure 100).

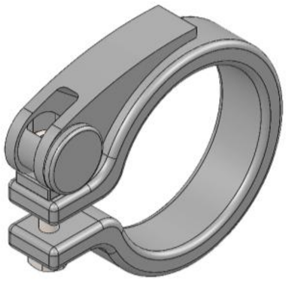


Figure 100 - Second prototype quick release mechanism

Considering all these changes, the second CAD prototype depicted in Figure 101 was created.

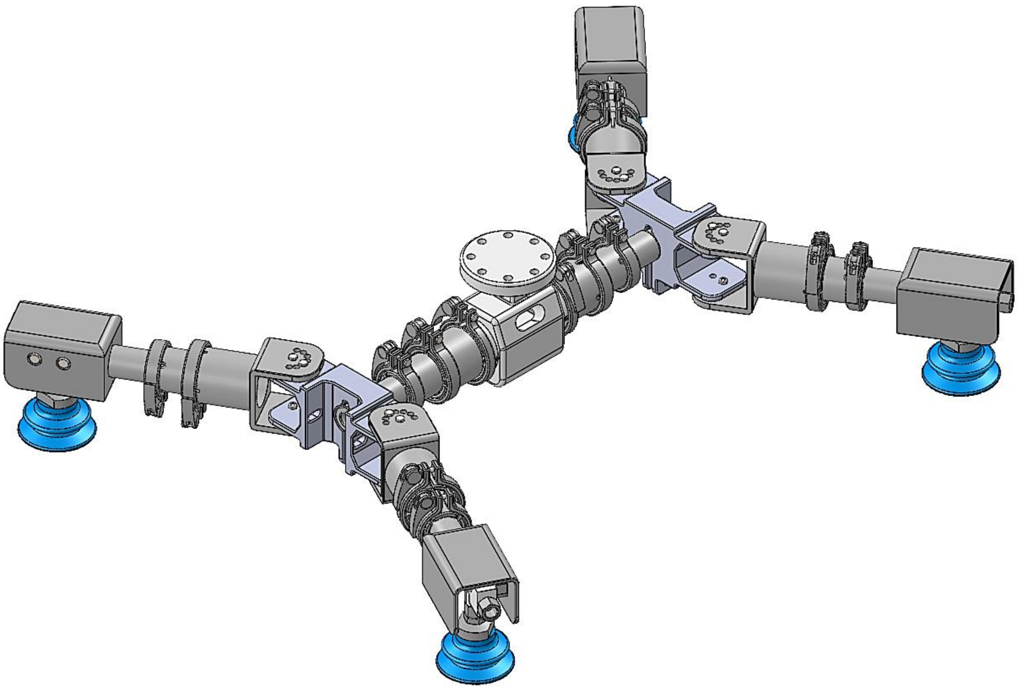


Figure 101 - Second prototype of the collaborative robotic gripper

To evaluate whether the design modifications enhanced the structural integrity of the gripper and reduced displacement during operation, simulations were conducted under the same conditions as those applied to the initial prototype (section 3.6.2). Specifically, the computational model included only the gripper structure, while the boundary conditions, applied loads, and mesh configuration were kept identical to ensure direct comparability of results. The Von Mises stress results are depicted in Figure 102.

