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Optimization and Analysis of Heavy Duty Steel Packaging Structure Using Numerical Finite Element Analysis

LUCAS LAGES SILVA

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Optimization and Analysis of Heavy Duty Steel Packaging Structure Using Numerical Finite Element Analysis

Lucas Lages Silva

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

Supervisor: Raul Duarte Salgueiral Gomes Campilho
Company supervisor: Nuno Ricardo Esteves Domingues
Jury:
President:
Armando José Vilaça de Campos
Vowels:
Victor Fernando Santos Neto
Raul Duarte Salgueiral Gomes Campilho

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Abstract

The increasing demand for safer, more sustainable, and more efficient transport solutions is driving innovation in the packaging industry, particularly in the context of heavy and voluminous cargo. Despite the standardisation of pallets, discrepancies persist in the protection of large equipment, necessitating the development of more robust and adaptable structures. This thesis focuses on developing and optimising a heavy-duty steel packaging structure for the safe and efficient transportation of heavy and oversized shafts. The project addresses critical challenges relating to load securing, operational safety, and logistical efficiency. The research methodology is based on a structured approach incorporating a literature review, design synthesis and validation, and iterative structural optimisation using Finite Element Analysis (FEA). Design Science Research (DSR) was adopted to ensure a systematic, application-oriented design process. Ashby's method was used to select structural solutions that focus on strength, durability, and manufacturability. Several design iterations were developed to accommodate various handling and transport conditions, such as lifting, stacking, and forklift compatibility. The final packaging solution incorporates functional elements such as adjustable axial brakes, lashing points, forklift entry channels, and stackable elements to improve usability and adaptability. FEA simulations confirmed compliance with mechanical resistance criteria, particularly von Mises stress limits, thereby ensuring the structural integrity of the solution. Furthermore, the packaging design contributes to sustainability goals by reducing long-term costs and minimising environmental impact through extending the product's life and increasing its potential for reuse.

KEYWORDS: Pallet; Heavy-Duty Steel Packaging Structure; Stacking system; Lashing solutions; Structure design iterations; Heavy shaft; NEFAB; CAD.

Resumo

A crescente procura por soluções de transporte mais seguras, sustentáveis e eficientes está a impulsionar a inovação na indústria de embalagens, particularmente no contexto de cargas pesadas e volumosas. Apesar da padronização das paletes, persistem discrepâncias na proteção de equipamentos de grande porte, exigindo o desenvolvimento de estruturas mais robustas e adaptáveis. Esta tese centra-se no desenvolvimento e otimização de uma estrutura de embalagem de aço resistente para o transporte seguro e eficiente de eixos pesados e de grandes dimensões. O projeto aborda desafios críticos relacionados com a fixação da carga, a segurança operacional e a eficiência logística. A metodologia de investigação baseia-se numa abordagem estruturada que incorpora uma revisão da literatura, síntese e validação do projeto e otimização estrutural iterativa utilizando Método de Elementos Finitos (MEF). Foi adotada a metodologia *Design Science Research* (DSR) para garantir um processo de design sistemático e orientado para a aplicação. Foi utilizado o método de Ashby para selecionar soluções estruturais que se concentram na resistência, durabilidade e capacidade de fabrico. Foram desenvolvidas várias iterações de design para acomodar várias condições de manuseamento e transporte, tais como elevação, empilhamento e compatibilidade com empilhadores. A solução final de embalagem incorpora elementos funcionais, tais como travões axiais ajustáveis, pontos de amarração, canais de entrada para empilhadores e elementos empilháveis para melhorar a usabilidade e a adaptabilidade. As simulações pelo MEF confirmaram a conformidade com os critérios de resistência mecânica, particularmente os limites de tensão de von Mises, de forma a garantir a integridade estrutural da solução. Além disso, o design da embalagem contribui para os objetivos de sustentabilidade, reduz os custos a longo prazo e minimiza o impacto ambiental através do prolongamento da vida útil do produto e do aumento do seu potencial de reutilização.

PALAVRAS-CHAVE: Palete; Estrutura de embalagem de aço para cargas pesadas; Sistema de empilhamento; Soluções de amarração; Iterações do projeto da estrutura; Eixo pesado; NEFAB; CAD.

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Acronyms and Symbols

Acronyms

AGV	Automated guided vehicle
AI	Artificial intelligence
CAD	Computer aided design
CAGR	Compound annual growth rate
CO_2	Carbon dioxide
DFX	Design for excellence
EN	European standard
FEA	Finite element analyses
HDPE	High density polystyrene
ISO	International organization for standardization
LCA	Life Cycle Assessment
LCF	Low Cycle Fatigue
MEF	*Método de Elementos Finitos*
NLTH	Non-Linear Time History
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
RoRo	Roll on-roll off
RPC	Reusable plastic crates
SF	Factor of safety
SLS	Serviceability limit state
ULS	Ultimate limit state

Symbols

β	Angle of lifting eyes	°
L	board length	mm
t	board thickness	mm
F_{ub}	Bolt tensile strength	MPa
F_{yb}	Bolt Yield stress	MPa
α_b	Correction coefficient for bearing in screws	-

α_v	Correction coefficient for cutting in screws	-
u^f_y	Deformation energy, at the momentum of specimen failure	J
$F_{b,Rd}$	Design bearing resistance per bolt	kN
$B_{p,Rd}$	Design punching shear resistance of the bolt head and nut	kN
$F_{v,Ed}$	Design shear force per bolt for the ultimate limit state	kN
$F_{v,Rd}$	Design slip resistance per bolt at the ultimate limit state	kN
$F_{t,Rd}$	Design tensile force per bolt for the ultimate limit state	kN
$F_{t,Ed}$	Design tensile force per bolt for the ultimate limit state	kN
N_{Ed}	Design value of the internal axial force in member	kN
σ_{eq}	Equivalent stress	MPa
σ_{eq}^{Tresca}	Equivalent stress by the Tresca criterion	MPa
γ	Final performance index of solution	-
F	Force	kN
F_{ins}	Force inside	kN
F_{out}	Force outside	kN
u	Free internal height between the bottom of the support and the top of the lower fitting	mm
k_1	Geometric coefficient for bearing resistance	-
Wi	Global weight	-
d_0	Hole diameter	mm
l	Internal channel width	mm
f_u	Material tensile strength	MPa
$WRmax$	Maximum relative value	-

δ_{max}	Maximum result displacement	mm
τ^{max}	Maximum shear stress	MPa
τ_y^{max}	Maximum shear stress, at the momentum of specimen failure	MPa
$N_{t.Rd}$	Maximum tensile value that the section can safely withstand.	kN
E	Modulus of elasticity	MPa
d	Nominal bolt diameter	mm
n	Number of bolts	-
λ_0	Partial safety factor 0	-
λ_2	Partial safety factor 2	-
WC	Performance index	-
ν	Poisson coefficient	-
R_A	Reaction in A	N
R_B	Reaction in B	N
Wi^*	Relative importance	-
WR	Relative scale number	-
u^f	specific strain energy	J
$\sum Wi^*$	Sum of all relative importance	-
$\sum M_A$	Sum of Moments at point A	Nm
$\sum F_y$	Sum of transversal forces	N
$\sigma_{eq}^{VonMises}$	The equivalent stress by Von Mises criterion	MPa
A	Total area	mm^2
F_t	Total force	kN
A_s	Useful area	mm^2
WB	Weighted value	-
σ_y	Yield stress	MPa

1. Introduction

In this section, a small presentation about the contextualization and objective of the work is made, as well as the structure of the report and a small presentation of the host company.

1.1. Contextualization

The packaging industry plays a vital role in the global economy, enabling the efficient and safe transport of goods across a range of sectors. Growing environmental concerns have increased the demand for sustainable materials and innovative solutions, leading to the development of recyclable and reusable packaging options. Among the various transport solutions, pallets stand out as an essential component in logistics, ensuring standardised handling and storage of goods.

The use of standardised pallets improves operational efficiency and reduces handling times, making them indispensable in modern supply chains. However, despite the standardisation of pallets, ensuring the safety of transported goods remains a significant challenge. Securing solutions during transport, such as lashing, are critical to prevent load shifting and damage, especially when dealing with valuable or fragile items. An even greater challenge arises when transporting heavy or oversized equipment. Traditional packaging solutions are often inadequate for such demanding loads, resulting in increased risks and costs. This gap in the market highlights the need for specialised solutions specifically designed for heavy-duty applications. The development of modular metal pallets and customised packaging systems for heavy equipment can address these challenges by offering improved strength, flexibility and durability. This work aims to contribute to the field by proposing innovative designs and methodologies tailored to the transport of heavy and abnormal loads, addressing the existing limitations in terms of safety, sustainability and efficiency.

1.2. Objectives

The main objective of this thesis is to develop a Heavy-Duty Steel Packaging Structure that fully meets the requirements defined by the client. The structure should integrate systems that enhance efficiency and safety, such as braking and securing mechanisms for transport, stacking capabilities to optimize storage, and handling solutions compatible with cranes and forklifts. Additionally, special attention will be given to sustainability, promoting reusable and durable solutions with minimal environmental impact. The final proposal aims to ensure functionality, robustness, ease of operation, and sustainable performance in an industrial environment.

1.3. Structure

This work is divided into the following main sections:

Introduction. The introduction presents the contextualisation of the report, the objectives, the methodology of development and research, the structure of the report, and the presentation of the company where the project was developed.

Literature review. This section provides the theoretical and technical basis necessary for the development of the thesis. The review covers a range of concepts, including those related to pallet design and sizing, materials commonly used in heavy-duty applications, and load distribution principles. In addition, the text describes existing solutions in the packaging and transport industry, with a particular emphasis on optimisation, durability, and customisation for non-standard loads.

Thesis development. This section outlines the detailed process of designing a pallet suitable for transporting heavy and exceptional loads. The project begins with a critical analysis of existing pallet solutions, identifying their limitations in terms of load capacity, adaptability, and structural efficiency, particularly when applied to non-standard industrial components such as large or asymmetrical axles. The initial phase consisted of preliminary design, during which several key decisions were made. These included the selection of the structure type, based on modularity and strength, the choice of material, the definition of joining methods (welded or bolted connections), and the specification of surface treatments. These initial choices were fundamental in proposing a design capable of supporting subsequent structural iterations. After the pre-design phase, development focused on the dimensioning of each structural component, ensuring that the pallet could withstand the expected loads while remaining compatible with handling equipment such as forklifts and warehouse racking systems. The von Mises yield criterion was adopted as the main mechanical strength criterion, applied through computer simulations performed in SolidWorks to evaluate stress distributions and ensure the structural integrity of the pallet under various load cases.

Conclusions. The project conclusions summarise the main results obtained throughout the project, highlighting the evolution of the proposed design and the improvements achieved in terms of structural performance, annual manufacturing costs, and environmental aspects. Finally, several suggestions for future developments are presented, such as the creation of a specific standard for heavy axles, the design of adjustable pallets capable of accommodating axles with variable diameters, and the implementation of bolted connections to improve modularity, ease of assembly, and maintenance.

1.4. Company presentation

This thesis was developed in collaboration with the company NEFAB. NEFAB is a company that stands out mainly in the packaging industry, with plenty of solutions and equipment for its customers. NEFAB have the objective of saving environmental and financial resources by optimizing supply chains.

2. Literature review

2.1. Packaging industry

The package is a very important product whose main purpose is to ensure that the items being packaged maintain their quality, preventing any physical damage or contamination. In other words, packaging serves to extend the product's shelf life. Because of this, packaging has been considered a vital procedure for human life since ancient times. Although not as effective during that period, it was still used to ensure the integrity of products. Today, packaging has evolved significantly, making it possible to guarantee product quality more effectively.

The packaging industry is utilized by various sectors worldwide, including military, automotive, food, and pharmaceutical industries, among others. For each specific industry, there are different types of packages designed to ensure the safety of the product while it is packaged. The package has the principal objective of protecting the product, but some of them can also be used to promote it, and increase the sales [1].

Currently, there is a growing market demand for packaging solutions that promote sustainability. Sustainable packaging should be included in all three levels of sustainability: social, economic, and environmental. It should be cost-effective, reducing expenses for companies and consequently minimizing the resources used in the packaging creation process. Additionally, it should be reusable and capable of fulfilling its primary objective of maintaining product quality [2, 3].

2.1.1. Characterization of packaging industry

Figure 1 illustrates how the global packaging industry was divided in 2023 [4]. The largest market is the Asia-Pacific region, representing 26% of the market share, followed by the North America market with 23%, and Europe with 21%. The remaining share is distributed across various regions of the world, including the Latin America, the Middle East and Africa market. Overall, this figure shows how the market is divided in every region in the world. Currently, the packaging industry is increasing sales volume. Figure 2 presents the global expected sales until 2030 and increase rate of presented [5, 6]. Following these results in 2030 it is expected that the industry increases approximately 30% and the CAGR factor (compound annual growth rate) is 3.16% in the analysed period, which emphasizes the reported growing trend.

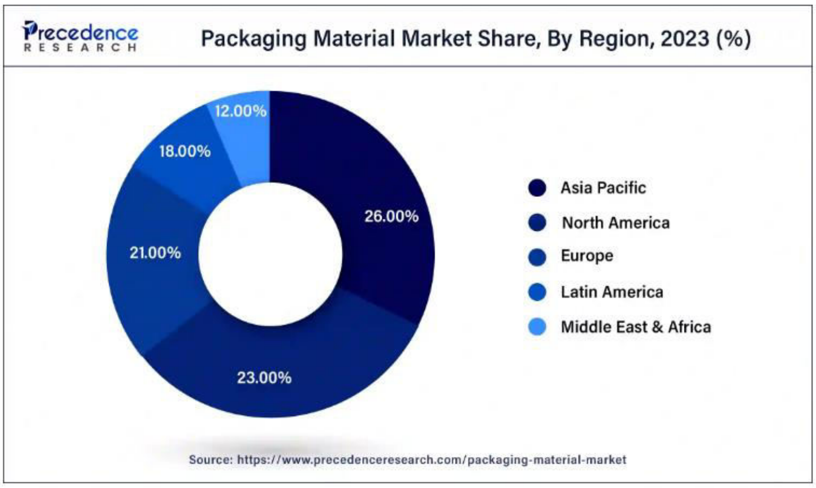


Figure 1 - Packaging material market share, by region in 2023 [4].

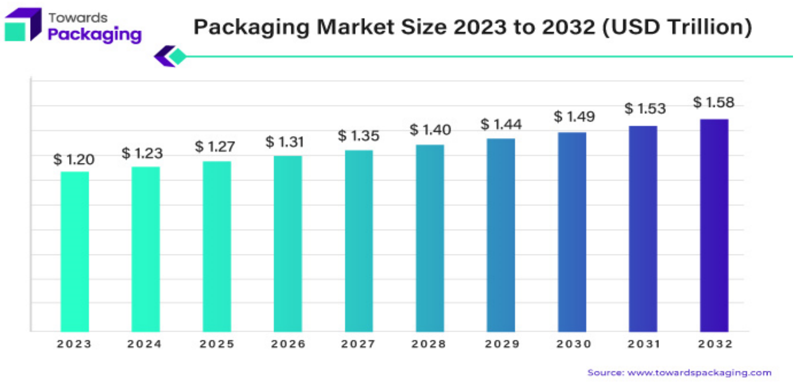


Figure 2 – Expected global packaging market size from 2023 to 2032 [5].

This increase of sales leads to higher package waste, which contributes to increasing the pollution. As a result, the packaging industry is investing in new sustainable solutions. In Figure 3, it is possible to visualize the increase of waste and recycling plastic packages [7].

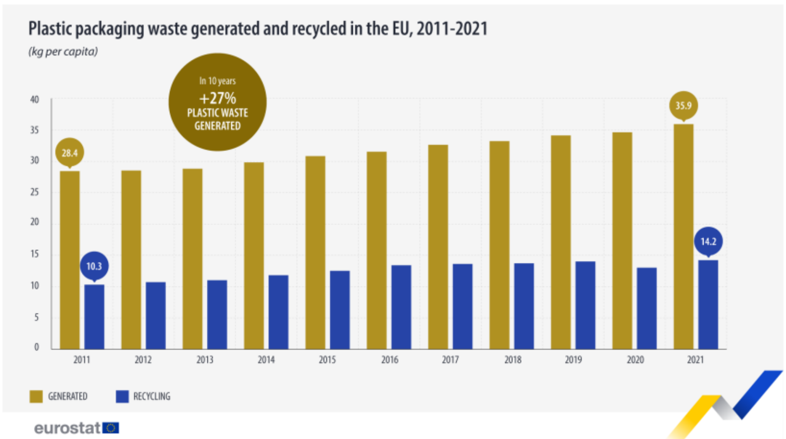
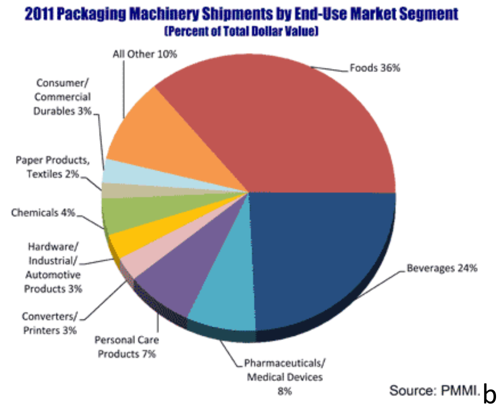
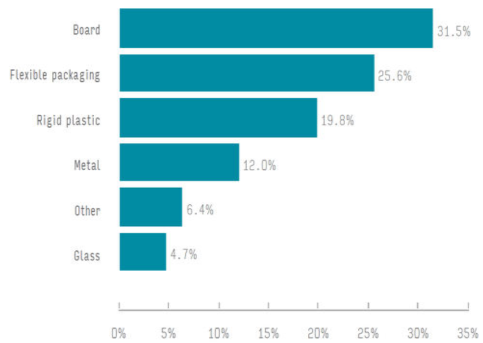


Figure 3 - Plastic waste generated and recycled in Europe from 2011 to 2021 [7].

Considering the growth in the packaging market, Figure 4 (a) reports on the industries that lead the use of packaging systems. It is possible to conclude that essential goods such as food and drinks are the top industries using the packages, having practically half of total allocation. The remaining half is divided into many industries such as medical, automotive, personal care and many others [8]. Between industries, different materials are used such as paper derivatives, types of plastic, steel and metal alloys, glass and others. Figure 4 (b) shows the principal materials used in the packaging industry [6]. It is possible to conclude that boards are the principal type of packaging, having 31.5% share, followed by flexible packages with 25.6%, rigid plastics with 19.8%, metals with 12.0%, other materials with 6.4%, and glass with 4.7%.



a)



b)

Figure 4 - Packaging machinery shipments by end use market segment [8] (a) and materials used in packaging industry in 2023 [6] (b).

2.1.2. Packaging industry in Portugal

In Portugal, the packaging activities have a considerable impact in economy of the country. Figure 5 shows the value of packaging activities in the Portuguese industry [9]. It is possible to conclude that in 2023, 68.39 million of U.S dollars are spent and until the final of 2024 is expected to spend 69.13 million of U.S dollars.

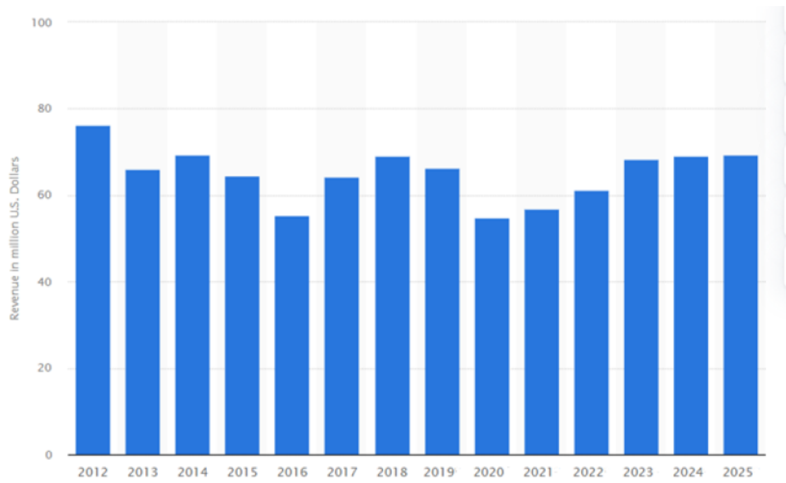


Figure 5 - Industry revenue of packaging activities in Portugal from 2012 to 2025 [9].

Figure 6 rates the European countries when it comes to recovery rate of packaging waste [10]. It is possible to observe that Portugal is above the recommended value of 60%.

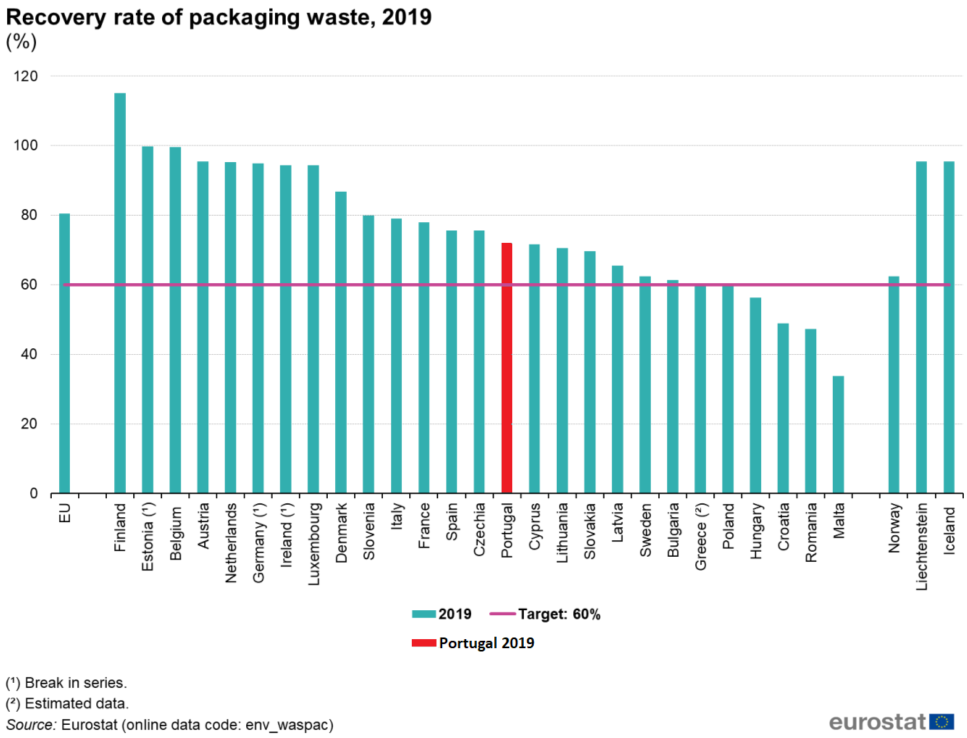


Figure 6 - Recovery rate of packaging waste in Europe, in 2019 (adapted from [10]).

As is the case in Europe, plastic recycling is a serious problem that must be tackled to reduce the negative environmental impact of pollution. It can be seen in Figure 7, that Portugal has the same problem of Europe in recycling plastic packaging and it is below the European average [11].

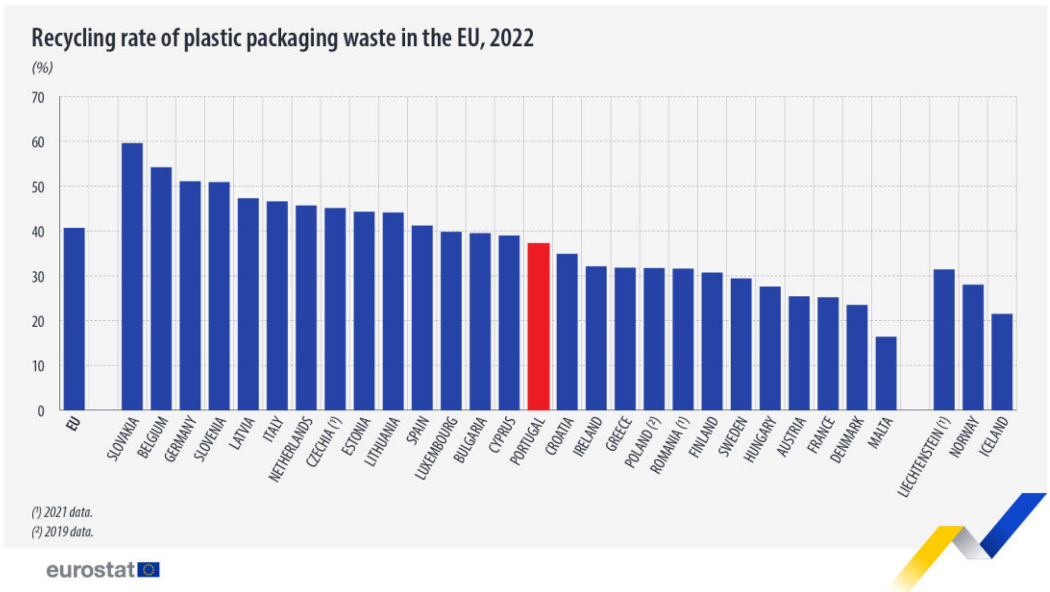


Figure 7 - Recycling rate of plastic packaging waste in Europe, in 2022 (adapted from [11]).

2.1.3. Packages type and solutions

In the global market, the packaging of products is crucial for the logistical operations because the products need to be stored and transported. When an organization orders a shipment, for example, it is necessary to transport the product from the place of production to the buyer location. To carry out this operation it is necessary to guarantee the quality of the product, avoiding any type of contamination or physical damage. Currently many solutions are over table to transport products. The products can be transported differently and can be subject to many types of environments, so the package needs to be prepared for varying conditions. As a result, many solutions are provided in the market to transport the products such as containers, paper boxes, steel packages, pallets and many others. Figure 8 presents some relevant types of solutions used by the industry to export goods internationally [12].

Figure 8 - Types of packaging solutions [12].

Under the scope of sustainable solutions, the recyclable packaging market is valued at 100 billion US$, representing 50% of the transit packaging solutions in 2023. Figure 9 shows the main recyclable solutions used in international transport of products.

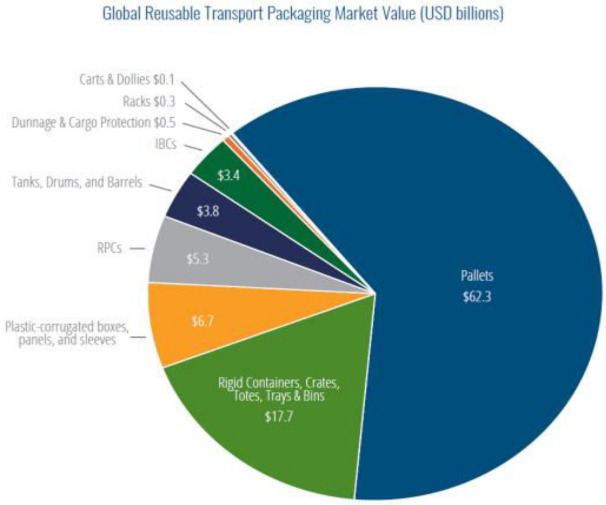


Figure 9 - Global Reusable transport packaging market value in 2023 [13].

In 2023, pallets were the most used recyclable solution with 62.3% of the share, followed by rigid containers and crates with 17.7%, while the other reusable package types have negligible shares [13]. Pallet solutions include wood pallets, cardboard pallets, steel pallets, pallets with dumping system, pallets with rigid plastic, and others. The purpose of the pallet solution is to transport the load, but it has the added feature of being able to transport the pallet with a forklift and pallet conveyor over a shorter distance, which makes it easier to handle in spaces such as factories and facilitates storage. The pallet has many different components to ensure its proper functioning, even if they are often made of the same material, and can be differentiated according to different classifications [14-16]:

- Dimensions:

  Pallets can be American style or European style. Normally the difference between these two styles is the dimension. The American pallet has 1000×1200 mm^2 while the European pallet has an 800×1200 mm^2.

- Number of entry points:

  Pallets can have two or four entry points. Pallets with four entry points enable the transportation mechanism, such as a forklift, to engage the pallet by all sides, two-entry pallets have access restricted by two sides.

- Material:

  Pallets can be fabricated from different materials such as wood, steel, plastic, and carboard. Generally, the wooden pallet is the most used having about 95% of market share.

- Design and purpose:

  Some types of pallets are reversible by enabling two contact surfaces with the products. Closed pallets have just one side that can be loaded and this side is closed by a slat, others are called wing pallets due to facilitating to facilitate the use of fastening systems. Figure 10 presents most used types of design of wood pallets.

Figure 10 - Different wood pallet designs (adapted from [14]).

Rigid plastic containers are other example of reusable solution. These provide an excellent resistance to degradation from chemicals and water, low weight, good flexibility, high strength, good tear resistance, and high impact resistance. Another rigid plastic solution are plastic crates. Plastic crates are used to store small products and can be stacked to guarantee less storage space and stability of the set. Some of them are RPC (reusable plastic crates), produced by reusable plastic and used in many industries, such as the food industry, to store biological food for example [17]. Figure 11 depicts an assembly of stacking crates [18].

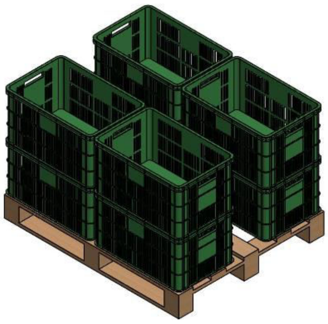


Figure 11 - Stacking Crates (adapted from [18]).

2.1.4. Manufacturing equipment

In parallel to the wide variety of packaging, there is also a huge variety of manufacturing equipment to fabricate packages. For recyclable solutions such as pallets, specific solutions exist for product loading. In Figure 12 (a) presents a specified machine to perform this task, with a COBOT (collaborative robot) that loads the product, in this case, inside a box, on the pallet. It is possible to perceive that the products loaded in the pallet need to be fixed to guarantee the stabilization of the product set. One method used to guarantee the safety of products on the pallet involves sealing the pallet with plastic film [19]. To seal the products around the pallet, a stretch wrapping machine or similar machine is necessary, which wraps the set with plastic film. Figure 12 (b) shows a stretch wrapping machine.

a)

b)

Figure 12 - Palettizing automated robot arm (a) and automatic stretch wrapping machine (b) [20].

Rigid plastic packages, which are the second most valued recyclable solution, use other types of machines to prepare and produce packaging. Plastic containers are made by injection molding using different types of plastics, such as PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), PS (Polystyrene), and many others [21]. The plastic crates, for example, are fabricated from PP (polypropylene) and HDPE, and can be produced by different processes [17, 18, 22]. An example of injection molding machine is presented in Figure 13.

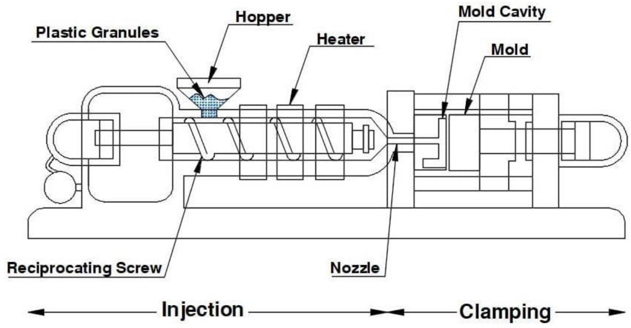


Figure 13 - Injection unit of an injection moulding machine [23].

Another solution in packaging industry involves using flexible plastic to transport an assembly of many small parts such as, for example, a bag of seeds. Normally these of bags are made by thermoplastics films. Thermoplastics are chosen due to their mouldability at high temperature, and solidification after cooling [23, 24]. Figure 14 shows a flexible plastic packaging machine.

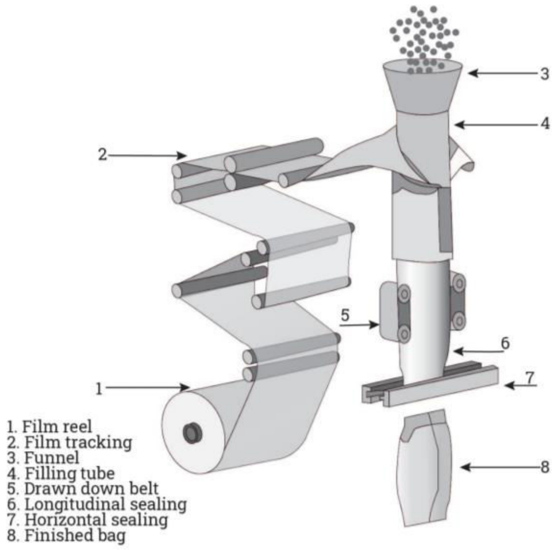


Figure 14 - Flexible plastic packaging machine [23].

2.1.5. Recent developments

Nowadays, most of the developments are made considering the evolution of the industry. The concept of industry 5.0 has different of definitions since it has not evolved to the fullest. However, under the scope of the packaging industry, it relates to adapting creativity and capabilities of expert human professionals with intelligent and efficient machines, many of them used in industry 4.0 [25]. In industry 4.0 and 5.0, manufacturing processes use AI (Artificial intelligence) to assist the design of smart factories using automation and intelligent robots. AI extends manufacturing capabilities by optimising workflows, automating processes, and analysing real-time data. It improves product quality through accurate defect detection and predictive maintenance, reducing errors and waste. In addition, AI accelerates research by simulating designs, optimising materials, and predicting performance, enabling faster innovation and increased productivity [26].

Nowadays the industry is focused on sustainability and circular economy, and the packaging industry has invested in these concepts to improve their products. Some developments for the packaging industry are being made, such as new types of materials to reduce waste and achieve solutions that satisfy sustainability and maintain the objective of storing and transporting products. Recently, a study addressed the transportation of fruits and vegetables with RSC and cardboard boxes and that showed that it is possible to create combined packaging, with the different materials, to store and transport the products, which means that it is possible to achieve more sustainable solutions with a mix of materials [27, 28].

Another example of sustainable development is edible packaging. This type of system is used to package food and is biodegradable and can usually be consumed, generating no waste and reducing the waste of other food packaging such as plastic. In addition to being practical, the edible package guarantees the protection, preservation, and safety of the food, and ensures no waste and sustainability [28, 29]. The field of biogenic materials such as natural biopolymers is increasingly being explored in packaging of food industry, and it involves packaging produced using materials from nature biological origin. Some of these materials are recyclable, others are biodegradable and some of them are compostable, all properties that are environmentally friendly [30-32]. This concept is schematically described in Figure 15.

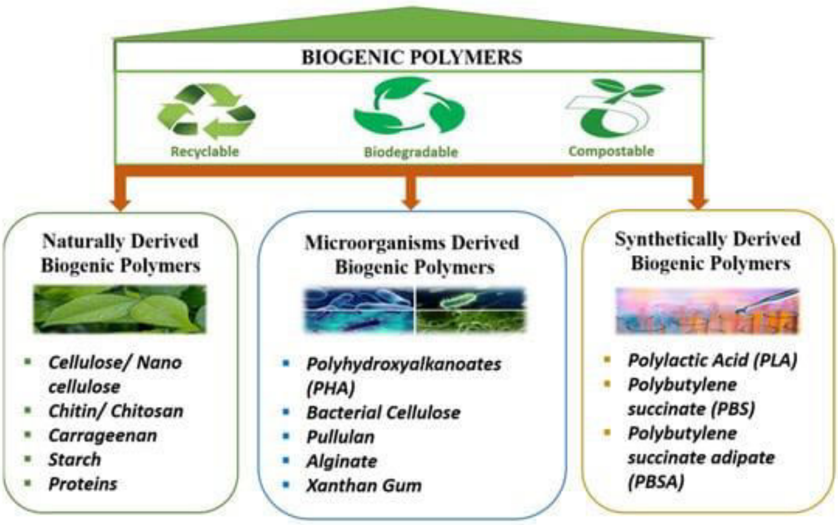


Figure 15 - Biogenic polymers [30].

2.2. Structural design

The term design is often associated with the appearance and aesthetics of an object, rather than the process of creating a functional product that meets customer needs. Mechanical structural design is typically associated with the development of a product that is safe, efficient, reliable, economical, and practical to manufacture, while above all complying with the customer's requirements [33].

2.2.1. Concepts and stages of design

Design can be associated to all the processes of conception, invention, visualization, calculation, refinement and specification of details that determine the shape of a product. When a product already exists and needs improvement or optimization, the design process focuses on addressing the limitations of the previous version.

Design is applicable to various industries whenever there is a need or an initial problem requiring optimization or improvement. If there were no new designs and optimization processes, there would not be a constant evolution of products and new solutions. A good example of this concept is the constant evolution in the car industry, which involves the development of new car models and innovative materials. Similarly, other industries rely on design to address challenges and achieve progress.

To develop a product design, several steps must be followed. Figure 16 shows the general design process and illustrates the iterative steps associated with the processes.

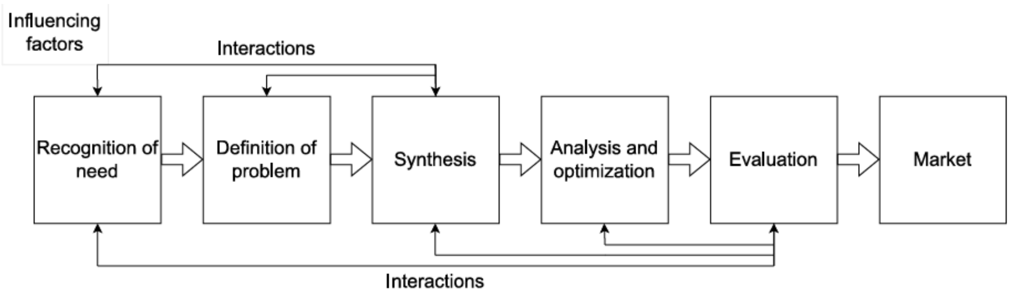


Figure 16 - Design process illustrating the associated iterative steps (adapted from [34]).

The steps used to develop product design are [34]:

Recognition of need: Usually, at this stage, a company recognises a need for improvement or upgrade of a product or process. Sometimes, this need is recognised in the market, through an analysis of equipment sales or because of feedback obtained from customers, which results in a statement sometimes called a market brief, project brief, brief, or statement of need. When a company has a need, it is necessary to improve that equipment to fulfils the requirements imposed by the customer.

Problem definition: This step serves to find the problem that leads to the customer's need. Sample problems are limited dimensions, limited power, quantities of production, and other activities that can compromise the usability or production of that equipment for example.

Synthesis: In the process, ideas are gathered and used to develop a potential new solution, fulfilling customer needs and design requirements. Some ideas appear because of the experience of the designers developing the equipment solution.

Analysis: This analysis stage is linked to the synthesis stage and usually involves engineering processes. Digital tools and engineering techniques such as FMEA (failure modes and effects analysis), CAD (computer-aided design), FEA (finite element analysis), and others are often used to assist in this stage. FEA simulations are carried out to understand if the equipment complies with the imposed restrictions.

Optimization: This part serves to repetitively refining a set of often-conflicting criteria to achieve the best compromise.

Evaluation: This is the process of identifying whether the design development fulfils the initially presented needs by the client. This stage can involve building and testing prototypes, evaluating analyses, and conducting market research. Once this stage is completed, the final equipment can be introduced to the market.

Structural mechanical design requires knowledge and skills. This knowledge includes technical drawing drafting, 2D and 3D CAD, material properties, material processing, and manufacturing processes, chemistry applications such as corrosion protection, galvanising and painting, statics, dynamics, strength of materials, kinematics and mechanisms, oral communication, listening comprehension, technical writing, teamwork skills, creativity, problem-solving, and project management [33].

Over time, industries have become more competitive and more efficient in terms of producing and selling equipment. This change to a high level of competition between organisations in the sector, which means that design engineers must reduce the time needed to launch products without losing quality and value. To this end, various techniques have been created to help the design engineer develop the product more easily. DFX techniques have been used to assist the design process, where the x represents a certain property that the client needs, such as quality, low cost, safety, sustainment or a specific life phase, such as assembly and manufacture for example. DFX stands for Design for Excellence, as it satisfies sustainability factors and client requirements [35]. DFX techniques, when used in isolation, focus mainly on the positive property and not on other factors. To develop the product in a global way, these DFX techniques should be adapted so that they are integrated into product development and not used in isolation.

The DFX technique can be applied in two variants. The first is product optimisation through its virtuous properties, and the second is product optimisation through a relationship with the specific life cycle of the product. Table 1 provides examples of DFX virtue and DFX life phase [36].

Table 1 - Types of DFX application (adapted from [36]).

DFX virtue	**DFX life phase**
Design for environment	Design for assembly or disassembly
Design for quality	Design for manufacturing
Design for cost	Design for recycling
Design for maintainability	Design for end of life

The virtue DFX does not dictate the virtues that the product must possess. Instead, it used to assess how well the design satisfies the virtue and assist the designers in expanding the product´s purpose beyond mere functionality, addressing other aspects that matter to consumers. The life phase DFX assists the designer assuring that the product's life cycle stages are considered when defining the product requirements [36].

2.2.2. Materials and processes

Figure 17 illustrates the historical evolution of materials used in engineering, highlighting changes in their importance over time. Metals have traditionally held a dominant position due to their strength, durability, and versatility. However, from the 1960s onwards, more advanced materials such as composites and ceramics began to gain prominence, reflecting technological advances and new industrial demands. After the 1960s, the development of industries such as aerospace, automotive, and electronics drove the need for materials that combine lightness with high strength and the ability to withstand extreme conditions. Composites became essential in applications where weight reduction was critical, while ceramics were increasingly used in environments requiring resistance to high temperatures and corrosion. In addition, growing concerns about energy efficiency and sustainability encouraged the adoption of lighter and more efficient materials, contributing to their widespread use in various industries. At the same time, advances in materials science have enabled the development of solutions that meet more specific technical requirements, such as thermal stability and insulation properties. Although metals are still widely used, rising costs and the need for innovation have led to increased use of modern alternatives. The increased use of composites and ceramics reflects their ability to meet the technological and industrial demands of today's society, which traditional materials can no longer fully satisfy. [37]

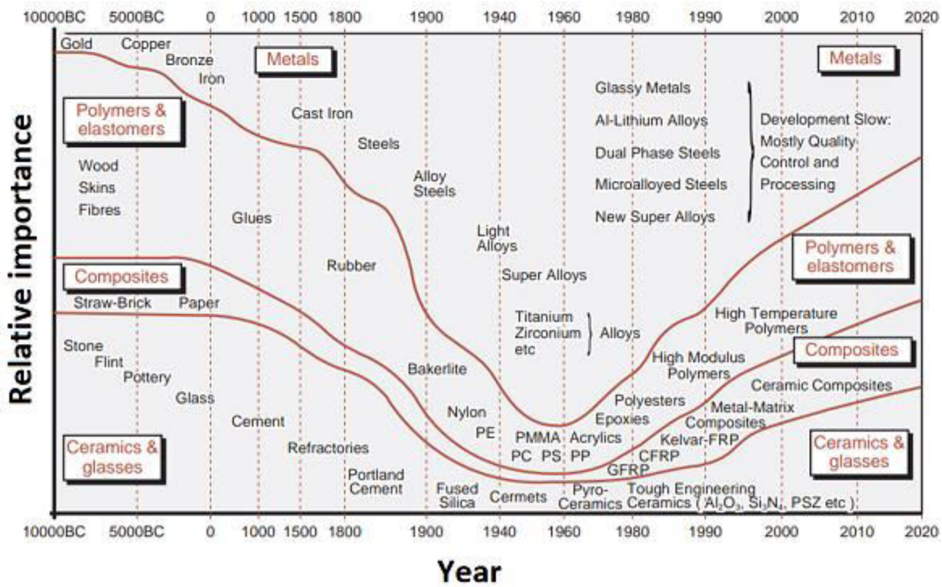


Figure 17 - Relative importance of materials over time (adapted from [37]).

In structural design, some stages require the selection of materials and production process for the equipment to be developed. These parameters are chosen considering the initially imposed restrictions by the client. These constraints can be related to the dimensions, the loads it will have to withstand, its shape, and others. In relation to the redesign, new materials can be applied to overcome current problems or limitations.

Material selection can be a difficult task because of the wide variety of materials. Normally, the material selection is made by the experience of the engineer in charge or by a comparation method. Figure 18 a) shows the strategy of comparation materials created by Michael Ashby.

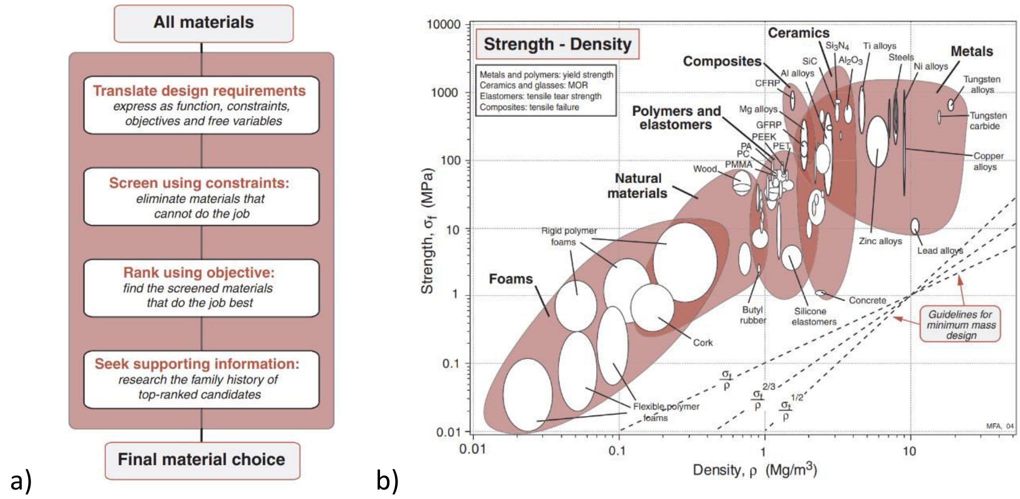


Figure 18 - Material selection Ashby method (a) and Ashby diagram for the strength vs. density (b) [37].

Using the comparative method for material selection requires first identifying the primary constraints of the project, such as the loads that the component must withstand, the component size, the operating environment, and other critical factors. Once these constraints have been defined, the designer selects the key objectives, which may include minimising cost, reducing weight, ensuring safety, or a combination of these priorities. This step, known as **translation phase**, involves outlining the component's function, constraints, objectives, and free variables. Constraints define the limits within which the material must operate, such as mechanical, thermal, or environmental limits. This phase defines the desired outcome to be optimised, for example making the design as economical or lightweight as possible. By formalising this process, translation serves as the basis for the next phases. This systematic approach ensures an optimal balance between performance, cost, and practicality.

Once the translation phase is complete, the material selection process moves to the **screening phase**, in which unsuitable candidates are eliminated. In this step, tools such as the Ashby diagram are used to establish attribute limits based on project constraints, such as temperature resistance or optical clarity. By identifying the range of materials that meet these constraints, the vast pool of options is significantly reduced. For example, in Figure 18 b), the diagram defines strength and density as the primary attributes, leaving only materials that meet these criteria.

Once screening is complete, the **ranking phase** is required to differentiate the remaining candidates. Ranking is based on material indexes that optimise performance by combining relevant properties. For example, the best material for buoyancy will minimise density, while for thermal insulation low thermal conductivity will be prioritised. In more complex cases, combinations of properties are used, such as maximising specific stiffness (E/ρ) for lightweight structures. These material indices act as performance metrics, ranking candidates according to their ability to meet the design objectives.

The next phase is to **seek supporting information**. A ranked shortlist provides a focused starting point to explore details such as corrosion resistance, environmental impact, cost, and availability. This descriptive data, found in case studies, supplier datasheets, or online resources, is critical to validate the selection. Supporting information ensures that the selected material has no hidden drawbacks and meets the project requirements [37].

Even with experience or a materials comparison matrix, it is sometimes difficult to choose one material, because for the same task there is more than one solution that satisfies or has a close performance index. Normally, the first time the equipment is manufactured, a material that satisfies the project is selected and, when the next model is needed, the previous material is analysed and optimised to arrive at a better solution if the previous one has problems.

The selection of a material and a process cannot be separated from the choice of the component shape. For the material to acquire its shape, it undergoes a process known as manufacturing. There are many types of manufacturing processes that can alter the internal structure of a material, change its shape, remove excess material volume, and others. The material selection is related to the function, the process, and the shape. The function of the equipment requires specific properties, which can be found in the material selection. Depending on the function of the equipment, a certain shape is required, and the manufacturing process is needed to condition that shape. This can be a problem when it comes to choosing a material for a project, but all four of these parameters must be considered [37].

2.2.3. Joining processes

Joining processes are all processes that involve joining two or more different elements. Considering the structural design, the joint must be able to effectively transfer the loads between the elements. These processes can be divided into three types of connection processes, such as pure mechanical connections, welded connections, or adhesive connections. These types of connections can be permanent or non-permanent.

Mechanically fixed joints, such as bolted connections, are non-permanent joints. This type of joint can be used in different materials, such as steel, wood, and others, can be used to join more than two materials, and can be removed when necessary [38].

Permanent joints can be divided into three different connections:

Riveted joints: This type of joint can be used to join two or more elements and is used in metal elements such as steel, aluminium alloys, and other materials. This type of joint consists of producing, by plastic deformation, counter-heads on rivets previously placed in holes common to the parts to be connected [39].

Welded joints: Welded joints are used to join metallic materials such as steel and other ferrous alloys. Welded joints normally exceed the base strength of the materials to be joined and constitute a very versatile process because of allowing various types of materials to be joined, in various sizes and shapes [40].

Adhesive joints: This type of joint can be used in metallic alloys and non-metallic materials such as thermoplastics, composites, glass, wood, and others. This type of solution has many advantages such as uniform stress distribution along the front width, vibration damping, joining of different materials, and others [41].

In steel structures, joints are used to transfer forces between elements or to supports. Normally, joints in steel structures are made up of mechanical and welded connections. The most used mechanical joints are bolted joints. There are various types of bolts, which can transfer different types of stress such as shear and bearing, friction and tension, and others [42]. Figure 19 (a) illustrates recurrent uses of bolts in different conditions.

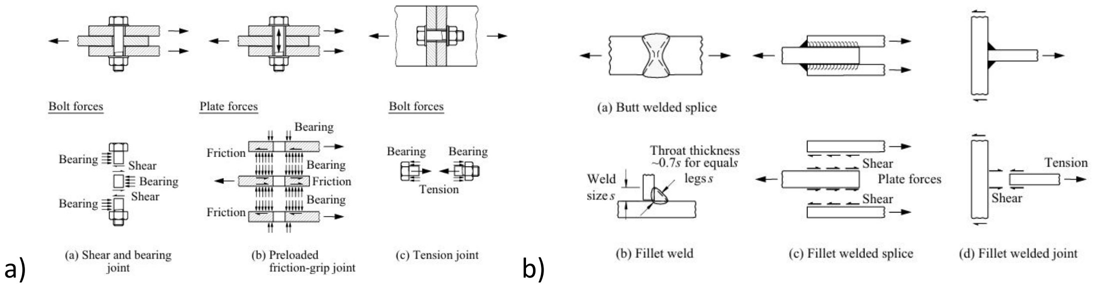


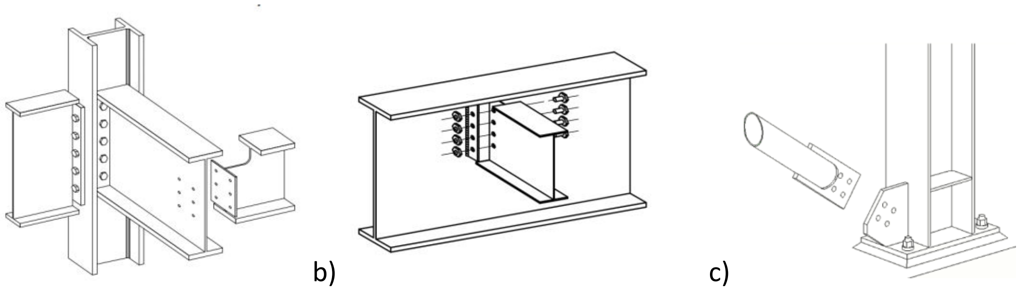
Figure 19 - Use of bolted joints and typical solicitations (a) and use of welded joints and typical solicitations (b) [42].

Bolted joints facilitate assembling elements in structures because complex tools are not necessary for assembly, which is relevant these are not available. Bolted joints have the advantage of not being a permanent joint, i.e., the structure can be dismantled when necessary. Bolted joints are easy to inspect and can be used with virtually no prior knowledge. The disadvantage of bolts in structural design is the cost of preparing the joint, because you have to drill into the material to create the bolt pocket and the connected elements weaken over time [42].

Welded joints are made using arc welding techniques, in which molten weld metal is fused with the base metal of the members or filler plates being connected in a joint. This method is used when it is possible to carry out control and inspection procedures to guarantee the quality of the weld. Welding is usually a more economical solution compared to mechanical joints, as no prior preparation involving drilling or specialized machines is required and, at the same time, it guarantees greater strength as there are no weakened areas due to bolt holes in the base materials. Welded joints are a permanent joint, which means that the joint is permanent, making it impossible to dismantle without aggressive techniques. In order to use welded joints, specific knowledge is required, which means that specialized operators are necessary for the task [42]. Figure 19 (b) shows recurrent welded joins and solicitations.

In metallic constructions, often joints are a combination between welded and bolted joining. End plate connections, presented in Figure 20 (a), are a popular type of joint in some countries such as UK. The end plate, previously drilled, is welded to the structural element, such as an I beam for example, and can be partial or full depth. Another possible solution for these joins is the fin plates solution, presented in Figure 20 (b). The difference between the fin plate joints and the end plate joints is the bonding surface. In end plate joint the surface of the plate where the holes are is welded directly to the beam or connected to other plate and the fin plates joint, the plate is welded to the perpendicular plan where the holes are situated to the beam and connected directly to the second beam.

Bracing joints, presented in Figure 20 (c), are used to work only in tension due to predominant axial force applied. Various profiles can be used as bracing elements, such as angles, I section, hollow sections and flats. Normally the bracing element is connected by bolts to a plate, and that plate is welded to the supporting element [43, 44].

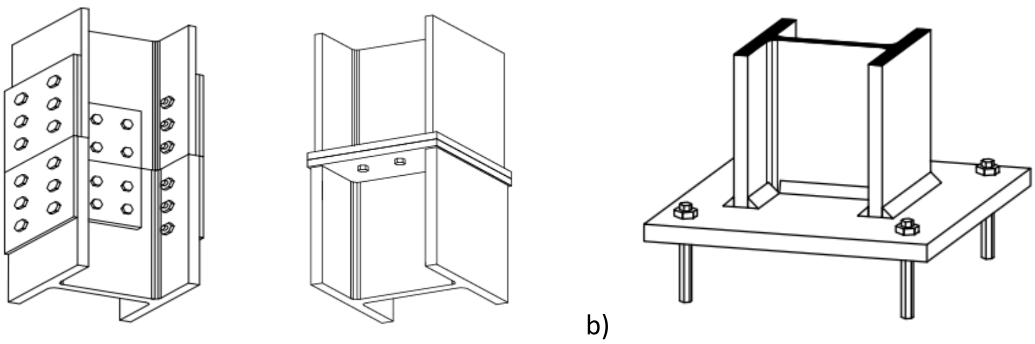


a) b) c)

Figure 20 - End plates joints (a) [43], fin plates joints (b) [43] and bracing joints (c) (adapted from [44]).

The column spice, showed in Figure 21 (a), is a usual type of joint in metallic construction. This joint is composed of two shear web plates and bottom flange plates. Each one of these plates have a different function. The shear plates transfer most of the shear force. The bottom flange plates are necessary to transfer the compression and tension forces. The joint can be welded in one side of the joint and bolted in the other side. Another way to join the elements is using an end plate in the end of each member. Normally this joint is less rigid, and a good practice involves placing a thicker plate and bring the bolts closer to the flange to guarantee added stiffness.

Column bases, presented in Figure 21 (b), is the most important elements in steel structures because is the base joint. This type of joint consists of a single plate welded to an end of a column and is joined to the foundation by bolts. The column bases are usually prepared to sustain to axial compression and shear [43, 44].



a) b)

Figure 21 - Beam and column splice joints (a) and base plate connection (b) [43].

2.2.4. Roughness and material treatments

Depending on the type of material and its function, there are different surface treatments. This treatment variety arises from the different properties and operating conditions of materials, i.e., these can be exposed to different types of environments. These environments may require good corrosion resistance, good wear resistance, low geometric deformation capacity with increasing temperature, good decoration, or improved wear resistance. Surface treatments ensure that the material fulfils its main purpose. These treatments are wide-ranging, depending on the type of material in question [45].

For metal element machines, roughness is an important parameter, depending on the machine's work requirements. The roughness for a given element depends on the manufacturing process and surface treatment. Some elements do not require surface treatment after the manufacturing processes because of no contact or sliding with other surfaces that could result in damage to the machine. It is possible to have different roughnesses on the same element, depending on the function of each surface of the element. Surfaces with fixed contact and surfaces with contact and relative movement require lower roughness than non-contacting surfaces. These surfaces are usually treated to reduce roughness [39]. Table 2 shows the roughness for different applications in machine elements according to UNI 3963 standard [46].

Table 2 - Examples of mechanical elements and his roughness (adapted from [46]).

Roughness (μm)	Applications
0.025	Mirrors; precision blocks; micrometer support face.
0.05	Workshop gauge faces; support plans for comparators.
0.1	Joint axes; precision tools; super finishing busters
0.2	Connecting rod shaft; turbine shafts; high speed bushing holders
0.4	Striated shafts; external piston surface; shaft bearings
0.8	Polished holes; gear teeth; sliding parts surfaces
1.6	Cylinder head; piston faces; characteristic faces of gear wheels
3.2	Surfaces between two fixed parts; manual transmission shafts and bushings
6.3	Flange retaining surfaces with common gaskets

To ensure optimum roughness, different types of machining can be used, such as turning and milling for roughnesses between 1.6 and 12.5 μm, cylindrical and flat grinding for roughnesses between 0.4 and 1.6 μm, and super-finishing and polishing for roughnesses between 0.025 and 0.2 μm [39].

Surface treatments are used in industry for different functions. For steel alloys, there are treatments that guarantee good hardness, such as carburizing and nitriding, the latter of which also guarantees good wear resistance [47]. Anti-corrosion and anti-oxidation treatments are normally used on metal alloys. These treatments can be galvanisation, coating or oxidation and are used in the field of building structures, vehicles, ships, and pipelines [45]. Other elements need to be painted to improve the machine aesthetics. Usually parts that are painted, are not subjected to significant loads [48].

Anodising is an electrochemical process commonly used on non-ferrous metals, primarily aluminium and titanium alloys. In this process, the metal is immersed in an electrolytic bath, where the metal part acts as the positively charged anode. A submerged cathode, which is the negatively charged electrode, causes hydrogen to be released from the solution, while oxygen is released at the surface of the metal, forming a thick oxide layer. This oxide layer is durable, corrosion-resistant, and can be decorative. Anodising increases the thickness of the natural oxide layer on the metal's surface, which enhances the material's protection and improves its appearance. The process is most commonly applied to aluminium and titanium alloys. [49, 50].

Innovative solutions are being recently developed to confer excellent surface properties for materials and for their function. Flame retardant surface treatments, for example, have emerged as a promising alternative to traditional bulk flame retardants due to their ability to localize fire-resistant properties on the material’s exterior, where ignition typically begins. Unlike conventional methods that require the incorporation of large amounts of additives into the material’s bulk, surface treatments preserve the original characteristics of the material while enhancing fire resistance. Although recent advancements have shown potential for improved fire suppression, challenges such as durability, scalability, and environmental safety remain critical obstacles to overcome. Continued research into innovative surface chemistries is essential develop more effective and sustainable flame retardant technologies [51].

In polymer composites, carbon fibres are highly valued for their strength and stiffness, but their chemically inert surfaces pose challenges in achieving strong bonding with the polymer matrix. Various surface treatments have been explored to improve fibre-matrix adhesion, including acid oxidation, plasma treatment, rare earth treatment, and gamma irradiation. These methods alter the surface morphology and chemical composition of the fibres, increasing surface roughness and promote better interaction with the matrix. The effectiveness of these treatments varies based on the specific application, highlighting the need for optimization to enhance composite properties while maintaining the integrity of the fibres [52].

Titanium, widely used in dental implants, relies heavily on surface modification to enhance its performance. The primary objective of these treatments is to accelerate osseointegration, ensuring a quicker and more stable integration with bone. Techniques such as sandblasting, acid etching, plasma spray deposition, and cathodic arc deposition improve surface roughness and wettability, critical factors for successful implant function. Emerging approaches, including advanced organic and inorganic coatings, show potential to actively promote biocompatibility and prevent bacterial colonization. Despite these advancements, further clinical research is necessary to validate the long-term benefits and widespread adoption of next-generation surface treatments for dental implants [53].

It is possible to conclude that the surface treatments are important depending on the principal use of the element and is used in different materials and different industries.

2.2.5. Component sizing

In industry, component sizing is not limited to structural design; it applies to various fields. For example, in the automotive industry, the correct sizing of components such as the battery in a hybrid car is crucial. This process must consider not only the physical space available, but also the energy efficiency and capacity of the battery. In addition, other components such as the chassis, the body, the combustion engine, the engine cooling system, the gearbox, among others, also require careful sizing. Each parameter has specific constraints that must be taken into account to ensure a functional and efficient design [54].

Sizing components is an important step in structural design. As shown in Figure 16, there are several phases during structural design. The component design part is included in the synthesis and analysis section, previously described in 2.2.1. It is usually difficult to select the correctly design for a structure from scratch, unless a previous version of the design is available that serves as a basis for prior analysis. When designing products from scratch, i.e., without improving previous versions, the design methodology described in section 2.2.1 is recommended. If the component design is complete and meets all the objectives, there is no need to revisit the previous stage for corrections. However, if the objectives are not met, it becomes necessary to return to the synthesis phase and redesign the equipment to ensure it fulfils the requirements.

The initial requirements that dictate the design of the components. Generally, these parameters are the loads applied at specific points on the structure, the overloads it may suffer, meteorological effects such as snow, rain, wind, and temperature, the altitude at which the structure is located, or its proximity to the sea. It is important to accurately define the loads applied to the components. Components that undergo traction cannot be sized in the same way as components that suffer compression or torsional solicitations [55].

For metallic materials, the design process involves analysing the stress state within the structure, which can be subjected to a triaxial stress state. By considering all the loads acting on the equipment, the principal stresses in each plane can be determined. This allows the triaxial stress state to be approximated to a notional uniaxial stress state. This equivalent uniaxial stress state can then be directly compared with the stress state at any point in the tensile test specimen [56]. The transformation of stress state is represented in Figure 22.

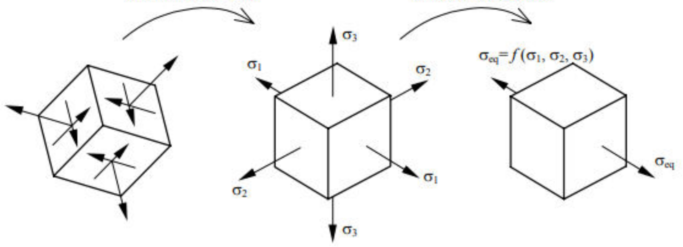


Figure 22 - Transformation of triaxial stress state to uniaxial stress state (adapted from [56]).

The strength limit at a point is reached when the equivalent stress (σ_{eq}) is equal to the limit stress of the material, which for a ductile material is equal to the yield stress (σ_y).

$$\sigma_{eq} = \sigma_y \,. \tag{1}$$

Steel elements are considered ductile materials because they have the ability to undergo significant plastic deformation before failure, i.e., they can be bent and stretched without immediately breaking. There are two criteria that can be used to dimension the equipment, taking into account the ductile behaviour of the materials:

Maximum shear stress criterion or Tresca criterion: This criterion states that yielding of the material occurs when the maximum shear stress (τ^{max}) at a given point in the component is equal to the maximum shear stress at a point in the tensile test specimen at the moment of yielding (τ_y^{max}), i.e.

$$\tau^{max} = \tau_y^{max} \quad (2)$$

The maximum tangential stress can be obtained as a function of the highest and lowest values of the three principal stresses

$$\tau^{max} = \frac{\sigma_1 - \sigma_3}{2} \quad (3)$$

The stress, at the moment of fracture of the specimen, is defined by:

$$\tau_y^{max} = \frac{\sigma_{ced}}{2} \quad (4)$$

By developing equation (2) and (3), it is possible to obtain the equation of equivalent stress by the Tresca criterion

$$\sigma_{eq}^{Tresca} = \sigma_1 - \sigma_3 . \quad (5)$$

Distortion energy criterion or Von Mises criterion: This criterion states that yielding of the material occurs when the specific strain energy installed at a given point (u^f) is equal to the specific strain energy installed at a point on the specimen at the moment of yielding (u_y^f)

$$u^f = u_y^f . \quad (6)$$

The distortion energy (u^f)can be calculated through the three principal stresses**:**

$$u^f = \frac{1+v}{6E}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]. \quad (7)$$

At the moment of specimen failure, the deformation energy (u_y^f), is defined by:

$$u_y^f = \frac{1+v}{6E} \cdot 2\sigma_y^2 . \quad (8)$$

By developing equation (6) it is possible to obtain the equivalent stress by Von Mises criterion ($\sigma_{eq}^{VonMises}$):

$$\sigma_{eq}^{VonMises} = \frac{1}{\sqrt{2}} \cdot \left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2 \right]^{0.5} . \tag{9}$$

The Tresca and Von Mises criteria are both used to evaluate failure in ductile materials, but they differ in their conservatism. To compare them, it is necessary analyse a plane stress state defined by the principal stresses σ_1, σ_2, and σ_3=0. Both criteria determine the yield limit through a geometric approach: Tresca forms a hexagonal boundary, while Von Mises forms an elliptical boundary in the σ_1-σ_2 plane. The Tresca criterion is more conservative because its boundary is entirely within the von Mises boundary, meaning that Tresca predicts yielding at lower stress combinations. This difference makes Tresca a more conservative criterion, but in some cases less accurate [56]. This can be visualized in Figure 23.

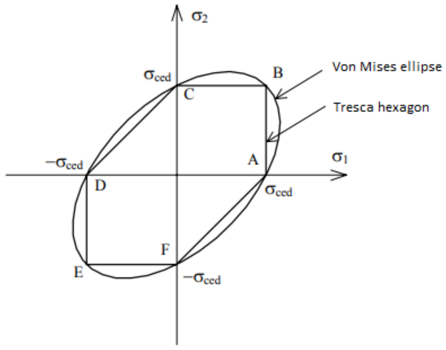


Figure 23 - Yield boundaries: Tresca hexagon vs. Von Mises ellipse (adapted from [56]).

In Europe, to correctly size steel structures to fulfil the technical specifications in public contracts, it is recommended to follow the EN Eurocodes. EN Eurocodes are a serie of ten European standards, EN1990 to EN1999, which provide a common approach to the design of buildings and structural projects in the field of civil engineering [55]. Eurocodes can provide more security in the construction sector in Europe.

Eurocodes are necessary and address many topics in the field of structural design and civil engineering. Figure 24 shows the structural design Eurocodes and the respective topics.

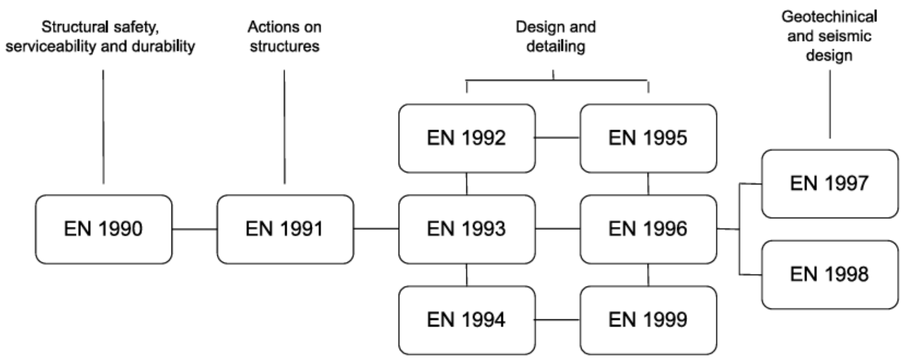


Figure 24 - Eurocodes for structural design (adapted from [55]).

The EN Eurocodes have been developed to support European policies and provide additional benefits. These rules facilitate the harmonisation of the civil engineering market, enable the free movement of engineering services, promote transparent competitiveness, and support the health and safety of the European population. By standardising practices, the Eurocodes simplify the marketing and use of materials, ensure a good level of safety, and enhance the competitiveness of companies [55].

Typically, civil structures, such as buildings and metallic structures, are subjected to various actions and require appropriate design based on these actions. Eurocode 1 deals with actions on structures and is divided into seven parts, each covering different types of actions and the environments to which the materials are exposed. Table 3 shows the seven parts of Eurocode 1 [57].

Table 3 - List of Eurocode 1 rules (adapted from [57]).

Eurocode (EN)	Description
EN 1991-1-1	Eurocode 1: Actions on structures: Part 1-1: General actions - Densities, self-weight, imposed loads for buildings
EN 1991-1-2	Eurocode 1: Actions on structures: Part 1-2 General actions - Actions on structures exposed to fire
EN 1991-1-3	Eurocode 1: Actions on structures: Part 1-3: General actions - Snow loads
EN 1991-1-4	Eurocode 1: Actions on structures: Part 1-4: General actions - Wind actions
EN 1991-1-5	Eurocode 1: Actions on structures: Part 1-4: General actions - Thermal actions
EN 1991-1-6	Eurocode 1: Actions on structures: Part 1-6: General actions - Actions during execution
EN 1991-1-7	Eurocode 1: Actions on structures: Part 1-7: General actions - Accidental actions from impact and explosions

Structural design in mechanical engineering considers various types of actions that affect the stability and performance of structures. These actions are typically divided into permanent and non-permanent actions based on their duration and variability. Permanent actions, also known as dead loads, are constant over time and include factors such as the dead weight of the structure, fixed equipment, and immobile installations. These actions predictable and can usually be determined with a high degree of accuracy. Non-permanent actions include variable actions such as wind, snow, and accidental actions such as, impacts, explosions, or earthquakes. These actions vary in intensity and frequency and require probabilistic approaches for their assessment. The design of structures must satisfy two key criteria established by the Eurocodes:

Ultimate Limit State (ULS): The ULS ensures the safety of the structure under extreme conditions, such as maximum loads or infrequent events. This criterion assesses the ability of the structure to withstand these loads without collapse. Permanent and non-permanent actions are combined using safety factors defined in Eurocode 0 (EN 1990), which considers worst-case scenarios for stability and strength.

Serviceability Limit State (SLS): The SLS is concerned with the functionality, comfort, and appearance of the structure under normal conditions. It ensures that deformations, vibrations, or deflections remain within acceptable limits, avoiding problems such as excessive damage or occupant discomfort. SLS is particularly relevant for non-permanent actions, as these often cause variations in the response of the structure during its lifetime.

In practice, permanent actions form the basis for design, while non-permanent actions are superimposed depending on the environmental and operational context of the structure. The Eurocodes provide combinations of actions, subfactors, and criteria to achieve a balance between safety and economy to ensure optimum performance of the structure over time. By distinguishing between these action types and applying the principles of ELU and ELS, engineers can design structures that are both safe and functional to meet the demands of modern construction [58].

2.2.6. Finite element method

The Finite Element Analysis (FEA) is a tool used in engineering to simulate mechanical systems and estimate their response to different applied loadings. FEA is not limited to structural mechanics and finds applications across numerous industries. These include stress and thermal analyses of mechanical and structural components, seismic analysis of buildings, crash testing in the automotive sector, fluid flow analysis for ventilation systems, electromagnetic studies, and even the simulation of surgical procedures in the medical field. Its adaptability allows for the analysis of systems with diverse materials, geometries, and complex interactions, making it an indispensable tool in modern engineering [59, 60].

The concept of FEA consists of replacing the original shape of the material, which is sometimes complex, with a sum of many simple shapes. These simple shapes can represent the original shape and are called finite elements, since each one occupies a limited region of the original shape.

FEA simulation depends on two main parameters: linearity and time. In terms of linearity, the analyses can be linear or non-linear, while in terms of time it can be static or dynamic. The time aspect depends on the system's loads and response. If these are constant over time the analysis is static, and if these are variable, the analysis is dynamic. As for linearity, a good example to demonstrate this is the tensile test of a steel specimen with proportional dimensions. In the elastic regime, the simulation can be considered linear because the relationship between stress and strain is proportional. In the plastic regime, after the specimen passes the elastic limit, the relationship between stress and strain is no longer proportional, which means that the simulation is non-linear. This is due to the properties of the steel, which change from the elastic to the plastic state, but also to the geometry of the material, which is altered by the stretch zone. The non-linearity is not only due to the non-linearity of the material and the geometry of the specimen, but also to the non-linear contact surface [59].

FEA allows simple and complex structures to be analysed and simulated. Figure 25 Figure 24 shows an FEA of a brake disc showing the deformation and stress distributed by the disc when the brake is activated and the friction force is transmitted from the brake pad to the disc [61].

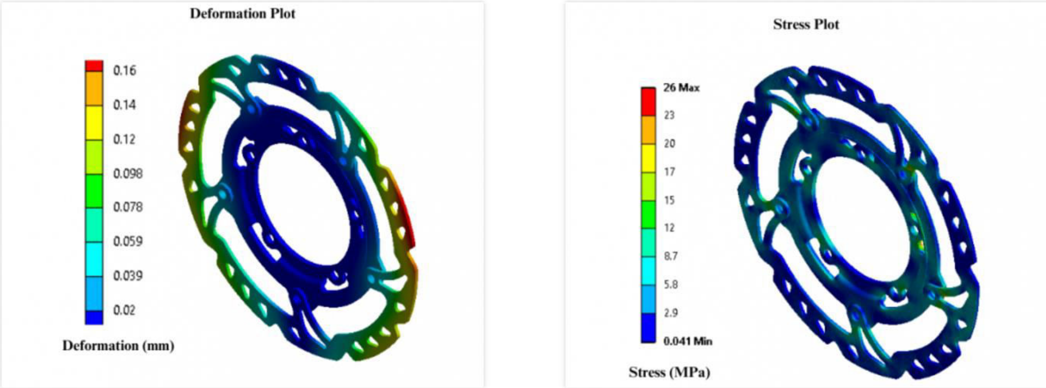


Figure 25 - FEA of a brake disk from a bicycle [61].

To do this simulation specified software are used and can be visualized in Table 4.

Table 4 - Software´s used in FEA.

Software	Description
Solidworks	SolidWorks is a user-friendly and integrated CAD software that provides robust FEA tools for design validation. It is ideal for analysing stresses, deformations, and thermal behaviour in parts and assemblies. Its simplicity and integration within the SolidWorks CAD environment make it a go-to tool for small to medium-sized projects where ease of use and efficiency are key [62].
Ansys	Ansys is a comprehensive FEA tool offering advanced capabilities for multiphysics simulations, including structural, thermal, fluid, and electromagnetic analyses. Renowned for its accuracy and versatility, Ansys is widely used in industries such as energy, electronics, and manufacturing. It offers a wide range of pre-defined elements and material models, enabling engineers to simulate complex systems efficiently [63].
Abaqus	Abaqus is a high-end FEA software widely used for advanced simulations. It supports complex nonlinear analyses and allows for the customization of simulations through programming. This software includes the ability to create user-defined elements and materials via subroutines, making it suitable for cutting-edge research and highly specific research and industrial applications. Abaqus excels in industries such as aerospace, automotive, and biomechanics [64].

2.2.7. Prototype and structural validation

Prototyping makes it possible to validate a new project before investing in production development. When the designer develops a new design for a piece of equipment, before launching the idea into the market it is necessary to test the equipment and get feedback from customers. Testing a prototype involves analysing the product and identifying potential issues that the software may not detect. Once the prototype is built, if no problems are found and the feedback is positive, the prototype can be validated, allowing the production of the equipment to begin.

Testing a prototype provides information such as usability, accessibility, design, user experience, concepts, and ideas. This information is important to validate the equipment. Normally, at this stage, the prototype does not need to have perfect dimensions and the ideal materials, but it does need to perform the basic function of the main equipment. Testing the prototype can be done manually in reality or with virtual tools [65].

The prototype can be classified by its fidelity and form of existence. Fidelity can be low, medium, or high. Low-fidelity prototypes are usually sketches of the product design. Medium-fidelity prototypes are more developed and provide an improved representation of the product. High-fidelity prototypes are very similar to the final product and usually allow for almost the same interaction as the final product. The prototype can be real or virtual. Real prototypes are fabricated and are used from the start of development, from sketches to complete equipment. These prototypes can be developed in various types of materials, not necessarily the same material as the final equipment. These are usually used to evaluate costumer interaction with the equipment, to perceive if the prototype runs smoothly and have good feedback. This type of prototype also has some disadvantages, such as the time and cost of production at later stages. A virtual prototype is a digital model or simulation. This one has advantages because permits the exploration of differentiated cases of study, such as manufacturing planning, analyses, and simulations. To development a virtual prototype exists various types of tools at its disposal, such as CAD and FEA. These software's are usually interconnected, which allows for great versatility in prototyping, simulation, and analysis. This type of prototyping allows parts to be altered relatively quickly, as it is done through repetitive computer modelling. Although virtual prototyping has many advantages, there are also some problems. Virtual prototypes are intangible, which means that the real aesthetics, scale ,and feel are harder for customers to absorb [66, 67]. Table 5 compares the main characteristic of each type of prototype.

Table 5 - Comparation between physical and virtual prototype (adapted from [66, 67]).

Properties	Physical prototype	Virtual prototype
Validity	High	Low
Time	Slow	Fast
Cost	High	Low
Visualization	High	Low
Fidelity	High	Low

Considering the positive and negative points of each of the prototypes, their selection depends on the type of project underway and the purpose of the prototype. If the purpose of the prototype is to test a mechanical structure that still needs to be intervened on after a few simulations, it is probably best to opt for a virtual prototype to facilitate simulation and reduce costs. When it comes to selling products to the public, it is advisable to opt for a real prototype to physically present to the customer, so that it can be tested.

2.2.8. State of the art

The state of the art in structural design explores the latest methods, standards and technologies used to ensure safety, efficiency, and sustainability in engineering practice. Table 6 provides an overview of these advances and their application in modern construction.

Table 6 - State of the art of structural design.

Author	Description
Castro et al. [68]	The aim of this work was to optimise a specific tool for crimping electrical terminals, improving its adaptability and cost effectiveness. The methodology involved analysing customer requirements, identifying design flaws in the original tool, benchmarking potential solutions and implementing design changes. Key improvements included the use of standardised components, improved punch guidance, modular design for greater adaptability and a simplified pneumatic control system. The results showed that the redesigned tool offered increased versatility, reduced production time and improved performance for a wider range of terminal types. In conclusion, the optimised tool provided a competitive and flexible solution for the wiring industry.

Table 6 - State of the art of structural design (continued).

de Oliveira et al. [69]	To address the growing industrial competitiveness driven by market globalization, the use of autonomous guided vehicles (AGVs) for transporting heavy loads within industrial parks has gained prominence. This work focused on designing a modular and cost-effective autonomous vehicle capable of carrying heavy loads efficiently. Through simulations, the drive system was developed and evaluated for transporting loads on level ground and within industrial park environments. FEA analysis identified structural weak points, leading to reinforcements that enhanced load-bearing capacity. The selected drive system used the Brusa HSM-10.17.12 motor, paired with a lithium-ion battery, which proved more efficient and economical compared to traditional lead-acid batteries. Structural modifications, including adjustments to the suspension system, allowed the vehicle to safely transport up to 8 tons. The final design demonstrates an efficient and cost-effective solution for industrial applications, offering improved transport speeds, durability, and operational efficiency.
Faria et al. [70]	The aim of this work was to design an automated device to assist healthcare workers in moving hospital beds, thereby reducing physical strain. The methodology involved gathering requirements from potential customers, developing design concepts, performing structural analysis using the FEA and performing structural optimisation. The results showed that the final solution, equipped with a 250 W motor and 8.9 kN electric actuator, outperformed the initial design, achieving 19% weight reduction and lower von Mises equivalent stresses. In conclusion, the developed device can significantly improve working conditions in hospitals and will proceed to the prototyping phase before mass production.
Vieira et al. [71]	Optimising intralogistics is critical to improving supply chain efficiency, especially in warehouses where smooth pallet handling is essential. This study focused on the development of a fully automated pallet turning and lifting device to address the lack of compact commercial solutions capable of performing combined movements such as lifting, turning and transferring. Designed to integrate with an existing roller and chain conveyor system, the device compensates for height differences between conveyors and facilitates forklift handling by rotating pallets. The system includes a rotation mechanism, lifting system, conveyors and safety features, all according to the customer's requirements. Compatibility with EURO and CHEP pallets was ensured, and the unit achieved a cycle time of less than 12 seconds. Electric actuators replaced pneumatic or hydraulic ones for reliability, and safety measures were implemented in accordance with ISO 13857. The result is a fully functional, autonomous machine that greatly simplifies pallet handling while ensuring operational efficiency and worker safety.
da Costa et al. [72]	The objective of this work was to design and improve buried urban waste collection equipment to meet safety regulations and reduce costs. The methodology involved reviewing existing equipment, analysing regulatory requirements and performing FEA simulations. The results showed that the redesigned structure, with modular elements and a new safety barrier, achieved a 6% cost reduction and a 15% weight reduction, while meeting European standards. The final design also included a new top bin system, allowing for increased waste storage and better adaptability. In conclusion, the proposed solution improved safety, reduced production costs and ensured compliance with current regulations.

2.3. Heavy duty pallet design

2.3.1. Contextualization and applications

Heavy-duty pallets are essential components in modern logistics and transportation systems, designed to handle the challenges of shipping heavy, bulky, or irregularly shaped products. Their role extends beyond basic transportation, offering solutions for safe handling, efficient storage, and cost-effective shipping. This section explores the contextualization and applications of heavy-duty pallets, emphasizing their importance in industrial and commercial settings. The use of heavy-duty pallets can be traced to the evolution of industrial logistics, where the need to move large quantities of goods efficiently became paramount. These pallets are specifically engineered to support substantial loads, ensuring stability and safety during transport. Heavy-duty pallets are commonly made from materials such as wood, plastic, or metal, each selected based on the specific needs of the application. Wooden pallets, for instance, are widely used due to their durability and adaptability, while plastic pallets are favoured for their lightweight and resistance to moisture. Metal pallets, including steel and aluminium variants, provide excellent strength and are often employed for extreme load capacities [73].

This type of storage and transportation system is normally used in industries such as manufacturing, construction, automotive, and agriculture, where handling oversized or weightily items is common. In automotive manufacturing and supply chains, heavy-duty pallets are used to transport engines, transmissions, and other large components. Their robust construction prevents deformation under heavy weights, ensuring the safety and integrity of the parts [73]. In the construction industry pallets designed for heavy loads are essential for moving construction materials like cement bags, steel rods, and concrete blocks. Their stability facilitates secure handling on construction sites, reducing the risk of accidents and material damage. In exportation and international trade, pallets complying with international standards, such as ISPM-15 for wooden pallets, are critical for exporting goods [74]. Their design ensures safe transport across long distances, whether by sea, air, or land, accommodating the different conditions of shipping environments [73, 75].

2.3.2. Design principles for pallets

Pallets are an essential part of modern logistics and supply chain management, enabling goods to be transported safely and efficiently. Commonly used in a wide range of industries, the typical pallet is designed to meet standardised requirements for size, strength, and functionality. These pallets are widely used for handling goods of varying weights and shapes, ensuring ease of storage, handling, and transport in different environments. The most common types of pallets are the Euro pallet, which is widely used in Europe, and the ISO standard pallet, which is widely used in international trade. These types of pallets are designed to be compatible with various handling equipment, such as forklifts, pallet jacks, and conveyor belts, which facilitate the loading and transport process. Pallets can be divided into two main categories, stringer pallets and block pallets. The difference between these two categories depends on the region and the type of product being carried. Figure 26 a) shows a typical stringer pallet and Figure 26 b) shows a typical block pallet, both conforming to ISO standards. Most of these pallets are made from wood, but they can also be made from plastic and metal alloys. Each material is used for different types of applications. Wooden pallets are the most traditional and widely used due to their affordability, durability and ease of repair. They are suitable for transporting a wide range of goods, from consumer products to industrial materials. Plastic pallets, on the other hand, are lighter, resistant to moisture and are often used in industries that require hygiene standards, such as food processing or pharmaceuticals. Metal pallets, made from steel or aluminium, offer exceptional strength and are used in environments where extra durability is required, such as the automotive industry or heavy manufacturing [73, 76].

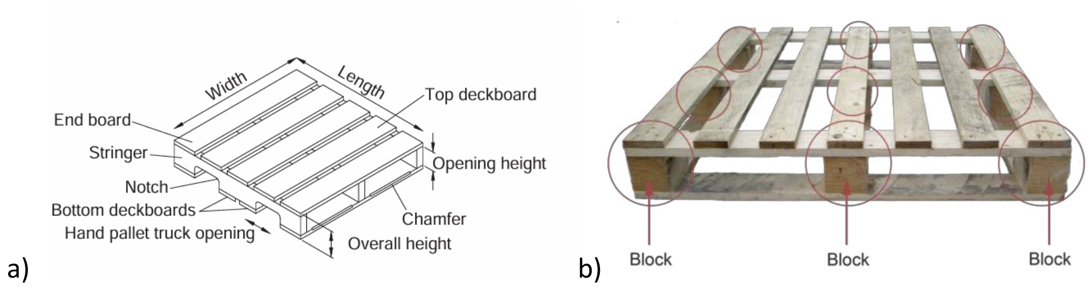


Figure 26 - Pallet types: Stringer pallet [34] (a) and block pallet b) [76].

Pallets used to transport relatively simple equipment, such as boxes, are already dimensioned according to ISO standards. ISO 8611 [77] specifies the test methods available for evaluating new flat pallets for materials handling . ISO 6780 [78] specifies the principal dimensions and tolerances for new single-deck and double-deck, reversible and non-reversible flat pallets, of all entry types and made of any material, related to their transportation and handling by pallet trucks, fork-lift trucks and other appropriate equipment. Table 7 presents the main dimensions of ISO standard pallets.

Table 7 - Pallet dimensions according to ISO standards [79].

Pallets according ISO code	Length [mm]	Width [mm]	Height [mm]	Regions typically used
ISO pallet 1 (known as Euro pallet)	1200	800	160	Europe
ISO pallet 2 (known as standard pallet)	1200	1000	162	South Africa
ISO pallet 3	1219	1016	142	America Regions
ISO pallet 4	1067	1067	140	North America and Eurasia
ISO pallet 5	1100	1100	160	Asia Pacific Region
ISO pallet 6	1140	1140	138	Europe

When it is necessary to transport more complex equipment, specially designed pallets are used. This type of pallet may be based on the ISO standard for ease of transport and handling but may not be compatible with all the restrictions imposed by the standard, such as standardization of dimensions and weight [73].

Design of a heavy-duty pallet that exceeds the specification for typical pallets follows the principles applied to conventional mechanical equipment. The methodology used to create and design the heavy-duty pallet can be the same as used in section 2.2.1.

Shipping large products presents common problems and requires special precautions. There are several issues that can make shipping large products difficult, and these should be considered when choosing the best packaging solution:

Weight: Heavy items present a challenge for both packaging and shipping. If is not possible to choose a durable packaging solution, there's a risk that the packaging could fail under the item's weight, potentially leading to damage during transit.

Size: Bulky items can be difficult to pack, especially if they have irregular shapes. Choosing the right packaging is key to ensuring safe shipping, especially if the product has irregular edges that are susceptible to damage during handling and transport.

Handling and transport considerations: Throughout the shipping process, packages are moved by both equipment and people. Due to the heavy weight of large items, it is essential to integrate systems that allow for the proper handling and storage of pallets. Advanced material handling systems such as forklifts, AGVs, and cranes are commonly used. This integration of systems helps to increase efficiency, reduce labour costs and minimise the risks of manual handling. Whether items are loaded onto a truck with a forklift or transported by ship for overseas delivery, it is critical that the packaging is designed to withstand handling by a variety of equipment and people. In addition, the mode of transport used, either land, air or sea, will affect the forces experienced by the items during transit. Thus, packaging must be strong and secure to protect the contents. Figure 27 shows an exterior packaging equipment for large and heavy products. It is possible to visualize that the system is transported by a truck and is removed from the truck by a crane [75].

Figure 27 - Exterior packing for large and heavy product (adapted from [75]).

2.3.3. Metal pallet sizing procedures

When designing heavy duty pallets, particularly those made from structural metal elements such as beams and profiles, accurate dimensioning is essential to ensure functionality and safety under extreme loads. Unlike wood or plastic pallets, metal pallets are designed for applications that require superior strength, durability and long-term reliability. The sizing process begins with determining the maximum weight and dimensions of the intended load. This procedure includes allowances for irregular shapes, concentrated load points and dynamic forces during handling and transport. These considerations are critical to avoiding structural failure and ensure that the pallet will perform reliably under demanding conditions. Once the load requirements have been defined, the next step is to select an appropriate metal. Materials such as steel are often preferred for their high strength, stiffness and cost effectiveness, while mechanical properties and environmental conditions guide the choice of metallic alloys. With the material selected, the design phase focuses on calculating the size, thickness and geometry of critical structural components, including girders, deck plates, and reinforcements. These calculations are based on engineering principles such as Tresca and von Mises criteria and incorporate Eurocode guidelines to ensure that the pallet can withstand static, dynamic, and concentrated loads with adequate safety margins [56]. To ensure seamless integration into logistics operations, the design also incorporates features that facilitate efficient handling. These include fork pockets, crane lifting points and compatibility with automated handling equipment such as AGVs and conveyors. These systems minimise the risks associated with manual handling and enhance the pallet's adaptability to different transport and storage environments [37, 75].

Compliance with international standards such as ISO 8611 [77] and EN 13698 [80] is another important aspect of the design process. These standards provide detailed guidelines for testing and dimensioning to ensure that the pallet will perform reliably under different loading scenarios, including static, dynamic, and racking loads. Adherence to these standards not only ensures safety, but also facilitates interoperability across regions and industries, simplifying logistics operations on a global scale. Durability and lifecycle considerations are particularly important for metal pallets, which are often designed for repeated use over long periods of time. Modular design and replaceable components can extend the life of the pallet, reduce maintenance costs and minimise environmental impact. For example, easily replaceable beams or deck plates can eliminate the need to replace the entire pallet, contributing to long-term cost savings and sustainability. Combining rigorous engineering principles, compliance with international standards, and practical design features, metal pallets provide a reliable and cost-effective solution to transport heavy and irregularly shaped loads. Their strength, durability, and adaptability make them the preferred choice in industries with demanding logistics requirements, ensuring safety and efficiency throughout the supply chain [75].

For example, to design a bolted joint between two metal elements that make up a metal pallet that are connected by bolted connections, it is possible to use the Eurocode to ensure that the connection is well designed and safely supports the imposed loads. To design a bolted connection, it is necessary to consider the shear and tensile forces that the bolt will be subjected to.

The EC3-1-8 standard considers two types of bolted connections, namely, non pre-loaded bolted joints and pre-loaded bolted joints. Consider the current bolted joint and consider that the joint going to be subject to traction, shear, and crushing forces is necessary guarantee that the next equations are fulfilled [81].

The tensile verification is based on Equation 10, to guarantee that the design tensile force per bolt for the ultimate limit state ($F_{t,Rd}$) does not exceed the design punching shear resistance of the bolt head and the nut ($B_{p,Rd}$).

$$F_{t,Rd} \leq B_{p,Rd}\,. \tag{10}$$

When checking the combination of shear and individual traction is used the Equation 11 that guarantees that the relation between the design shear force per bolt for the ultimate limit state ($F_{v,Ed}$), the design slip resistance per bolt at the ultimate limit state ($F_{v,Rd}$), the ratio between the design tensile force per bolt for the ultimate limit state ($F_{t,Ed}$) and ($F_{t,Rd}$) is not superior than 1.

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4F_{t,Rd}} \leq 1\,. \tag{11}$$

From equation 11 it is possible to obtain the number of bolts in the joint because ($F_{v,Ed}$) is defined by equation 12 which (N_{Ed}) is the design value of the internal axial force in member and (n) is the number of bolts.

$$F_{v,Ed} = \frac{N_{Ed}}{n}\,. \tag{12}$$

To do the shear effort verification is used the equation 13 that guarantee the ($F_{v,Ed}$) does not exceed the design slip resistance per bolt at the ultimate limit state ($F_{v,Rd}$).

$$F_{v,Ed} \leq F_{v,Rd}\,. \tag{13}$$

To the crushing verification is used the equation 14 that guarantee the ($F_{b,Ed}$) does not exceed the design bearing resistance per bolt ($F_{b,Rd}$)

$$F_{b,Ed} \leq F_{b,Rd}\,. \tag{14}$$

Such as bolted joints, other types of joints and structures can be sizing through the Eurocodes.

2.3.4. Automated sizing procedures

Designing a heavy-duty metal pallet to Eurocode principles can be accomplished by automated tools to optimise its structural performance and simplify its design procedures. By following standardised guidelines, it is possible to establish reliable calculation frameworks and software that show critical aspects of the design process, particularly for joints and structural members. One key area where automated tools can provide significant benefits is in the design of joints. Automated calculation tools, based on the calculation methods described in the Eurocode standards, can help engineers quickly determine the optimum size, grade, and placement of joints. This procedure ensures structural integrity while avoiding oversizing. The previous example of bolted joint showed in section 2.3.3 is a good case of an automated sizing procedure. Through an automated sizing calculation sheet is possible to insert the parameters of entrance, such as the weight of the metallic elements of the structure, respective loads, and obtain the characteristics of one specific joint, such as the number of bolts and the relative placement [57, 81].

Another key application of automated sizing is to support FEA, particularly for complex or non-standard loading scenarios. While traditional calculations provide a basic understanding, FEA enables a deeper evaluation of how the pallet responds to different forces and environmental conditions. For a metal pallet, such tools can be invaluable in analysing fatigue, which is particularly relevant for long-term use in demanding environments such as maritime transport. Automated FEA processes can simulate the repeated loading and unloading cycles experienced during shipping, as well as the dynamic forces exerted by waves and vibration. By identifying critical areas prone to fatigue failure, designers can optimise pallet geometry or material properties to extend pallet life. In addition, automated tools enable efficient testing of different design scenarios, such as varying load distributions or environmental conditions. For example, the pallet's response to temperature changes, corrosion potential or high humidity in marine environments can be included in the FEA analysis, as shown in section 2.2.6. This possibility allows engineers to create designs that are not only structurally sound, but also durable and cost effective in real-world conditions [60, 64].

2.3.5. Concept solutions

While standard pallets provide efficient and reliable solutions for the transport and storage of many heavy materials, certain scenarios require a customised approach. When dealing with oversized, irregularly shaped or exceptionally heavy items, relying solely on conventional pallets can pose significant challenges. In such cases, it is necessary to develop differentiated solutions that simplify and improve the transport and storage processes. These specialised solutions are designed to meet the unique requirements of specific applications, ensuring not only the safe handling of heavy equipment, but also the optimisation of logistics operations. By overcoming the limitations of standardised systems, such customised designs enable the efficient movement of materials that would otherwise be impractical or unsafe to transport using traditional methods [73].

In some situations, unlike standardized pallets, which adhere to pre-defined dimensions and weight capacities, custom pallets are designed and manufactured to fit the exact specifications of the item being transported. These custom-built pallets are often created after the piece itself is finalized, ensuring a precise fit that minimizes the risk of damage during handling. By tailoring the pallet to the product, the solution becomes an extension of the item’s design, providing superior stability and protection. The process of creating custom pallets involves selecting appropriate materials, such as reinforced wood or metal, to meet the weight and structural demands of the load. The dimensions, load points, and support structures are engineered to distribute the weight evenly and accommodate any specific handling requirements, such as forklift access or crane lifting points. This level of customization ensures that even the most complex or delicate items can be transported safely and efficiently [73].

As a good example of a differentiated transport system, skids are a versatile and robust solution, often used to transport heavy materials and oversized equipment. Although often confused with pallets, skids are distinguished by their simplified construction and the absence of a bottom deck. These characteristics make them an effective alternative in specific scenarios where traditional pallet solutions do not adequately meet the requirements. Skids consist of a single platform supported by longitudinal skids or beams, rather than the double deck structure typical of conventional pallets. This simplified design is specifically designed to handle extreme loads, ensuring even weight distribution to prevent damage to products during transport or storage. One of the main advantages of skids is their exceptional load capacity. They are ideal to transport items weighing tens or even hundreds of tonnes, such as nuclear generators, turbine rotors or industrial pumps. Unlike standard pallets, skids can be fully customised to specific dimensions and weights, ensuring the safety and stability of products in extreme conditions. In addition, the absence of a bottom deck simplifies handling with forklifts and cranes, reducing the complexity of loading and unloading operations. Skids are also highly durable and can withstand adverse conditions. They are commonly used in maritime transport, where the cargo is subjected to forces along six axes of motion, 3 displacements and 3 rotations. Using materials such as wood and steel, skids are designed to withstand these dynamic forces, minimising the risk of cargo shifting and ensuring safe transit. The use of skids is essential in scenarios where requirements exceed the capabilities of standard pallets. For example, they are essential for transporting exceptionally heavy equipment, such as machinery weighing over 50 tonnes. They are also critical for long-distance or maritime transport, where significant dynamic forces require greater structural strength. Skids are also the ideal solution for irregularly shaped or oversized loads that cannot be accommodated by standard pallets [75]. Figure 28 shows a skid for heavy products [82].