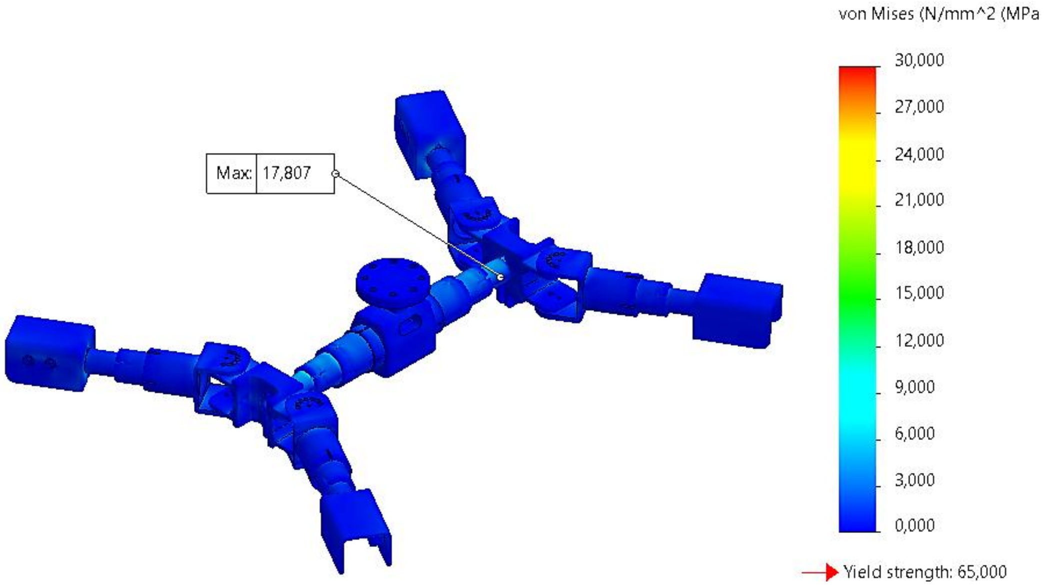


Figure 102 - Von Mises stress results for the second CAD prototype

Considering the Von Mises stress results, as expected, the increased thickness of the tubes led to a 10 MPa decrease in the maximum recorded Von Mises stress, which is a 54 % reduction. In regard to the displacement results (Figure 103) the modifications led to a reduction of the maximum displacement from 7.3 mm to 4.2 mm, which is a 73 % reduction. This change was important, as excessive displacement was one of the major problems verified in the original prototype.

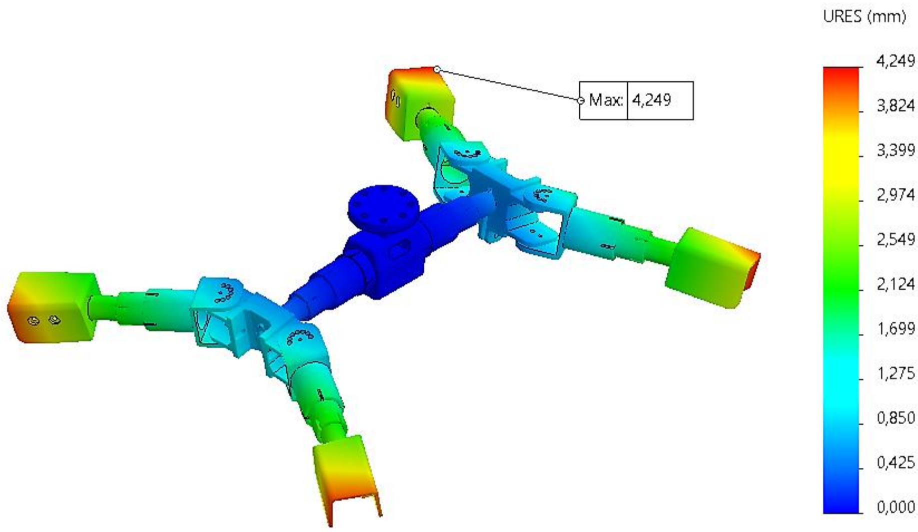


Figure 103 - Displacement results for the second CAD prototype

Regarding the factor of safety results (Figure 104), the smaller Von Mises stress values corresponded to an increase of the factor of safety to 3.6 (a 50 % improvement). This enhancement reduced the likelihood that component defects could propagate into operational failures.