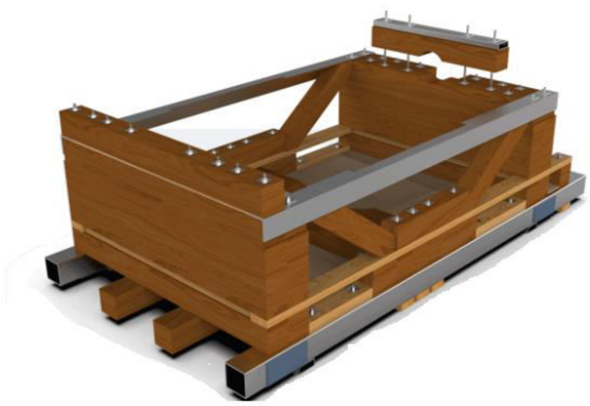


Figure 28 - Skids for heavy duty products (adapted by [82]).

Another type of packaging solution is steel pallet racking, which is commonly used in industry to store a wide range of static goods placed on pallets. Typically constructed from cold-formed structural elements, these racks provide a robust and efficient storage system. In addition, pallet racking is designed to be stackable, allowing good utilisation of space. Figure 29 shows the steel pallet racks [83].

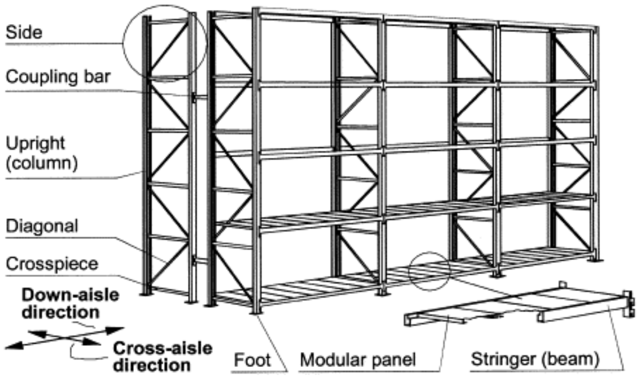
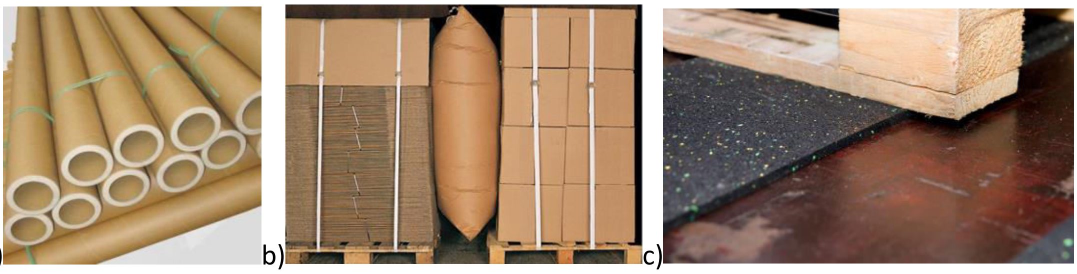


Figure 29 - Steel pallet racks [83].

2.3.6. Lashing solutions

Lashing, or the process of securing cargo using straps, chains, or other restraints, is a critical component in ensuring the stability and safety of loads during transportation, storage, and handling [75]. Effective lashing minimizes the risk of cargo movement, which can lead to accidents or damage to both goods and vehicles. Different lashing solutions are chosen based on the type of cargo, the mode of transport, and the specific challenges posed by the journey [84]. Even the most robust packaging has limits regarding the shocks and vibrations it can withstand during transportation. Proper load securing protects products and people while offering potential cost reductions. Securing cargo against rolling, tipping, and shifting reduces the absorption of shocks and vibrations, minimizing risks of packaging deterioration and ensuring better protection for the packed goods. Furthermore, proper load securing protects employees, road users, and others from accidents caused by poorly secured loads. Incorrectly secured packaging can also lead to leaks of hazardous substances, causing pollution and health risks, while securing loads helps prevent traffic hazards from falling cargo. By reducing product damage, handling time, and potential health or environmental costs, load securing contributes to significant savings. Additionally, ensuring cargo arrives in good condition maintains a company's image and reduces negative publicity from accidents [85, 86].

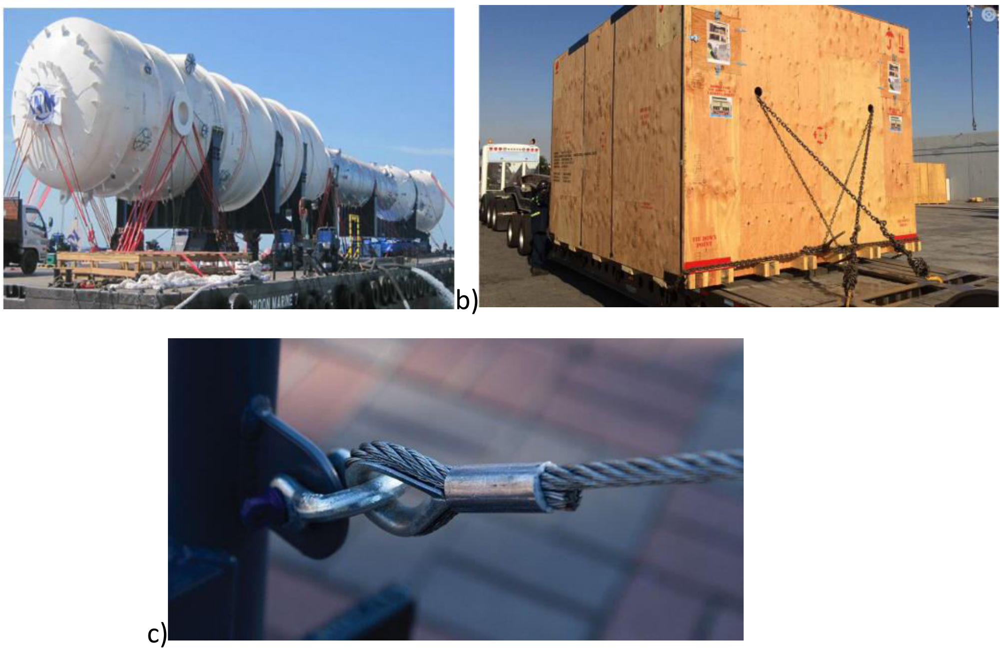
Several lashing systems can improve load securing during transport, including sustainable solutions. **Cardboard lash tubes**, made by cardboard with their strong corrugated and water-resistant construction, are clasped between container ribs to prevent cargo movement. **Paper dunnage bags**, made from kraft paper and polyethylene, block goods inside the load carrier and are suitable for road, sea, or rail transport, while **anti-slip rubber mats** enhance friction between the floor and the load, preventing movement [85]. Normally these type of sustainable lashing solutions must comply with the ISPM-15 standard, which provides the basis for the harmonisation of international phytosanitary measures and specifies the permitted treatments for quarantine pests [74].



a) b) c)

Figure 30 - Sustainable Lashing solutions: cardboard lash tubes [87] (a),paper dunnage bags [88] (b) and anti-slip rubber mats [89] (c).

Webbing straps, typically made from polyester, are among the most versatile lashing solutions. They are lightweight, flexible, and resistant to environmental factors such as UV rays and moisture. These straps are widely used for securing pallets and lighter loads due to their ability to conform to irregularly shaped cargo while maintaining high tensile strength [90]. Webbing straps can be used to secure packages inside containers during transit [85]. For heavier or more rigid loads, **chains** coupled with tensioners provide superior strength and durability. Chains are particularly effective for securing heavy machinery, construction materials, and large containers. They are designed to withstand high stress and are often equipped with load binders (hooks) to adjust tension precisely [91]. **Steel wire ropes**, on the other hand, offer a high-strength solution for securing exceptionally heavy or fragile items. Although less flexible than webbing straps or chains, they provide unparalleled resistance to tension and cutting, making them commonly used in industries such as shipping and heavy machinery transport [84, 90, 92]. Figure 31 a) shows webbing straps securing a huge industrial equipment, Figure 31 b) shows a package secured by chains, and Figure 31 c) shows a steel wire rope.



a) b) c)

Figure 31 - Lashing solutions: webbing straps [86] (a), chains [84] (b) , and steel wire ropes [92] (c).

Some systems can combine different types of lashing solutions to leverage the benefits. For example, a system might use steel cables for high-tension areas and webbing straps for more delicate zones, ensuring both strength and adaptability. These solutions are often customized based on the specific needs of the cargo [93].

Adherence to the European Standard EN 12195 [94] ensures the reliability and safety of lashing systems. This standard outlines the performance requirements, testing procedures, and labelling for lashing equipment, covering all aspects of load securing, from the strength of the components to the methods of securing. Compliance with EN 12195 minimizes risks and fulfils legal obligations in cross-border transportation. Effective lashing design takes into account the cargo's weight, dimensions, and centre of gravity, as well as factors such as acceleration forces during braking and cornering to prevent load displacement. Tools like lashing calculators can help determine the appropriate equipment and configuration according to EN 12195 for each specific situation. Lashing solutions are integral to the safety and efficiency of cargo transportation. By understanding the properties and applications of various lashing tools, advanced load securing materials, and adhering to established standards, transporters can ensure secure and compliant operations. The choice of lashing equipment should always align with the cargo's unique requirements, prioritizing both performance and safety [84, 91, 93].

2.3.7. State of the art

The state of the art in heavy-duty steel pallets focuses on advanced technologies designed to enhance safety, efficiency, and sustainability in engineering applications. Table 8 provides an overview of these advances and their application in modern construction.

Table 8 - State of the art of heavy-duty pallet design.

Author	Description
Ceraolo and Lutzemberger [95]	This book chapter focuses on the design and modelling of heavy-duty transport systems, with an emphasis on energy management strategies. First, general concepts and definitions are introduced, followed by a detailed analysis of energy management using heuristic methods and global optimisation techniques. A comprehensive case study is presented involving the design of a transport system for a construction machine. The process includes modelling a conventional hydraulic system, identifying an electrified hybrid architecture, and selecting a real-time heuristic energy management strategy. Verification is carried out by comparing the online strategy with an offline optimal control solution, establishing a benchmark that evaluates the efficiency of the proposed method.

Table 8 - State of the art of heavy-duty pallet design (continued).

Bernuzzi and Simoncelli [96]	Industrial steel storage pallet racks are among the most economical solutions to store goods in limited spaces. However, their structural response, especially under seismic conditions, is difficult to predict. Current design procedures do not fully address the unique features of these racks, which behave as moment-resisting frames with thin-walled cold-formed members. This paper combined the non-linear time-history (NLTH) analysis with the low-cycle fatigue (LCF) approach to assess damage, residual fatigue life, and post-earthquake load-carrying capacity. The case study highlighted critical issues in seismic design and suggested improvements, including replacing damaged beams to maintain rack performance.
Eldensjö and Söderman-Lundqvist [97]	The objective of this study was to assess the transportability of heavy skid-mounted machinery for Climeon, focusing on dimensional constraints and features required for safe transport by road and sea. The methodology included a literature review on logistics and load carriers, interviews with Climeon staff, FEA simulations for lifting heavy equipments, and MATLAB analysis to estimate the lashing forces. Dimensional limits were identified, and cost estimates were made by contacting freight forwarders. The results showed that trucking was the most economical solution within Europe, while roll-on-roll-off systems (RoRo) and flat racks were viable for sea transport of larger machinery. Lashing with direct straps and high-friction mats proved sufficient for stability, and a single-hook lifting method was feasible with the correct arrangement of lifting eyes. It was concluded that keeping machine dimensions below 2.44 m in width and 2.8 m in height provides greater transport flexibility, and that well-designed lashing and lifting systems were key to safe handling and reduced costs.
Petraška et al. [98]	This work focuses on creating an approach to improve the transport of heavy and oversized goods by developing a structured system for route evaluation and selection. By examining key elements such as road conditions, potential obstacles and regulatory constraints, it aims to provide solutions that minimise costs while ensuring safe and efficient transport. The analysis incorporates both technical and economic perspectives to assess route feasibility under different scenarios. The results provide a comprehensive understanding of how different factors affect transport performance and costs. Ultimately, the research highlights the need for a detailed evaluation framework to support decision making in specialised freight transport.
Zacchei et al. [99]	This study presents the design and analysis of modular metal pallets to improve the efficiency and sustainability of load handling systems. Unlike traditional solutions, these pallets feature interchangeable components, providing flexibility and adaptability for different industrial applications. Advanced modelling techniques, including FEA and experimental validation, were used to evaluate key performance factors such as structural strength, stiffness and deformation under different loading scenarios. In addition, a Life Cycle Assessment (LCA) was conducted to assess the environmental impact, which showed that steel pallets outperformed wooden and plastic counterparts in terms of recyclability and durability. The research highlights the potential of modular designs to improve operational efficiency and reduce costs in the logistics sector.

3. Thesis development

3.1. Welcoming company

NEFAB is a Swedish company founded in 1949 by the Nordgren brothers, which began their activity with the production of bread boxes. Over the decades, the company has evolved significantly, positioning itself today as a global provider of industrial packaging solutions, logistics services, and digital solutions. With more than 75 years of accumulated experience, NEFAB's main objective is to optimise supply chains, promoting resource savings.

With its global headquarters in Jönköping, Sweden, NEFAB has a consolidated international presence, being represented in more than 38 countries and with around 100 production and service units. Its workforce exceeds 4,900 people, enabling the company to offer customised solutions that combine specialised technical knowledge with local support and global coordination. It is possible to visualize all the locations of NEFAB in the world in Figure 32.

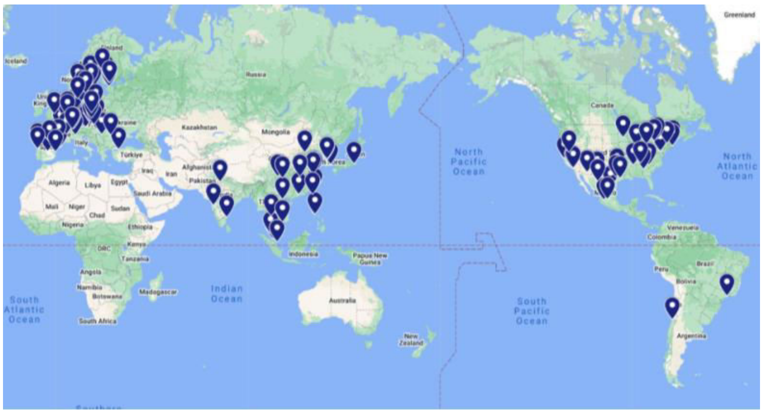


Figure 32 - Global view of NEFAB headquarters[100].

Current trajectory: Today, NEFAB's main objective is to become the global reference partner for complete packaging solutions, offering a range of services that goes far beyond the supply of physical packaging, integrating consultancy, logistics and digital technologies. The company's mission, expressed in the phrase *'We save resources in supply chains, for a better tomorrow'*, reflects its commitment to sustainability and operational efficiency. This mission is realised through a collaborative approach with its customers, with the aim of developing intelligent solutions adapted to the specific characteristics of each industrial sector. NEFAB's key industries include energy, semiconductors, datacom and cloud services, medical devices, mining, construction and electric mobility.

NEFAB's corporate culture is based on three fundamental pillars: simplicity, respect and empowerment. These values guide all practices, fostering a collaborative, people-centric environment and building sustainable, long-term relationships - both internally and with external partners. These principles are present not only in day-to-day management and internal communications, but also in strategic and operational decisions. On the strategic horizon for 2030, NEFAB has set ambitious goals, including a commitment to help its customers avoid 10 million tonnes of CO_2 emissions through optimised packaging solutions. This goal not only reflects a clear commitment to sustainability but also positions the company as an active player in the environmental transformation of supply chains. NEFAB's strategy for this decade is therefore focused on sustainable innovation, global expansion and the digitalisation of processes to create shared value for customers, communities and the planet. Figure 33 presents the five focus areas for NEFAB 2030 strategy.

Figure 33 - Five focus areas for NEFAB 2030 strategy [100].

NEFAB Portugal

In Portugal, NEFAB has its headquarters in the municipality of Maia, more specifically at Rua Jorge Ferreirinha, no. 1096, parish of Vermoim, dedicated to the development and manufacture of industrial packaging solutions, with a special focus on the automotive sector. The company works with a wide range of materials and configurations in its packaging solutions, adapting each solution to the specific needs of its customers (Figure 34).

Figure 34 - Main façade of NEFAB Portugal facilities.

Its activity covers the entire production cycle, from design to the production of technical and reusable packaging. NEFAB Portugal, as a business entity, places significant emphasis in sustainability, promoting solutions that aim to reduce logistics costs and environmental impact. Its commitment focuses on creating efficient, safe, and environmentally responsible packaging.

3.2. Methods

3.2.1. DSR Methodology

To develop the design of the heavy-duty steel packaging structure, the DSR method (Design science research methodology) was used. This method is used to solve complex structural problems in the design industry, develop a system and carry out the respective validation. Figure 35 shows a diagram that demonstrates the six steps of the DSR methodology [101].

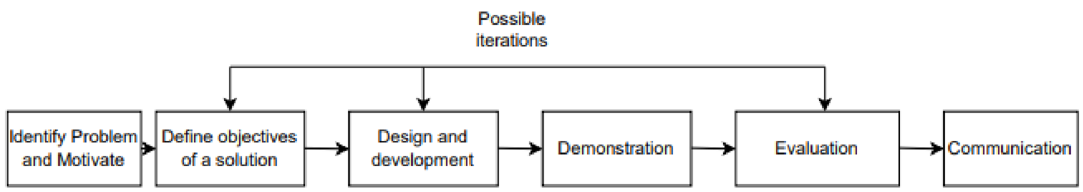


Figure 35 – Steps of DSR Methodology [101].

The following is a detailed description of each step:

Identify problem and motivate: This step involves identifying a real-world problem that requires an innovative solution. It is essential to justify the relevance of the problem, explaining why it is significant for research and practice.

Define objectives of a solution: Once the problem is defined, the next step is to establish the objectives and requirements for a potential solution. These objectives should be grounded in an understanding of the problem and supported by a literature review or industry needs.

Design and development: At this stage, the artifact (a model, framework, method, system, or technology) is created. The design should be guided by theoretical principles and best practices.

Demonstration: The equipment is applied in a real-world scenario, case study, or simulation to demonstrate its feasibility and functionality.

Evaluation: The packaging structure is assessed to determine how well it solves the identified problem. This evaluation can be based on empirical testing, expert feedback, simulations, or performance metrics. The results may lead to refinements and iterations.

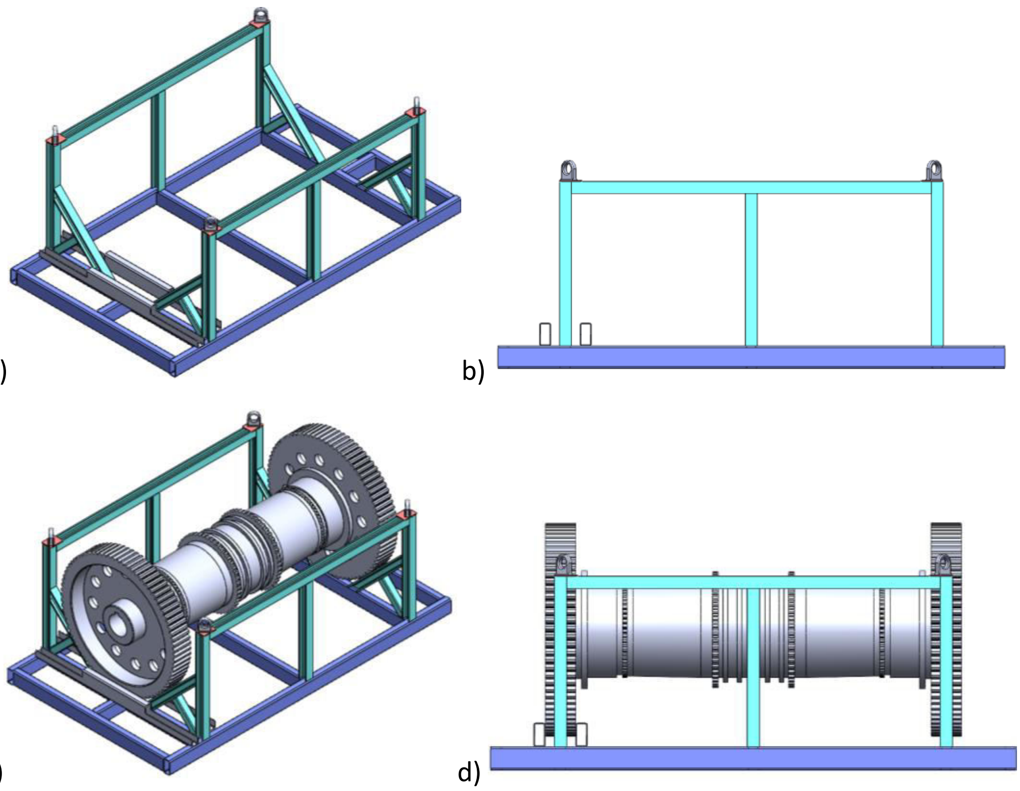
Communication: Finally, the research findings, including the problem, the developed equipment, the demonstration, and evaluation results, are documented and shared with relevant audiences.

3.2.2. Description of similar products

In this area of packaging and transport heavy equipment, industrial available documentation and research results available are not very common. The shaft to be transported is a heavy steel shaft, which has a non-uniform weight distribution, i.e., its centre of mass is not in the geometrical centre of the part. This will be an obstacle that will have to be overcome during the realization of the project. The shaft to be transported is used in the wind turbine industry and in Figure 36 it is possible to visualize two examples of the type of shaft that needs to be transported. Figure 37 shows a model to transport heavy uniform shafts and Figure 38 the respective diagram of sub-assemblies.

a)  b) 

Figure 36 - First (a) and second examples (b) of heavy shaft to transport.



a) b) c) d)

Figure 37 - Model of heavy packaging structure (a, b) and structure with shaft (c, d).

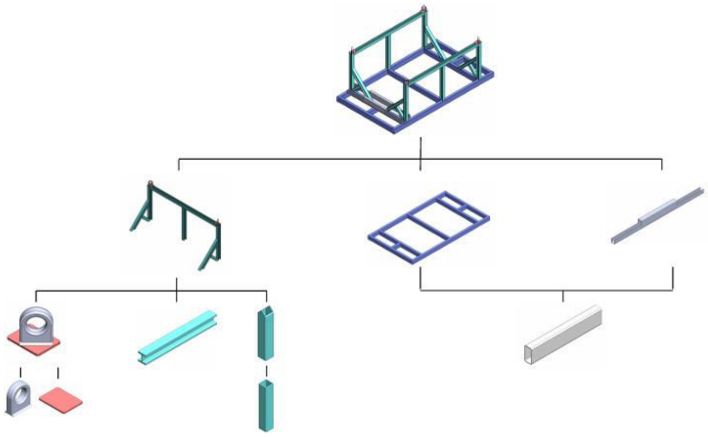


Figure 38 - Diagram of sub-assemblies of the original pallet.

To transport this type of shaft, it is necessary to develop a transport system that guarantees the stability of the product during transport and storage. This type of structure can be divided into four different parts, which are as follows:

Structural parts: Guarantees the stability of the structure during its lifetime, which means that these should assume the required stiffness. These parts are made up of the bases and sides, and structural steel elements are normally used to guarantee stiffness, strength, and geometric stability. This solution ensures that the structure meets the imposed requirements during the stages of its useful life, storage, transport and handling.

Peripherical parts: These parts are used to guarantee the handling and storage of the product. Due to the heavy weight of the structure, heavier transport systems are normally used that allow the pallet to be handled using cranes and similar systems. These lifting points must be able to keep the stability of the pallet. Lashing systems and brakes are used to guarantee lateral and axial locking, respectively. The brakes lock the part axially. On the other hand, during transport, due to changes in trajectory, it is possible for the shaft to induce higher loads at one side of the pallet. To avoid this load eccentricity, it is necessary to use lashing elements to hold the shaft against these adversities. In scenarios where the packaging frame is not carrying the shaft, it is advisable to implement systems that enable both stacking and forklift handling, as these would significantly improve operational efficiency and facilitate the manoeuvrability and storage of empty units.

Support parts: Ensure that the shaft is locked transversely. These parts need to be very strong so that the pallet does not deform. Because of the high weight, the possibility of shaft rotation during transport and handling is practically non-existent due to the contact force between the supports, usually made of softer material to prevent damage, such as polyesters, and the shaft

Lashing and brakes: They guarantee axial and lateral locking by means of brakes that lock the part axially. During transport, due to changes in trajectory, it is possible for the shaft to induce higher loads at one side of the pallet. To avoid this load eccentricity, it is necessary to use straps to hold the shaft against these adversities.

These components are fundamental to ensuring the correct functioning of the system, guaranteeing both its operational safety and efficiency. Each element of the system plays an essential role in stability, strength and precision of transport, minimizing the risk of failure and ensuring compliance with technical and regulatory requirements. In addition, the appropriate choice of materials and the correct sizing of components are determining factors for the durability and efficiency of the system.

3.2.3. Materials

The equipment described in 3.2.2 consists of a structural framework and several peripheral systems that work together to fulfil its main purpose. These components are made of different materials. The structural framework consists of steel sections. When properly designed and connected by joints, steel profiles can support considerable loads, leading to several applications in the structural part of the equipment. These elements are also commonly used in metal structures that comply with Eurocode 3. According to Eurocode 3, Figure 39 lists the typically used standards and steel grades. The choice of steel depends on several parameters, including the expected mechanical stresses, environmental conditions, weldability and formability requirements, component thickness, and ease of fabrication.

Standard and steel grade	Nominal thickness of the element t [mm]			
	$t \leq 40$ mm		40 mm < $t \leq 80$ mm	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025-2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	490	335	470
S 450	440	550	410	550
EN 10025-3				
S 275 N/NL	275	390	255	370
S 355 N/NL	355	490	335	470
S 420 N/NL	420	520	390	520
S 460 N/NL	460	540	430	540
EN 10025-4				
S 275 M/ML	275	370	255	360
S 355 M/ML	355	470	335	450
S 420 M/ML	420	520	390	500
S 460 M/ML	460	540	430	530
EN 10025-5				
S 235 W	235	360	215	340
S 355 W	355	490	335	490
EN 10025-6				
S 460 Q/QL/QL1	460	570	440	550

Figure 39 - Standards and steel grades according to Eurocode 3 (adapted from [102]).

To ensure that the shaft is supported without surface damage, it is essential that a suitable material is used at the contact points between the shaft and the pallet. Direct contact between the shaft and structural components can result in scratches, dents, or wear over time, compromising the integrity and functionality of the shaft. Therefore, a material with cushioning properties and lower hardness should be selected to minimize the risk of abrasion or impact damage. This protective interface material must also have adequate wear resistance, dimensional stability, and compatibility with the operating environment, particularly if the equipment is subject to vibration, movement, or varying loads. In NEFAB, PVC has been successfully used as the contact interface between the support and the shaft. PVC offers a good balance between mechanical strength and surface softness, making it effective in preventing damage while maintaining support. Its ease of machining, low coefficient friction and resistance to moisture and chemicals also contribute to its suitability for this function [103].

3.2.4. Critical evaluation and limitations

One of the primary limitations encountered during this project is the absence of specific standards or formal design regulations for heavy-duty transport and storage structures. In contradistinction to the case of standardised systems, which are governed by well-established engineering codes, transport solutions frequently fall outside the scope of conventional documentation. This absence of normative guidance poses a significant challenge during the design phase, as there are no predefined criteria for structural validation or performance benchmarking. Consequently, engineers substantially depend on customer-specific requirements, expert judgement, and advanced computational simulations. While these tools offer valuable insight, they may not fully capture broader safety requirements or real-world operational complexities, increasing the need for iterative validation and conservative design approaches.

In addition to regulatory gaps, another significant challenge arises from the physical characteristics of the shaft being transported. The shaft's geometry is non-uniform, resulting in an off-centred centre of mass. This imbalance necessitates asymmetric structural reinforcement, particularly on the side subjected to higher loads. Moreover, this imbalance complicates the design of lifting and handling systems, which are required to ensure stability and prevent unsafe tilting or overturning during operations.

Even though some of these issues are partially addressed by the proposed support and fixing systems, limitations persist. The distribution of weight over the transporting vehicle is not uniform, and this off-balanced load continues to pose a risk to the structural balance, especially when the load is dynamic. Such dynamic loads may be sudden stops or abrupt directional changes, which can induce additional stresses that are not captured in a static analysis. It is imperative that these risks are given full consideration during the design phase to ensure operational safety and structural reliability.

It is imperative that the development of this system is approached with the utmost caution, given the prevailing regulatory uncertainty and technical complexity. A robust design process should incorporate realistic loading scenarios, account for manufacturing tolerances and material behaviour, and emphasise modularity and adaptability where possible. Iterative testing, encompassing both physical and virtual evaluations, becomes imperative to compensate for the absence of empirical benchmarks and to refine the design towards safe and effective implementation.

3.2.5. Objectives, specifications, and requirements

The main purpose of this pallet is to optimise a structure for the transport and storage of a heavy, non-uniform shaft, ensuring its safety and preventing falls, accidental displacement or damage to the component. To this end, the structure must be dimensioned to support the loads involved and absorb any shocks or vibrations that may occur during transport or handling. Furthermore, it is imperative to ensure that the shaft remains intact and in satisfactory condition, without any permanent deformations or damage that could compromise its integrity. In functional terms, the structure must preserve its shape and strength, ensuring the geometric stability of the pallet during transport, handling and storage. In accordance with the requirements specified by the customer, the following main requirements and specifications are highlighted:

- The maximum pallet weight is 1800 kg;
- The structure must be capable of supporting a point load up to 25 t;
- The shaft must be transported exclusively on the two support surfaces indicated in green in Figure 40, to avoid damage to the remaining areas;
- The loaded pallet must be lifted using lifting eyes;
- The structure must incorporate a stacking system, allowing for the stacked storage of several pallets;
- The structure must incorporate a forklift lifting system, facilitating manoeuvrability and compatibility with the transport methods used;
- A braking system that obstructs the shaft axially is necessary to ensure its immobilisation during transport;
- To ensure the stability of the load, it is imperative that lashing systems are incorporated to laterally block the shaft;
- During project development, a legislative change occurred that required the width of the structure below 2500 mm, in accordance with the customer's transport legislation.

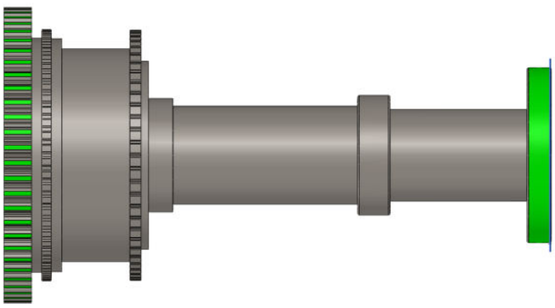


Figure 40 - Shaft surfaces of contact with the supports of the packaging system, represented by colour green.

3.3. Pre-design

3.3.1. Ashby selection method

The Ashby selection method is a widely used method in engineering for comparing and differentiating between different possible solutions for engineering problems [37]. This method is used not only for material selection, but also other important parameters that involve decision between several options. In the present design process, the Ashby selection method is used to assist selecting the material, structural profiles, metallic joints, and surface treatments.

To apply this method, initially the most relevant attributes to classify the possible solutions, should be selected. Next, it is necessary to attribute their relative weight. For a static structural part, for example, it is more important for the material to have a high yield stress than a high fatigue stress, i.e., in the Ashby diagram the yield stress should have a higher percentile weight than the fatigue stress. By placing all the attributes on a table with the determined percentual weight, it is possible to compare all the attributes. It is necessary to select a principal attribute that will be given the maximum percentile importance of 100%, i.e., it is the relative importance (W_i*) is 1, making it the most important attribute for a given solution. The relative importance of the remaining attributes selected for the solution will be directly related to the main parameter relative weight. After having W_{i*} of each attribute, it is possible to obtain the global weight (W_i) of each attribute using equation 15, where $\sum W_i$* is the sum of all the W_i*.

$$Wi = \frac{Wi^*}{\sum Wi^*} \tag{15}$$

In Table 9 it is possible to visualize an example of an attribute ponderation table.

Table 9 - Attribute ponderation table.

	1-2	1-3	1-4	W_i*	*Wi*
Attribute 1	60	60	75	1	0.375
Attribute 2	40			0.67	0.25
Attribute 3		40		0.67	0.25
Attribute 4			25	0.33	0.125
			Σ	2.67	1

Now having the weight of all attributes, it is necessary to allocate in a weighted rating decision matrix the solutions and the attributes to assess the best solution to be used in the project. The higher value of a given attribute for a solution does not mean that it is the best solution, i.e., if the objective of the solution is to have the lowest possible mass, it is best to opt for a solution with the lowest absolute mass value. On the other hand, some attributes cannot be directly quantified. In these cases, a relative scale is created to evaluate each attribute of a solution with a relative scale number (*wR*) between 1 and 5, in which 1 is the worst and 5 the best rating. After quantifying all the attributes in all materials, the weighted value (*wB*) results from dividing *wR* attribute by the maximum relative value of the same attribute (wR_{max}).

$$wB = \frac{wR}{wR_{\max}} \cdot 100 \tag{16}$$

After having *wB* for each solution, it is necessary to multiply it by the *Wi* of the respective attribute, resulting in the performance index (*wC*). Having all the performance index of each solution, it is necessary to sum all to obtain the final performance index (ϒ). With the value of ϒ, it is possible to compare all solutions and obtain the best product for the project. Table 10 shows an example of a weighted rating decision matrix, in which all attributes are quantified using a relative scale.

Table 10 - Weighted rating decision matrix.

wR / **wB** — **wC**	**Attribute 1**		**Attribute 2**		**Attribute 3**		**Attribute 4**		
	W1 = 0.375		W2 = 0.25		W3 = 0.25		W4 = 0.125		**ϒ**
Solution 1	3	37.5	5	25.0	4	20.0	4	10.0	**92.50**
	100		100		80		80		
Solution 2	3	37.5	3	15.0	5	25.0	1	2.5	80.00
	100		60		100		20		
Solution 3	4	28.1	4	20.0	2	10.0	2	5.0	63.10
	75		80		40		40		
Solution 4	5	22.5	4	20.0	2	10.0	5	12.5	65.00
	60		80		40		100		

Between the proposal solution of Table 10, the ideal solution is solution 1 because it presents the higher ϒ amongst all solutions. In sections 3.3.2, 3.3.3 and, 3.3.4 this method is going to be used for the selection of the solutions. The attribute ponderation tables and weighted rating decision matrixes are presented in Appendix A. It should be noted that the solution selected for the case does not necessarily have to be the final selection, since during the CAD iterations it may be necessary to apply specific modifications.

3.3.2. Structure and material selection

For the development of the structure, the selection of the structural aspect is a crucial factor in guaranteeing the required pallet strength and stiffness. In addition to these factors, it is also important to guarantee certain parameters so that the established requirements are met. The first proposal is the solution presented in the previous section 3.2.2, shown in Figure 41. This pallet allows the installation of various systems, such as lashing systems for transport, axial braking systems and forklift lifting systems. In addition, this pallet contains eyebolts that are used to handle the assembly. This solution presents a limitation linked to the loading of asymmetrical shafts, i.e., it can only transport symmetrical shafts. Adapting a packaging system originally designed for symmetrical loads to accommodate asymmetrical loads requires a complete redesign of the solution. The primary challenge lies in changing the position of the assembly's centre of mass, which is no longer at the longitudinal geometric centre. This modification compromises the stability and balance of the structure during handling and transport operations. As a result, the pallet must be redesigned to compensate for the asymmetrical weight distribution, which generally involves reinforcing the heavier side. In addition, functional components such as lifting eyes, forklift entry points, and lashing systems must be repositioned in accordance with the new centre of mass to ensure safe and efficient handling.

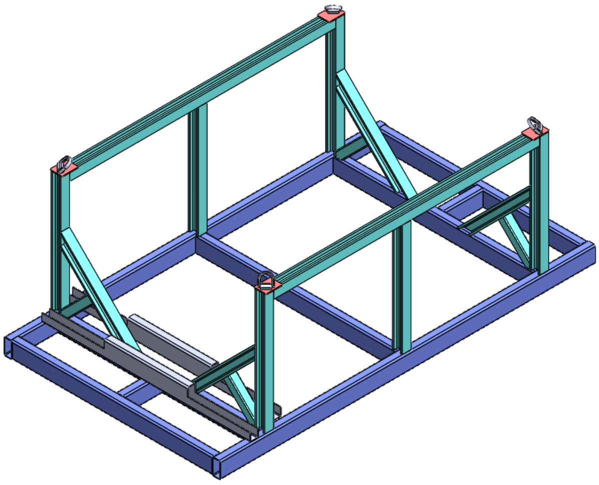


Figure 41 - First solution: Two connected points of support with high side parts for uniform shaft (original structure).

The second solution presented for this type of application is shown in Figure 42.

Figure 42 - Second solution: Two separated points of support system.

The structure is made up of just two fixed supports that are not connected to each other. This solution has its advantages when there is not a lot of material to be used in this type of equipment, and is also relatively easy to store, as the two supports are not connected, and can be leaned against or stacked when not in use. This system also has disadvantages, especially when it comes to handling and transporting the equipment. Since there is no rigid structural connection between the two pallet supports, it is practically impossible to handle the set without removing the shaft from the two supports, which greatly complicates transport operations. This type of pallet also does not include any kind of inbuilt brake to lock the shaft axially, nor does it have any lashing systems to lock the assembly during transport.

The third solution, which consists of two connected points of support system with low reinforced parts, is presented in Figure 43.

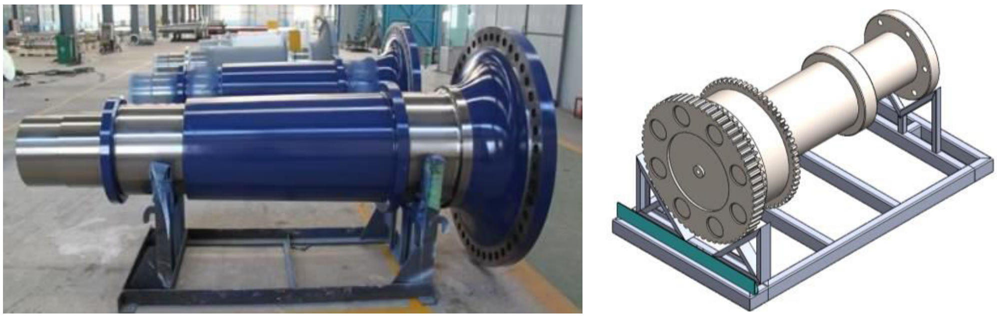
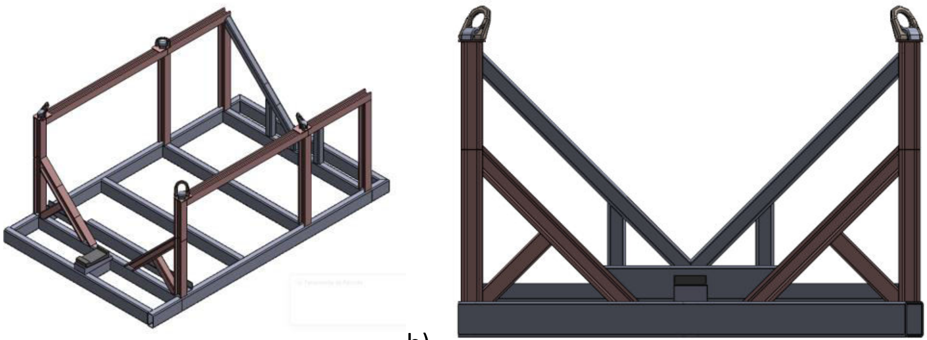


Figure 43 - Third solution: Two connected points of support system with low reinforced parts.

With this solution it becomes possible to transport the equipment more conveniently, by fitting axial brakes built into the pallet and components to tie down the structure, since this pallet already has a structural connection between the two shaft supports. When it comes to storing the pallet, if stacking is required, the pallet can be stowed effectively, but only when it is empty. It is also possible to install a forklift handling system. In addition to the advantages mentioned previously, this structure can present a significant problem. The placement of the lifting eyes can be difficult, as the sides of the pallet are all well below the shaft. Thus, if eyebolts are placed on the sides, it is very likely that, during the lifting of the pallet, the lifting cables will touch the shaft, resulting in possible damage and instability during the lifting process.

The fourth and final solution would be the system presented in section 3.2.2 remodelled so that an asymmetric shaft can be accommodated. The model developed is depicted in the Figure 44.



a) b)

Figure 44 - Fourth solution: Two connected points of support with high side parts for non-uniform shaft: isometric view (a), and front view (b).

This model, with similarities to the original one, makes it possible to load an asymmetrical shaft safely. This model was designed for the dimensions of the customer's shaft, and the lifting eyes are placed in strengthened areas between the centre of mass of the assembly. This means that the system is balanced during lifting by a crane. This model has axial brakes, and it is possible to fit a stacking system and a system for lifting with a forklift.

To select the structure, it is necessary to select attributes and use the respective selection matrix. The most relevant attributes for structural selection are:

- **Weight;**
- **Cost;**

- **Strength;**
- **Ease of transport;**
- **Ease of handling;**
- **Easy to store;**
- **Stability during transport;**
- **Stability during storage.**

Due to NEFAB's established partnerships with steel suppliers, the choice of structural materials is limited to two specific steel grades: S235 and S355. These two grades, both commonly used in structural applications, offer adequate mechanical performance and are readily available through NEFAB's supply chain, ensuring cost efficiency and ease of procurement.

The final choice between S235 and S355 is made after the complete structural design has been completed and all peripheral systems have been integrated. Once this stage has been reached, detailed finite element simulations and structural analyses will be carried out to evaluate the stresses, deformations and safety factors throughout the assembly. This procedure will allow a more accurate selection of the most suitable material, taking into account both mechanical performance and economic considerations.

Both S235 and S355 exhibit identical behaviour in the elastic region. Therefore, during the simulation phase, where analyses are typically confined to the elastic domain, there are no significant differences, in the predicted structural behaviour between these two materials, except for the factor of safety. The final choice will depend primarily on the yield stress requirements, with S355 offering higher resistance, which may be advantageous in sections subject to higher loads or critical stress concentrations.

In terms of the material used for contact between the shaft and the pallet, NEFAB has established partnerships with companies that supply a material capable of withstanding heavy loads. This material has already been used in previous models by NEFAB, with a view to ensuring the integrity of the equipment. The material selected to establish the connection between the shaft and the pallet was PVC-CAW from SIMONA [103], in which CAW is the company designation for rigid PVC with normal impact strength and chemical resistance.

3.3.3. Joining methods selection

When designing a pallet for the transport of a heavy shaft, it is essential to analyse different mechanical joints methods between structural profiles to assess the most suitable solution. Three main types of joints have been considered: welded, bolted and adhesive. Each method offers specific advantages depending on the application requirements. Welded joints provide a permanent and highly stiff connection, making them ideal for applications where structural integrity and strength are paramount. Due to their excellent load-bearing capacity, welded joints are well suited to supporting heavy components such as the shaft in question. In addition, welded connections eliminate potential movement between parts, ensuring a stable and durable structure. However, welding can be more costly and complex, particularly in terms of labour and specialised equipment. Nevertheless, the superior impact resistance and robustness make welded joints a strong candidate for critical load-bearing areas of the pallet [40, 42]. Bolted joints offer a versatile and removable solution that balances strength with ease of assembly and disassembly. These joints allow for easy maintenance and potential structural changes, which can be beneficial if the pallet design requires adaptability for different shaft sizes or future adjustments. Bolted joints may not offer the same stiffness as welded joints but, if correctly designed, these still offer considerable strength and good impact resistance. In addition, bolted joints are generally less complex and can be more cost effective to manufacture and assemble. Bonded joints provide a lightweight and uniform width stress distribution solution, which can be beneficial in reducing localised stress concentrations. This method also eliminates the need for drilling or welding, maintaining material integrity while providing a clean and aesthetically pleasing finish [42]. Although adhesive joints may have limitations in terms of ultimate strength and impact resistance compared to welded or bolted joints, these can be effective in non-critical areas where high stiffness is not required. Adhesive bonding also reduces assembly complexity and, depending on the materials used, it can also reduce costs.

Considering the evaluated attributes, each joining method offers unique advantages for different pallet structural requirements. Depending on the specific part of the structure and its intended use, a combination of all three solutions may be used to optimise performance. Critical load-bearing areas could use welded joints for maximum stiffness and strength, while bolted joints could be used where ease of maintenance or modularity is required. Bonded joints can complement these methods in areas where reduced complexity and material integrity are priorities. This tailored approach ensures a robust, efficient and adaptable pallet design for the safe transport of the heavy shaft.

Several key attributes were considered in the selection process, including:

- **Joint stiffness;**
- **Joint strength;**
- **Joint cost;**
- **Joint complexity.**

3.3.4. Surface treatments selection

For the design of a steel pallet intended to transport a heavy shaft, the choice of surface treatment is crucial to ensure protection against corrosion while maintaining economic and technical feasibility. In this project, two main surface treatments were considered: painting and galvanization. Painting offers a cost-effective and relatively simple method for protecting steel surfaces. Given that the pallet will be stored mainly in closed environments such as warehouses or sealed transport units and will only occasionally be exposed to direct humidity during loading and unloading operations, painting provides sufficient corrosion resistance. Furthermore, painted surfaces can be easily repaired in case of localized damage during handling, which is an important factor for maintaining the pallet's performance over time. Galvanization, particularly hot-dip galvanizing, provides an exceptionally durable corrosion-resistant coating by applying a layer of zinc to the steel surface. However, complete galvanisation of the assembled pallet is technically challenging and economically impractical. Large structures often cannot be galvanised in a single piece due to the size limitations of galvanising baths and the risk of permanent deformation caused by thermal stresses during the immersion process. Given the predominantly protected environment in which the pallet will operate and the significantly higher cost and logistical complexity of galvanising the entire assembly, the only viable approach to galvanising would be to treat each component separately before final assembly. However, because the structure is almost entirely welded, galvanising treatment becomes even more difficult due to the complexity of welding galvanised steel [104].

The selection process was based on the evaluation of the following parameters:

- **Cost;**
- **Complexity;**
- **Exposed environment;**
- **Repairability;**
- **Applicability for Large structures.**

3.3.5. Selected solutions

In summary, after evaluating all viable options and applying the Ashby method, the final solutions were established in the pre-design phase:

- **Fourth structure**, in which the pallet is designed for non-uniform shafts, connected between supports to facilitate the assembly of stacking and transportation systems;
- **S235** for the fabrication of the component parts;
- **PVC-CAW** is imperative for the establishment of the shaft/pallet contact;
- Welded joint, in accordance with **ISO 5817:2023**;
- Painted, degreasing or sand blasting **RAL: 5012.**

The selected solutions presented in this section are presented in Annex A.

3.4. Design

3.4.1. Description of the final solution

The final structure can be visualized in Figure 45. The structure designed within the scope of this project has a total weight of approximately 1750 kg with the main dimensions given as (2450 × 1270 × 3760) mm. The final pallet can be organised into three main components: the base, the side parts and the support for the smaller diameter area. Each of these elements fulfils specific structural and functional roles to ensure the mechanical integrity of the assembly and its operability during transport, lifting and storage.

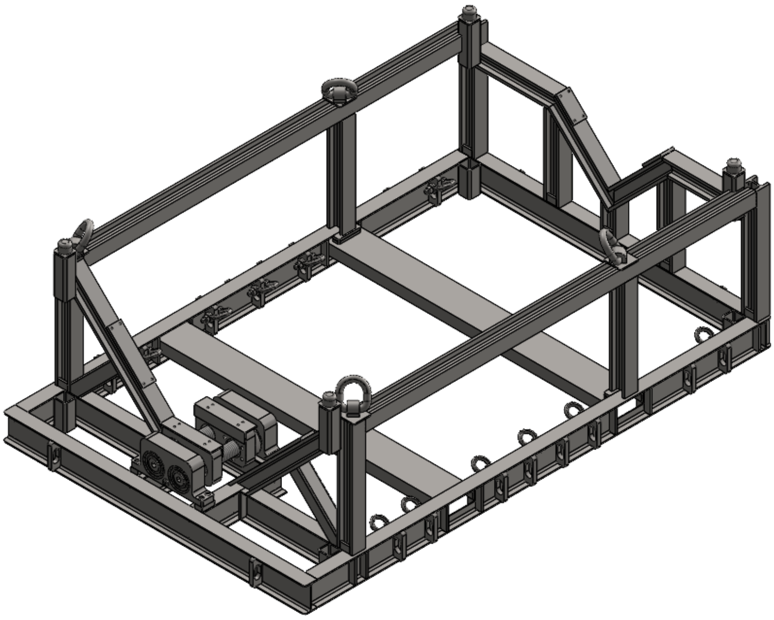


Figure 45 - Final structure.

The base is the fundamental element of the structure, as it supports the other components and houses most of the integrated peripheral systems (Figure 46).

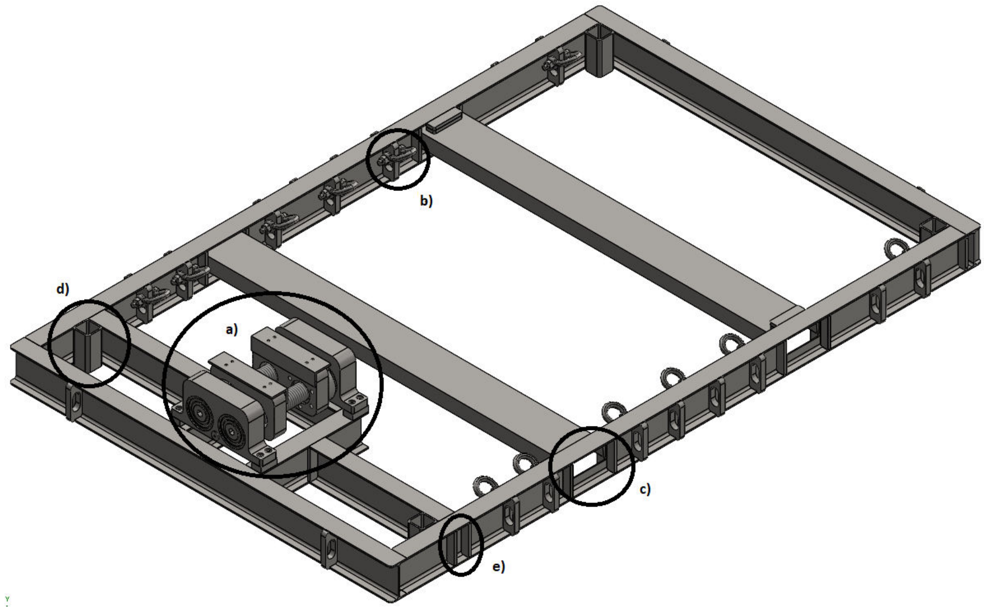


Figure 46 - Structure base: Axial brake (a), notches and rings for fastening straps (b), entry channels for forklift (c), lower part of stacking system (d), and structural reinforcements (e).

The base in question incorporates an axial braking system that can be adjusted in both directions, designed to support the total weight of the shaft, ensuring that the load is securely locked along the axis of greatest stress. In addition, strategically positioned structural reinforcements have been incorporated to respond to the expected mechanical stresses. The base also features specific notches that accommodate the rings used in the lashing system, which are essential for the safe securing of the load during transport operations. Similarly, entry channels for forklift forks are integrated, allowing up to two pallets to be lifted. This ensures that the structure can be moved using conventional warehouse equipment. A stacking system has been incorporated into the lower part, allowing up to five units to be stacked securely on top of each other, optimising storage height.

The side parts of the structure have complementary functions, being responsible for supporting the end of the shaft, corresponding to the section with the largest diameter (Figure 47).

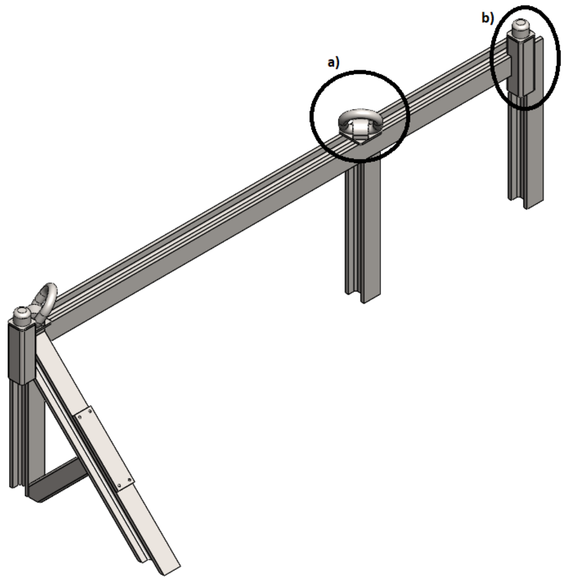


Figure 47 - Lateral assembly: Lifting eyes (a) and superior stacking system (b).

These components also include metal lifting eyes designed to lift the structure by means of vertical movement, allowing safe hoisting by cranes or other lifting systems. In addition, the upper part of the stacking system is also fixed to the sides, completing the pallet stacking circuit and ensuring its stability during storage.

The last structural component consists of the support for the end of the shaft with the smaller diameter (Figure 48).

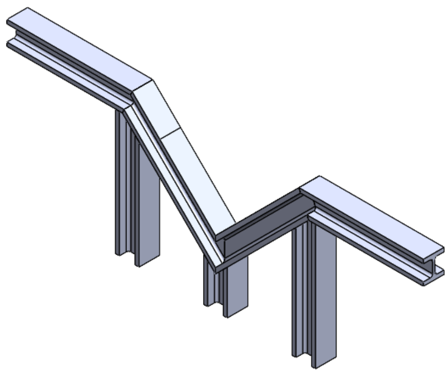


Figure 48 - Support of the shaft with the smaller diameter.

Although less complex geometrically, this part plays a crucial role in stabilising the load, contributing to the support and the correct positioning of the shaft along the pallet.

The comparison between the pallet developed in this study and the pallet currently used by NEFAB will be presented in sections 3.5 and 3.6, where the differences in structural performance, functionality, and weight and material optimisation will be analysed. The drawings of the structure are presented in Appendix B.

3.4.2. Peripheral elements

In addition to the structural part of the equipment, there are also peripherals, which are very important for the proper functioning of the system.

3.4.2.1. Lifting eyes

The first peripherical elements to consider are the lifting eyes. To lift the system correctly, it is necessary to select lifting eyes that can support the total weight of the system. Lifting eyes for heavy weights can come in various shapes. Figure 49 shows the existing types of lifting eyes.

Figure 49 - Type of lifting eyes: Fixed screw-in lifting eye (a), fixed welded lifting eye (b) [105], Screw-in hinged lifting eye (c), and hinged welded lifting eye (d) [106].

Fixed screw-in lifting eye (Figure 49 a)):

The fixed lifting eye with screw is a feasible solution when the rotation of the eye is not very important, i.e., more often in situations with low load requirements. This system is efficient when there is space to place a screw in the remaining structure and the imposed load does not significantly vary. However, due to the lifting angle of the developed structure, this eye bolt does not guarantee support for the total weight of the structure, since lateral displacements may occur during lifting that alter the loading slope and increase the concentrated loads on the surface of the eye bolt.

Fixed welded lifting eye (Figure 49 b)):

This solution is similar to the fixed solution with screws, the difference being that the lifting eye is attached to the structure using a welded joint. This system is more popular than the screw solution when it is necessary to attach the system to structures that are not suitable for screws. The model presented in section 3.3.3 has a lifting eye of this type.

Screw-in hinged lifting eye (Figure 49 c)):

The screw-in lifting eye is a good solution for situations where fluctuations during lifting must be considered, which is the case with the pallet developed in the present work. This lifting eye allows the load to be lifted within a geometrically larger range, as it is designed for this geometric variation. This solution ensures greater strength and stiffness due to its screw-mounted system. The position of the lifting eye in the structure can be a problem if the contact surface has a shallow depth, preventing the screw from securing itself.

Hinged welded lifting eye (Figure 49 d)):

The welded lifting eye with rotational capability is the most effective solution in cases where limited depth prevents the use of a bolted system, as it can be securely installed by welding without requiring a thick contact surface. These lifting eyes guarantee a good lifting capacity identically to the screw-in hinged lifting eye during angular variation due to the instability of the crane's lifting chains, ensuring the strength and stiffness of the lifting eyes.

Selected choice:

The model selected was the TWN 0119 from THIELE. The lifting eye in question, characterised by its lifting capacity of up to 31.5 t, is a **hinged welded lifting eye** equipped with a welding fastening mechanism. The load supported by this device is determined by the lifting angle applied by the lifting equipment [106]. The Datasheet of this product is presented in Annex C.

3.4.2.2. Lifting rings

To laterally secure the axle to the pallet, straps must be used. Notches must first be created to accommodate the lifting rings inside the base of the pallet. The lifting rings enables the straps to be tightened, ensuring that the axle remains as static as possible for safety reasons. These types of lifting rings can be visualized in Figure 50.

Figure 50 - Solutions for securing lashing straps [105].

It is also necessary to create notches on the outside of the pallet base so that the pallet does not slide inside the transport vehicle. The notch used both inside and outside is the same and was designed to withstand the stresses involved. This notch can be seen together with the ring in Figure 51.

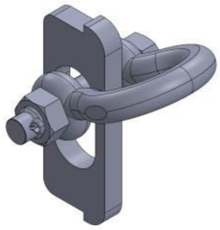


Figure 51 - Set developed with notch and ring for placing lashing straps.

A lashing system consisting of a fixing bolt and a ring designed to support 8 t, manufactured by Crosby, will be attached to this notch [107]. Considering that the shaft weighs approximately 25 t, four internal slots were placed on each side of the pallet to secure the shaft laterally to the pallet. Slots were placed on the outside to block the pallet when requested during transport.

To secure the shaft to the sides and the pallet to the transport system, the Cord lash 150 HDB12C lashing straps from Cordstrap was selected (Annex D). This model has a maximum load capacity of 5 t, which is more than sufficient, especially considering that there are six internal lashing points on each side of the pallet and eight external lashing points on each side of the pallet [108].

Figure 52 shows the position of the lashing straps mounted in the final structure.

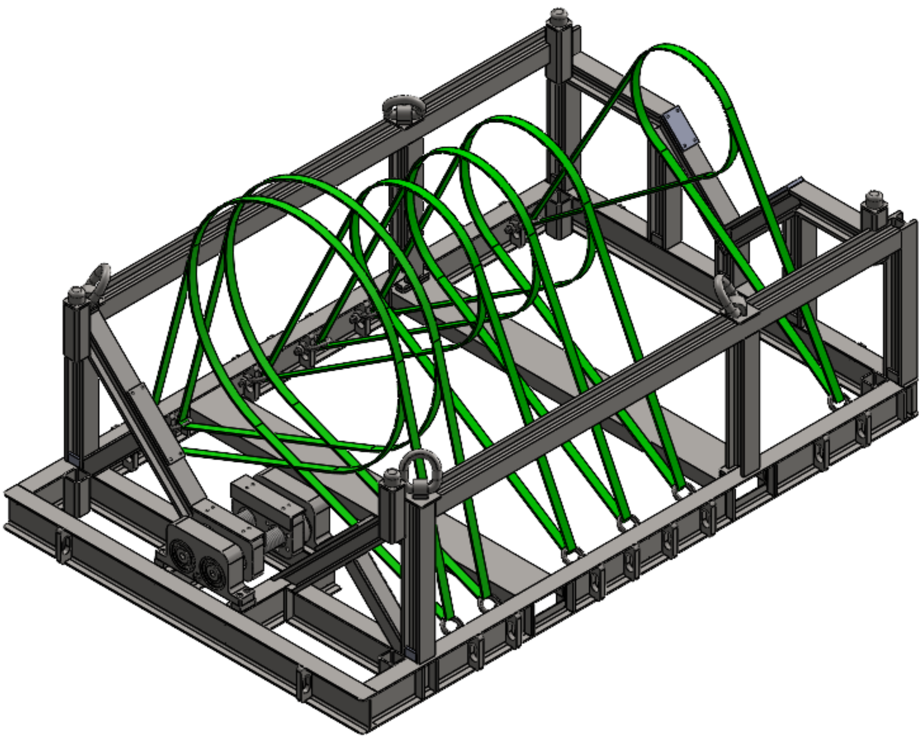


Figure 52 - Model with shaft straps and notches for the strapping system.

3.4.2.3. Axial brake

The axial braking system is a critical component in pallet design, as the shaft placed on top of the pallet can be subjected to axial loads during handling and transportation. During handling and transportation, the pallet may experience axial forces, for instance, due to sudden braking of the vehicle. In light of these potentially undesirable stresses, it is essential to develop systems that ensure that the shaft is securely locked in the axial direction while positioned on the pallet. The axial brake is crucial to guarantee both the structural integrity of the shaft and the safety of nearby personnel.

The initial axial braking concept consisted of a fixed system using two tubes directly welded to the structure. Although this simple solution was not evaluated through computational simulations, it may fulfil the locking function depending on the components used in its assembly, namely the thickness and type of braking elements. However, this system presents several issues, primarily due to the difficulty in placing the shaft without interference from the axial brakes. Since the system does not allow for adjustability, it becomes particularly challenging for operators to position the shaft on the pallet without causing unwanted contact between the shaft and the pallet.

To address this issue, it is necessary to develop a system capable of axially locking the shaft in an adjustable manner, while also ensuring that it can withstand critical braking scenarios during the pallet's handling and transportation. Figure 53 shows the initially developed fixed braking system for the uniform shaft transport model.

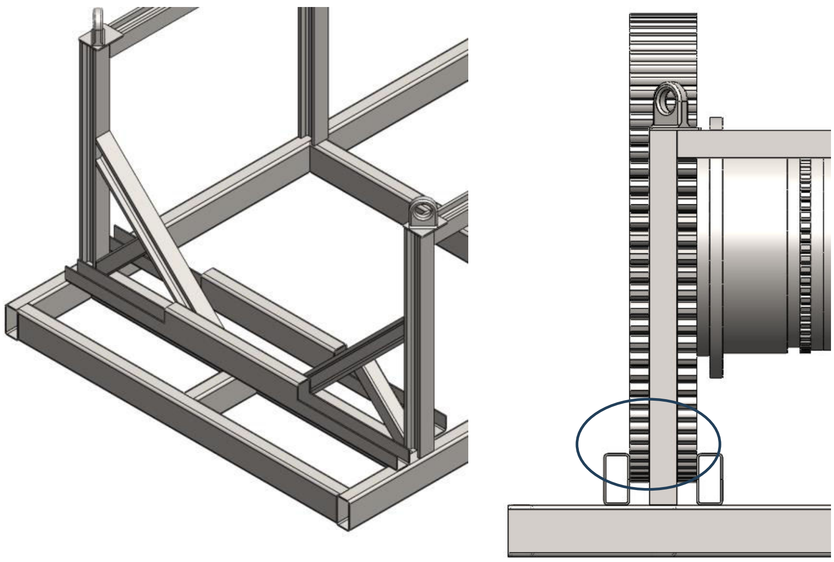


Figure 53 - Fixed axial brake.

The originally conceived mechanism is an adjustable axial brake operated via a leadscrew. This solution allows the operator to easily adjust the shaft using a wrench or a motor, without significant time loss. By rotating the leadscrew, the brake grips tighten or release the shaft. Throughout the structural development, three different brake designs were developed, all based on the same operating principle and described next.

First adjustable brake

The first adjustable axial brake was conceived with the specific purpose of securing the load in a single way (Figure 54).

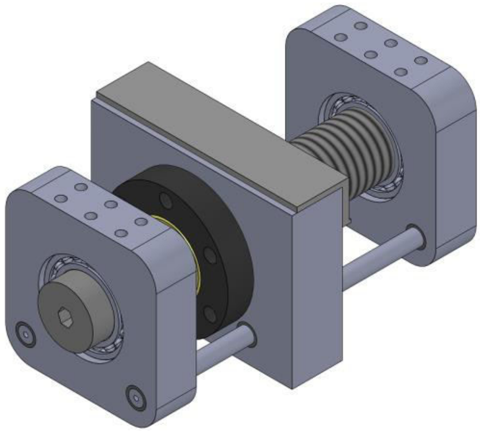


Figure 54 - First adjustable brake.

Consequently, it operated as a unidirectional locking mechanism. Therefore, in the opposite direction, a fixed component attached to the structure was required to support the shaft. The design of this braking system began by selecting a threaded nut and a corresponding leadscrew capable of withstanding the dynamic load of the shaft. The 20332F model threaded nuts and the corresponding threaded shaft 13332 from THOMSON were selected. This assembly has a maximum load capacity of 26.6 t [109]. The leadscrew was not threaded at its ends to prevent linear movement relative to the threaded nut. Figure 55 shows the threaded nut used for the brake, along with the corresponding leadscrew.

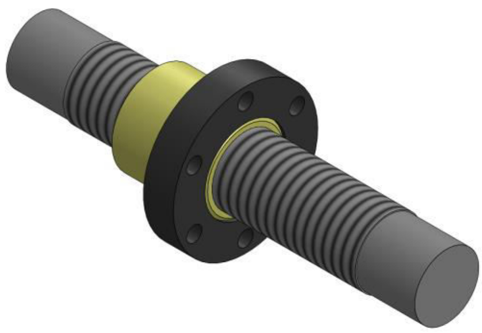


Figure 55 - Threaded nut and leadscrew for the first adjustable brake.

Using these two fundamental components, the remaining parts that would constitute the brake were developed. A bearing housing was designed to allow the rotation of the shaft at the end. This bearing housing consists of two pairs of bearings, 6316 2RSJEM manufactured by SKF, which are designed to withstand the dynamic load of the transported component [110]. Additionally, it was necessary to create a part to guide the brake grips linearly, ensuring that these remain in the correct position and do not rotate along with the nut. For this purpose, two simple shafts were used, which were to be placed in the two holes adjacent to the main hole of the leadscrew shaft. The initial idea was for the bearing housing to be connected to the structure using bolts, enabling the connection to be designed according to the Eurocodes. Figure 56 shows the modelled bearing housing.

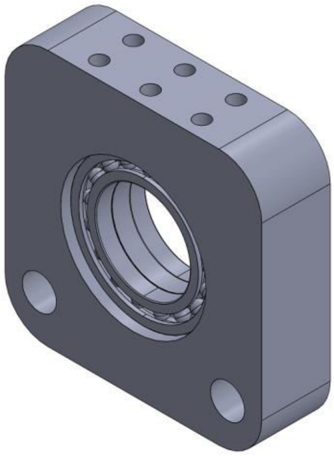


Figure 56 - Bearing housing assembly of first adjustable brake.

The brake grip was also developed. this part is connected to the nut and moves linearly to tighten and release the shaft. Figure 57 shows the developed brake grip.

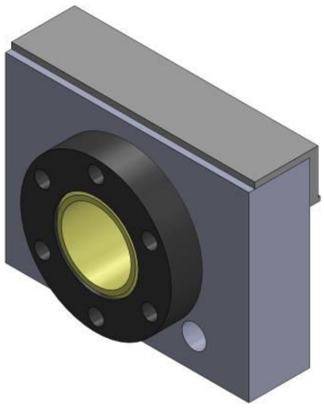


Figure 57 - Movable grip of the first adjustable brake.

Considering the structural changes throughout the project, the brake had to be modified accordingly. Therefore, at this stage, the design of the brake's fixation connections had not yet been thoroughly dimensioned.

Second adjustable brake

Due to structural changes during the project and the requirements of the braking system, the second version of the axial brake was developed (Figure 59).

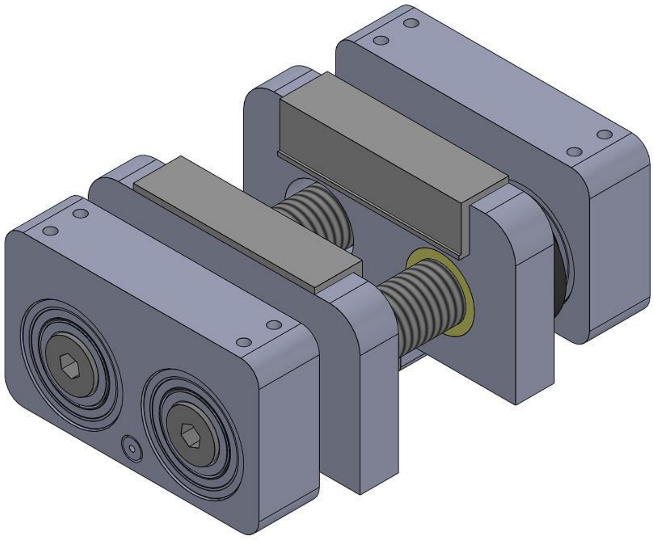


Figure 58 - Second adjustable brake.

This axial brake presents functional improvements compared to the first version, as it allows the shaft to be locked in both directions, with both fixation sides being adjustable. This feature also facilitates the positioning of the shaft on the pallet, considering that none of the contact surfaces are fixed. The threaded nut and leadscrew were replaced with lighter solutions that still meet the requirements. In this model, since the brake is adjusted in both directions, two rotation axes are necessary. Therefore, a bearing housing with two rotation axes was designed for the two leadscrew shafts, and the guidance system was simplified from two shafts to a single central shaft. In this model, KH30-PP linear ball bearings manufactured by SCHAEFFLER were selected, to prevent direct contact between the guide shaft and the other parts (bearing and grip) [111]. Figure 59 shows the bearing housing of the second adjustable brake.

Figure 59 - Bearing housing assembly for the second adjustable brake.

For this mechanism, there are now two movable grips with two shafts, each connected to a screw thread. The grips operate symmetrically, sharing the same mechanism. Figure 60 shows the grip assembly of the second brake.

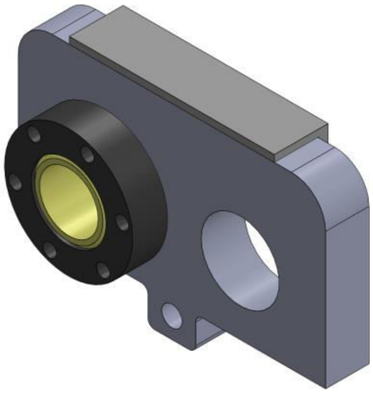


Figure 60 - Grip assembly for the second developed brake.

Third adjustable brake

After reducing the width of the structural base, it became necessary to adapt the braking system, as it had initially been designed for a base with a width of 2600 mm. This geometric change was motivated by logistical constraints related to the transport of the structure, requiring the axial brake to be redesigned to suit the new available width (Figure 61).

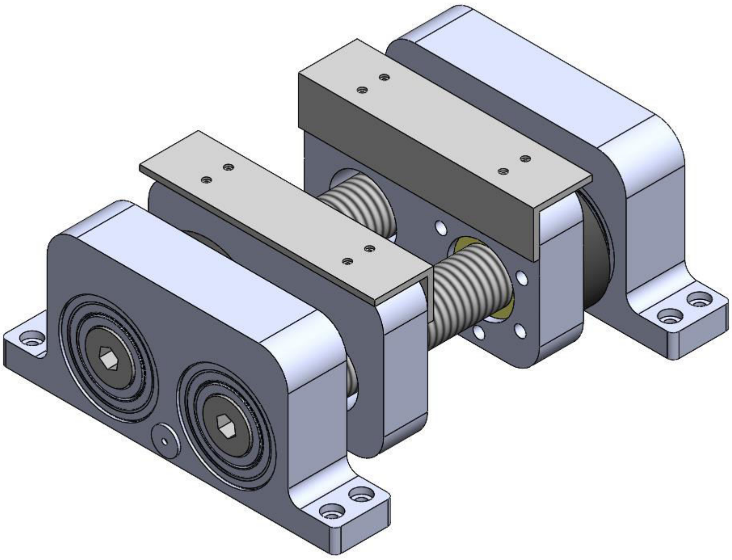


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Figure 61 - Third adjustable brake.

The braking mechanism of the third prototype remained functionally identical to that of the two previous models. The main differences from the second model lie in the type of bearings used and the fastening method adopted. In this case, the bearing was fastened to the structure by means of bolted connections positioned on the underside. The base width reduction resulted in the supports being brought closer together, which caused a slight elevation of the shaft. This geometric change, together with the new assembly requirements, contributed to the need to redesign the axial braking system. It should be noted that, in this third model, the bolted connections were properly dimensioned in accordance with the criteria defined in the

Eurocodes, thus ensuring the structural conformity and safety of the system. Initially, the bearing system was adapted so that it could be bolted, initially modelled with 4 bolts. Figure 62 shows the bearing remodelled for third adjustable brake.

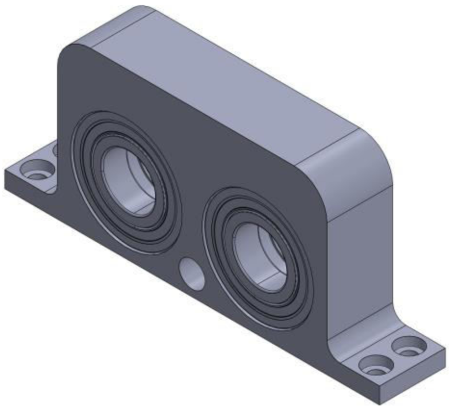


Figure 62 - Adjustable third brake bearing assembly.

The clamp remained virtually identical to the previous one. However, due to the unevenness caused by the change in the bearing, it was necessary to make a slight adjustment to the guide shaft area. Figure 63 shows the clamp used in this model. All solutions used in this section is presented in Annex E.

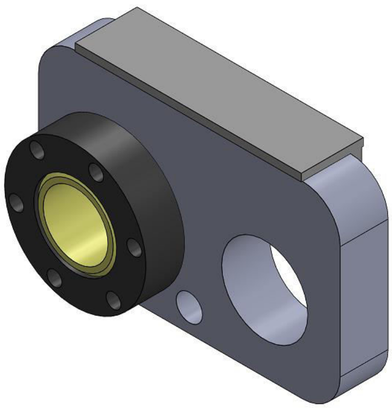


Figure 63 - Grip assembly for the third developed brake.

3.4.2.4. Fastener dimensioning

Considering the non-linear and non-uniform nature of the bearing, it was decided to use a four-bolt plate to secure the brake bearing assembly, considering that the area of the bolted zone of the bearing would be the relevant area for this purpose. Figure 64 shows the area considered for adaptation of the uniform plate.

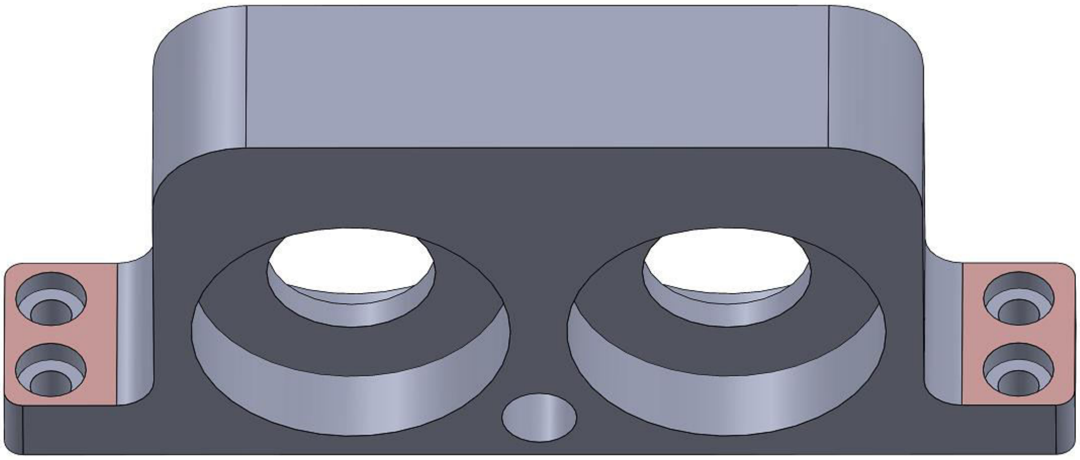


Figure 64 - Bearing area considered for equivalent plate (in red).

After determining the bearing area required for the dimensioning of the connections, an equivalent plate was developed that adequately represented the connection conditions. Based on this first iteration of the equivalent plate, the preliminary dimensioning of the bolted connections was carried out. The dimensions of the plate and the arrangement of the holes were defined in accordance with the criteria established by the applicable standards, ensuring consistency with the strength and assembly requirements. Figure 65 shows the technical drawing of the equivalent plate and its dimensions.

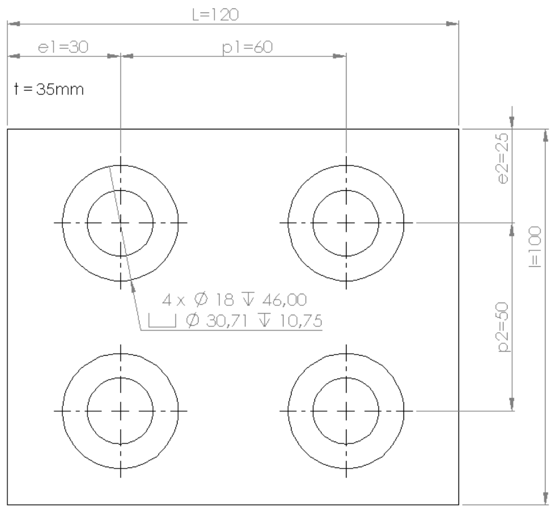


Figure 65 - Technical drawing of the equivalent plate of the brake bearing.

Eurocode 3-1-8 (2010) considers two types of bolted connections: standard bolted connections and preloaded bolted connections. In this case, the bolted connection, which is mainly subjected to shear, was considered standard. For the first iteration, an M16 class 10.9 bolt was chosen, and the transverse stress and the bending moment of the bolt were calculated, considering the mass of the shaft. Table 11 shows the relevant parameters to the design of the connections.

Table 11 - Relevant bolt parameters for dimensioning connections according to Eurocode 3.

M16 Screw Class 10.9	
Nominal diameter (d) = 16 mm	Hole diameter (d0) = 18 mm
Useful area (A_s) = 157 mm^2	Total area (A) = 201.66 mm^2
Tensile strength (F_{ub}) = 1000 MPa	Yield stress (F_{yb}) = 900 MPa
Number of screws (n) = 4	

Based on the parameters from the first iteration, it was possible to begin the dimensioning of the screws. The connections were initially sized based on an estimate of the screw positioning and spacing considering the available space to mount the brake bearing plate, with preliminary values defined to assess the structural feasibility of the assembly. Table 12 shows the permissible values for the positioning of the screws.

Table 12 - Screw position values.

Variable	Equations		Values		
	Minimum	Maximum	Minimum	Maximum	Selected
e1	1.2d0	4t+40 mm	21.6	180	**30**
e2	1.2d0	4t+40 mm	21.6	180	**25**
p1	2.2d0	min[4t;200 mm]	39.6	200	**60**
p2	2.4d0	min[4t;200 mm]	43.2	200	**50**

Considering the intervals obtained in Eurocode 3, it can be concluded that, in terms of positioning, the equivalent plate and, consequently, the brake bearing are validated. In addition to positioning, it is also necessary to validate the bolts for shear and crushing. To this end, all the constants that will be used in the design equations are gathered. Table 13 shows the values of the constants to be used.

Table 13 - Eurocode 3 parameters.

Parameters	**Values**
λ_0	1
λ_2	1.25
α_v	0.5
α_b	0.56
k_1	2.18

To validate the bolts, the equation 17 must be satisfied, where $F_{v,Ed}$ is the transverse stress applied to each of the bolts and $F_{v,Rd}$ is design shear resistance per bolt.

$$F_{v,Ed} \leq F_{v,Rd} \tag{17}$$

$F_{v,Ed}$ is calculated using equation 18, where Ft is the force applied by the shaft to the bearing structure:

$$F_{v,Ed} = \frac{Ft}{n} \tag{18}$$

Given the presence of two bearings, each with a shaft, one for each grip, it can be assumed the force exerted on the centre of the bearing is 125 kN, which is equivalent to half the mass of the shaft. It is evident from the application of equation 18 that $F_{v,Ed}$=31,25 kN.

To ascertain the values of $F_{v,Rd}$, equation 19 applies.

$$F_{v,Rd} = \frac{\alpha_v f_{ub} A}{\gamma_{M2}} \tag{19}$$

Applying this equation leads to $F_{v,Rd}$=25.2kN. In this way, it is feasible to validate equation 17, i.e., the connection is validated in relation to the shear stress on the bolts. Currently, it is imperative to validate the crush resistance, which requires applying the following equation, where $F_{b,Rd}$ is the design shear resistance per bolt:

$$F_{v,Rd} \leq F_{b,Rd} \tag{20}$$

To determine $F_{b,Rd}$ it is necessary to apply equation 21:

$$F_{b,Rd} = \frac{k_1 \alpha_v f_u dt}{\gamma_{M2}} \tag{21}$$

Variable replacement gives $F_{b,Rd}$=22.472kN. Since equation 20 is fulfilled, the connection with respect to crushing is validated. It is essential to validate the strength of the equivalent plate. Validation of the plate strength requires application of equation 22, which N_{Ed} defines as the tensile force in the plate and $N_{t,Rd}$ the maximum tensile value that the section can safely withstand.

$$N_{Ed} \leq N_{t,Rd} \tag{22}$$

Since N_{Ed} is equivalent to the tensile force of the plate, it is equal to $F_{v,Ed,}$ i.e. equal to 125 kN. Therefore, the next step is to calculate the value of using equation 23:

$$N_{t,Rd} = \frac{0,9(Lt - ntd_0) f_u}{\gamma_{M2}} \tag{23}$$

Substituting in equation 23, $N_{t,Rd}$=408.24kN is obtained. Therefore equation 22 can be validated. Thus, it can be concluded that, according to Eurocode 3, the bolted connections are correctly dimensioned to withstand the dynamic stress caused by the shaft in a critical braking case during transport.

3.4.3. Structural analysis

3.4.3.1. CAD design iterations

This section describes the structural evolution of the pallet for a non-uniform heavy shaft. Initially, the pallet for a uniform shaft presented in section 3.2.2 was adopted as a basis, with the necessary adjustments suggested by NEFAB, to obtain the most efficient and practical solution.

First iteration

Initially, the uniform shaft pallet was adapted to become a pallet that could support a non-uniform shaft. As the maximum diameter of the non-uniform shaft is identical to that of the uniform shaft, it was possible to maintain one side of the support where the larger diameter would contact the pallet, while at the other end a support consisting of tubes was placed. It was also necessary to determine the centre of mass of the assembly so that the central point between the lifting eyes could be obtained. In accordance with the company's requirements, only the geometry of an unbalanced shaft was considered. This is important to ensure that, when lifting the pallet, there is no imbalance of masses, which could result in undesirable accidents. After obtaining this central point, it was possible to determine the areas where the lifting eyes would be placed (Figure 66).

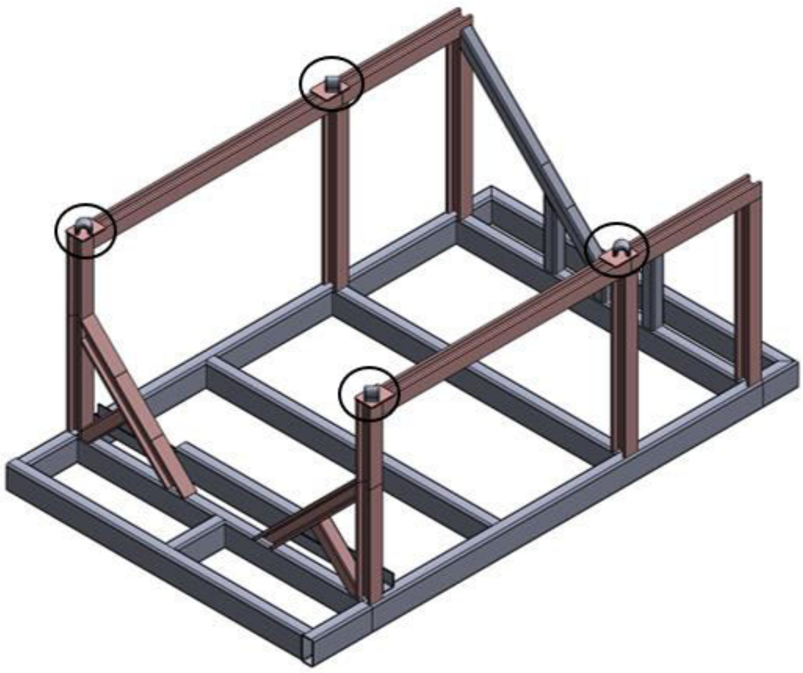


Figure 66 - First iteration of the pallet and representation of the location of the lifting eyes.

Second iteration

After the first modelling iteration, the components identified as necessary at the start of the project began to be installed. The second iteration served mainly to develop a system that would allow the pallets to be stacked. This system consists of a tubular piece and another circular piece, with the necessary diameter to fit into the inside of the tube. Figure 67 shows the components of stacking system (a), a cross-section of the stacking zone (b), and a stacked pallet (c).

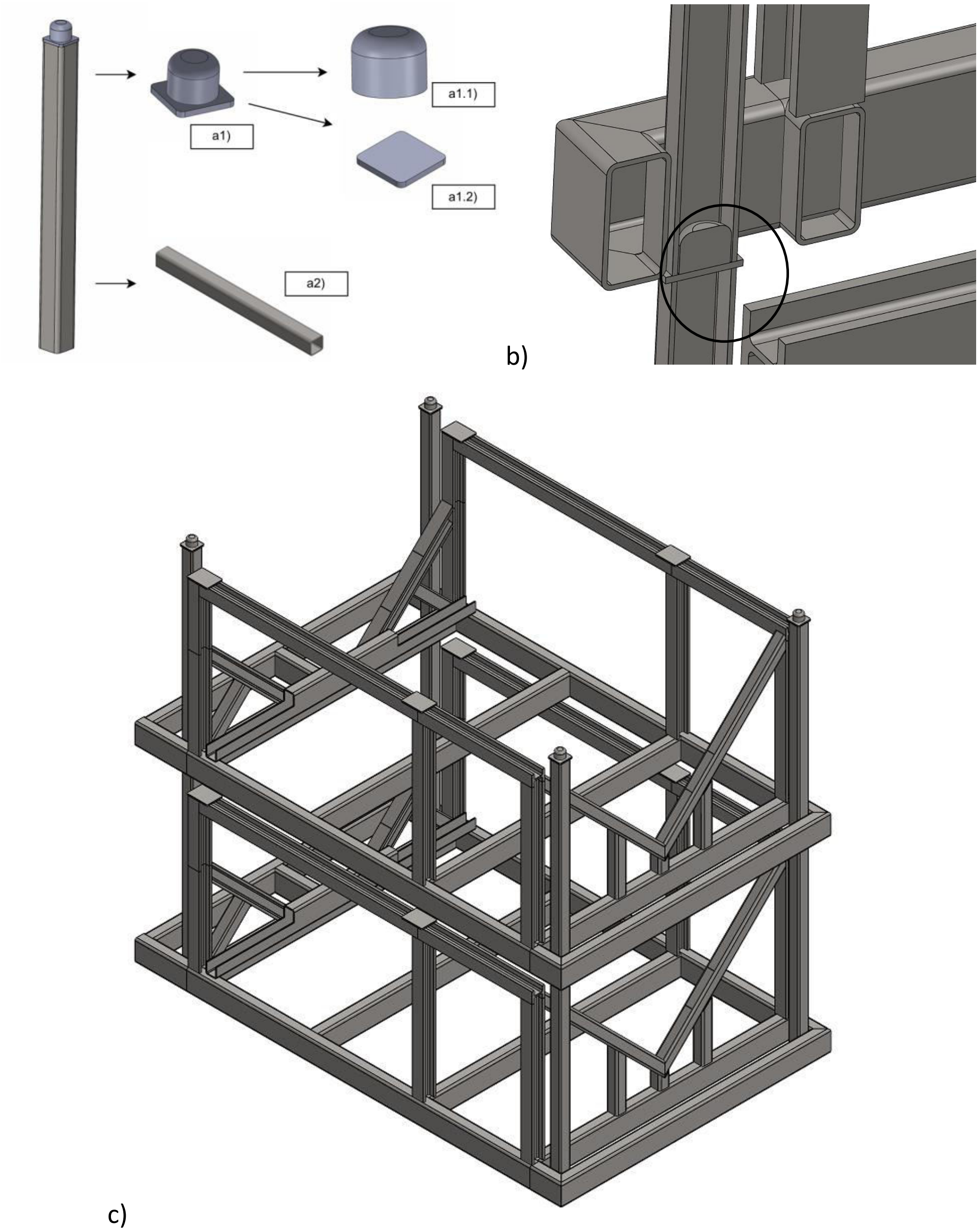


Figure 67 - Stacking system: Components (a) - Stacking block (a1), Stacking tip (a1.1), Stacking block base (a1.2), Stacking tube (a2), Stacking area in cross-section (b), and Stacked pallet (c).

Third iteration

The third iteration mainly served to add a new initial requirement proposed by NEFAB, namely a forklift handling system. presents the complete structure with the addition of the lifting system.

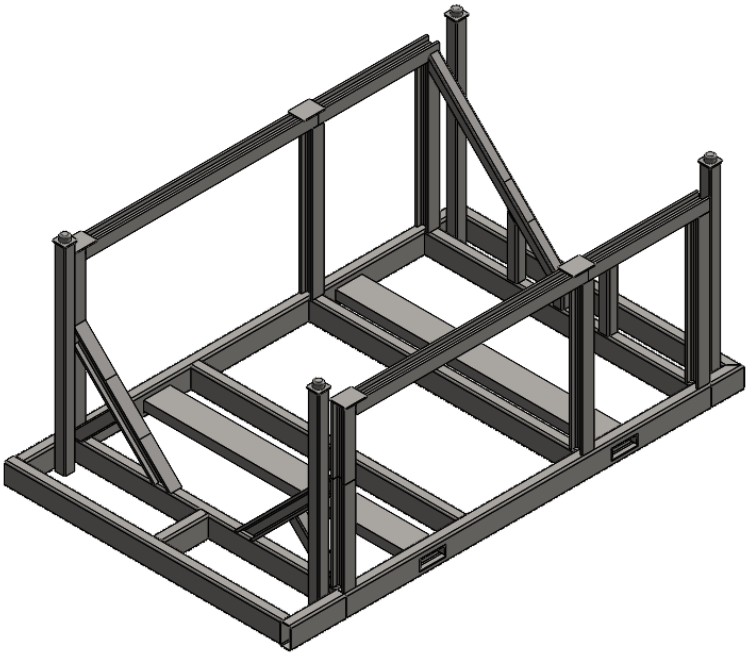


Figure 68 - Third iteration with the addition of forklift system.

This system must also be installed considering the pallet's centre of mass to avoid problems, such as the fall of the shaft. Given the dimensions of the pallet (2.6 m × 4 m), it is necessary to consult the standards relating to forklifts to obtain the necessary dimensions for the entry channels that will be placed in the system. To ensure compatibility between the pallet and handling equipment, namely forklifts, it is essential to refer to ISO 2328:2011 standard, which establishes the mounting dimensions of fork arms and attachment brackets for forklifts with a capacity of up to approximately 11 t [112]. According to this standard, forklifts are classified into five different classes based on their load capacity. In this case, it is easy to identify the class, as the pallet has a weight that cannot exceed 2000 kg, which corresponds to class 2 of the respective standard. The standard includes several tables which, although not directly applicable to pallet entry channels, provide relevant dimensions for pallet sizing to ensure they can be moved by forklifts. Based on the previous tables from the ISO 2328:2011 standard and the typical dimensions of forklift forks, it is possible to obtain some relevant dimensions of the channel section, which can be found in Table 14.

Table 14 – Relevant parameters to size pallet entry channels.

Parameter	Class 2	Definition
u	>95 mm	Free internal height between the bottom of the support and the top of the lower fitting
l	>100 mm	Internal channel width

Using these values, it is possible to obtain the dimensions of the pallet channel entrance section, taking into account the lateral clearances, so that there are no problems arising from possible friction and blockages between the forklift fork and the pallet. With regard to the length of the channels, the standard does not define a specific value, but it is recommended that the forks can penetrate at least halfway into the pallet to ensure stability during lifting. Regarding the distance between channels, forklifts typically have a distance between channels that varies between 1 and 2 m. After defining the dimensions, a system was developed that complied with the minimum dimensions established by the standard. A UPN240 profile was selected for the system to act as an upper stop for the forklift forks. A slot was cut into the tubular base with the necessary dimensions so that the forklift could operate without problems. Considering that the minimum length for the system to function correctly during lifting is half the width where the fork will penetrate the pallet, the total length was considered so that the UPN profile used could have two supports in the structure, i.e., crossing from outside to outside. It should also be noted that the importance of the entry channel having rounded corners was taken into account so that there is less likelihood of blockage, friction problems, and stress concentrations.

Figure 69 shows a detail of the entry section of the forklift fork into the pallet and the respective dimensions used.

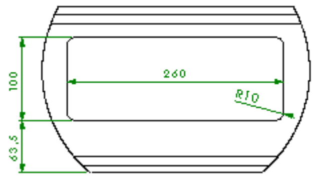


Figure 69 - Dimensions of the entry channels of forklift system.

Fourth iteration

The fourth iteration was mainly used to make changes to the base, which was previously constructed with tubular elements. During this stage, the square tube structure was adapted to an IPE200 profile (Figure 70).

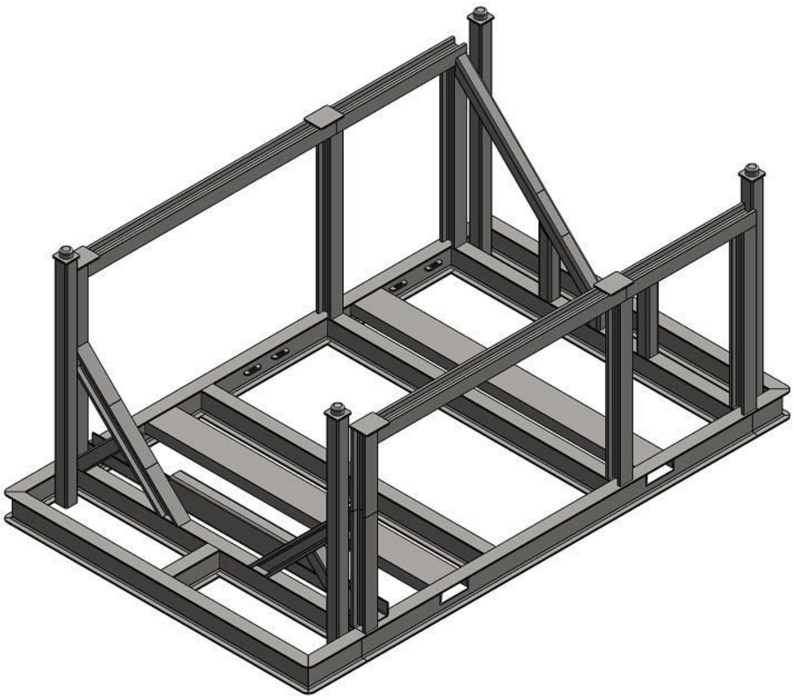


Figure 70 - Fourth iteration structure with new IPE base.

IPE 200 profile offers a significantly lower mass while maintaining adequate mechanical performance. Table 15 shows the mass values for both bases.

Table 15 – Values of mass for each base.

Element	Mass (kg/m)
Square tube 200×100×8 mm^3	**35.1**
IPE200	**22.4**

In a later section, the base will be subjected to computational simulations to ensure that it can support the expected loads and operating conditions. This analysis will serve to validate the design and confirm its structural adequacy of the base. It should also be noted that, at the customer's request, the base should not have sharp corners, i.e., the edges of the base were modelled so that they are rounded at all four corners.

Fifth iteration

In the fifth iteration, the stacking system underwent an adaptation to ensure a further reduction in pallet weight. To achieve this goal, it was necessary to divide the stacking system tubes. To this end, the tube that previously connected the lower part of the pallet to the upper part was split, resulting in two smaller tubes (Figure 71).

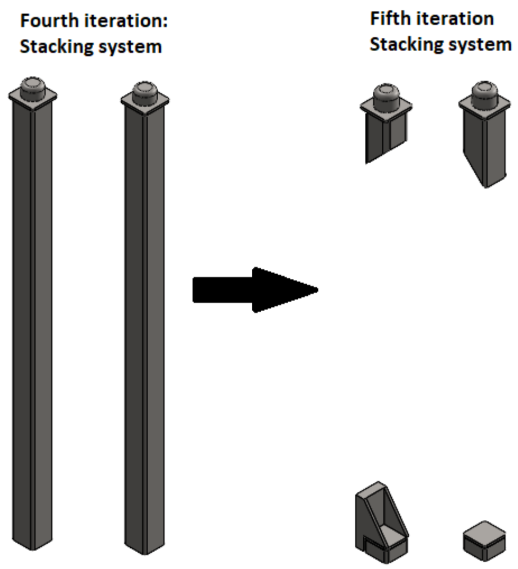


Figure 71 - Optimization of stacking system (fourth iteration to fifth iteration).

It is important to note that the adaptation was not uniform for both ends of the pallet, as each one has distinct geometries. A Figure 72 a) and b) illustrates the two-piece stacking system used in the larger and smaller shaft diameter regions, respectively.

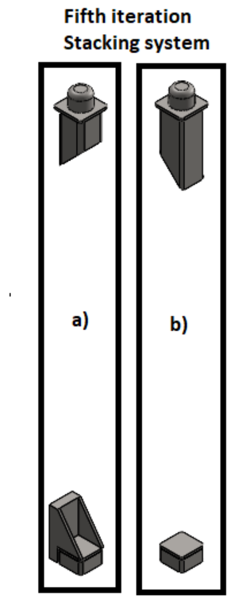


Figure 72 - Fifth iteration stacking system: larger diameter zone (a) and smaller diameter zone (b).