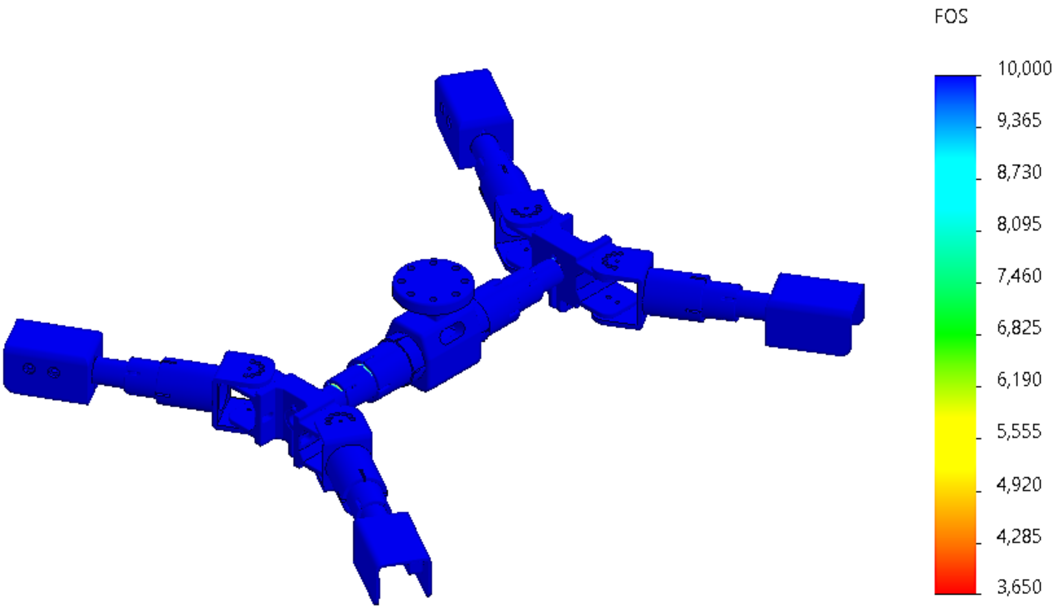


Figure 104 - Factor of safety results for the second CAD prototype

Regarding the weight of the second CAD prototype, it was measured at approximately 1.654 kg. Although this weight exceeds the nominal target of 1.5 kg, stakeholders indicated that weight was not a critical parameter for this application. Consequently, the CAD model was approved for the creation of a new physical prototype.

In addition to the visible modifications, other decisions were made that could enhance gripper functionality. The slotted holes used in the rotating telescopic structures were replaced with six different holes. Although this modification diminished the number of possible positions for the rotating telescopic structure, it ensured that all of them would be positioned in the same exact positions. This is modification is largely relevant to guarantee the stability of the handling procedure. Similarly, although not visible in the CAD model, the addition of stickers on the telescopic structure tubes was considered beneficial, as they would provide users with clear visual indicators of the extension length of each telescopic segment. To further reduce adjustment time, it was decided that the conventional nuts, which require tools for fastening, should be replaced with wing nuts, as these can be tightened and loosened manually without the need for additional equipment. In regard to the 3D printing process, the clearance between components should be adjusted to 0.25 mm. As previously noted, a clearance of 0.20 mm prevented proper assembly of the components, whereas the 0.30 mm clearance applied in the physical prototype resulted in excessive gaps, which compromised optimal functioning of the quick release mechanisms

5. Conclusions and future work

5.1. Conclusions

The aim of this dissertation was to assess the feasibility of combining gripper functionality and safety for collaborative applications with the integration of Ecodesign principles throughout the development process, thereby improving sustainability. A review of common strategies to enhance sustainability indicated that higher modularity, the use of AM, and the selection of environmentally friendly materials were key factors to achieve Ecodesign goals. Considering these factors, a collaborative robotic gripper was developed using 13 different modules, which included six different telescopic structures that were introduced to improve adjustability. A CAD model of the gripper was created and subjected to structural simulation, showing that, under the loads defined in the use case, the maximum recorded Von Mises stress reached 27.45 MPa, the maximum displacement was 7.3 mm, the factor of safety was 2.4, and the total weight was 1.343 kg. Following this analysis, a physical prototype was manufactured using PLA basic filament. This prototype was tested in a pick-and-place operation and demonstrated the ability to handle boxes of up to 5 kg, which validated it as a proof-of-concept. Ideally, the prototype was originally developed to handle loads of up to 10 kg. However, a defect on one the components compromised the gripper's integrity during testing. In regard to functionality, the prototype successfully managed boxes with edge size of 150 and 550 mm, and the telescopic structures were able to be easily adjusted. Based on the gained insights, areas for improvement were identified, leading to the development of a second CAD prototype. This updated model achieved a maximum Von Mises stress of 17.81 MPa, representing a 54 % reduction when compared with the original prototype. Similarly, the maximum displacement was reduced to 4.25 mm (a 73 % decrease), and the factor of safety increased to 3.6 (an 50 % improvement). The weight increased to 1.654 kg (23 % increase). After finishing the development process, it was possible to answer to the research question, which asked if Ecodesign could be integrated into the development of collaborative robotic grippers to reduce their environmental impact without compromising their functional performance. The work developed during the course of this dissertation helped assess that the full introduction of Ecodesign requirements during the development of collaborative robotic grippers does not compromise their functionality and performance and reduces their environmental impact. Actually, the introduction of Ecodesign requirements through the use of AM and modularity, improved functionality and offered new design options for the gripper that enhanced its capability to handle boxes of different sizes.

5.2. Future work

For future work, the immediate step should involve the fabrication of a physical prototype derived from the second CAD model presented in this dissertation. Additionally, in this prototype, the infill of all components should be 100 % to ensure full agreeability between the FEM analysis and performance testing. TO should be conducted to minimize the overall mass of the gripper while maintaining its structural integrity and load bearing capacity.