At the region of larger shaft diameter, there was no need to machine any elements, as the parts were welded directly to the base and side of the structure (Figure 73 a)). At the region of smaller shaft diameter, it was necessary to machine the base profile to position the lower part inside the profile, while the upper part remains in contact with the tubular support (Figure 73 b)).

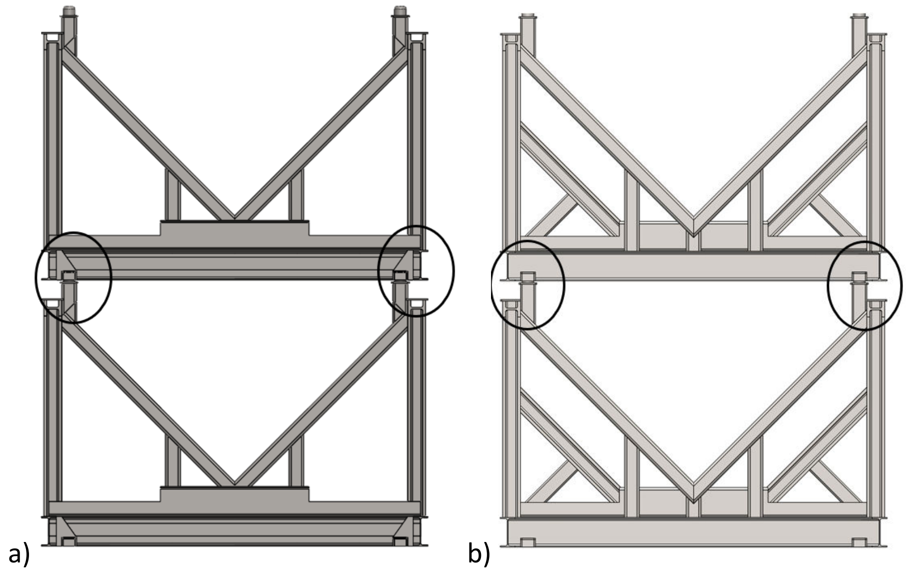


Figure 73 - Support for the shaft: larger diameter (a) and smaller diameter (b).

In this iteration, a part of the base that served only as a contact surface with the stacking tubes was also removed, since structurally it did not add any strength to the pallet. Figure 74 shows the adaptation made to the structure in the fifth iteration.

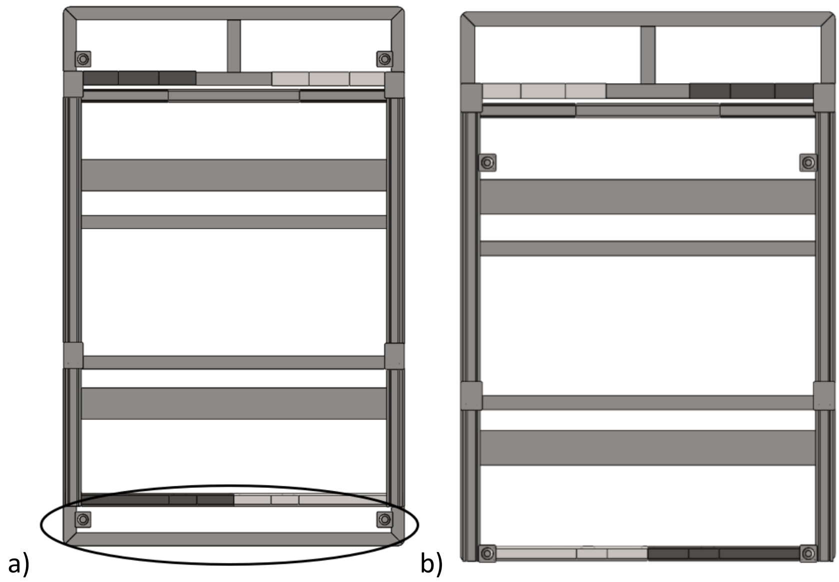


Figure 74 - Structure upside view: Structure in fourth iteration (a), and structure in fifth iteration (b).

Sixth iteration

In the sixth iteration, the focus returned to reducing the weight of the overall structure (Figure 75). To reduce weight, the support for the smaller diameter area of the shaft was changed. It had been connected from the part where it would come into contact with the shaft to the upper side of the structure, where the stacking system was located. This support was adapted so that it did not extend up to the upper stacking area.

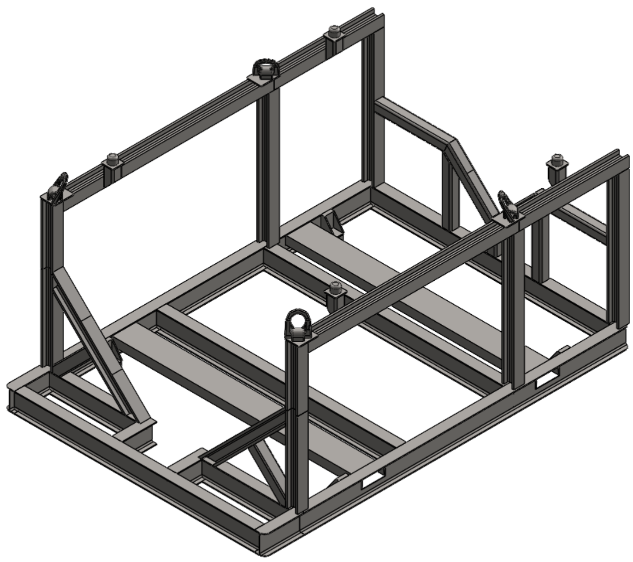


Figure 75 – Sixth iteration of the structure.

In Figure 76 it is possible to visualize the evolution of the smaller support for the smaller diameter of the shaft. When performing this transformation, the stacking system shown in Figure 72 b) is no longer applied, being adapted with the same system shown in Figure 72 a).

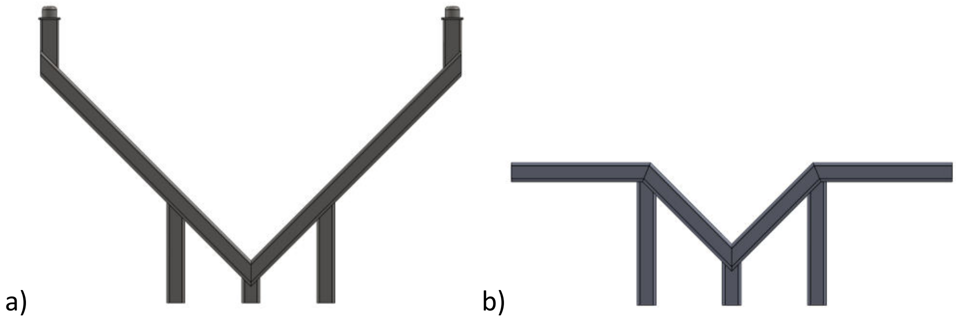


Figure 76 - Optimisation of support for the area with the smallest diameter.

This iteration was also the first in which the first movable brake, presented in the previous section, was implemented. To install the movable brake, it was necessary to adapt the base for its placement. Figure 77 shows the adaptation of the base that was made for the installation of the movable brake.

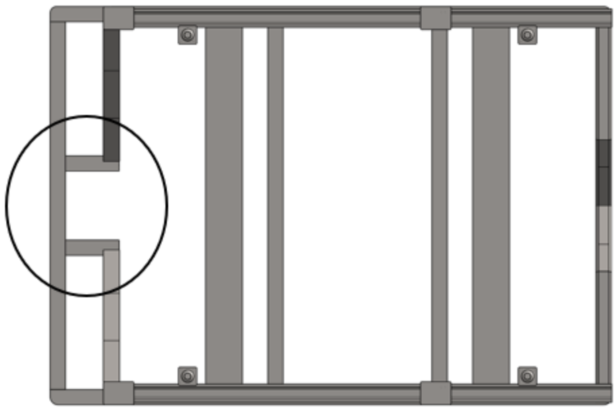


Figure 77 - Base in sixth iteration.

Seventh iteration

In the seventh iteration, the largest weight reduction in the structure took place (Figure 78).

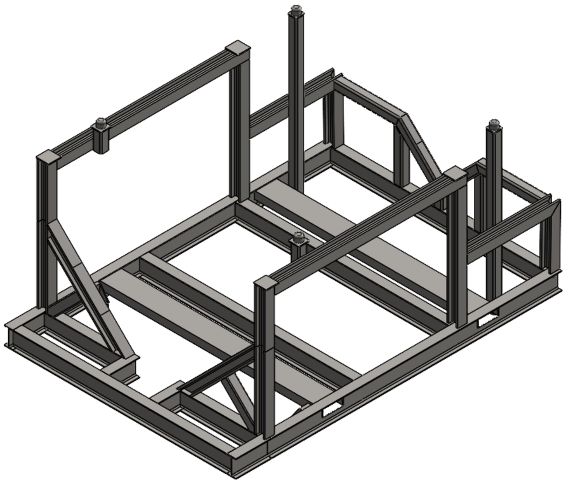


Figure 78 - Seventh iteration of the structure.

Throughout the iterations, it was found that the sides were too high because the shaft also had a considerable diameter. Not to alter the configuration of the lifting eyes initially proposed by NEFAB (configuration at 45°), only the structure height that was not between the lifting eyes was reduced. Due to this reduction, it was necessary to return to the original stacking system in the zone where the side was reduced, as it was no longer possible to weld the tubes to the upper part.

Eight iteration

To reduce the height also between the lifting eyes, it was necessary to modify the eyes configuration (Figure 79).

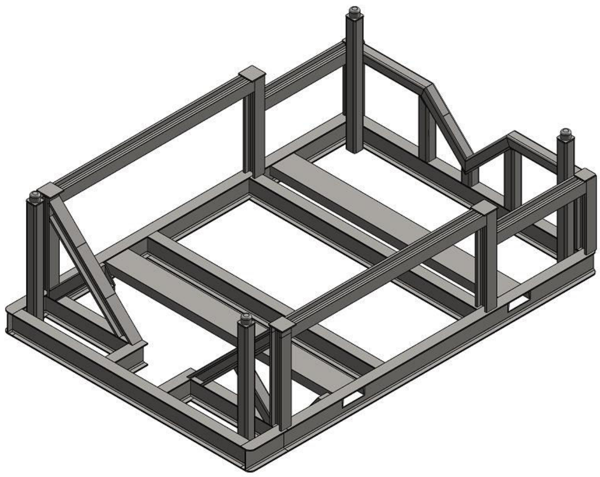
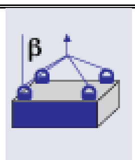


Figure 79 - Eighth iteration of the structure.

Initially, it was proposed by NEFAB that the structure could be lifted using four points at 45°. The greater the eye angle (β), higher lateral forces will be applied to the pallet and the greater the resulting lateral deformation. Considering that when the eyes are installed in a square four-eye configuration, it is possible to perform the eye within two different angular ranges. If the lateral height of the pallet is reduced without changing the lifting angle of the eyes, contact will occur between the shaft and the crane chains. However, if the angle reduces, it becomes possible to reduce the lateral width such that the crane chains do not come into contact with the shaft during lifting. Table 16 shows the importance of the working angle of the lifting eyes [106].

Table 16 - Importance of the working angle of the lifting eyes (load comparison) [106].

	β	Load (t)
	>45	22.4
	45 – 60	31.5

This simplification resulted in a significant reduction in the weight of the structure, considering that a large part of the side would be removed. In addition, room was gained for eyebolt manoeuvre, which could be reduced, considering that they would no longer work with an inclination angle of β<45. Therefore, the side was reduced to the support area.

Nineth iteration

In the ninth iteration, the manufacturing perspective was taken into account with regard to optimising the structure (Figure 80).

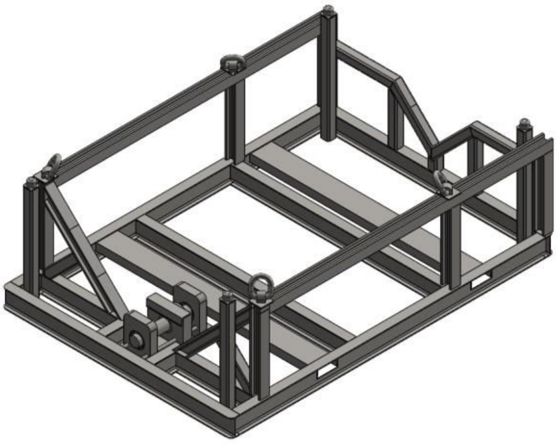


Figure 80 - Nineth iteration of the structure.

Given that the structure is practically welded, it was necessary to ensure that the required welding work required was as minimal as possible, i.e., the structure was made as linear and straight as possible. To achieve this goal, it was necessary to increase the width to reduce the number of structural elements connected to the side of the structure.

Tenth iteration

This iteration aimed to standardize the structural configuration with respect to the profiles employed, thereby establishing a consistent basis for subsequent computational simulations. Additionally, it contributed to an improvement in the system by reinforcing the support mechanism for the smaller diameter section of the shaft (Figure 81).

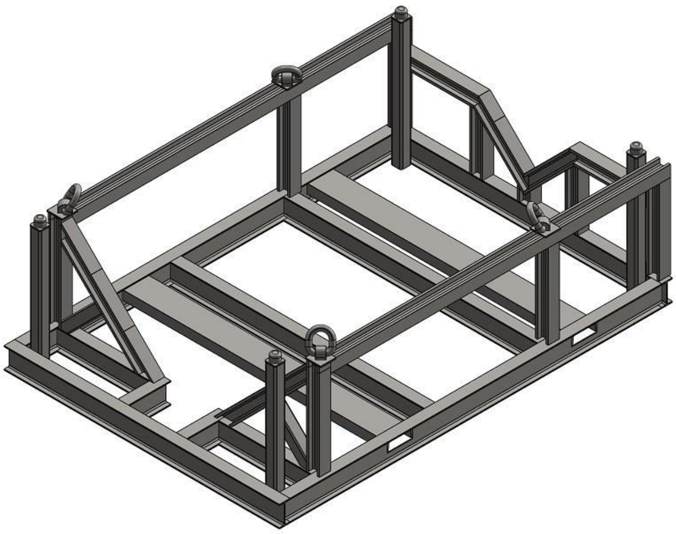


Figure 81 - Tenth iteration of the structure.

Initially, the support was adapted to the support zone of the smaller diameter part of the shaft. The support initially modelled by tubes was replaced by the same profile used in the rest of the structure, namely the HME profile, to ensure uniformity of profile throughout the structure.

Eleventh iteration

This iteration focused on reducing the pallet width, taking transportation methods into account (Figure 82).

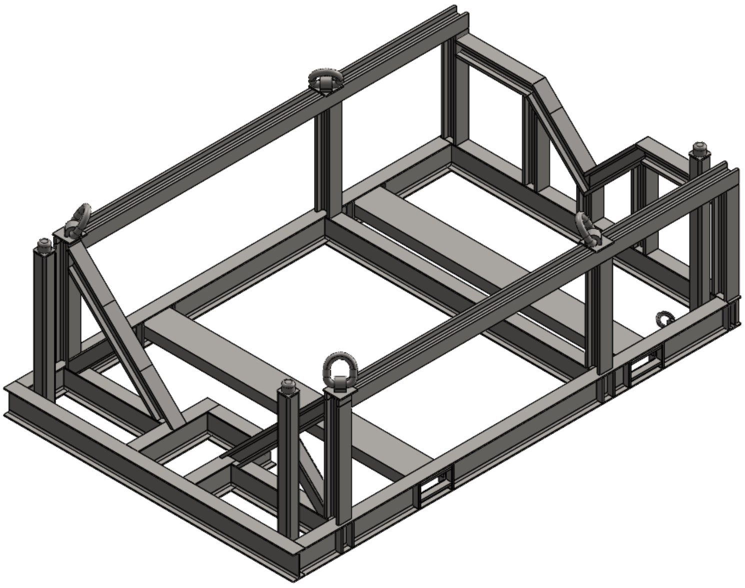


Figure 82 - Eleventh iteration of the structure.

Due to a transportation recommendation from the client, it was necessary to decrease the base width because trucks can only transport goods under normal transportation conditions if the width does not exceed 2500 mm. If this value is exceeded, the transport is classified as exceptional, which may result in additional costs. Therefore, the pallet width was reduced from 2600 mm to 2400 mm, reducing costs. This change required a redesign of the axial brake, which in turn required the addition of profiles at the base for bolting. On the other hand, it was also concluded that the central beam of the pallet was not providing significant structural reinforcement, so it was removed. Figure 83 shows the upside view of eleventh iteration.

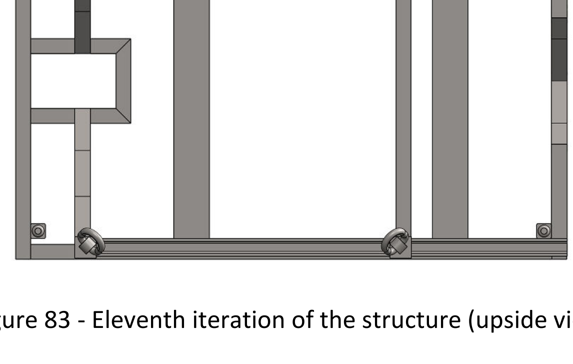


Figure 83 - Eleventh iteration of the structure (upside view).

Twelfth iteration

In this last iteration, the computational simulations conducted on the previous model were considered (Figure 84).

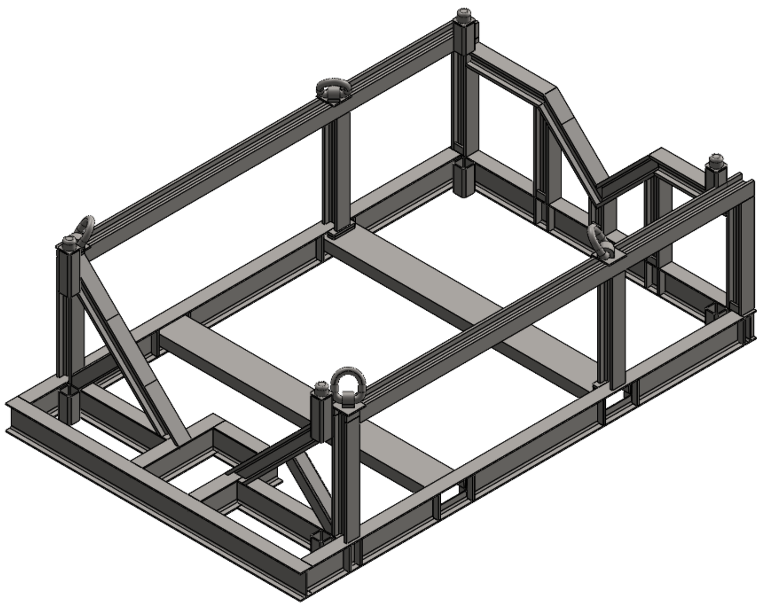


Figure 84 - Twelfth iteration of the structure.

By simulating the pallet lifting via the lifting eyes, stress concentrations exceeding the allowable limits for S355 and S235 steels were identified. As a result, it became necessary to reposition the forklift entry channels to eliminate these stress concentrations. To address this issue, the entry channel was shifted to a position directly beneath the column supporting the lifting eye, thereby eliminating the moment arm between the eye and the channel. This modification effectively removed the previously observed peak stresses, enhancing the structural viability of the model. Furthermore, this change allowed for the removal of the central IPE beam, making it possible to incorporate a UPN profile as the forklift entry channel. This replacement led to a significant reduction in the overall weight of the structure. Figure 85 a) illustrates the position of the forklift entry channels in the eleventh iteration, while Figure 85 b**)** presents the configuration adopted in the twelfth iteration.

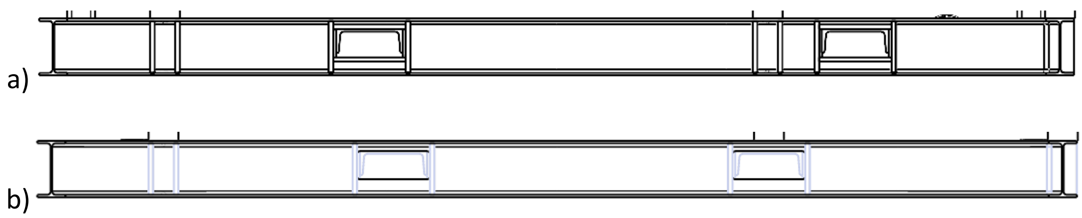


Figure 85 - Difference of input channels of iterations: input channel in the eleventh iteration (a) and input channel in the twelfth iteration (b).

Iterations conclusions

Table 17 compiles all the structural iterations carried out, with a particular focus on the most relevant parameters for evaluating the project's performance and development. This synthesis provides a clear and objective overview of the continuous improvement process, facilitating the identification of the progress made, the decisions taken at each stage, and the actual impact of each modification. It is important to note that the data presented in the following table do not consider the peripheral materials mentioned in section 3.4.2.

Table 17 - Summary of relevant information on the development of iterations.

Iteration	Weight [kg]	Height [-]	Length [m]	Width [-]	Main differences
1	1620	1663	4110	2600	First non-uniform system developed. There is no stacking or forklift handling system
2	1790	1860	4110	2600	Installation of the stacking system
3	1955	1860	4110	2600	Installation of forklift handling system
4	1745	1860	4110	2600	Change of base section (square tube(100x100x8) to IPE200)
5	1495	1838	3810	2600	Changing the stacking system
6	1490	1838	3660	2600	Reduction of support for the smaller shaft diameter area
7	1470	1838	3360	2600	Reduction of the sides in the area not related to the lifting eyes
8	1380	1273	3660	2600	Reducing the sides by adjusting the eyelet configuration
9	1395	1273	3710	2600	Adaptation of the side profile to facilitate manufacturing
10	1470	1273	3710	2600	Changing the support to the smaller diameter part of the shaft.
11	1450	1273	3710	2400	Reduction in width for transportation purposes and structural additions at the base to compensate for change
12	1355	1273	3710	2400	Adjustment of the lifting system by forklift. Removal of central beam.

With the date of Table 17, it is possible to visually represent the evolution of the structure in relation to weight and main dimensions. Figure 86 shows the graph of the weight of the structure for each iteration and Figure 87 the main dimensions of the structure for each iteration.

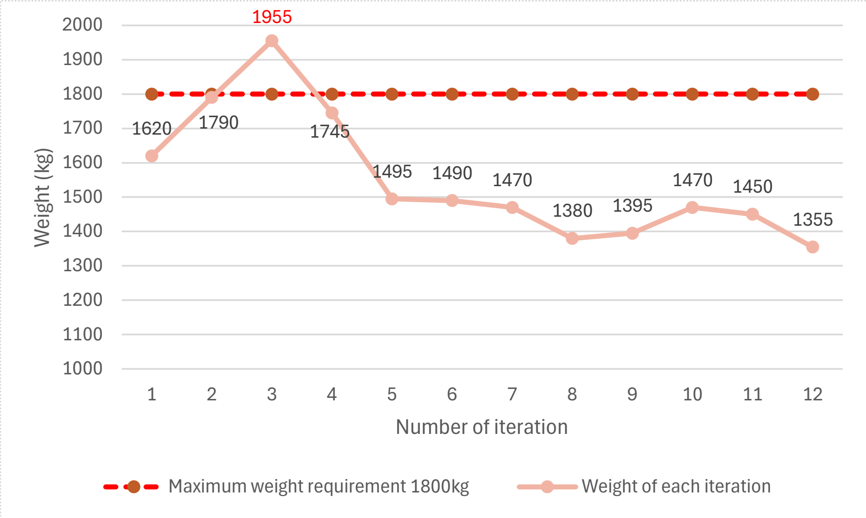


Figure 86 - Weight of the structure in each iteration.

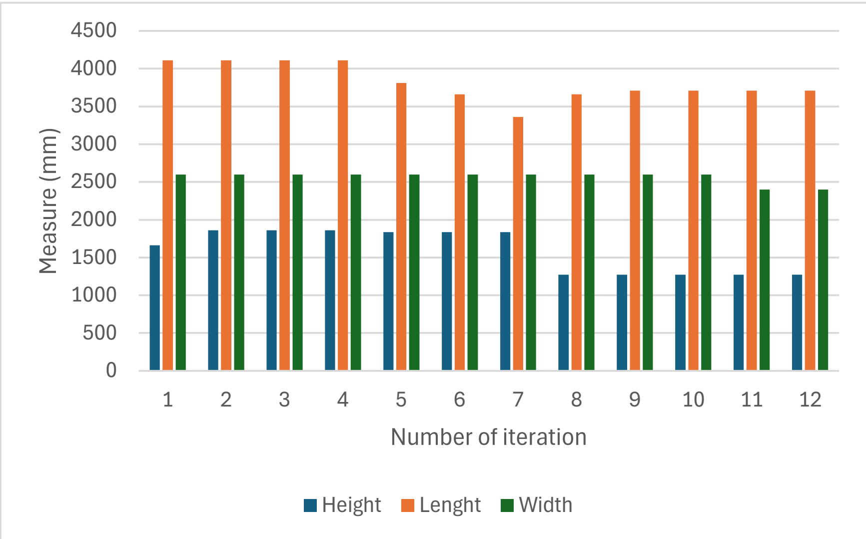


Figure 87 - Overall dimensions of each iteration.

Based on the obtained data, mass reduction of the structure was made possible from the first iteration to the last. Furthermore, it was observed that practically all iterations, except the third, satisfy the initial requirement of a maximum weight of 1800 kg. As demonstrated in the analysis, the last iteration showed an approximate reduction of 25% of the maximum weight accepted by the customer and 31% compared to the third iteration, which was the first iteration that fully satisfied the customer's requirements. This weight could have been reduced even further, but due to the importance of ease of assembly and the cost of manufacturing the structure, a compromise was achieved between an optimised weight, satisfactory assembly capability, and reduced production costs.

In addition, it was possible to reduce the main dimensions that were initially employed. There was a reduction of approximately 32% in height, 10% in length, while the width remained unchanged in all iterations, except in the last ones, which experienced a decrease of approximately 8%. These improvements allowed the stacking systems to take up less space vertically, as the height significantly decreased, and the pallet storage space was also reduced.

After completing these iterations, the peripherals were placed on the model, as well as some reinforcement parts in areas subject to greater stress.

3.4.3.2. Selection of load cases

To analyse the safety and behaviour of the structure during its lifetime, it is necessary to identify and examine different load scenarios that represent the actual conditions to which it is subjected, to understand the structure's resistance to the different stages of its working cycle. Through these simulations, it is possible to assess the structural integrity of the equipment and ensure that it can withstand the loads to which it will be exposed.

First case – Loaded shaft at rest

For the first simulation case, a static load was used, i.e., stationary pallet on the ground with only its own weight and the weight of the shaft. This situation simulates the pallet when it is in the warehouse space, for example, storing the shaft. In this case, the pallet was simulated at rest, with the only boundary conditions being contact with the ground and the weight of the shaft. This simulation checks if the pallet can store the shaft correctly, which is one of the most common phases in the model's work cycle.

Figure 88 shows the example of the first case, i.e., the shaft is simply supported on the two supports.

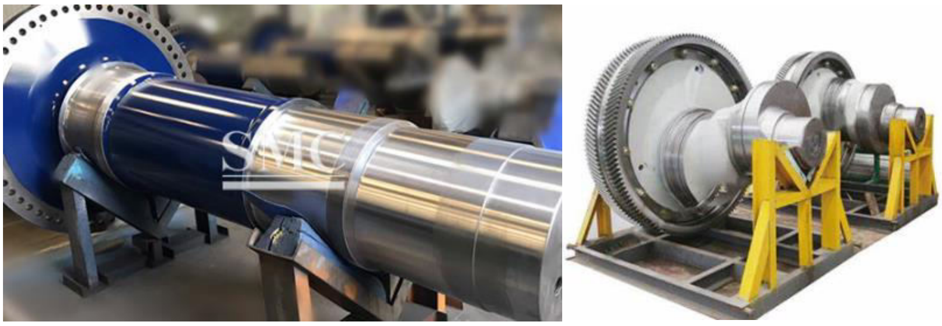


Figure 88 - Example of first load case (static): First example (a) and second example (b).

Second case - Lifting the shaft by the eyelets

For the second simulation case, the loaded structure was lifted using the four lifting eyes on the structure. This case presents the most critical stresses and simulates loaded pallet handling inside a warehouse, as well as loading onto a means of transport, for example. This simulation aims to validate whether the structure is capable of withstanding deformations and stresses applied during one of the stages of its work cycle. Figure 89 shows a case in which a structure is subjected to the same forces as those to be simulated, i.e. the structure is being lifted by chains using four lifting eyes.

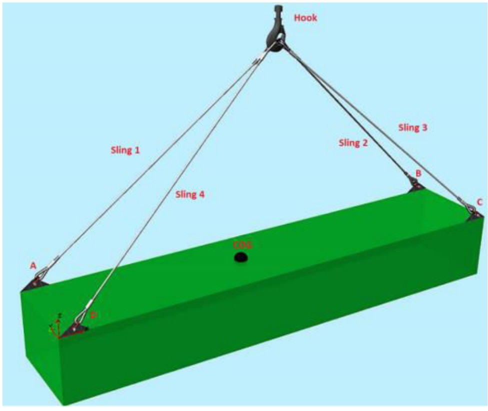


Figure 89 - Example of second load case (lifting pallet) [113].

Third case – Pallet stacking

One of the objectives established at the beginning of this work was to install a stacking system so that empty pallets could be stored stacked to occupy less space. The third simulation case evaluates this scenario, i.e., whether the stacking system created meets the minimum strength requirements for the selected material. Figure 90 shows the example of structures stacking.

Figure 90 - Example of third load case (stacking).

Fourth case – Lifting by a forklift

The fourth simulation case simulates whether lifting the pallet with a forklift truck ensures the safety of the structure and maintains its structural rigidity and resistance. Figure 91 shows a example of a forklift truck in the process of elevating a stack of pallets.

Figure 91 - Example of fourth load case (Forklift lifting)[114].

Fifth case– Lashing straps solicitation

In the fifth simulation case, the focus was on the securing of the shaft to the pallet, as well as the securing of the pallet to the means of transport. The lashing straps ensure that, during transport, both the shaft and the pallet have the necessary stability to prevent any type of accident during transport due to undesirable movement of the shaft and pallet.

Figure 92 - Example of fifth load case (lashing with straps) [90, 115].

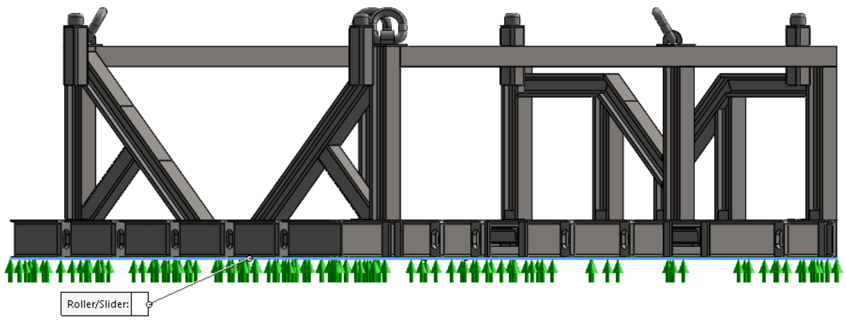
Sixth case – Axial brake

To ensure that the pallet can hold the shaft axially, it was necessary to simulate the axial brake, in addition to dimensioning the bolted connections, to ensure that it supports the shaft during unwanted braking during transport or handling. This simulation allows the safety of the pallet during transport to be validated, thus preventing unwanted accidents.

3.4.3.3. Numerical analysis conditions

As noted in the previous section, six simulation cases were performed to understand whether the pallet meets several fundamental requirements throughout its life cycle. The simulations were performed in SolidWorks, as was the pallet modelling. The material selected for the simulations was S235JR steel. However, the choice of this material is not particularly relevant, since all steel alloys behave similarly in the elastic domain. In the first five simulation cases, the structure was simplified, i.e. the axial braking elements, lashing rings, and other peripherals included in the final model were removed, as they did not contribute to the performance of the simulations, but rather increased their complexity. It was considered that the weight of the pallet was equivalent to that of the developed pallet, i.e., 1.8 t, even though this weight was not achieved in the developed pallet. This fact allows for the creation of a slight clearance in the simulation. The last simulation case will be submitted to an individual test model and all simulations were performed using static analyses.

In the **first simulation case** the boundary conditions consisted of clamping one vertex of the pallet base. In addition, a roller/slider support (restricting perpendicular movements to the plane) was placed at the bottom of the pallet. These boundary conditions were established to simulate the ground on which the pallet will be supported. Figure 93 shows the boundary conditions in this case of study.



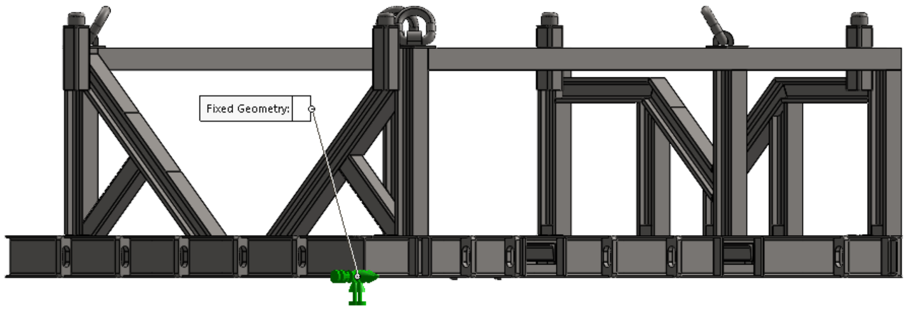


Figure 93 - Boundary conditions for the first simulation case: roller/slider support at the bottom base (a) and clamping at one vertex (b).

With regard to the forces, the mass of the shaft was placed on the two supports. Given that the centre of gravity is displaced 514 mm from the mid length of the shaft, the force will be greater in the direction of the axis with the larger diameter. Figure 94 illustrates a diagram of the shaft and its relevant dimensions for calculating the forces on the supports.

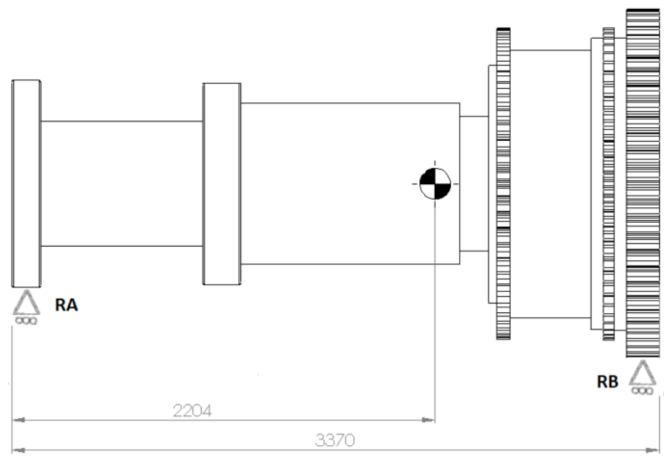


Figure 94 - Diagram of the shaft and its relevant dimensions.

To calculate the section forces at each support, equilibrium equations are applied, shown in equation 24, where R_A is the reaction at the support with the smaller diameter and R_B is the reaction at the support with the larger diameter. The distance between points A and B is approximately the length of the shaft, i.e., 3370 mm.

$$\begin{aligned} \sum F_y &= 0 \Leftrightarrow R_A + R_B = 250000 \\ \sum M_A &= 0 \Leftrightarrow R_B * 3380 = 250000 * 2199 \end{aligned} \tag{24}$$

Solving these equations, it is possible to obtain that R_A=87009 N and R_B=162990 N. Since in both supports the shaft will rest on two surfaces, it is possible to place the forces on each surface for the simulation. A force was also tested in the same position but horizontally in order to understand the behaviour of the structure if the shaft were to fall to one side during transport in a critical situation. Figure 95 shows the position of forces applied in first simulation case.

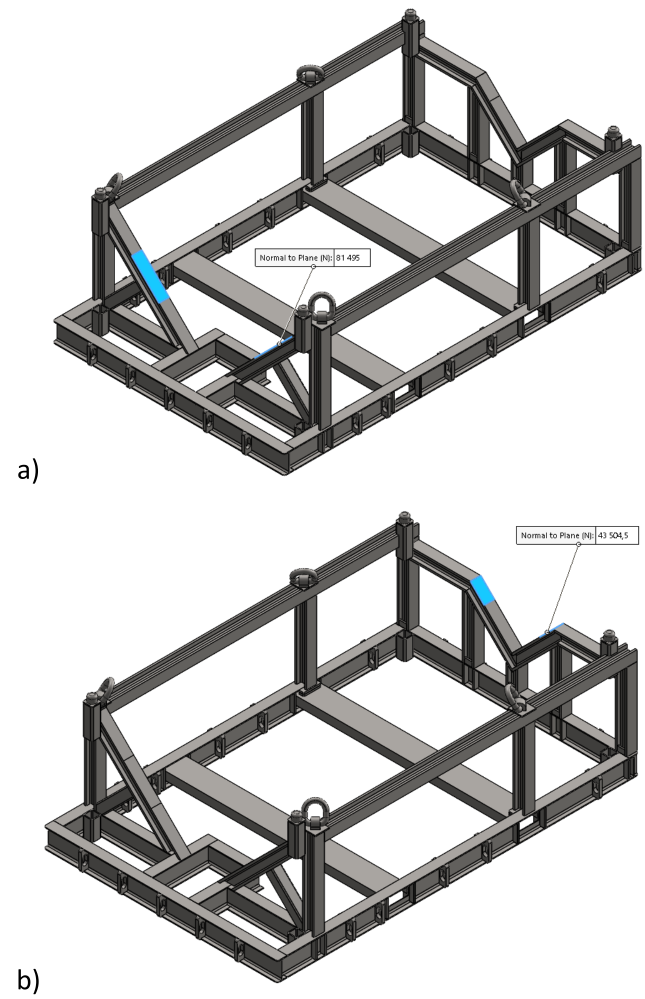
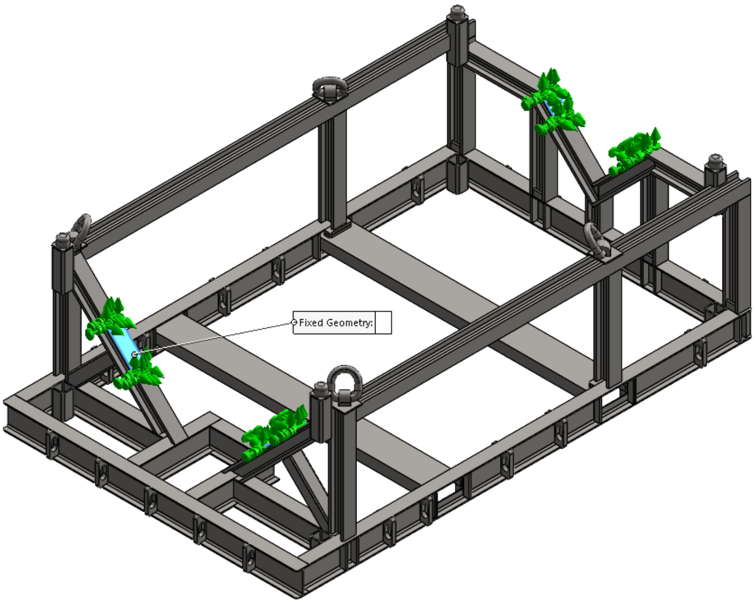
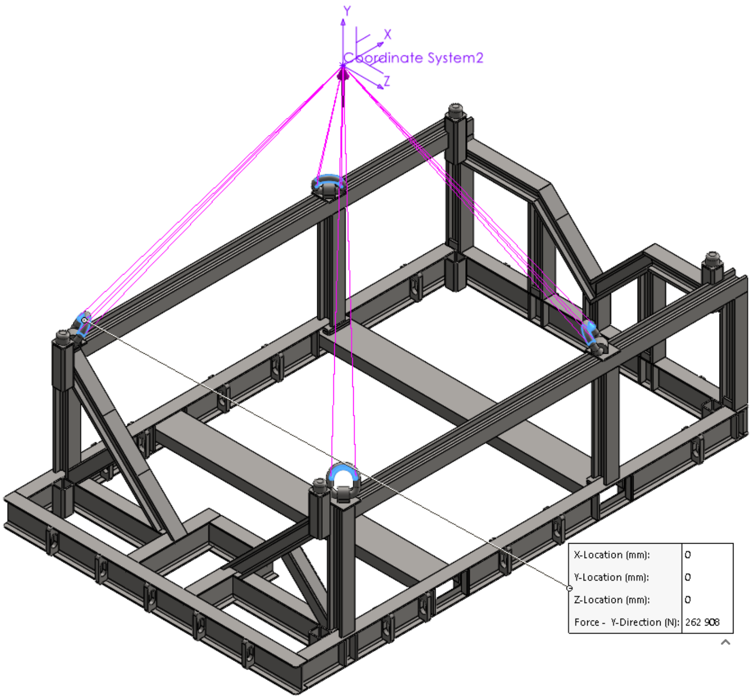


Figure 95 - Solicitations imposed in the first simulation case: larger diameter support (F=81.495 kN) (a) and smaller diameter support (F=43.504 kN) (b).

In the **second simulation case**, the objective is to simulate lifting by the eyebolts. This test was carried out in which the boundary conditions would be placed in the area where the shaft would be supported. The lifting force was simulated by applying a remote force, associated with the four lifting eyebolts, whose value amounts to 26.8 t. Figure 96 shows the parameters for the second simulation case.



a)



b)

Figure 96 - Parameters for the second simulation case: Boundary conditions (a) and remote load on the lifting eyes (F=262.908 kN) (b).

Although this is not the real loading, it is statically equivalent, aiming to assess the behaviour of the structure when subjected to the tension of the eyebolts and the supporting forces that oppose this movement. Under real circumstances, the support areas are not clamped, resulting in the lifting of the pallet.

In the **third simulation case**, the stacking system was tested. In this simulation, the boundary conditions were defined by clamping the bottom of stacking system, while the force was applied at the top of the same system. The force applied was equivalent to five stacked pallets, i.e., approximately 9 t. Given that there are four stacking points, the force per stacking system is approximately 2.25 t. Figure 97 shows the parameters for third simulation case.

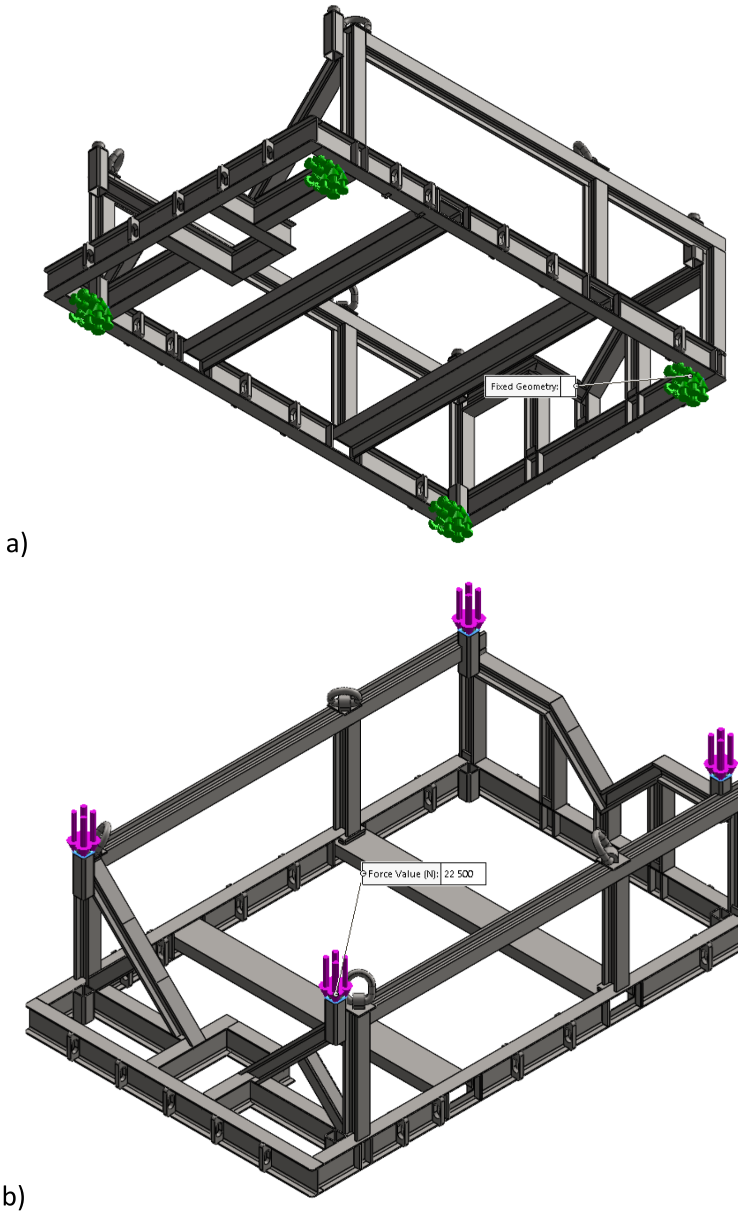
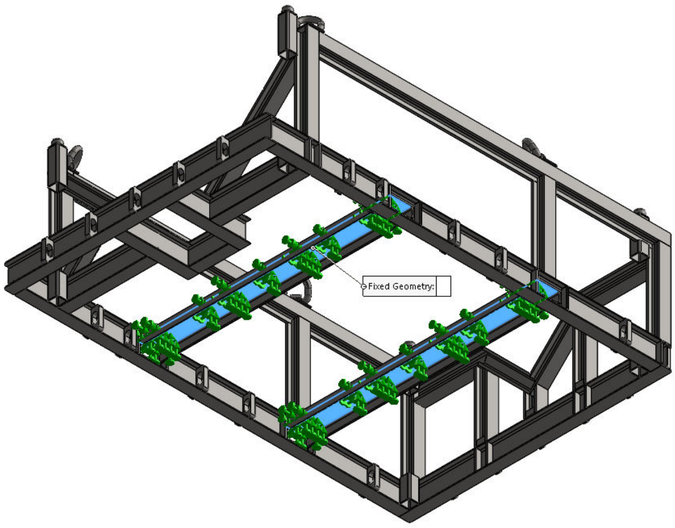
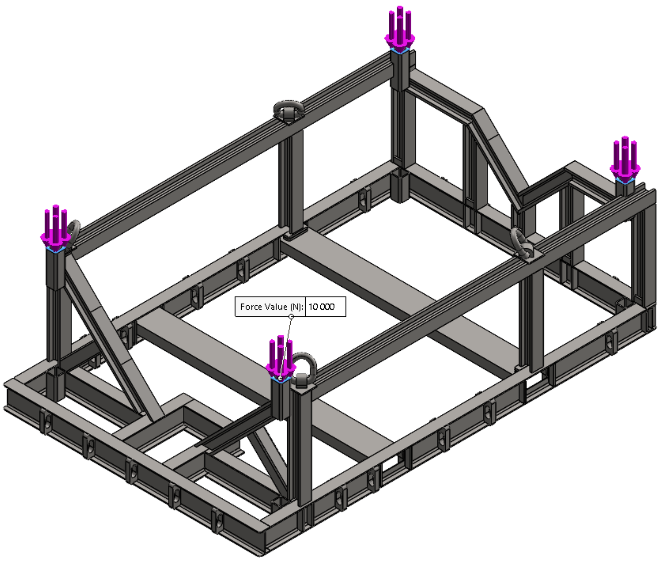


Figure 97 - Parameters for the third simulation case: Boundary conditions (a) and loads on the top of the stacking system (F=22,500 kN) (b).

The **fourth simulation case** aimed to simulate lifting by a forklift, not only of the pallet alone, but also of the stacked pallet. Thus, the boundary conditions were placed at the top inside of the forklift fork inlet channel, while the force was applied at the top of the stacking system. The magnitude of the force was approximately 1 t per stacking system, i.e. the load of two stacked pallets.