Regarding collaborative operation safety, it would be pertinent to investigate the feasibility of integrating a sacrificial bumper mechanism into the gripper. This component would be designed to detach upon collision with an operator, simultaneously triggering a signal to the cobot controller to halt operation. Such a feature would enhance worker safety while also increasing gripper protection from potential damage due to unexpected impacts.

In the material selection process, stakeholders should be made aware of the potential to employ PLA composites with fibre reinforcements to improve mechanical strength and durability, which can extend the applicability of the gripper in industrial environments.

To finish, it is also important to test the collaborative robotic gripper in an industrial environment and to perform a cost analysis to ensure its economic viability.

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Declaration of Integrity

I declare that I conducted this academic work with integrity. I did not plagiarize or apply any form of misuse of information or falsification of results throughout the process that led to its preparation. I declare that the work presented in this document is original and my own and has not previously been used for any other purpose. I further declare that I am fully aware of the Code of Ethical Conduct of P.PORTO, ISEP.

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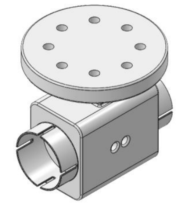
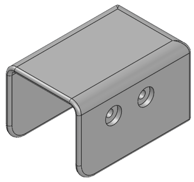
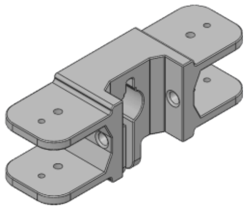
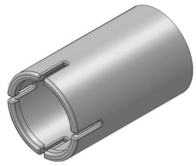
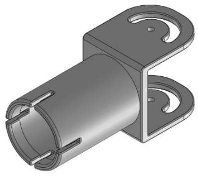
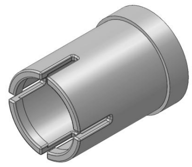
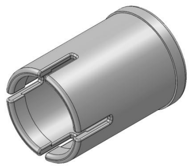
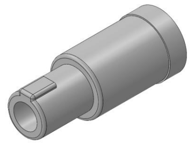
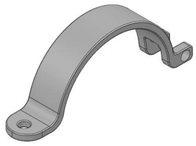
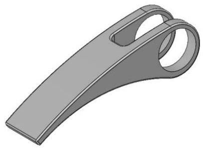
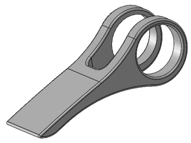
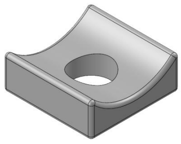
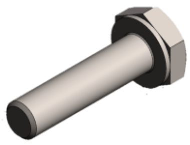
Porto, September 13th, 2025

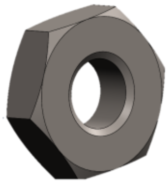
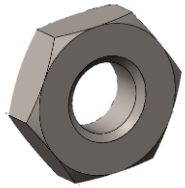
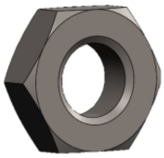
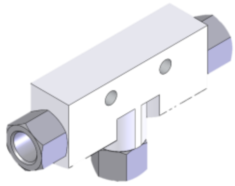
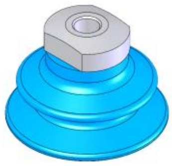
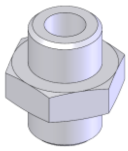
Appendix A

Table A. 1 - List of all the gripper components

Component name	Number of units	Illustration
Gripper mount	1	
Suction cup mount	4	
Telescopic structure coupler	2	
33 mm circular tube_1	2	
33 mm circular tube_2	4	
27 mm circular tube_1	2	
27 mm circular tube_2	4	

22 mm circular tube_1	2	
22 mm circular tube_2	4	
Clamping body_1_35 mm	2	
Clamping body_2_35	2	
Clamping body_1_33 mm	6	
Clamping body_2_33 mm	6	
Clamping body_1_27 mm	6	
Clamping body_2_27 mm	6	
Clamping body_1_19 mm	4	

Clamping body_2_19 mm	4	
Lever_1	14	
Lever_2	4	
Cam	18	
Cam seat	18	
Pivot pin	18	
ISO 4017 – M3 x 12-N screw	26	
ISO 4014 - M4 x 30 x N screw	8	
ISO 4017 – M5 x 20-N screw	2	

ISO 4035 – M3 – N nut	26	
ISO 4035 – M4 – N nut	8	
ISO 4035 – M5 – N nut	2	
Vacuum VN generator	4	
Suction cup with OGVN connection	4	
NPFC-D-2G18-M threaded insert	4	
QS-G1/8-4 push-in fitting	4