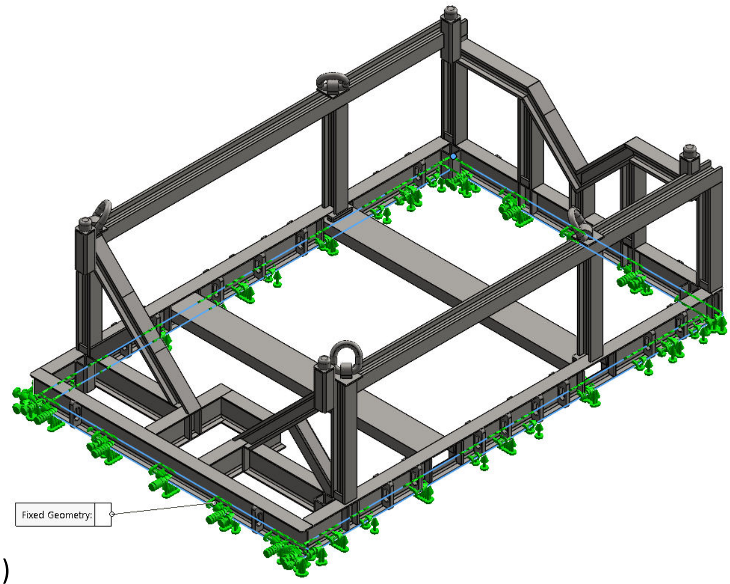
a)



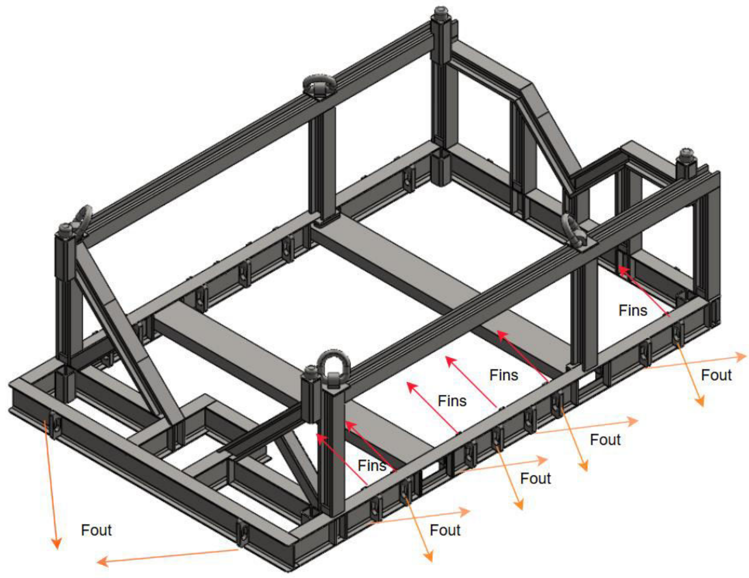
b)

Figure 98 - Parameters for the fourth simulation case: Boundary conditions (a) and loads in stacking system(F=10kN) (b).

The **fifth simulation case** aims to simulate the interior and exterior side straps during transport. Both lashing straps were analysed identically, in which the main boundary condition consisted of fixing the structure to the ground. The forces applied to the model were distributed between the inner and outer notches. In the inner notches, forces equivalent to the mass of the shaft, divided by the six respective notches (Force inside (F_{ins})= 25 kN/6 = 4.17 kN), were applied in the direction of the shaft. In the outer notches, the applied forces corresponded to the combined weight of the structure and the shaft, divided by the eight outer notches (Force outside (F_{out}) = 26.8 / 8 = 3.35 kN), and were applied at inverted 45°, to realistically simulate the typical positioning of the straps during transport securing. Figure 99 shows the parameters of fourth simulation case.



a)

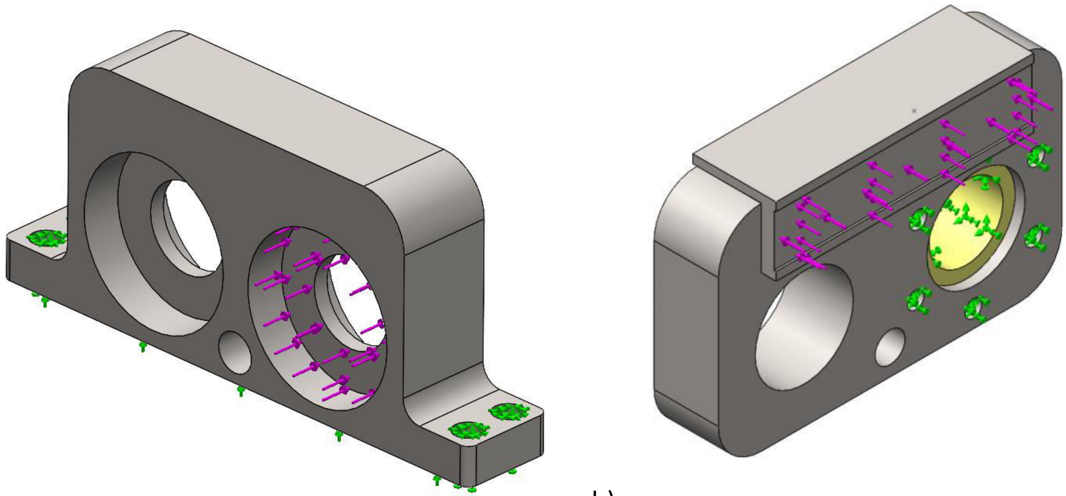


b)

Figure 99 - Parameters for the fifth simulation case: Boundary conditions (a) and loads on notches (F_{ins}=4.17 kN and F_{out}=3.35 kN) (b).

The **sixth simulation case** aimed to simulate a braking event. In this regard, the bearings, whose dimensions had been previously established in accordance with Eurocode 3, were subjected to tests, as were the brake shoes. The remaining brake parts were selected to withstand the dynamic load imposed by the shaft in extreme situations, so they were not simulated. Regarding the bearing, the boundary conditions consisted of clamping in the four holes to simulate the bolts and roller/slider at the bottom to simulate the base support. A force equivalent to half the weight of the shaft was imposed, as there are two bearings supporting the weight. Regarding the brake shoe, the boundary conditions consisted of embedding in the threaded shaft area. On the other hand, the forces applied were equivalent to the total weight of the shaft in the clamping part of the brake shoe, as each of the brake shoes locks the shaft in each direction.

Figure 100 a) illustrates the boundary conditions applied to the bearing and respective forces, while Figure 100 b) shows the boundary conditions and stresses imposed on the grip.



a) b)

Figure 100 - Sixth simulation case: Boundary conditions and forces applied to the bearing (F=125kN) (a) and boundary conditions and forces applied to the grip (F=250kN) (b).

3.4.3.4. Model setup and convergence analysis

To ensure the quality of the mesh, a mesh convergence study was performed. Several analyses were carried out for the first loading case, varying the size of the finite elements of the mesh. The objective of this study was to find a balance between the accuracy of the results and the computational processing time, to avoid unnecessary overload on the system. A blended curvature-based mesh was used for all cases, with only the length and height values of the element being changed. To perform this mesh convergence, the first static analysis of the structure was applied, i.e., the case in which the pallet is stationary, with only stresses due to the weight of the shaft itself. For this simulation, all structural elements were modelled as solid bodies, since SolidWorks simulation does not allow the application of clamped boundary conditions to geometrical faces with beam elements. As in any finite element computational analysis, it is necessary to establish the boundary conditions, which are identical between all simulations performed in this study:

- Clamping of the lower part of the pallet that will be in contact with the ground;
- Load distributed across the four support points on the pallet;
- The minimum number of 8 elements per circle and the growth rate of 1.4 between the maximum and minimum length of the element. This configuration is established based on the SolidWorks default data.

The mesh convergence study was carried out starting with a mesh with a maximum element size of 100 mm and a minimum size of 20 mm (100/20). The mesh size was then reduced so that the ratio between length and height was always 5. The values obtained for the maximum stress in the structure and maximum displacement in the structure were always taken at the same point to maintain the reliability of the mesh convergence study. Table 18 shows the values recorded at the same point for each mesh.

Table 18 – Mesh convergence analyses: Values of stress and displacement in same point of the structure.

Mesh convergence analysis								
Case of study	Dimensions [mm]		Number of elements	σ max [MPa]	relative difference σ	δ max [μm]	relative difference δ	Time (Meshing)
	Max	Min						
1	100	20	173046	3.765	-	6.980	-	01:15
2	75	15	264955	4.247	0.128	7.291	4.456E-02	01:19
3	60	12	362426	5.669	0.335	7.346	7.544E-03	01:26
4	50	10	440750	5.959	0.051	7.339	-9.529E-04	01:27
5	45	9	501394	5.533	-0.071	7.340	1.363E-04	01:33
6	40	8	538850	5.772	0.043	7.339	-1.362E-04	01:40
7	**35**	**7**	**610534**	**5.549**	**-0.038**	**7.394**	**7.494E-03**	**01:35**
8	30	6	673822	5.336	-0.038	7.420	3.516E-03	01:32
9	25	5	765825	5.496	0.030	7.405	-2.022E-03	01:45

Figure 101 shows the line representing the convergence of the mesh in relation to the maximum stresses installed at the point, from the initial mesh (100/20) to the last tested mesh (25/5) and Figure 102 presents the maximum resulting displacement at the same point, both as a function of the number of elements.

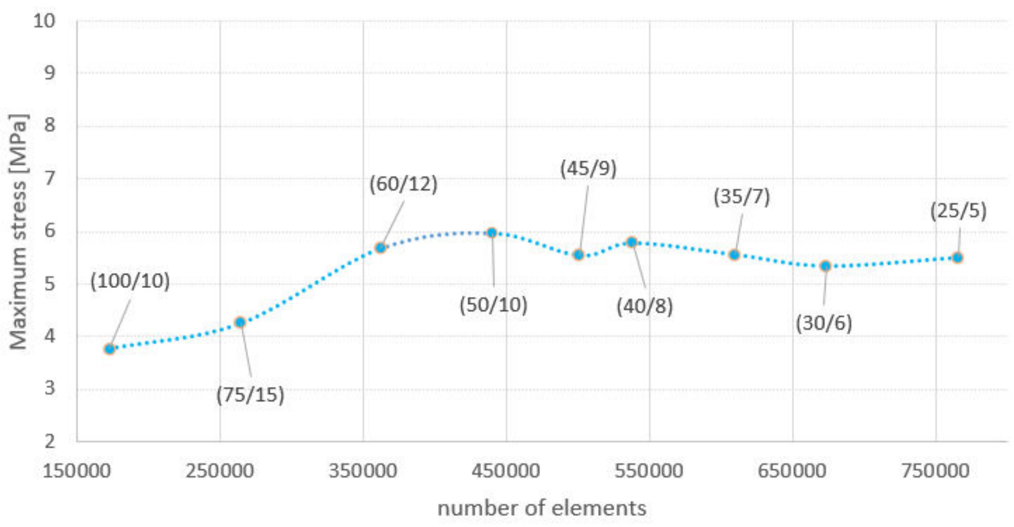


Figure 101 – Maximum von mises stresses installed at the point for all meshes.

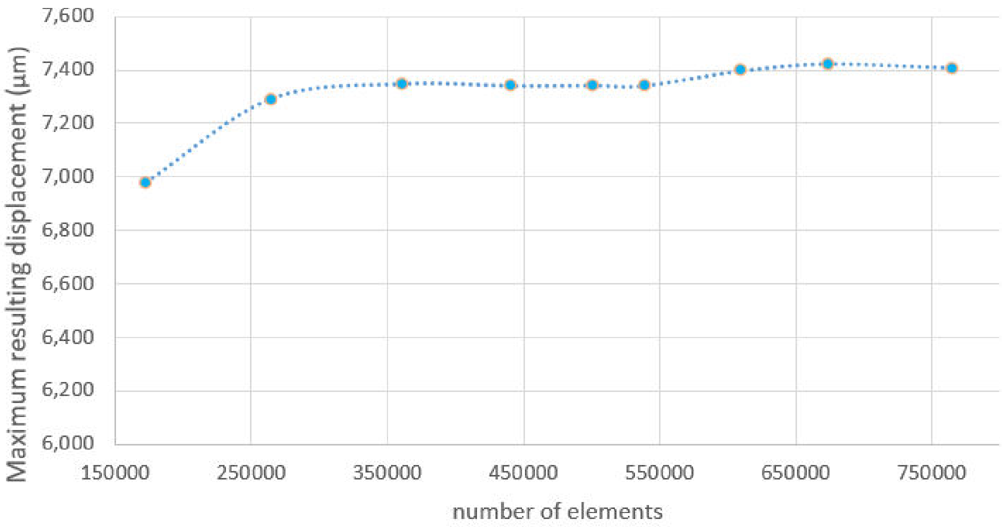


Figure 102 – Maximum resulting displacement installed at the point for all meshes.

Considering the various simulation cases that were tested, it was necessary to choose a mesh that would provide good results and allowing the simulation to run smoothly. The seventh mesh was chosen, with a maximum element edge dimension of 35 mm and a minimum of 7 mm, to obtain a good result and computational performance.

3.4.3.5. Numerical design process

This section presents the computational analyses carried out using the FEA, with the objective of evaluating the structural performance of the developed solution under different loading and support conditions.

In the first simulation case (Figure 103), with vertical loading, a maximum stress of 94.14 MPa was obtained in the structure. Given the choice of S235JR material for the simulation, it can be concluded that the yield stress of the material is not reached in either the first or second case. This means that, in both situations, the pallet supports the shaft under static storage conditions. The minimum safety coefficient value of the structure recorded in this simulation is approximately 2.5.

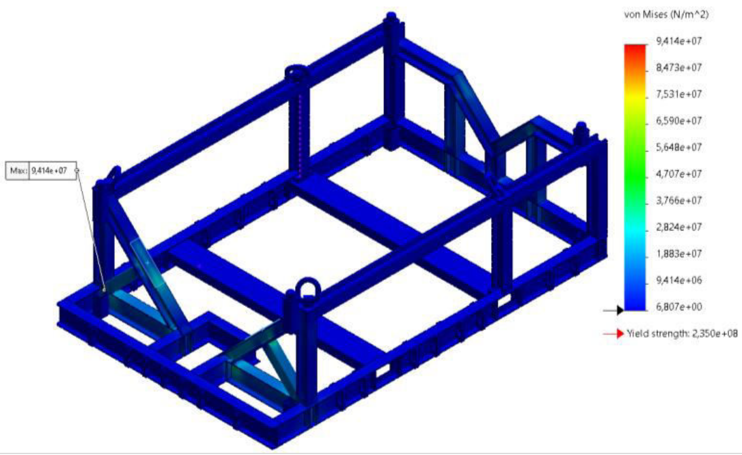


Figure 103 – Distribution of von Mises stresses on the pallet in the first simulation case (vertical force).

Considering identical forces, but this time horizontal (Figure 104), certain tiny areas are obtained that exceed the maximum yield stress value. The maximum value recorded in this simulation with the horizontal force is 345.8 MPa and the factor of safety is 0.58.

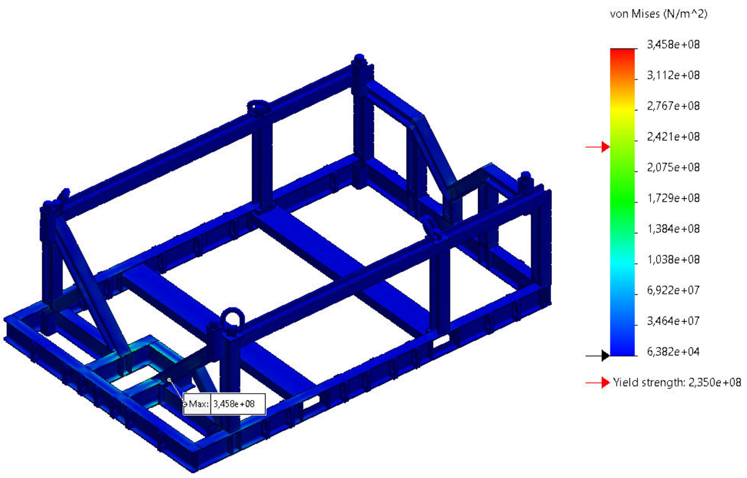


Figure 104 – Distribution of von Mises stresses on the pallet in the first simulation case (horizontal force).

The application of the stress filter at 235 MPa shows that the peak stress zones are not a cause for concern (Figure 105), since they cover a very small area and do not extend over a large part of the surface. The area in question does not exceed 0.02% of the total volume of the structure.

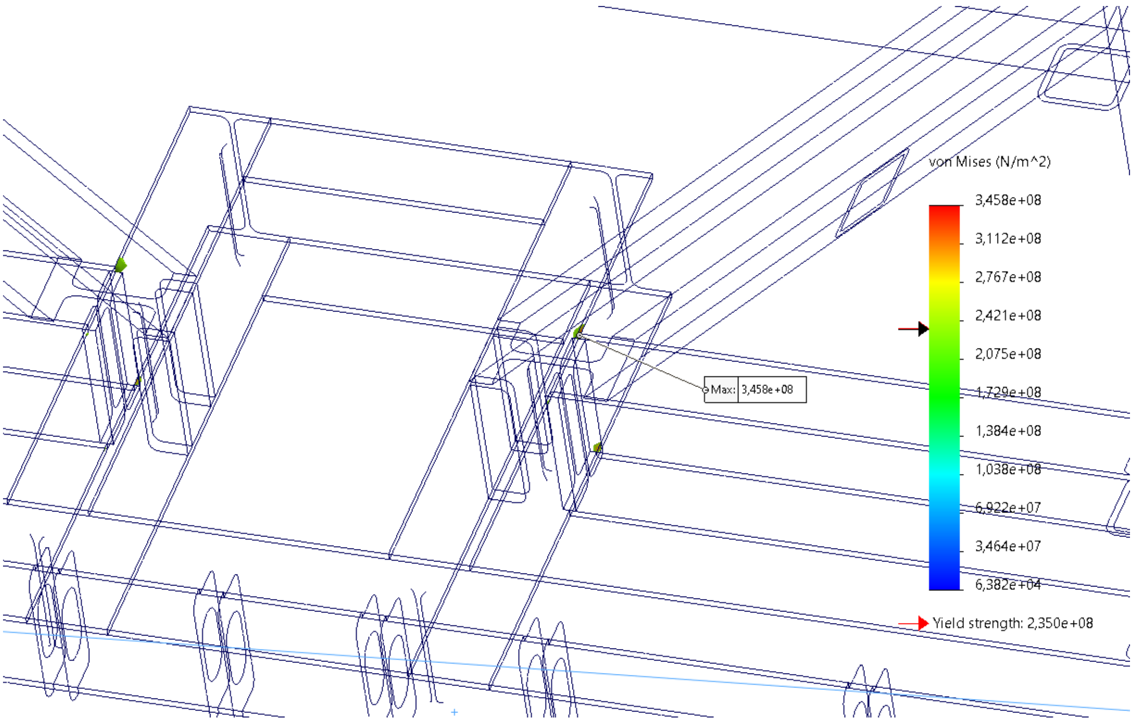


Figure 105 - Stress filter (>235 MPa) – Stress peak zone for the first case (horizontal force).

The safety coefficient shows a reduction in the stress zone (Figure 106), but it automatically stabilises outside this zone. This phenomenon is common in cases where the volume of stress zone is too low to be considered significant.

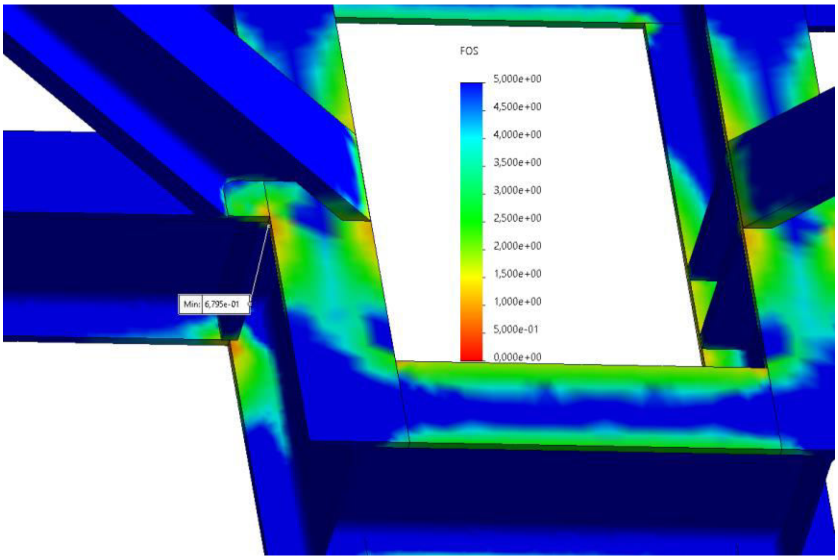


Figure 106 – Safety coefficient in the maximum stress zone for the first case study (horizontal force).

With regard to the second case study, more pronounced stresses were observed compared to the first case (Figure 107), given that the latter is a more demanding case. In this circumstance, the maximum stress recorded exceeded the yield stress of the material, reaching 403 MPa at the eye. Considering the case in question, it is plausible to ignore this value, since the eyelets, in this arrangement, support a maximum load of 31.5 t.

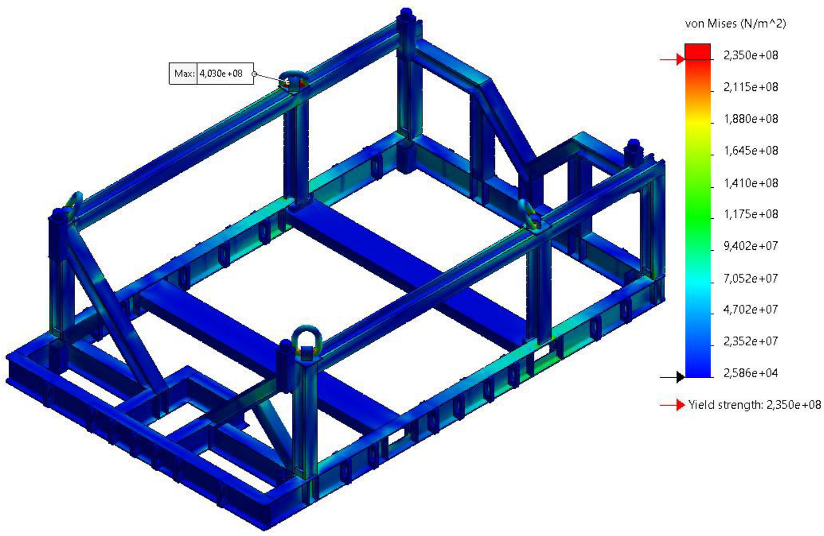


Figure 107 – Distribution of von Mises stresses on the pallet in the second simulation case.

Upon closer inspection, using a stress filter of 235 MPa, it was possible to verify the existence of areas where the yield stress of the material is exceeded (Figure 108). However, these areas are restricted in extension and located predominantly at edges and vertices of the pallet. Therefore, it is possible to ignore these locations. The volume of these stress peaks does not exceed 0.1% of the total volume of the structure and, therefore, these can be considered irrelevant.

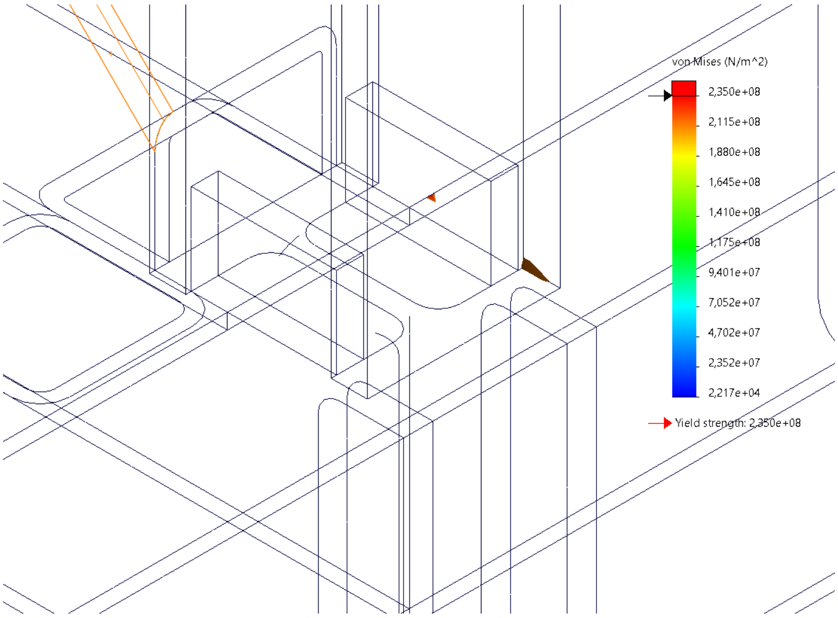


Figure 108 – Stress filter (>235 MPa) – Stress peak zone for the second case.

In addition, there are some vertices and areas with less rounding, where stresses surpass the yield stress. In accordance with the previously presented argument, the simulation validation is feasible. Figure 109 illustrates the safety coefficients in the structure.

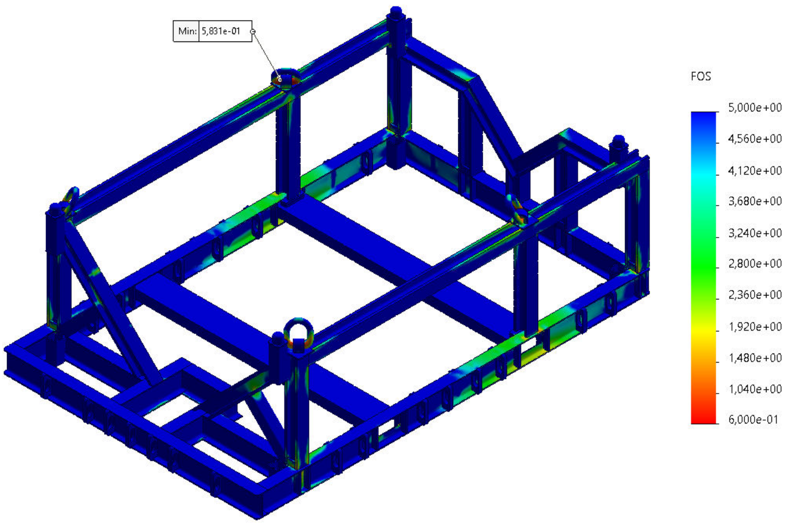


Figure 109 – Safety coefficient for the second case study.

In the third simulation test, the maximum stress on the structure reached 111.6 MPa, thus without reaching the material's yield stress. Therefore, it can be concluded that the stacking system can transport up to five pallets. Upon further examination, it is plausible that the number of stacked pallets could exceed the current amount even further, considering that the structure's safety coefficient is 2.1. Figure 110 presents the distribution of von Mises stresses in the structure in the third simulation case.

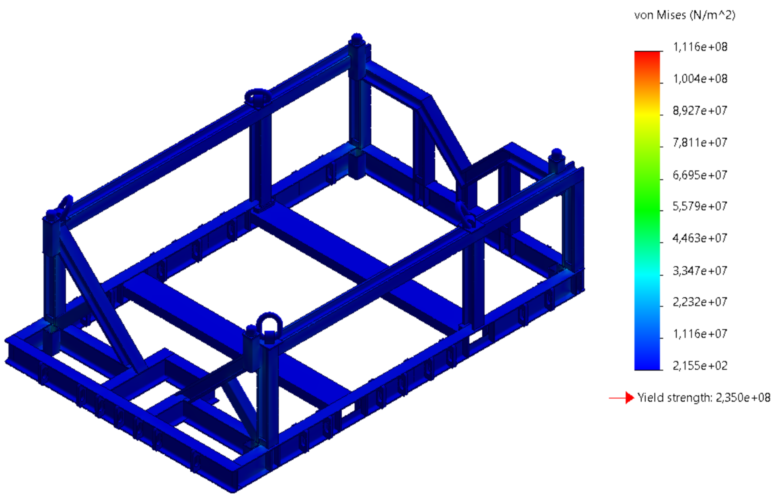


Figure 110 – Distribution of von Mises stresses for the third simulation case.

In the fourth simulation case (Figure 111), which consisted of lifting by a forklift, the structure was also validated, presenting a maximum stress of 84.84MPa and a safety coefficient of approximately 2.8. This configuration allows the forklift's entry channels to lift two pallets simultaneously, facilitating handling.

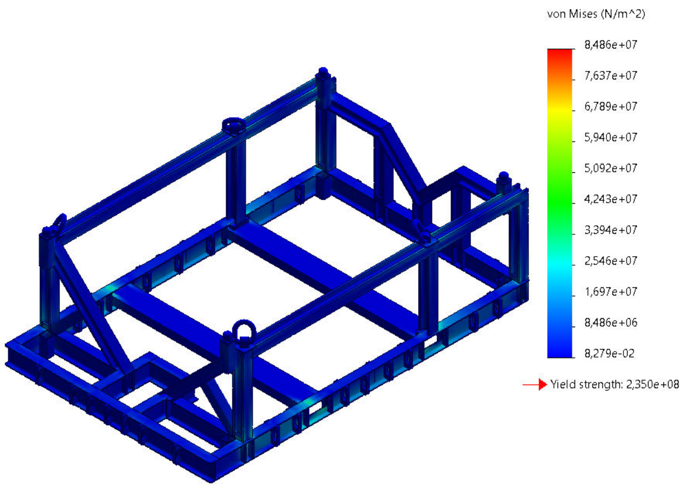


Figure 111 - Distribution of von Mises stresses for the fourth simulation case.

In relation to the fifth simulation case (Figure 112), it can be concluded that the mooring system exhibits stress peaks through the simulations. The maximum recorded stress level was found to be 392.5 MPa and the factor of safety 0.6.

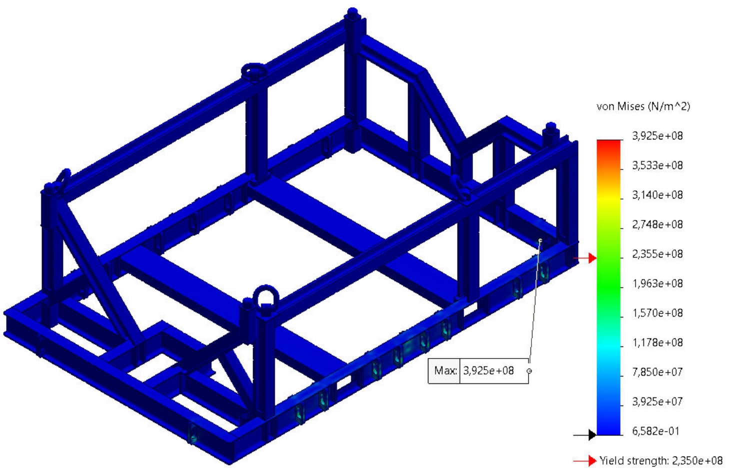


Figure 112 – Distribution of von Mises stresses for the fifth simulation case.

The application of the stress filter at 235 MPa highlights that the volume of the zone exceeding the yield stress does not exceed 0.01% of the total volume of the structure. This procedure enables the elimination of stress peaks, as observed in previous simulations.

In the sixth simulation case, it was possible to assess the feasibility of the adjustable brake on the structure. This brake has already been validated in accordance with Eurocode 3, in section 3.4.2. Initially, the brake bearing was tested, resulting in a maximum stress of 177.7 MPa and a safety factor of 1.3 (Figure 113).

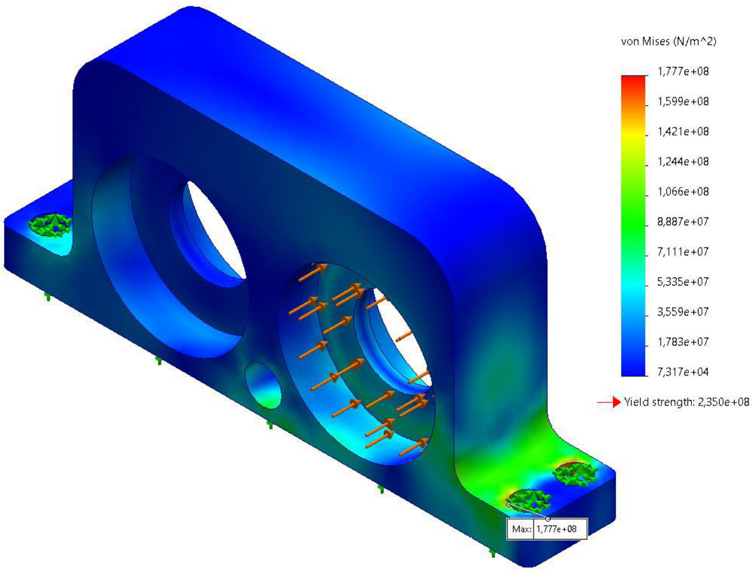


Figure 113 – Distribution of Von Mises stresses for the adjustable axial brake bearing.

Furthermore, it was imperative to test the brake grip to ensure its optimal performance. Peak stresses were observed in the screw section of the brake grip. The maximum stress in the brake shoe was 307.3 MPa and the factor of safety was 0.76 (Figure 114).

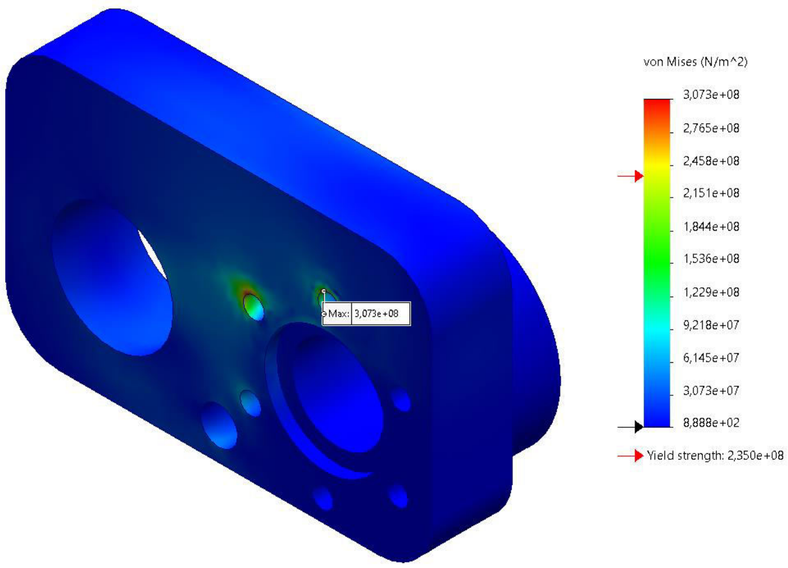


Figure 114- Distribution of von Mises stresses in the adjustable brake grip.

The application of a 235 MPa filter (Figure 115), corresponding to the material stress, shows that the area where it exceeds the yield stress is quite small, representing approximately 0.1% of the total volume.

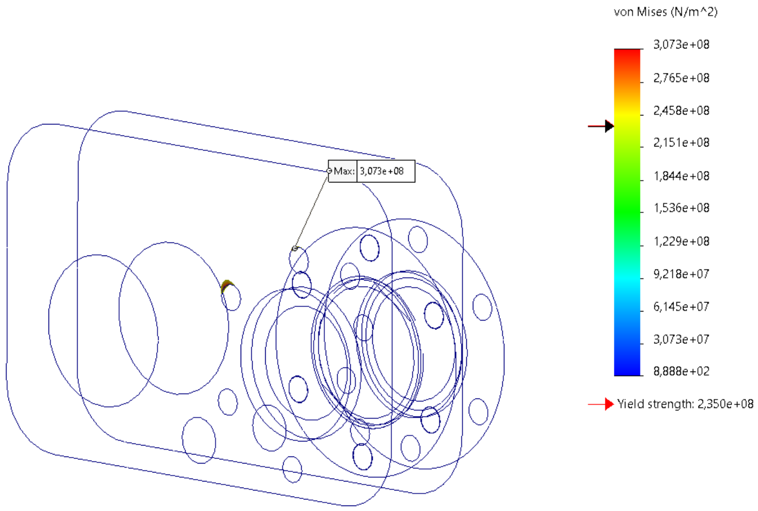


Figure 115 – Stress filter (>235 MPa) – Stress peak zone for the sixth case (grip).

Since the brake grip is a smaller part with functional surfaces that should not undergo much significant displacements, the S355JR steel was selected for the grip to prevent the peak stress in the screw area from being exceeded. This choice reduces the likelihood of brake problems, such as, rupture of the system.

3.5. Performance assessment

This section presents a summary of the relevant values obtained in developed pallet and in the confidential NEFAB model. The objective of this study is to facilitate a comparative analysis between the two models and to comprehend the developmental trajectory of the initial NEFAB model and the subsequent optimised model. In some simulation cases, the values from NEFAB's confidential pallet were not provided or were not considered due to the existence of different types of simulation cases. Table 19 shows the relevant values for the pallet.

Table 19 – Relevant simulation values comparation table.

		NEFAB pallet	Developed pallet	Percentile difference (%)
Case 1 (Static1)	Stress	136.03	94.14	-30.78
	SF	2.1	2.5	19.05
Case 1 (Static2)	Stress	412.08	345.8	-16.08
	SF	0.57	0.58	1.8
Case 2 (Lifting eyes)	Stress	404.59	403	-0.4
	SF	0.50	0.50	0
Case 3 (Stacking pallet)	Stress	-	111.6	-
	SF	-	2.1	-
Case 4 (Forklift lifting)	Stress	-	84.84	-
	SF	-	2.8	-
Case 5 (Lashing straps)	Stress	578.96	392.5	-32.21
	SF	0.41	0.60	46.34
Case 6 (Axial brake - bearing)	Stress	-	177.7	-
	SF	-	1.3	-
Case 6 (Axial brake - grip)	Stress	-	307.3	-
	SF	-	0.76	-

The results obtained from the simulations demonstrate a clear improvement in the structural performance of the optimized solution compared to the initial configuration. In case 1 (static1), a significant reduction of 30.78% in maximum stress was achieved, accompanied by a 19.05% increase in the safety factor, evidencing a more efficient stress distribution. Similarly, in case 1 (static2), a 16.08% reduction in stress was observed, with a slight increase in the safety factor from 0.57 to 0.58 (1.8%), indicating an improvement despite the remaining peak stresses in the structure. In case 2 (lifting eyes), the stress variation between the two configurations was negligible (-0.4%), suggesting that the optimization had limited impact in this specific scenario. In cases 3 and 4 (stacking and forklift lifting), which were evaluated only after optimization, safety factors of 2.1 and 2.8 were obtained, respectively, demonstrating good structural performance under these specific loading conditions. Notably, case 5 (lashing straps) showed the most significant improvement, with a 32.21% reduction in maximum stress and a 46.34% increase in the safety factor (from 0.41 to 0.60), reflecting a substantial enhancement of structural strength against transport-related loads. In case 6 (axial brake), the bearing achieved a safety factor of 1.3, confirming its adequacy under load. The grip presented a safety factor of 0.76, with stress concentration due to its small volume, but it still withstands the applied loads. The grip material was reinforced to S355 steel to improve structural capacity and safety margin.

In both analysed models, safety factor values below 1 occurred in residual volumes that were practically negligible in terms of the geometry. The developed pallet exhibited such values in no more than 0.1% of its total volume. Given the highly localised nature and structural insignificance of these regions, it can be concluded that they do not compromise the system's overall integrity and can therefore be disregarded in the safety evaluation.

In summary, the optimisation process generally allowed for a reduction in critical stresses and an increase in safety margins in most of the scenarios analysed, validating the effectiveness of the improvements implemented in the project.

3.6. Cost analysis and sustainability

To complete the development of the pallet designed to transport a heavy shaft, a comparative analysis of the environmental impacts and associated costs was carried out, using the currently used pallet by NEFAB as a reference. To obtain an accurate and well-founded assessment of the environmental and financial performance of the proposed transport and packaging system, GreenCalc software was used a widely recognised tool in the field of sustainability for calculating the ecological footprint [116]. This tool enables the simulation of various logistics scenarios, evaluating variables such as the materials used, transport routes and packaging configurations, allowing for the optimisation of resources, reduction of emissions and improvement of economic efficiency. NEFAB itself uses GreenCalc in the development of its solutions, which ensures a reliable basis for comparison in line with best practices in the sector.

Firstly, it is essential to simulate the route that the pallet will take from the production process to the end customer (Figure 116).

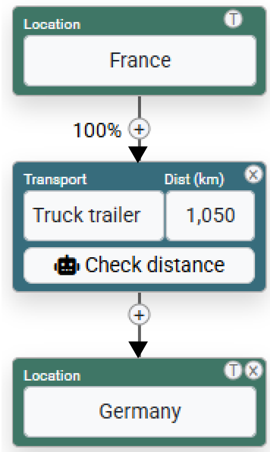


Figure 116 - Pallet path from production to the end customer.

After defining the route to be followed by the pallet from the production process to the end customer, it is imperative to specify the initial parameters for the analysis of each pallet. The parameters in question cover the weight of the pallet, the main dimensions and, finally, the materials used and their respective weight. Figure 117 a) illustrates the values for the initial parameters of the NEFAB pallet, while Figure 117 b) shows the values for the initial parameters of the pallet developed during this work.

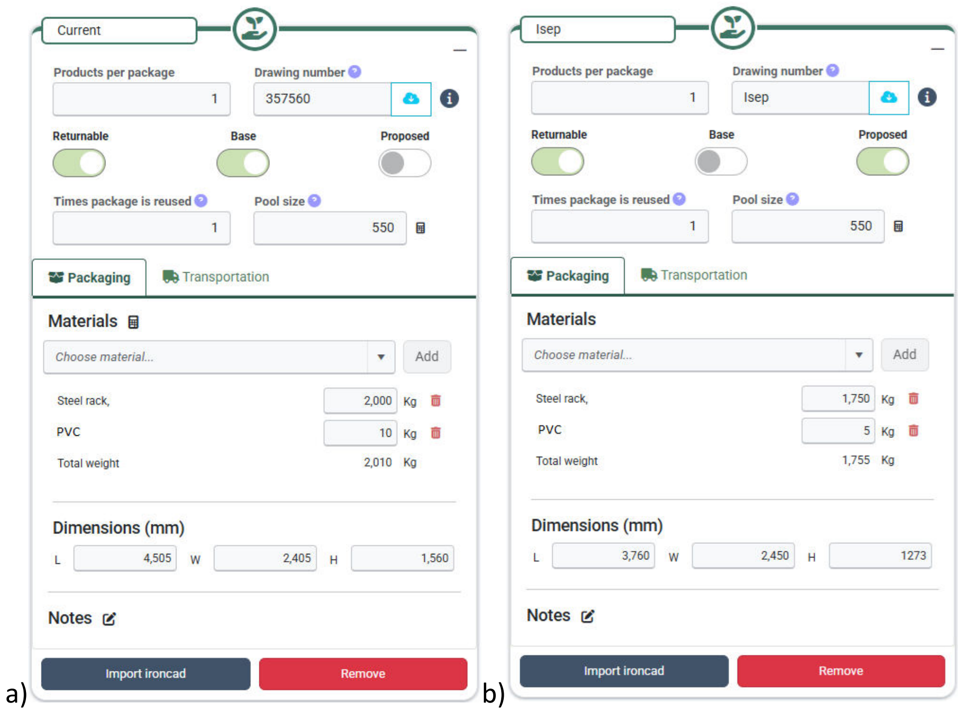


Figure 117 – GreenCalc structure initial parameters: NEFAB solution (a) and Developed solution (b).

After entering the input parameters and considering production, assembly, logistics, and storage costs, it is possible to obtain a result regarding annual environmental savings (Figure 118 a)) and annual financial savings (Figure 118 b)).

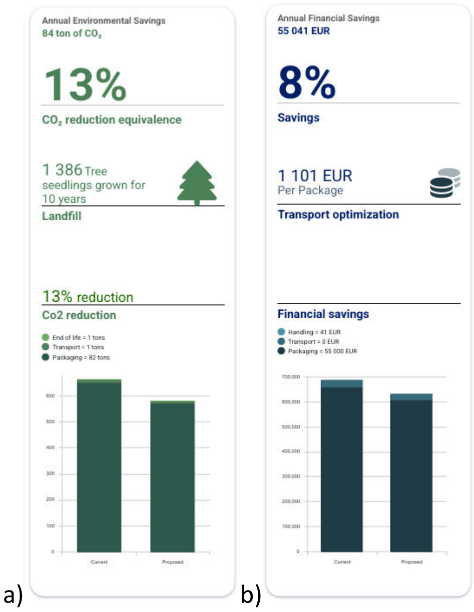


Figure 118 – GreenCalc: annual environmental savings (a) and annual financial savings (b).

Based on the obtained results, it can be concluded that there was an annual reduction of 13% in carbon dioxide (CO_2) emissions and an 8% decrease in costs.

In addition, this analysis allowed for a more in-depth comparison between various environmental aspects. In Figure 119 it is possible to observe comparative graphical representations referring to climate changes, quantity of waste, water depletion acidification, and land occupation.

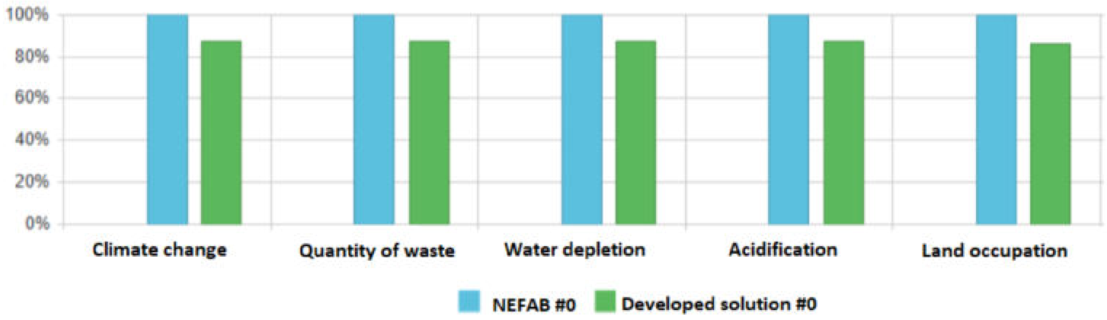


Figure 119 – Environmental comparison between pallets (first part).

Following on from the previous analysis, Figure 120 shows a comparison between depletion of mineral, fossil, and renewable resources, particulate matter, eutrophication of freshwater, landfill waste and amount of plastic.

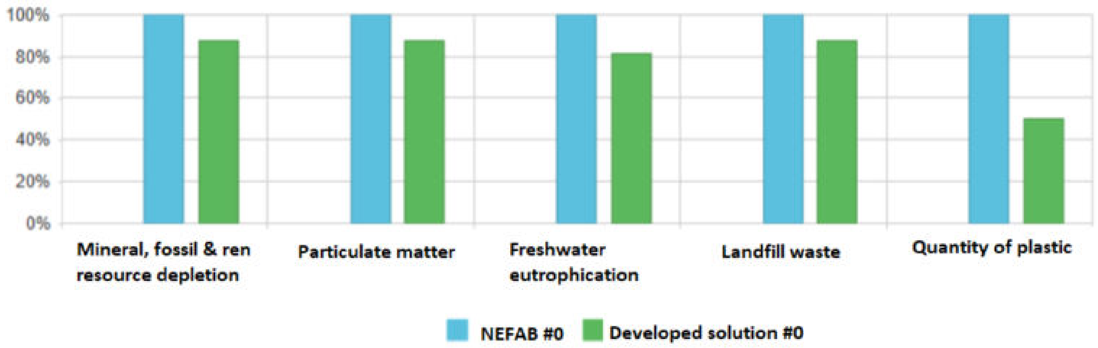


Figure 120 - Environmental comparison between pallets (second part).

Based on the analysis carried out, it can be concluded that there has been a significant improvement in terms of CO_2 reduction, financial costs and environmental aspects, as shown in the previous figures.

4. Conclusion

4.1. Final Conclusions

The main objective of this project was to develop and optimise a pallet for the transport and storage of a heavy metal shaft with a non-uniform geometry. The main focus was to ensure the integrity of the component during all stages of the logistics chain, from handling to storage, guaranteeing its safety, stability and structural preservation.

To this end, a structure was designed capable of supporting a load of up to 25 t, while keeping the total weight of the pallet below the maximum limit of 1800 kg. The design was based on structural dimensioning criteria, focused on the mechanical strength of the system, considering the stresses associated with the transport of heavy loads, namely shocks, vibrations and accidental movements. The geometry of the pallet was designed to ensure the stability of the shaft, through its axial immobilisation by a braking system and its lateral containment by appropriate strapping systems. In addition, the shaft can only rest on the two defined support surfaces. These design strategies were fundamental to ensure that no permanent deformation or structural damage occurs that could compromise its performance. The structure also includes solutions aimed at its functionality and compatibility with existing logistics systems, namely the incorporation of lifting eyes for crane lifting, access areas for forklifts and a modular stacking system that allows for the vertical storage of multiple units, optimising the available space in the warehouse. During the project, it was necessary to adjust the total width of the structure to a new legal limit of 2500 mm, imposed by changes in the customer's transport legislation. This adaptation required a review of some aspects of the design, while maintaining all the functional and structural requirements initially defined. To validate the safety and effectiveness of the developed solution, computational simulations were performed using FEA. These simulations made it possible to assess the structural behaviour of the pallet under different load scenarios and identify critical stress areas, ensuring that the designed structure has adequate safety margins in relation to the requirements imposed. In addition to the technical and functional aspects, a comparative analysis was also carried out between the proposed pallet and an existing solution from NEFAB, taking into account production and operating costs, as well as the environmental impact of the two options. The results showed a significant improvement in cost efficiency, with a considerable reduction in the total cost per package, as well as an optimisation in terms of sustainability, reflected in a reduction in the carbon footprint and a reduction in waste and plastic materials. The analysis was supported by recognised tools, such as GreenCalc software, also used by NEFAB, which made it possible to quantify the environmental and economic gains of the proposed solution. The new design proved to be lighter, more functional and more sustainable, reducing CO_2 emissions by 13% and saving more than 55,000€ (8%) per year compared to the previous solution.

In short, the work carried out successfully achieved the defined objectives, resulting in a technically robust, economically viable and environmentally responsible pallet. The proposed structure ensures the protection of the transported component, complies with operational and legal requirements and represents an optimised solution to the challenges of heavy and exceptional cargo logistics.

4.2. Limitations and Future Work

With regard to future work, three lines of development with high potential for technical and operational impact in the context of heavy cargo transport and storage have been identified.

The first proposal consists of creating a technical standard for the dimensioning and modelling of pallets for demanding industrial applications. The absence of specific regulations for heavy-duty pallets currently leads to customised approaches that are time-consuming and sometimes incompatible with each other. The development of a standardised reference framework will not only speed up the design and structural validation process, but also promote the standardisation of design criteria, ensuring greater reliability, repeatability and ease of integration of companies' production and logistics systems.

Secondly, research and development of a pallet adjustable to different metal shaft diameters is proposed. This solution aims to respond to the growing need for logistical flexibility in industrial companies, whose difference in components often coexist and requires specialised supports and transport. The implementation of a structure with adjustable elements will enable the optimisation of logistics asset management, as well as the reduction of operating costs, storage space, and load preparation time. The design of the device must ensure adaptability without compromising safety, ensuring the effective immobilisation of shafts with variable geometries.

Finally, the development of a structural solution with bolted connections, replacing the welded connections currently used, is an area of high interest. This modification will enable the pallet to be dismantled into individual components, facilitating not only transport and storage at the end of its useful life, but also maintenance and replacement of damaged parts. In addition, it will enable the individual surface treatment of each element, namely through galvanisation, promoting higher resistance to corrosion and, consequently, increasing the durability of the structure in aggressive industrial environments. This modular and demountable approach is in line with the principles of the circular economy, promoting reuse and extending the product's life cycle.

These three strategic guidelines symbolise a logical progression of the work carried out, enabling the expansion of the solution's applicability to various industrial contexts, strengthening the sustainability of logistics systems and maximising economic and environmental gains in the medium and long term.

References

1. Chan, F., H. Chan, and K. Choy, *A systematic approach to manufacturing packaging logistics.* The International Journal of Advanced Manufacturing Technology, 2006. **29**: p. 1088-1101.
2. Guillard, V., S. Gaucel, C. Fornaciari, H. Angellier-Coussy, P. Buche, and N. Gontard, *The Next Generation of Sustainable Food Packaging to Preserve Our Environment in a Circular Economy Context.* Frontiers in Nutrition, 2018. **5**.
3. Eissenberger, K., A. Ballesteros, R. De Bisschop, E. Bugnicourt, P. Cinelli, M. Defoin, E. Demeyer, S. Fürtauer, C. Gioia, and L. Gómez, *Approaches in sustainable, biobased multilayer packaging solutions.* Polymers, 2023. **15**(5): p. 1184.
4. *Packaging Material Market Size, Share, and Trends 2024 to 2034*. 2024 July 2024 [cited 10/2024; Available from: https://www.precedenceresearch.com/packaging-material-market.
5. *Packaging Market Size, Growth and Industry Developments (2023 - 2032)*. 2024 [cited 10/2024; Available from: https://www.towardspackaging.com/insights/packaging-market-sizing.
6. *World's $1.17 trillion packaging market set for further growth latest Smithers research data forecasts*. 2023 [cited 10/2024; Available from: https://spnews.com/worlds-1-17-trillion-packaging-market-set-for-further-growt/.
7. *EU packaging waste generation with record increase*. 2023 [cited 10/2024; Available from: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20231019-1.
8. *Packaging equipment shipments up 19 percent in 2011*. 10/2024]; Available from: https://www.foodengineeringmag.com/articles/89646-packaging-equipment-shipments-up-19-percent-in-2011.
9. *Industry revenue of "packaging activities" in Portugal from 2012 to 2025*. 2024 [cited 10/2024; Available from: https://www.statista.com/forecasts/395431/packaging-activities-revenue-in-portugal.
10. *Packaging Waste Statistics - Statistics Explained*. 2022 [cited 10/2024; Available from: https://www.fulimachinery.com/news/packaging-waste-statistics-statistics-explai-58901377.html.
11. *41% of plastic packaging waste recycled in 2022*. 2024 [cited 10/2024; Available from: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20241024-3.
12. Thompson, B. *Types Of Packaging For Export*. 2024 [cited 10/2024; Available from: https://incodocs.com/blog/export-packages/.
13. *2023 Reusable Packaging Industry Outlook: Why Reusable Packaging for Supply Chains is Business Critical Today*. 2023 [cited 10/2024; Available from: https://reusables.org/2023-reusable-packaging-industry-outlook-why-reusable-packaging-for-supply-chains-is-business-critical-today/.
14. *Palletizers*. 2024 10/2024]; Available from: https://www.iqsdirectory.com/articles/palletizer.html.
15. Dykstra, J. *13 Different Types of Pallets (by Style, Design and Material)*. [cited 10/2024; Available from: https://www.homestratosphere.com/types-of-pallets/.
16. *Types of Pallets and uses*. 2024 [cited 10/2024; Available from: https://www.ar-racking.com/en/blog/types-of-pallets-and-uses/.
17. Tua, C., L. Biganzoli, M. Grosso, and L. Rigamonti, *Life cycle assessment of reusable plastic crates (RPCs).* Resources, 2019. **8**(2): p. 110.

18. *Plastic crates*. 2024 [cited 10/2024; Available from: https://www.iqsdirectory.com/articles/plastic-container/plastic-crates.html.
19. Klein, D., M. Stommel, and J. Zimmer. *Influence of the stretch wrapping process on the mechanical behavior of a stretch film*. in *AIP Conference Proceedings*. 2018. AIP Publishing.
20. *ROBOPAC*. 2024 10/2024]; Available from: https://www.robopac.com/en.
21. *Plastic containers*. 2024 [cited 10/2024; Available from: https://www.iqsdirectory.com/articles/plastic-container.html.
22. *Plastic Crates Injection Molding Machine*. 2024 [cited 10/2024; Available from: https://guanxin-machinery.com/plastic-crates-injection-molding-machine/.
23. *Packaging equipment*. 2024 [cited 10/2024; Available from: https://www.iqsdirectory.com/articles/packaging-equipment.html.
24. Bamps, B., M. Buntinx, and R. Peeters, *Seal materials in flexible plastic food packaging: A review.* Packaging Technology and Science, 2023. **36**(7): p. 507-532.
25. Maddikunta, P.P., Quoc-Viet, B. Prabadevi, N. Deepa, K. Dev, T. Gadekallu, R. Ruby, and M. Liyanage, *Industry 5.0: A survey on enabling technologies and potential applications.* Journal of industrial information integration, 2022. **26**: p. 100257.
26. Rizvi, A., A. Haleem, S. Bahl, and M. Javaid, *Artificial intelligence (AI) and its applications in Indian manufacturing: a review.* Current Advances in Mechanical Engineering: Select Proceedings of ICRAMERD 2020, 2021: p. 825-835.
27. Linders, M., *Combining the strength of reusable and one-way systems into a secondary packaging design*. 2023, University of Twente: Enschede, Netherlands.
28. Kusuma, H.S., V. Listiawati, D.E.C. Jaya, N. Illiyanasafa, and R.A. Nida, *Analysis of Edible Film as Future Packaging using Bibliometric Method.* Egyptian Journal of Chemistry, 2023. **66**(13): p. 725-731.
29. Petkoska, A.T., D. Daniloski, N.M. D'Cunha, N. Naumovski, and A.T. Broach, *Edible packaging: Sustainable solutions and novel trends in food packaging.* Food Research International, 2021. **140**.
30. Chaudhary, V., S. Punia Bangar, N. Thakur, and M. Trif, *Recent advancements in smart biogenic packaging: Reshaping the future of the food packaging industry.* Polymers, 2022. **14**(4): p. 829.
31. Nwabor, O.F., S. Singh, J.C. Ontong, K. Vongkamjan, and S. Voravuthikunchai, *Valorization of wastepaper through antimicrobial functionalization with biogenic silver nanoparticles, a sustainable packaging composite.* Waste and Biomass Valorization, 2021. **12**: p. 3287-3301.
32. Ibzhanova, A.A., R.K. Niyazbekova, K.M. Al Azzam, E. Negim, M.A. Serekpayeva, and O.S. Akibekov, *Biodegradabiity of Non-wood Packaging Paper.* Egyptian Journal of Chemistry, 2022. **65**(10): p. 131-139.
33. Mott, R.V., E.; Wang, J., *Machine elements in mechanical design*. 6 ed. 2018, 330 Hudson Street, NY, NY. 873.
34. Childs, P., *Mechanical Design*. 2 ed. 2004, University of Sussex, UK: Elsevier Butterworth Heiemann. 373.
35. Howars, M. *What is Design for Excellence (DfX)*. 2023 [cited 11/2024; Available from: https://www.ansys.com/blog/what-is-dfx.
36. Holt, R. and C. Barnes, *Towards an integrated approach to "Design for X": an agenda for decision-based DFX research.* Research in engineering design, 2010. **21**: p. 123-136.
37. Ashby, M., *Materials selection in mechanical design*. 3 ed. Metallurgia Italiana. 2005, Amesteram, Netherlands. 622.
38. Jiang, W., *Analysis and design of machine elements*. 2019, New Jersey, USA: Wiley Online Library. 457.

39. Morais, S., *Desenho técnico básico - 3*. 26 ed. 2020, Porto, Portugal: Porto editora. 312.
40. Silva, F., *Tecnologia da Soldadura . Uma Abordagem Técnico-Didática*. 2 ed. 2016, Porto, Portugal: Publindústria.
41. Silva, L.M., A; Moura, M., *Juntas adesivas estruturais*. 2007, Porto, Portugal: Publindústria.
42. Trahair, N.B., MA; Nethercot, DA; Gardner, L., *The Behaviour and Design of Steel Structures to EC3*. 2008.
43. Standard, E., *Joints steel construction: Simple joints to Eurocode 3*. 2014: SCI Assessment. 484.
44. *Steel Connections – Design Guidelines*. Available from: https://steelexplained.com/steel-connections-design-guidelines/.
45. *Metal Surface Treatment | What You Need To Know*. 2023 [cited 11/2024; Available from: https://www.hlc-metalparts.com/news/metal-surface-treatment-73768751.html.
46. *UNI 3963*. Ente Nazionale Italiano di Unificazione (UNI).
47. Soares, P., *AÇOS - Caracteristicas e tratamentos*. 6 ed. 2009, Porto, Portugal Publindústria.
48. *8 Common Types of Surface Treatments in Manufacturing Processes for Metal Parts*. 2018 [cited 11/2024; Available from: https://www.kellertechnology.com/blog/8-common-types-of-surface-treatments-for-metal-parts/.
49. *A Guide to Anodizing Aluminum and Other Metals*. 2021 [cited 11/2024; Available from: https://sybridge.com/anodizing-guide/.
50. *What is Anodizing?* 2024; Available from: https://www.anodizing.org/page/what-is-anodizing.
51. Lazar, S., T. Kolibaba, and J. Grunlan, *Flame-retardant surface treatments.* Nature Reviews Materials, 2020. **5**(4): p. 259-275.
52. Tiwari, S. and J. Bijwe, *Surface treatment of carbon fibers-a review.* Procedia Technology, 2014. **14**: p. 505-512.
53. Mandracci, P., F. Mussano, P. Rivolo, and S. Carossa, *Surface treatments and functional coatings for biocompatibility improvement and bacterial adhesion reduction in dental implantology.* Coatings, 2016. **6**(1): p. 7.
54. Huang, Y., H. Wang, A. Khajepour, B. Li, J. Ji, K. Zhao, and C. Hu, *A review of power management strategies and component sizing methods for hybrid vehicles.* Renewable and Sustainable Energy Reviews, 2018. **96**: p. 132-144.
55. *About the EN Eurocodes*. [cited 11/2024; Available from: https://eurocodes.jrc.ec.europa.eu/en-eurocodes/about-en-eurocodes.
56. Domingues, J.S., *Apontamentos de orgãos de máquinas*. 2003, Porto, Portugal: Instituto Superior de Engenharia do Porto.
57. Standard, E., *Eurocode 1: Actions on structures*. 2024, European Comission: brussels, belgium.
58. Fonseca, E., *Apontamentos CONSM.* 2024.
59. Fish, J. and T. Belytschko, *A first course in finite elements*. Vol. 1. 2007, New Jersey, USA: John Wiley & Sons Limited. 344.
60. Campilho, R., *Método de elementos finitos*
Ferramentas para análise estrutural. 2012, Porto, Portugal: Publindústria.
61. *Automotive FEA*. [cited 11/2024; Available from: https://tefugen.com/service/automotive-fea/.
62. *Solidworks*. 2024 [cited 11/2024; Available from: https://www.solidworks.com/.
63. *Ansys Mechanical*

Finite Element Analysis (FEA) Software for Structural Engineering. 2024 [cited 11/2024; Available from: https://www.ansys.com/products/structures/ansys-mechanical.
64. *General-Purpose Finite Element Analysis Software*. 2024 [cited 11/2024; Abaqus]. Available from: https://www.3ds.com/products/simulia/abaqus.
65. *Evaluate and Validate: A Step-by-Step Guide to Prototype Testing*. 2024 [cited 11/2024; Available from: https://maze.co/guides/prototype-testing/.
66. Liker, J. and R. Pereira, *Virtual and physical prototyping practices: Finding the right fidelity starts with understanding the product.* IEEE Engineering Management Review, 2018. **46**(4): p. 71-85.
67. Kent, L., C. Snider, J. Gopsill, and B. Hicks, *Mixed reality in design prototyping: A systematic review.* Design Studies, 2021. **77**: p. 101046.
68. Castro, T., F. Silva, and R. Campilho, *Optimising a specific tool for electrical terminals crimping process.* Procedia Manufacturing, 2017. **11**: p. 1438-1447.
69. de Oliveira, H., R. Campilho, and F. Silva, *Design of a modular solution for an autonomous vehicle for cargo transport and handling.* Procedia Manufacturing, 2019. **38**: p. 991-999.
70. Faria, N., R.D. Campilho, F.J. Silva, and L.P. Ferreira, *Concept and design of automated moving device for healthcare equipment.* FME Transactions, 2021. **49**(3): p. 598-607.
71. Vieira, J., R. Campilho, F. da Silva, and I. de Jesús Sánchez-Arce, *Development of a rotation and lifting system for pallet rotary tables.* The International Journal of Advanced Manufacturing Technology, 2022. **122**(11): p. 4321-4339.
72. da Costa, J., R. Campilho, F.J. Silva, and I. Sánchez-Arce, *Design of buried equipment for the collection of urban solid waste.* Journal of Testing and Evaluation, 2022. **50**(5): p. 2358-2381.
73. NEFAB. *Custom Pallets*. 2024 [cited 12/2024; Available from: https://www.nefab.com/solutions/packaging-solutions/pallets/custom-pallets/.
74. EPAL, *ISPM15 - International Standard for Phytosanitary Measures*.
75. *How to Pack Heavy and Large Products*. 2016 [cited 12/2024; Available from: https://www.nefab.com/news-insights/2016/heavy-duty-packaging/.
76. *Block Pallet vs Stringer Pallet: Which One Is Really Stronger?* 2024 [cited 12/2024; Available from: https://www.connerindustries.com/block-pallet-vs-stringer-pallet/.
77. Standardization, I.O.f., *ISO 8611-1:2011 - Pallets for materials handling — Flat pallets*. 2011, ISO - International Organization for Standardization.
78. Standardization, I.O.f., *ISO 6780:2003 - Flat pallets for intercontinental materials handling — Principal dimensions and tolerances*. 2003, ISO International Organization for Standardization.
79. Louw, L. and S. Nel, *Analysis of the use of space and module-configured packaging to improve fruit export mass in a refrigerated container.* South African Journal of Industrial Engineering, 2019. **30**(1): p. 94-109.
80. Normung, D.I.f., *DIN EN 13698-1 - Pallet production specification - Part 1: Construction specification for 800 mm x 1200 mm flat wooden pallets*. DIN Deutsches Institut für Normung.
81. Standard, E., *Eurocode 3: Design of steel structures - Part 1-8: Design of joints EN 1993-1-8*. 2010, EN European Standards.
82. *Skids for Heavy Duty Products*. 2017 [cited 12/2024; Available from: https://www.nefab.com/solutions/packaging-solutions/pallets/heavy-duty-skids/.
83. Baldassino, N. and C. Bernuzzi, *Analysis and behaviour of steel storage pallet racks.* Thin-Walled Structures, 2000. **37**(4): p. 277-304.
84. NEFAB. *Load Securing Solutions*. 2017 [cited 12/2024; Available from: https://www.nefab.com/news-insights/2017/load-securing-solutions/.

85. NEFAB. *Load Securing*. 2017 [cited 12/2024; Available from: https://www.nefab.com/solutions/packaging-solutions/packaging-requirements/load-securing/.
86. *Industrial and Logistical Lashing Solutions - Total Pack Solutions - Packaging | Logistics Solutions*. [cited 12/2024; Available from: https://totalpacksolutions.com/industrial-and-logistical-lashing-solutions/.
87. *Heavy-duty Cardboard Tubes*. 2024 [cited 01/2025; Available from: https://www.innovepackage.com/cardboard-tubes/heavy-duty-paper-tubes/.
88. *Dunnage Bags | Paper and Woven Dunnage Bags*. 2024 [cited 12/2024; Available from: https://www.megafortris.eu/product/dunnage-bags/.
89. *Regupol Load Secure Friction Anti-Slip Mats*. 2024 [cited 12/2024; Available from: https://www.stopslip.co.uk/anti-slip-products/cargo-mat.aspx.
90. *The Importance Of Using Lashing Straps To Restrain Cargo*. 2024 [cited 12/2024; Available from: https://xpak.com.au/the-importance-of-using-lashing-straps-to-restrain-cargo/.
91. Macioszek, E., *Essential techniques for fastening loads in road transport.* Zeszyty Naukowe. Transport/Politechnika Śląska, 2021(110): p. 97-104.
92. *An Introduction to Wire Rope and Wire Rope Hardware*. 2021 [cited 12/2024; Available from: https://www.huyett.com/blog/wire-rope-hardware-guide.
93. *Transport Information Service - Load securing*. 2020 [cited 12/2024; Available from: https://www.tis-gdv.de/tis_e/verpack/verpackungshandbuch/36verpackungshandbuch_12-htm/.
94. Standards, E., *Standard for Load restraining on road vehicles - EN 12195*. 2001, EN European Standards.
95. Ceraolo, M. and G. Lutzemberger, *Heavy-duty hybrid transportation systems: Design, modeling, and energy management*, in *Hybrid Technologies for Power Generation*. 2022, Elsevier. p. 313-336.
96. Bernuzzi, C. and M. Simoncelli, *An advanced design procedure for the safe use of steel storage pallet racks in seismic zones.* Thin-Walled Structures, 2016. **109**: p. 73-87.
97. Eldensjö, E. and I. Söderman-Lundqvist, *How Does Skid Design Affect Transportability and Handling of Heavy Machinery?* 2022.
98. Petraška, A., K. Čižiūnienė, O. Prentkovskis, and A. Jarašūnienė, *Methodology of selection of heavy and oversized freight transportation system.* Transport and telecommunication journal, 2018. **19**(1): p. 45-58.
99. Zacchei, E., A. Tadeu, J. Almeida, M. Esteves, M. Santos, and S. Silva, *Design of new modular metal pallets: Experimental validation and life cycle analysis.* Materials & Design, 2022. **214**: p. 110425.
100. NEFAB. *NEFAB*. 2025 [cited 2025; Available from: https://www.nefab.com/.
101. Vom Brocke, J., A. Hevner, and A. Maedche, *Introduction to design science research.* Design science research. Cases, 2020: p. 1-13.
102. Standard, E., *EN 1993-1-1: Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings*. 2010, European Comission: brussels, belgium.
103. *SIMONA PVC-CAW*. 2025 [cited 05/2025; Available from: https://www.simona.de/en.
104. Peißker, P.M.a.P., *Handbook of Hot-dip Galvanization*, ed. WILEY-VCH. 2011: WILEY-VCH.
105. RUD. *Lifting Points*. Available from: https://www.rud.com.
106. THIELE, *Product Overview Lifting Points*, THIELE, Editor. 2018, THIELE.
107. Crosby, *Crosby® HR-125 UNC Swivel Hoist Rings*. Crosby.
108. *Cordstrap*. 2025 [cited 05/2025; Available from: https://www.cordstrap.com/en/.

109. *THOMSON*. 2025 [cited 04/2025; Available from: https://www.thomsonlinear.com/es/indice.
110. *SKF*. 2025 [cited 04/2025; Available from: https://www.skf.com/pt/products/rolling-bearings.
111. *SCHAEFFLER*. 2025 [cited 04/2025; Available from: https://www.schaeffler.com/en/.
112. Standardization, I.O.f., *ISO 2328 - Fork-lift trucks — Hook-on type fork arms and fork arm carriages — Mounting dimensions*. 2011.
113. consultants, M. *Padeye design and calculation*. 05/2025]; Available from: https://www.mermaid-consultants.com/padeye-design-and-calculation.html
114. Pallets, A. *Protecting Pallets From Forklift Damage*. 2025 [cited 05/2025; Available from: https://associated-pallets.co.uk/blog/protecting-pallets-forklift-damage/.
115. transport, S.-P.c.a.h. *LASHING & PACKING CARGO*. 05/2025]; Available from: https://saigontrans.vn/en/service/lashing-packing-cargo/.
116. *Greencalc*. 2025 [cited 06/2025; Available from: https://www.greencalc.pt/?page_id=1049&lang=en.

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.

NAME: Lucas Lages Silva

Porto, (June 14, 2025)

Appendix A

Table A.1 - Structure attribute ponderation table.

	1-2	1-3	1-4	1-5	1-6	1-7	1-8	Wi*	Wi
Weight	50	50	55	55	55	55	55	1,00	0,14
Cost	50							1,00	0,14
Strength		50						1,00	0,14
Ease of transport			45					0,82	0,12
Ease of handling				45				0,82	0,12
Easy to store					45			0,82	0,12
ability during transpo						45		0,82	0,12
tability suring storag							45	0,82	0,12
							Σ	7,09	1,00

Table A.2 - Structure weighted rating decision matrix.

								Ease to				Stability during				
wR	wC	**Weight**		**Cost**		**Strength**		**transport**		**store**		**transport**		**storage**		
wB		0,14		0,14		0,14		0,12		0,12		0,12		0,12		**Y**
S1		5,0 / 40,0	5,60	5 / 40,00	5,60	3 / 100,00	14,00	5 / 100,00	12,00	3 / 60,00	7,20	3 / 100,00	12,00	5 / 100,00	12,00	68,40
S2		2,0 / 100,0	14,00	2 / 100,00	14,00	1 / 33,33	4,67	1 / 20,00	2,40	5 / 100,00	12,00	1 / 33,33	4,00	2 / 40,00	4,80	55,87
S3		3,0 / 66,7	9,33	3 / 66,67	9,33	3 / 100,00	14,00	1 / 20,00	2,40	5 / 100,00	12,00	1 / 33,33	4,00	3 / 60,00	7,20	58,27
S4		5,0 / 40,0	5,60	4 / 50,00	7,00	5 / 166,67	23,33	5 / 100,00	12,00	3 / 60,00	7,20	3 / 100,00	12,00	5 / 100,00	12,00	**79,13**

Table A.3 - Joint attribute ponderation table.

	1-2	1-3	1-4	Wi*	Wi
Stiffness	50	60	75	1,00	0,33
Strength	50			1,00	0,33
Cost		40		0,67	0,22
Complexity			25	0,33	0,11
			Σ	3,00	1

Table A.4 – Joint weighted rating decision matrix.

		Joint								
wR	wC	**Stiffness**		**Strength**		**Cost**		**Complexity**		
wB		0,33		0,33		0,22		0,11		**Y**
S1(Weld)		5 / 100,0	33,33	4 / 50,00	16,67	3 / 100,00	22,22	3 / 100,00	11,11	83,33
S2(Bolt)		4 / 80,0	26,67	4 / 50,00	16,67	4 / 75,00	16,67	4 / 75,00	8,33	**68,33**

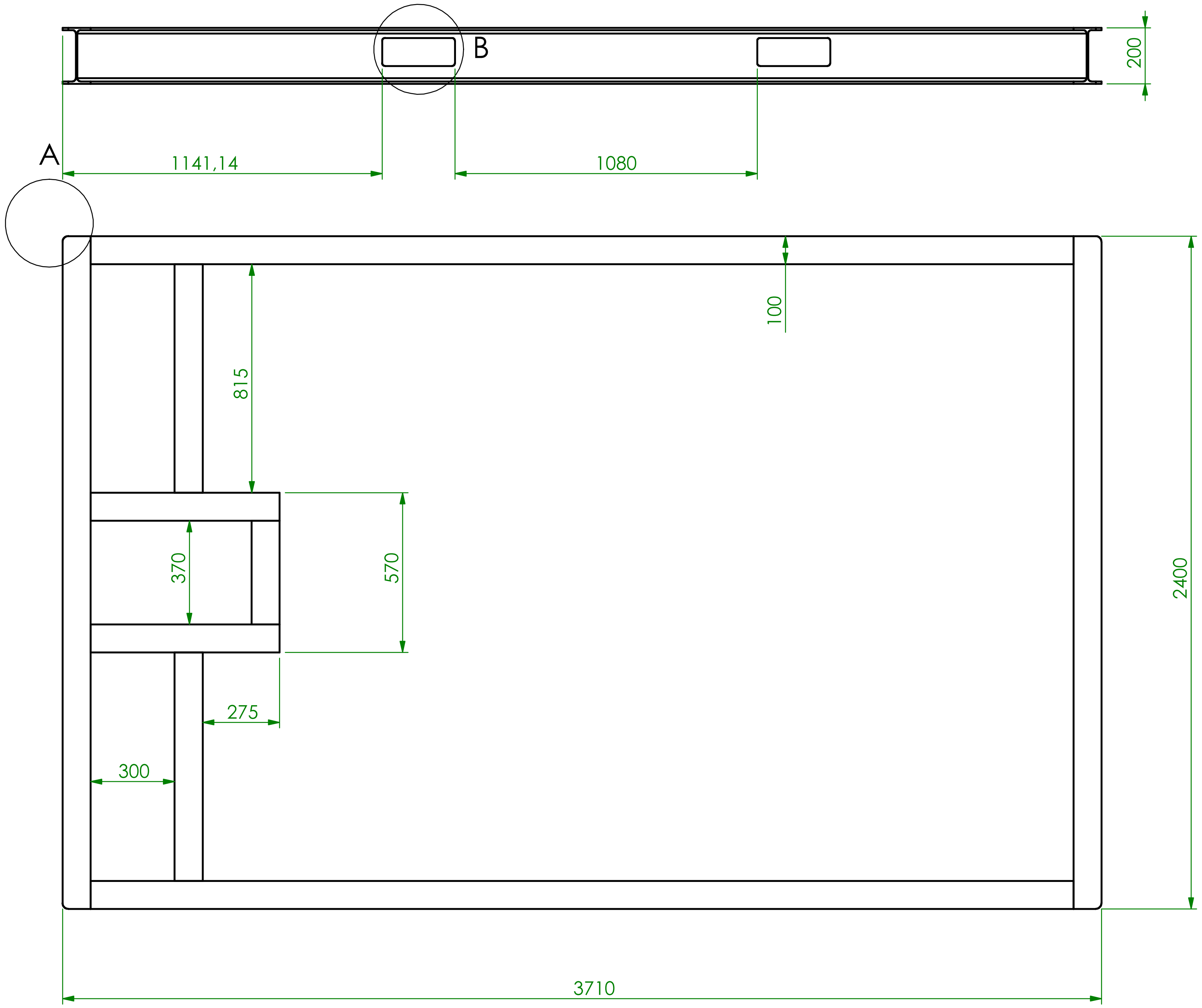
Table A.5 - Surface treatment ponderation table.

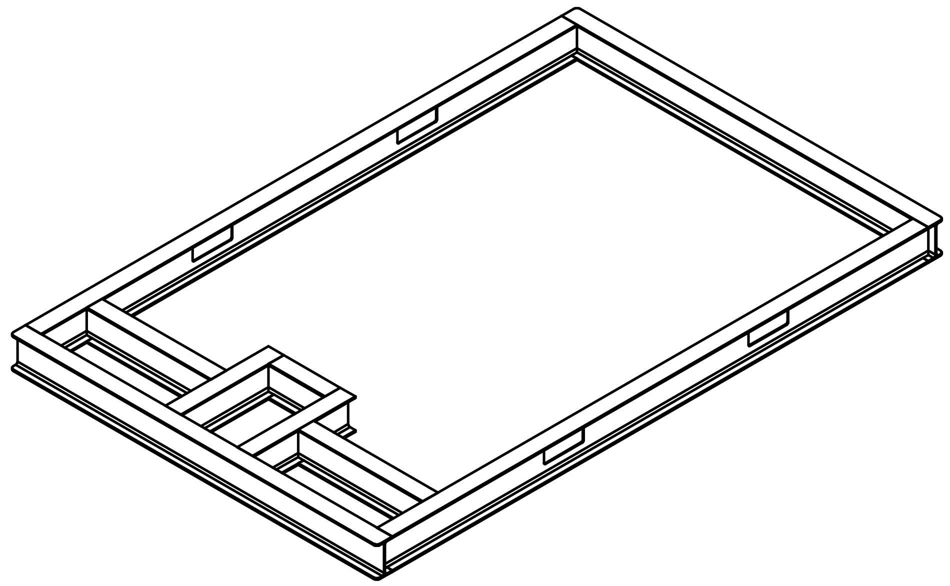
	1-2	1-3	1-4	1-5	Wi*	Wi
Cost	50	75	75	75	1,00	0,33
Complexity	50				1,00	0,33
Exposed environment		25			0,33	0,11
Repairability			25		0,33	0,11
Applicability for large structures				25	0,33	0,11
				Σ	3,00	1,00

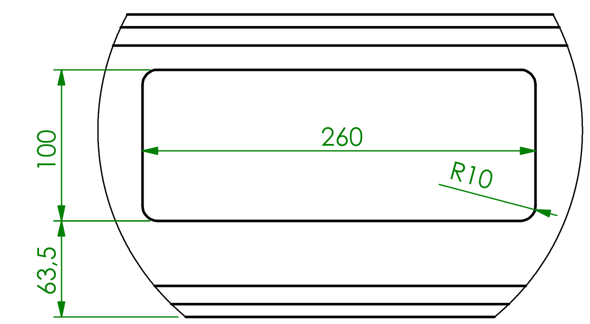
Table A.6 – Surface treatment weighted rating decision matrix.

wR	wC	**Cost**		**Complexity**		**Exposed environment**		**Repairability**		**Applicability large structures**		
wB		0,33		0,33		0,11		0,11		0,11		**Y**
S1(Galvanised		5	33,33	4	16,67	3	11,11	3	11,11	3	11,11	83,33
		100,0		50,00		100,00		100,00		100,00		
S2 (Paint)		3	20,00	4	16,67	4	8,33	4	8,33	4	8,33	**61,67**
		60,0		50,00		75,00		75,00		75,00		

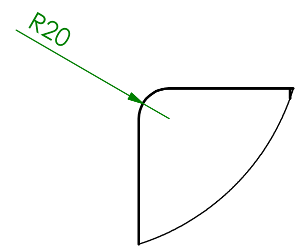
Appendix B







DETAIL B
SCALE 1 : 5



DETAIL A
SCALE 1 : 5

ESCALA
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Proprietário legal: *DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto*		Título: 1201133_2025_01 S235	Número: 1201133_2025_01
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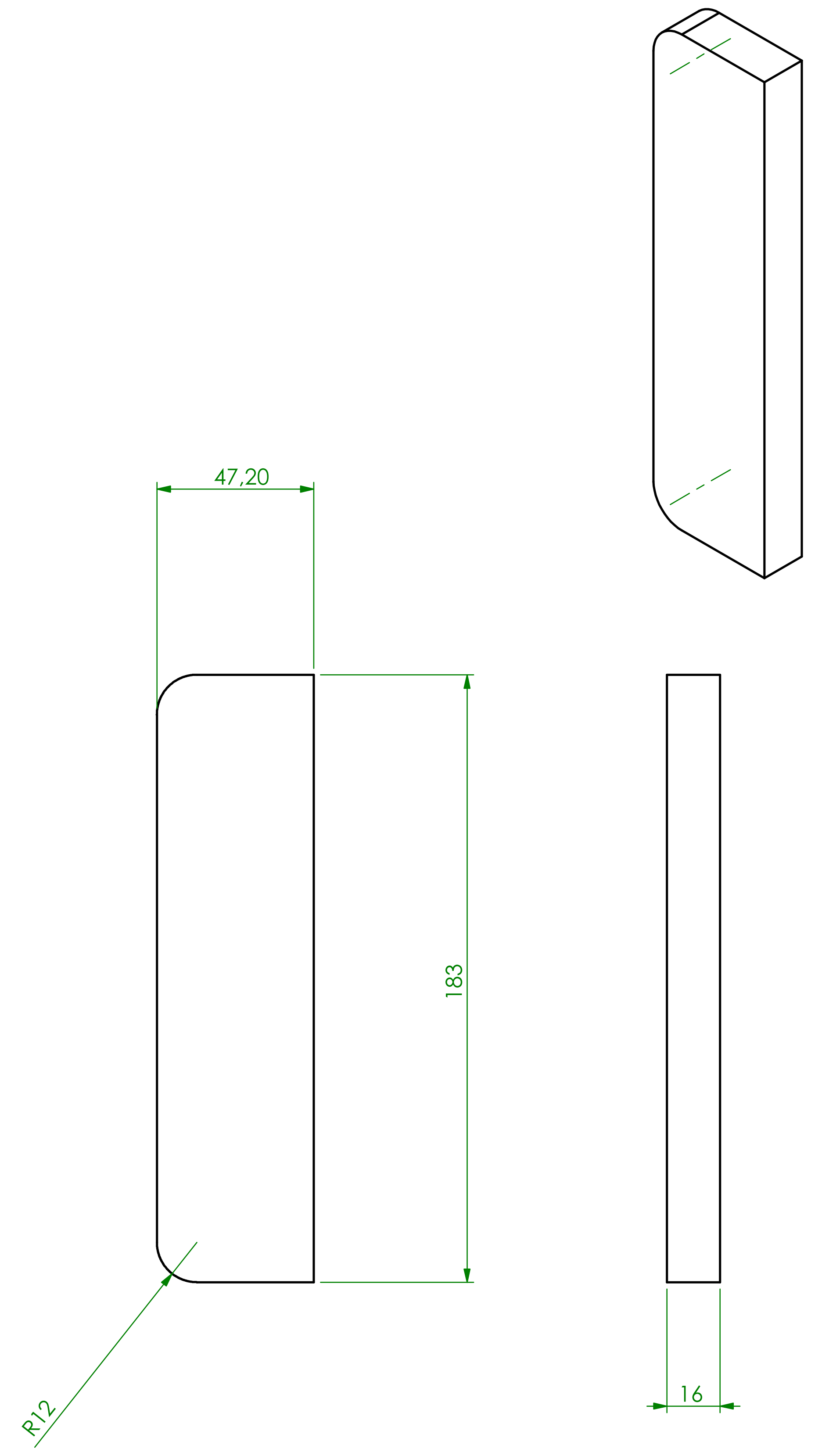

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Proprietário legal		Título	Número			
DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		1201133_2025_02 S235	1201133_2025_02			
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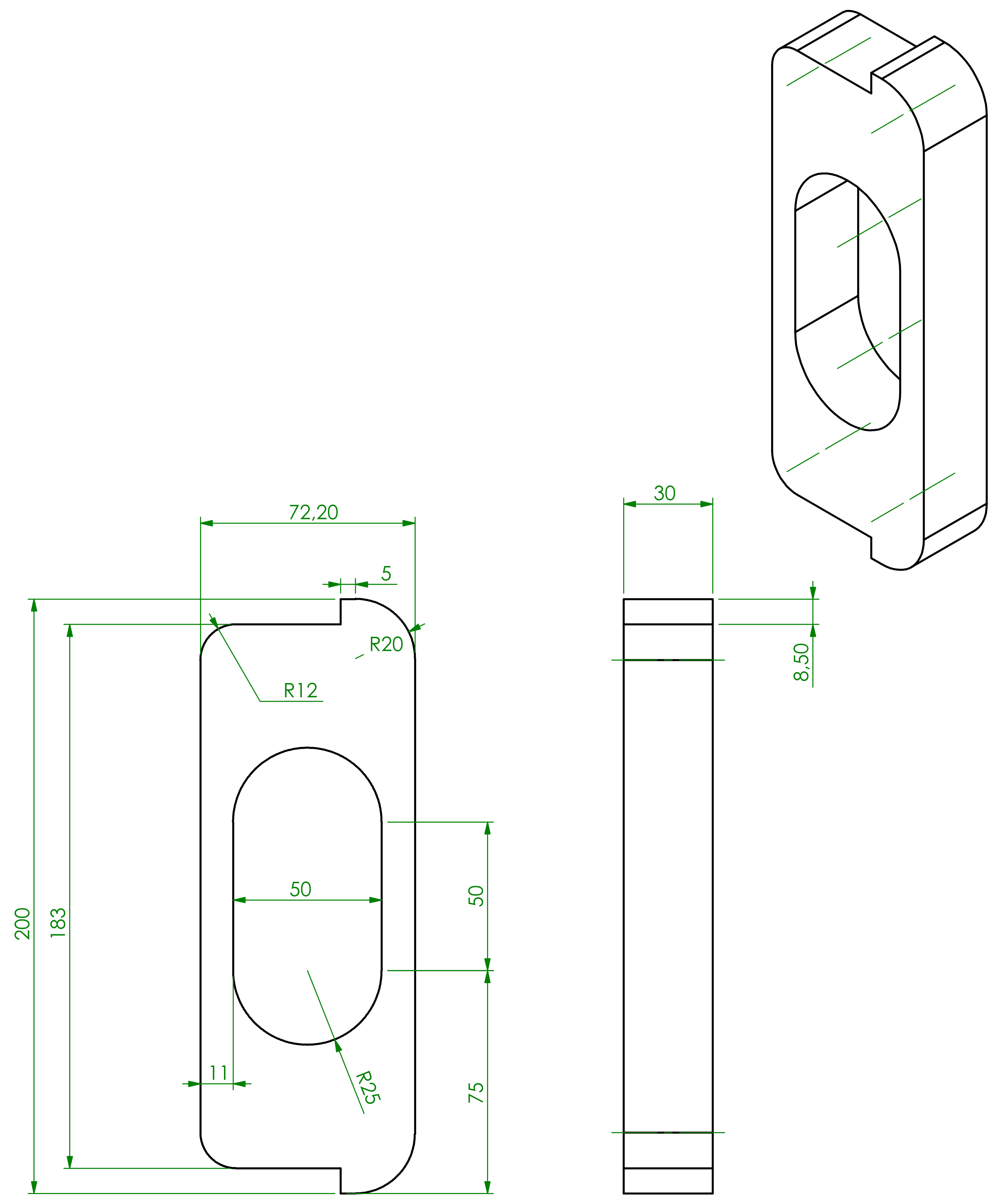

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Revisão	Data de edição	Lingua	Folha
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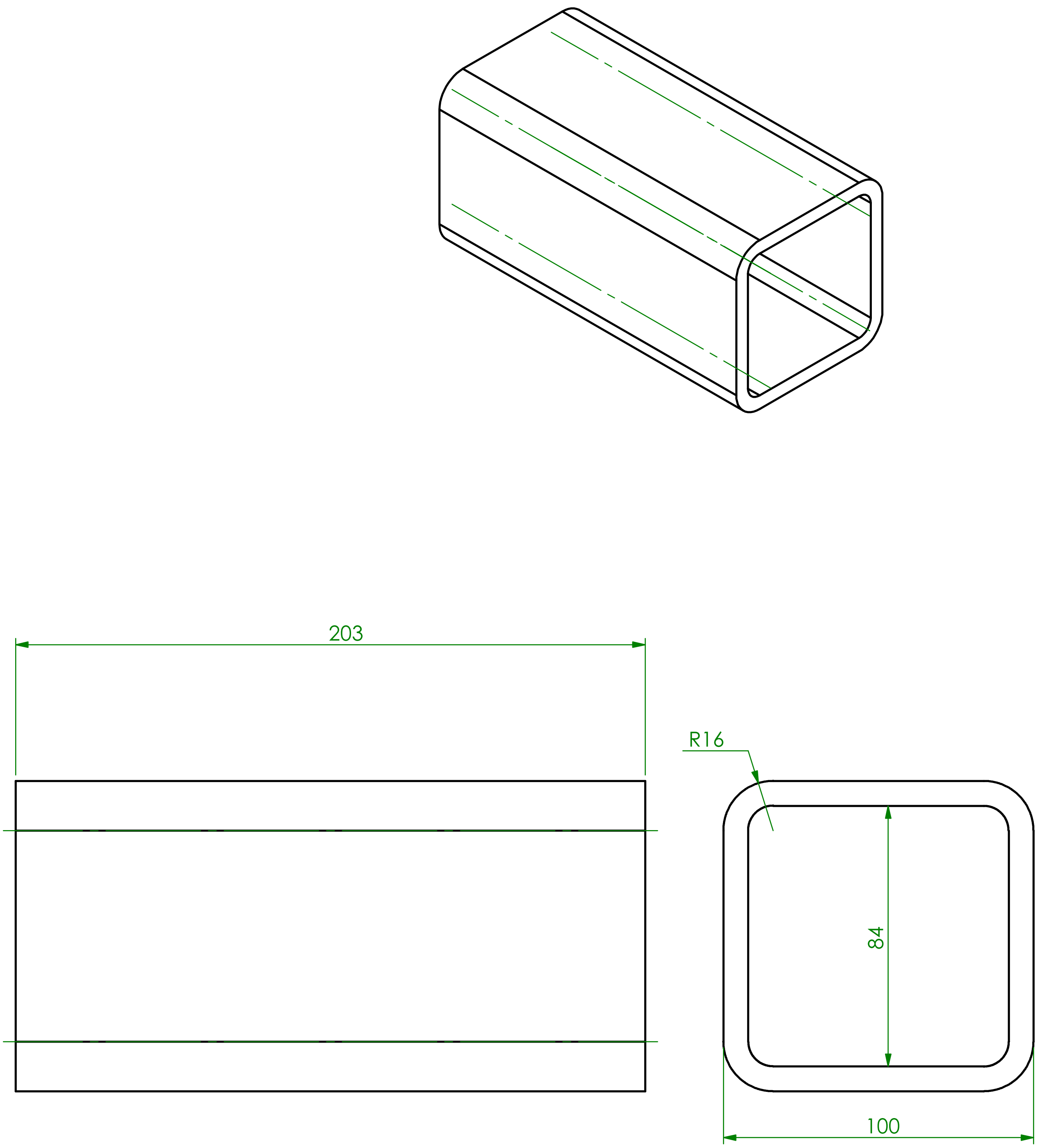

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Proprietário legal	Título	Número
DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*	1201133_2025_04 S235	1201133_2025_04

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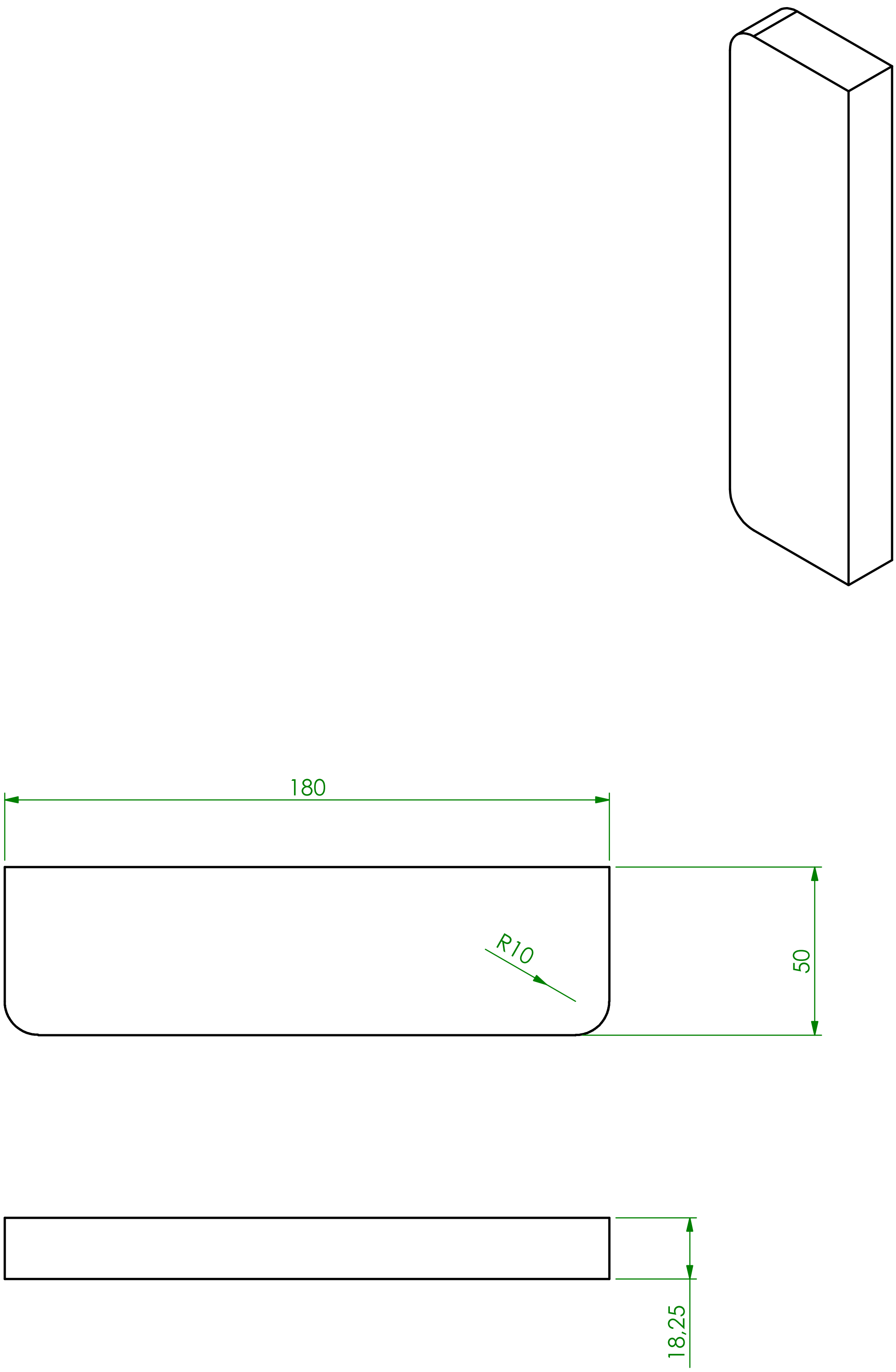

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DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		1201133_2025_05 S235	1201133_2025_05			
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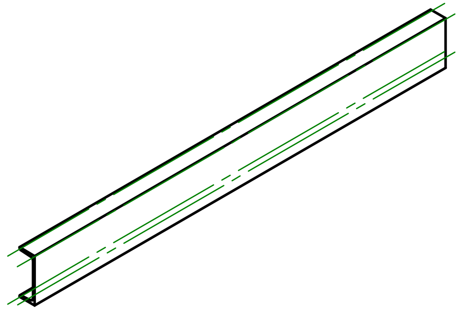

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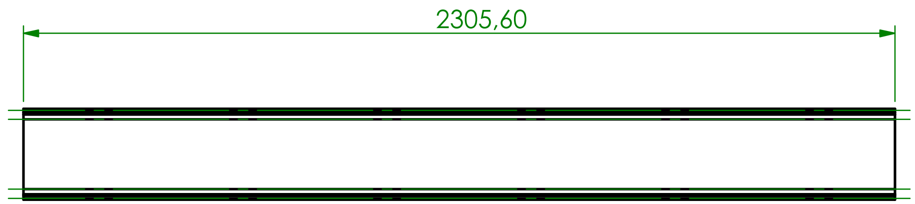

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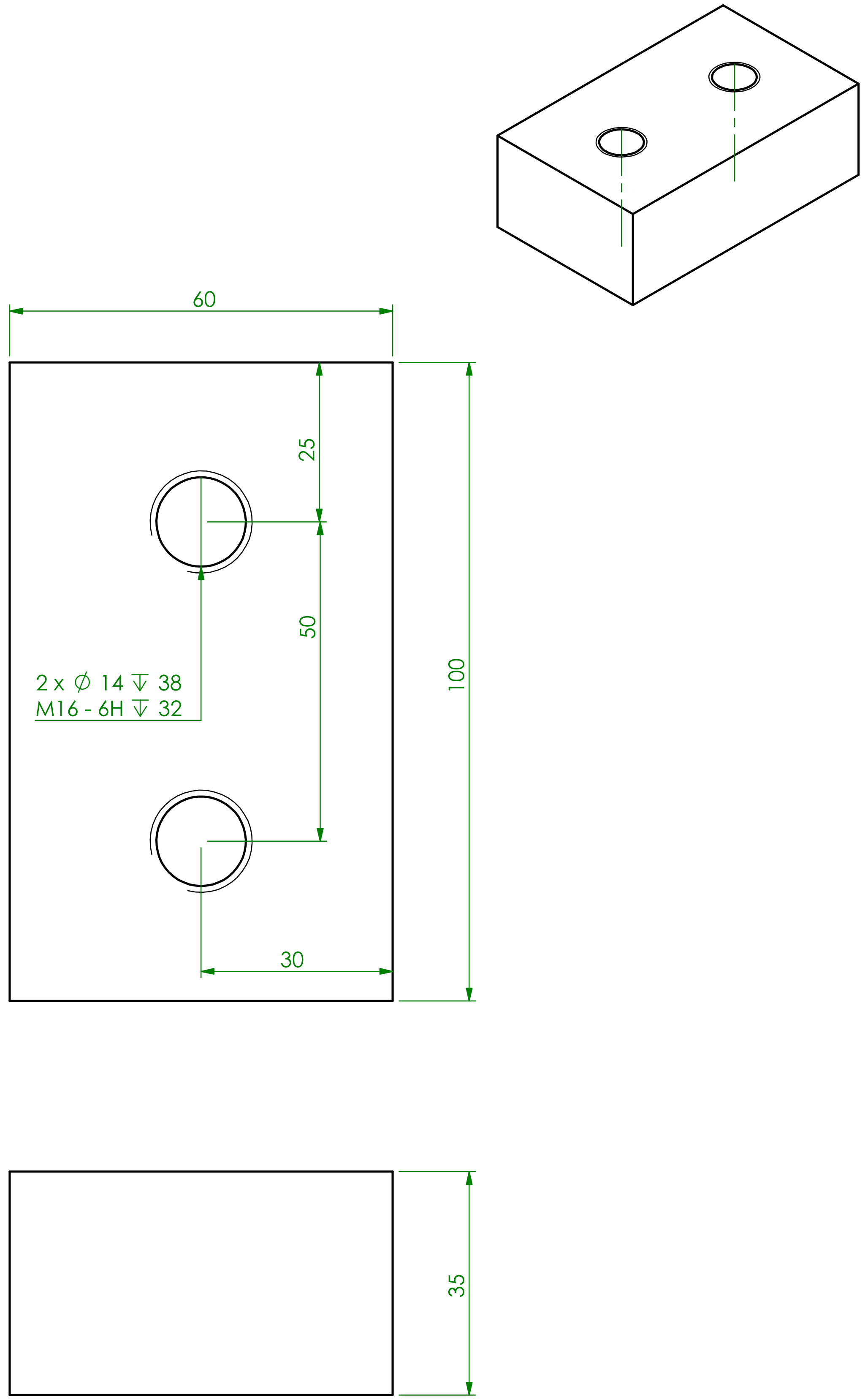

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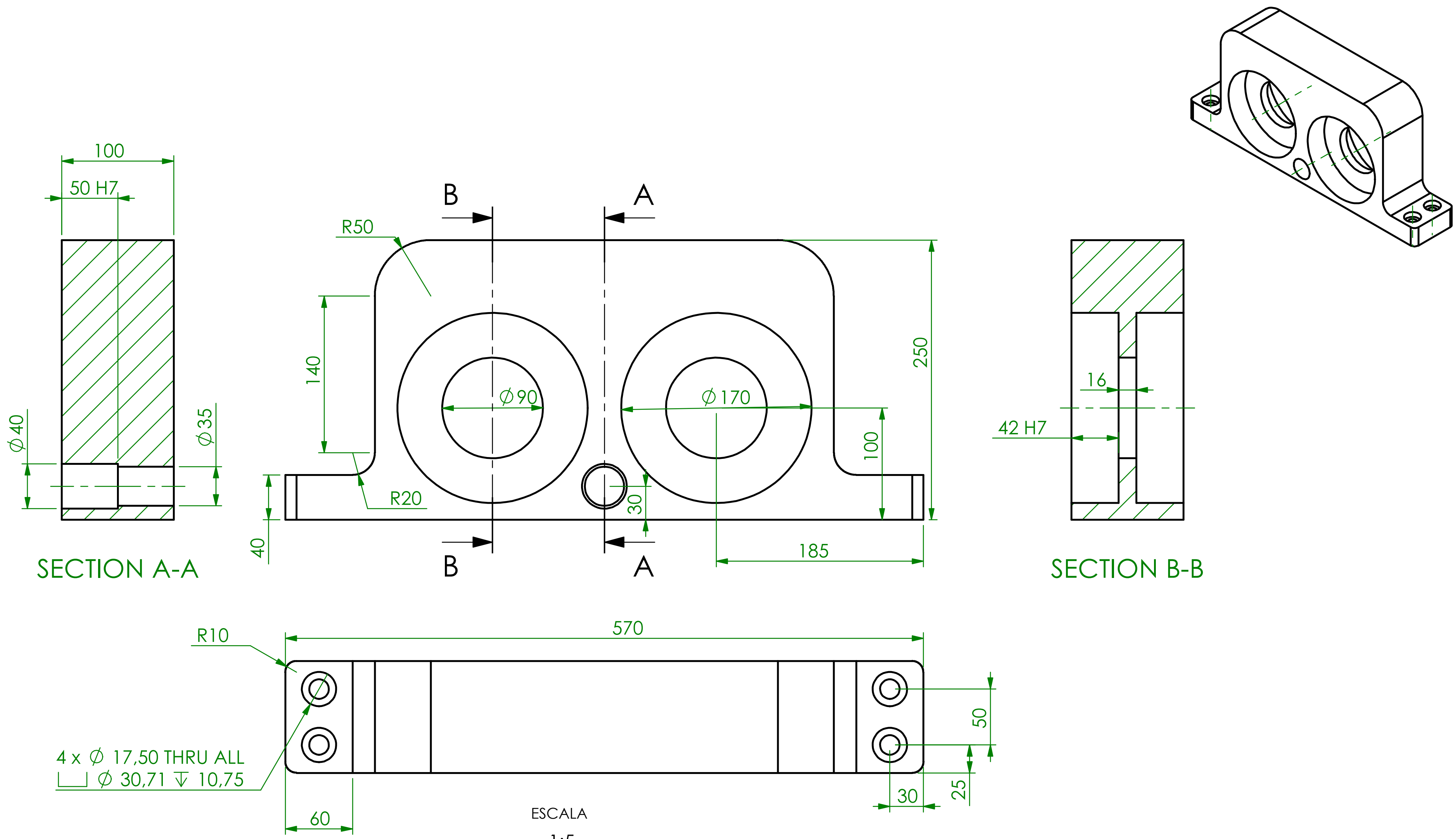

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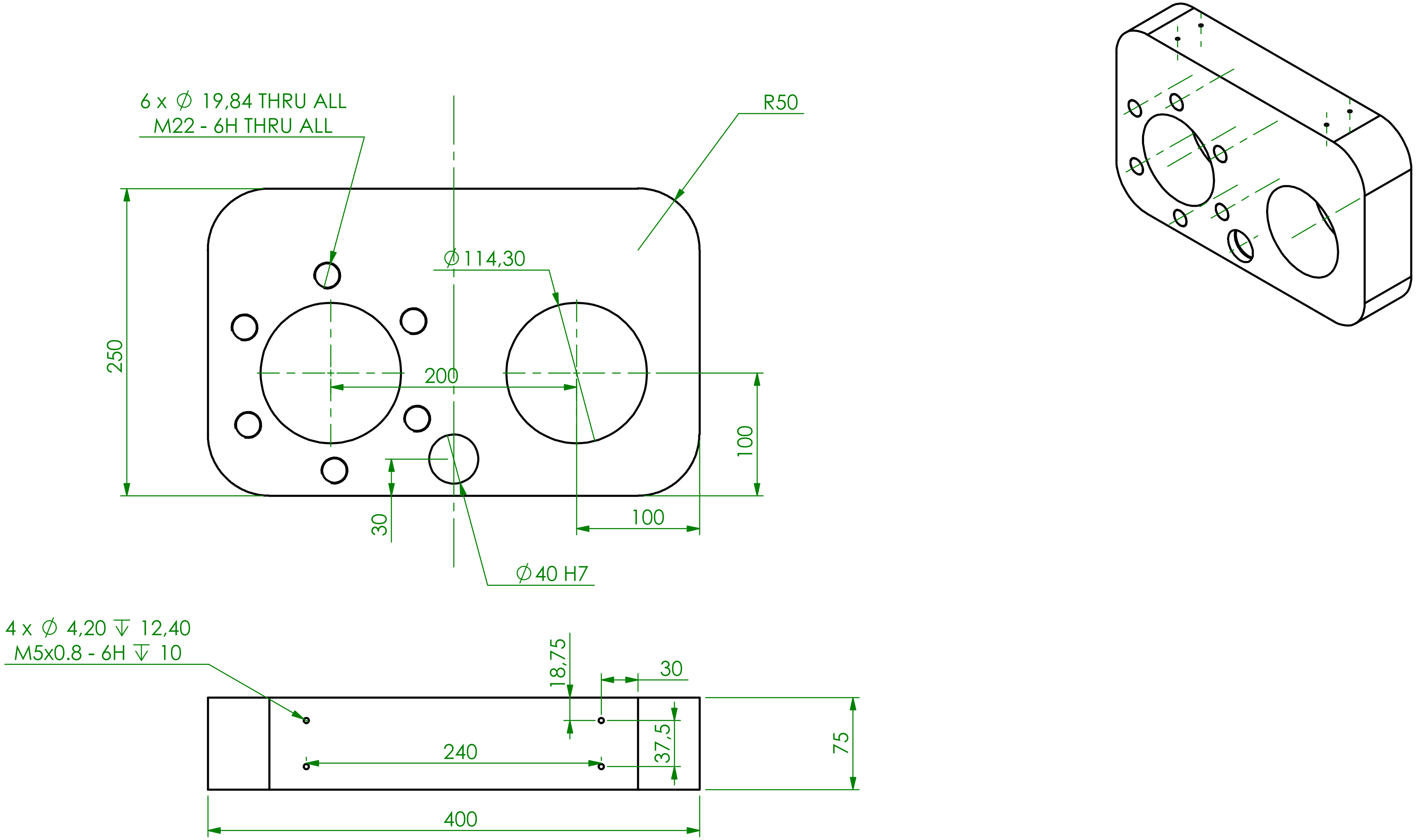

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DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		1201133_2025_09 S235	1201133_2025_09			
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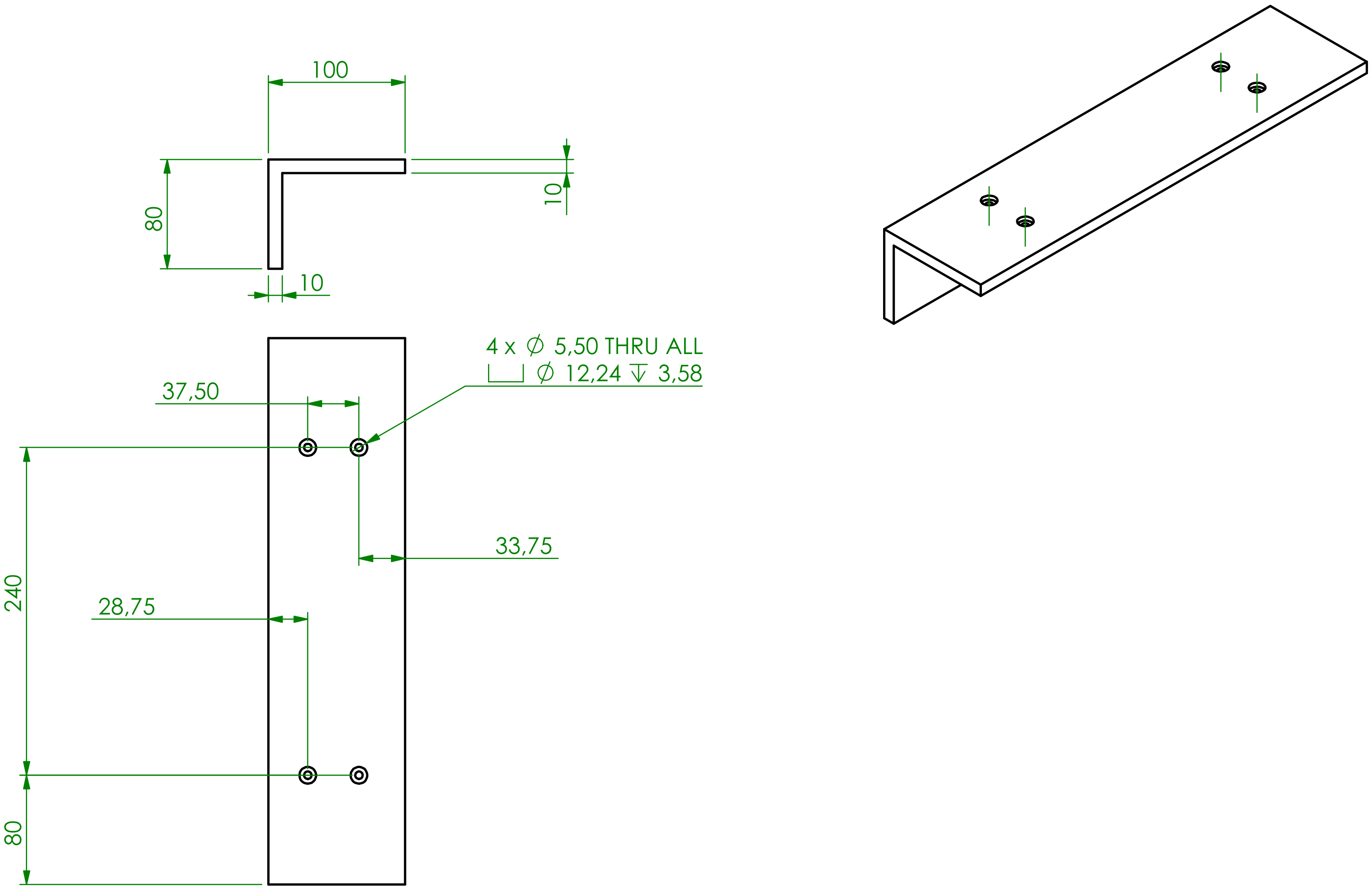

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título

1201133_2025_10
PVC-CAW SIMONA

Número

1201133_2025_10

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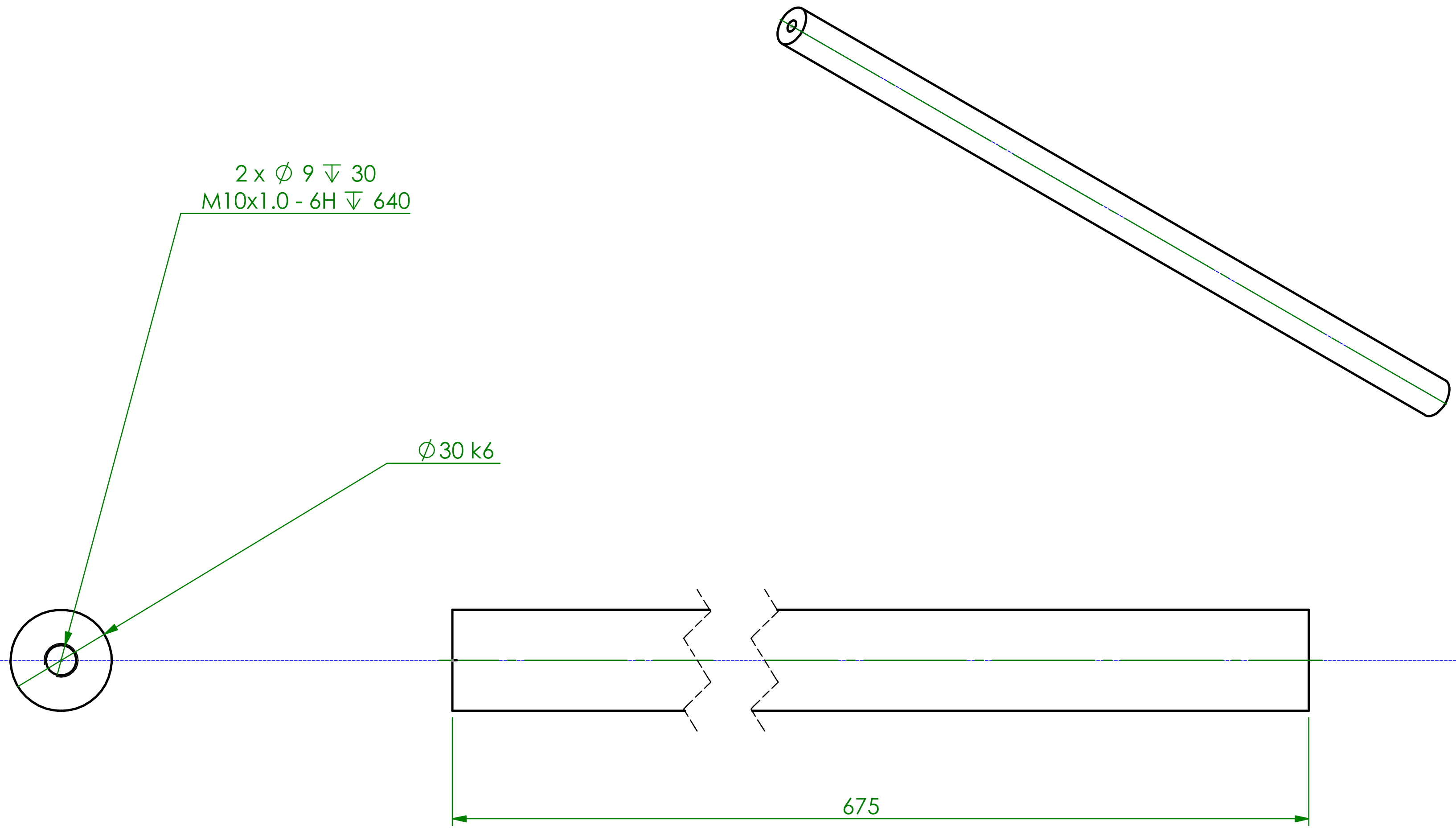

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DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto		1201133_2025_11 S235	1201133_2025_11			
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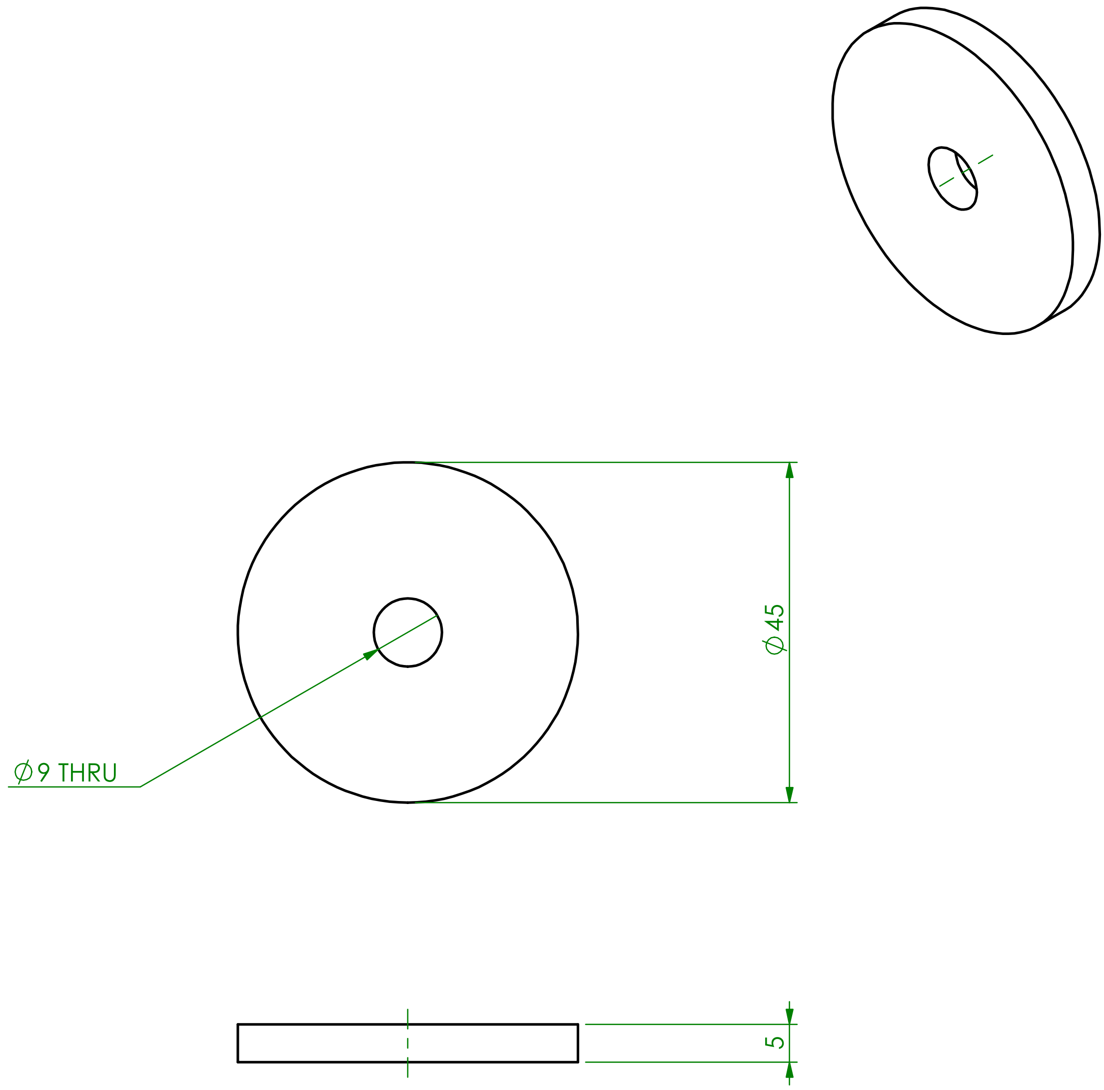

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título

1201133_2025_12
S235

Número

1201133_2025_12

Revisão	Data de edição	Lingua	Folha
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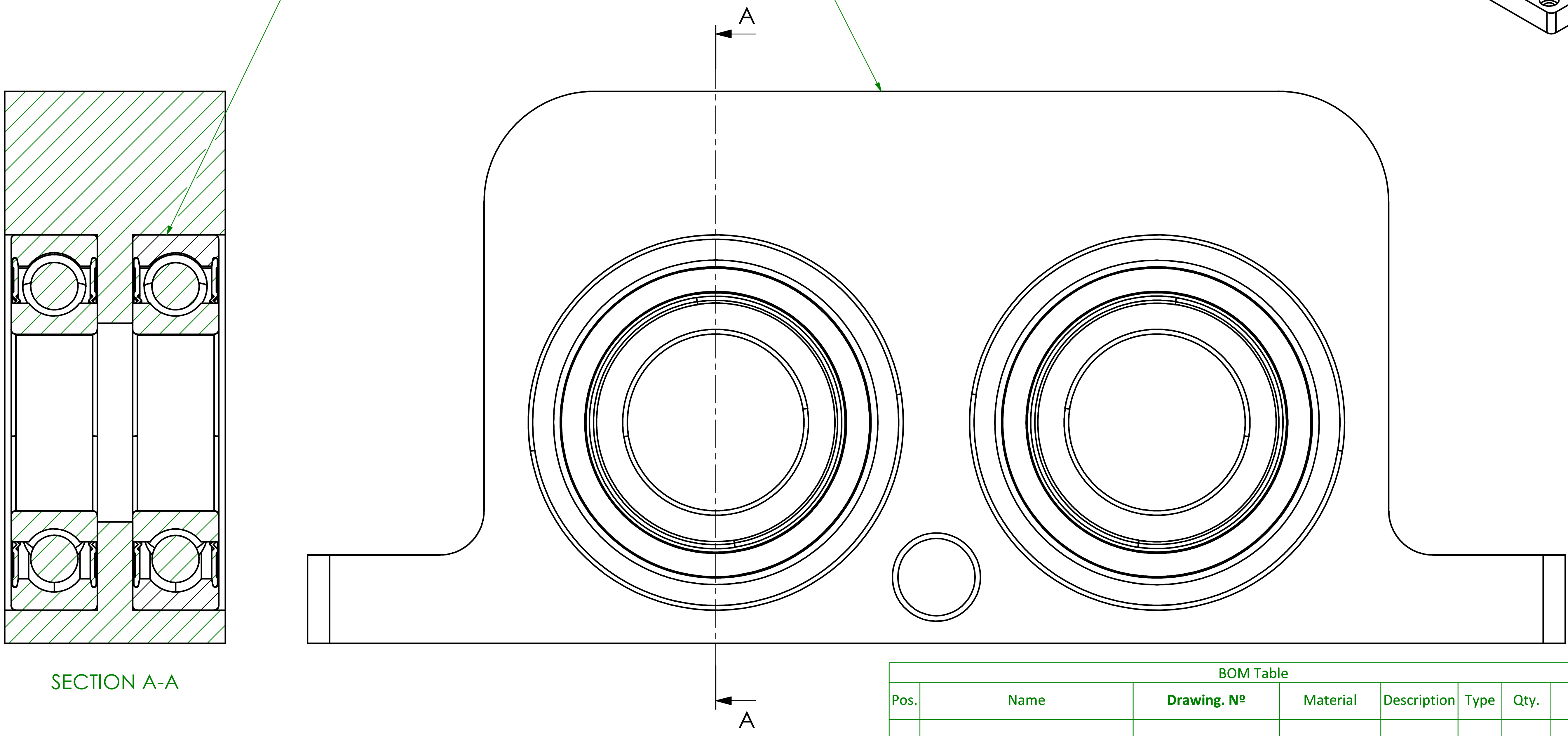

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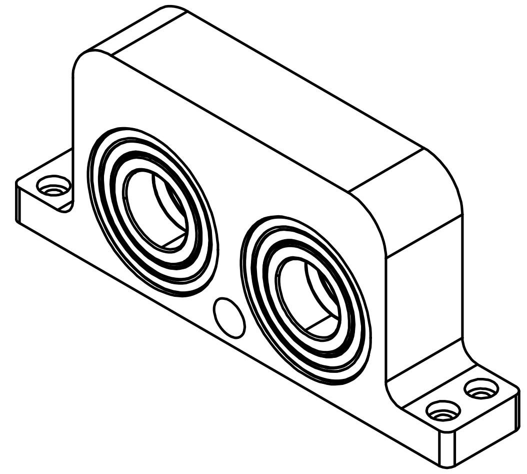

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2	6316_2rsjem_Rolamentoesferas 170x80	**Buy**	SKF 6316 2RSJEM			4	

Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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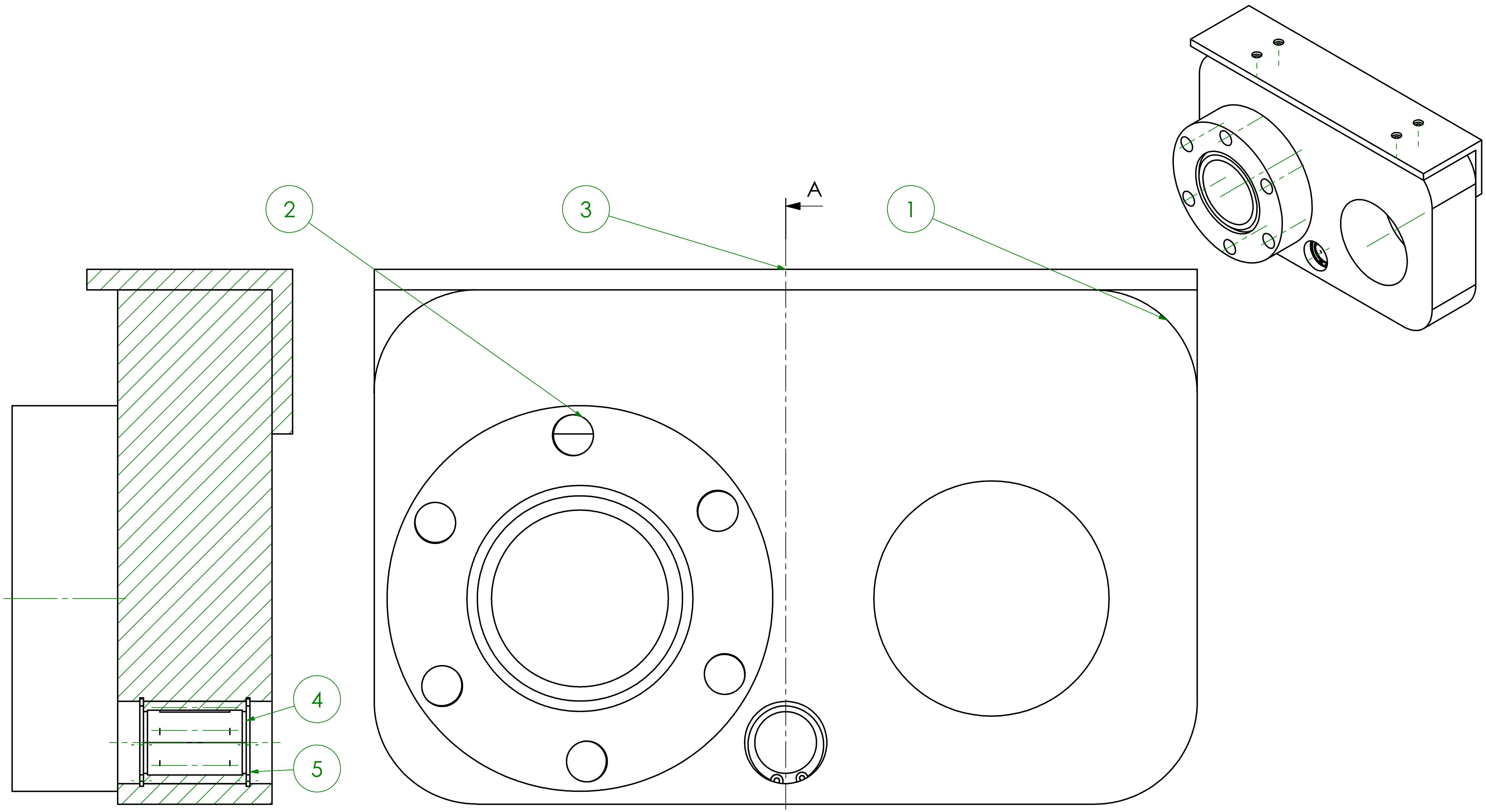
Revisão	Data de edição	Lingua	Folha
		PT	1/1



SECTION A-A

Pos.	Name	Drawing. Nº	Material	Description	Type	Qty.	CL
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2	Rosca modelo travao 2	**buy**	THOMSON 20332F			1	
3	borracha do mordente	**1201133_2025_10**				1	
4	inafag_kh30-pp_ccw3s5bdkb5dccpb35tyunit2(Part	**buy**	SCHAEFFLER KH30-PP			1	
5	07331-401750	**buy**	NORELEM 07331-401750			2	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto	1201133_2025_14_A2	1201133_2025_14_A2

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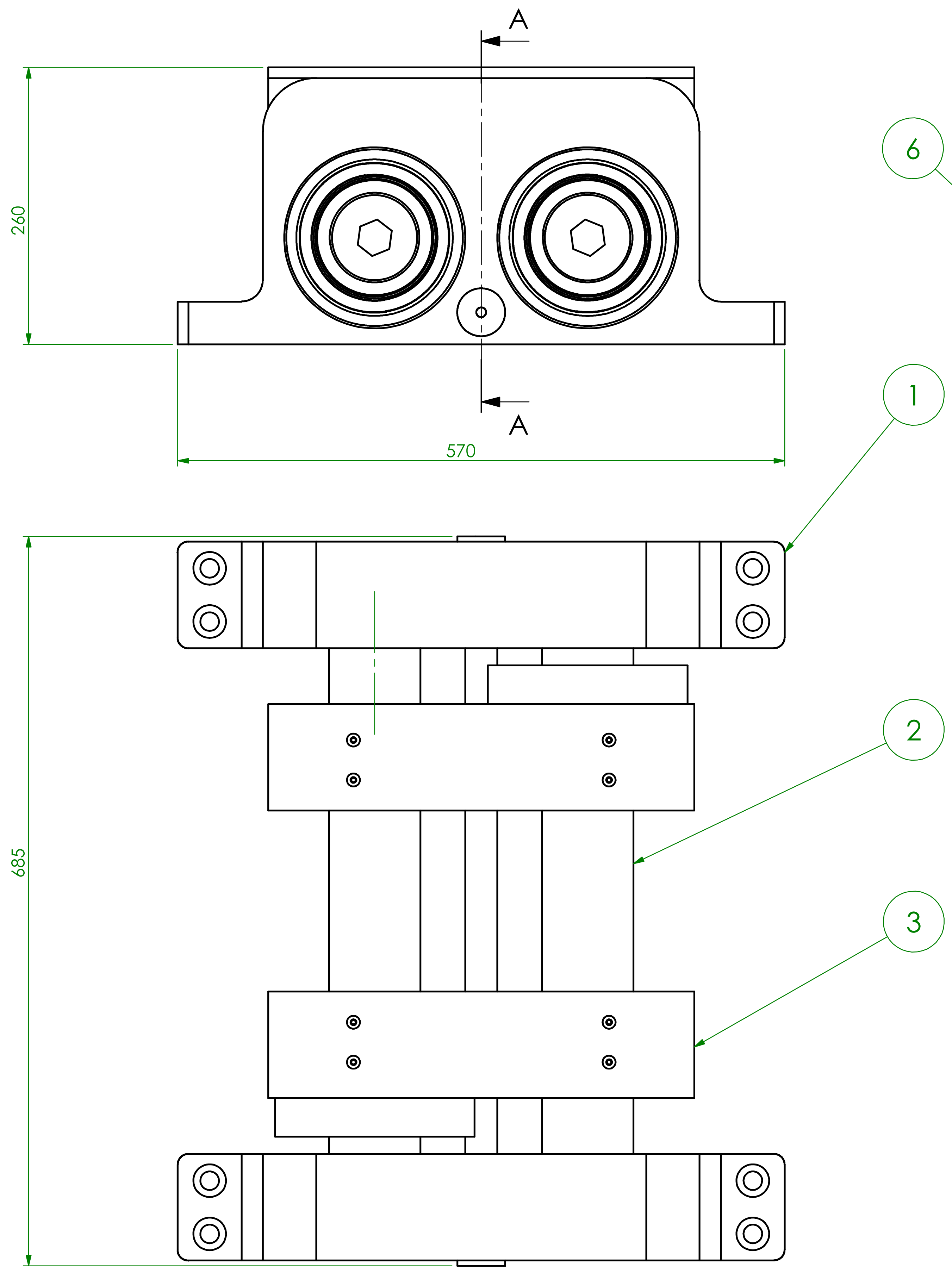

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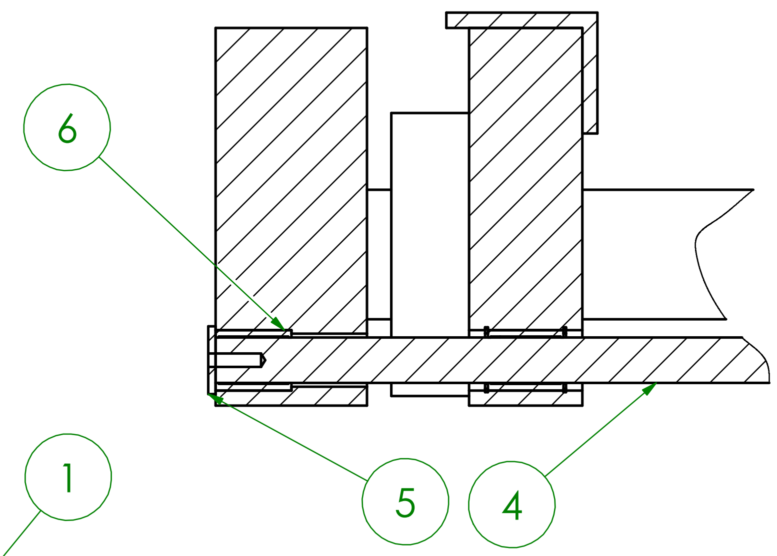

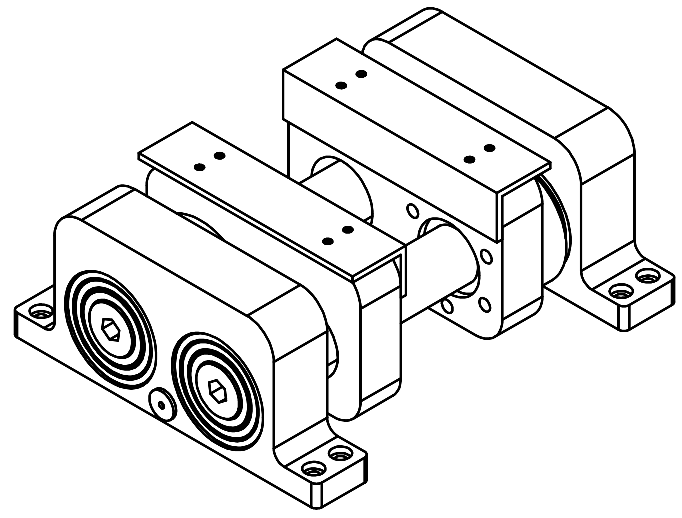

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3	Peça de aperto_s_mordente	**1201133_2025_14_A2**				2	
4	veio guia	**1201133_2025_11**				1	
5	Tamapa veio guia	**1201133_2025_12**				2	
6	inafag_kh30-pp_ccw3s5bdkb5dccpb35tyunit2(Part	**buy**	SCHAEFFLER KH30-PP			2	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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Proprietário legal	Título	Número
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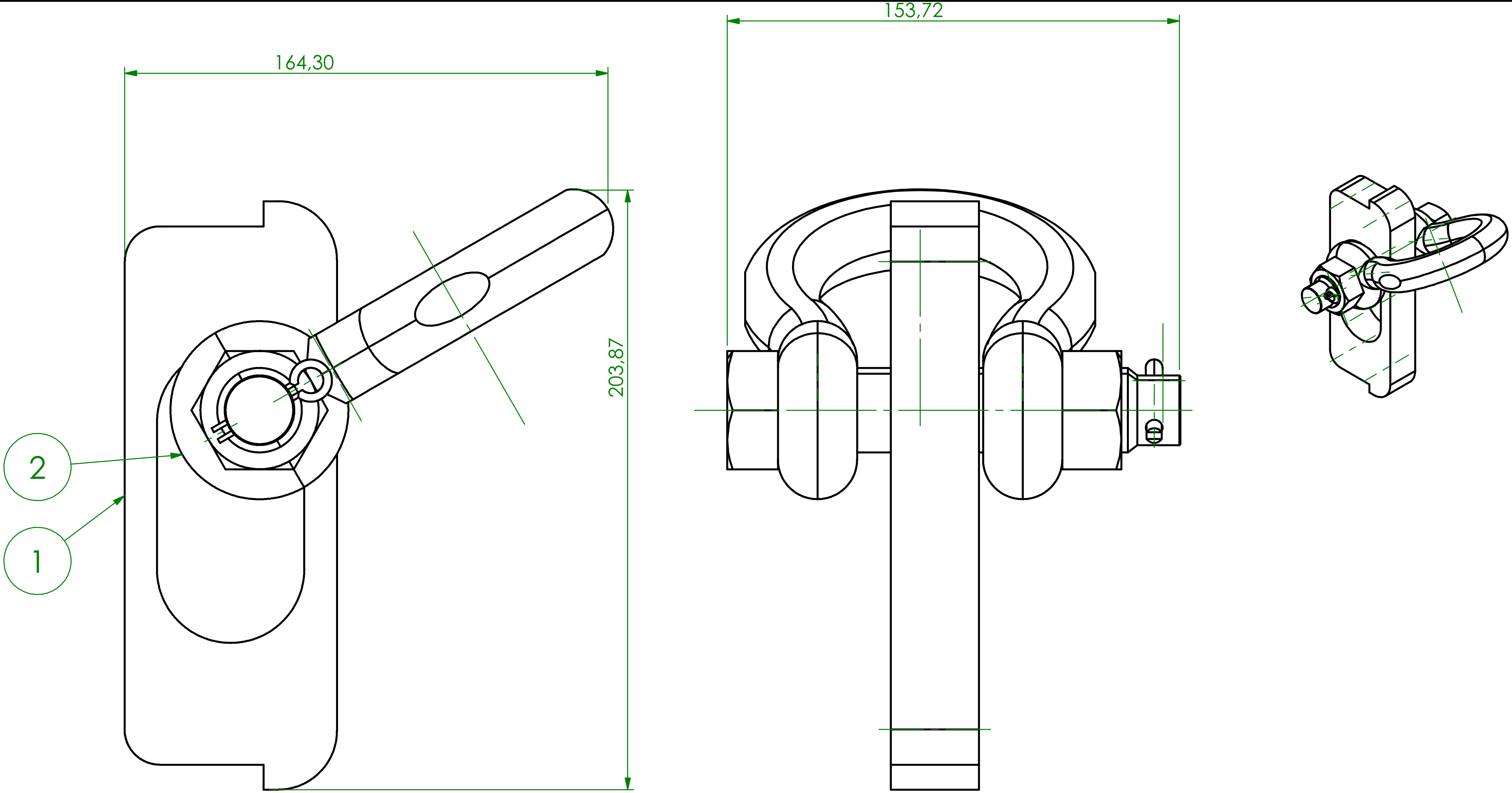

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título
1201133_2025_16_A4

Número
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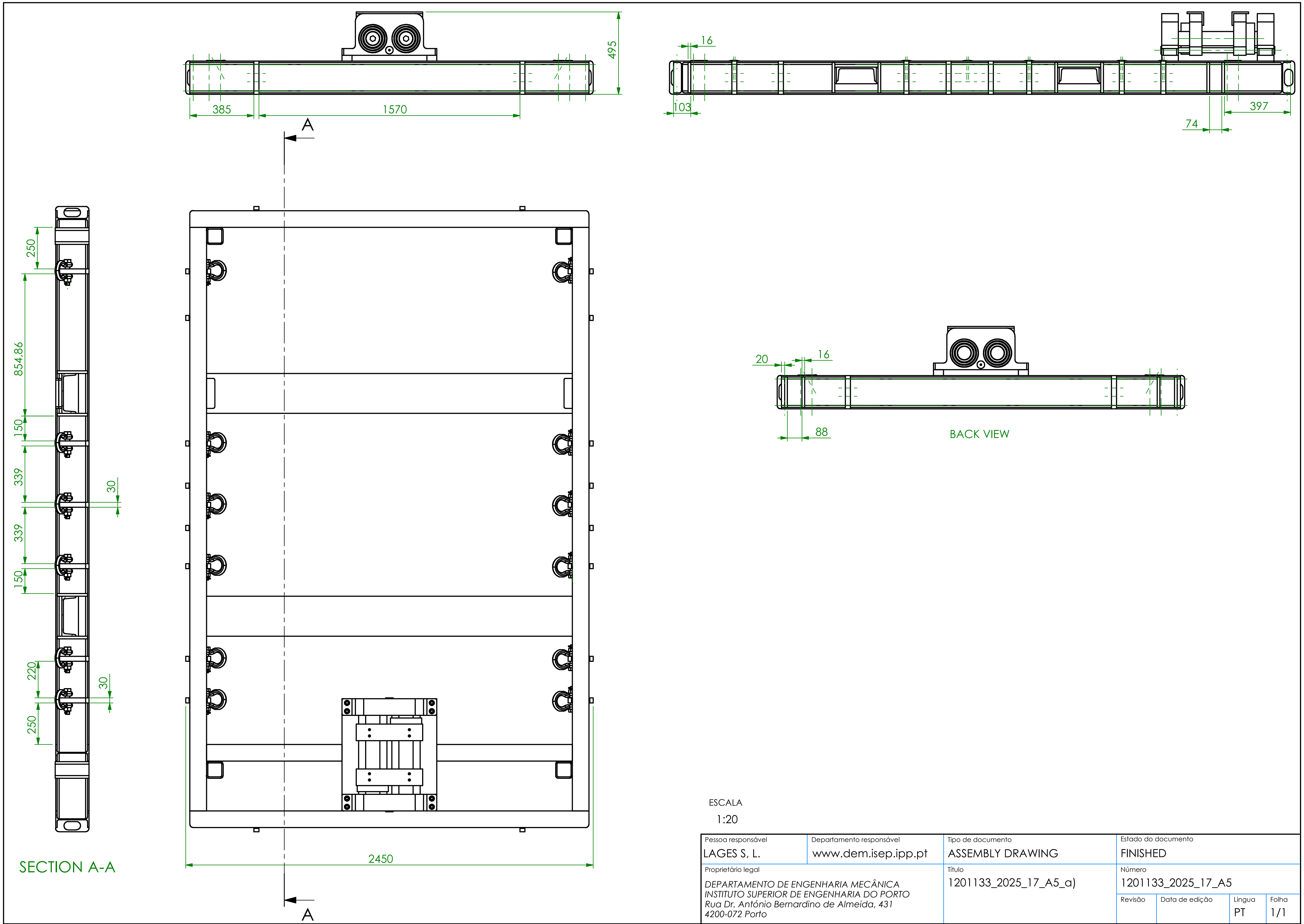

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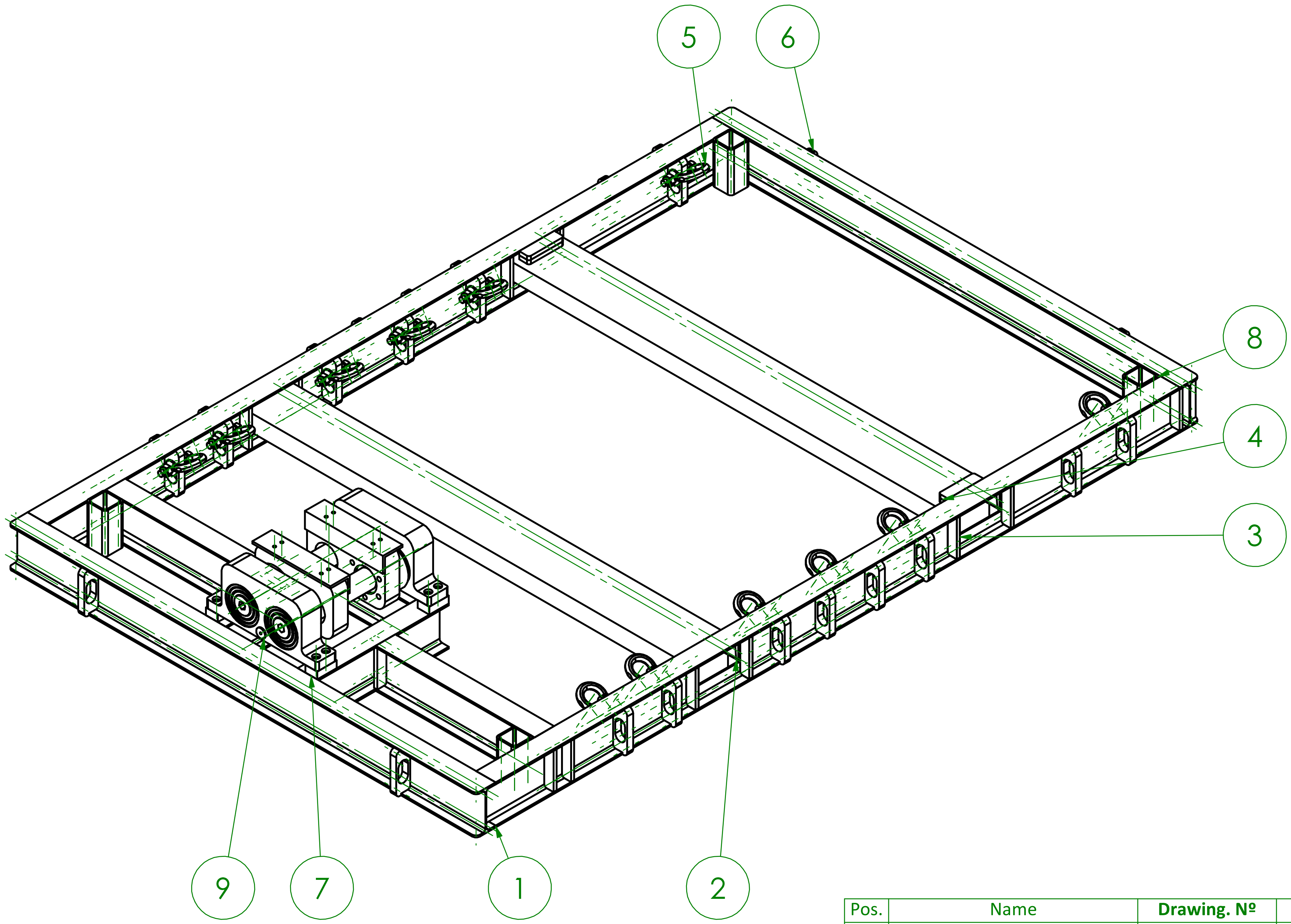

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2	UPN240_Empilhadora	**1201133_2025_06**				2	
3	Reforço base	**1201133_2025_02**				38	
4	REFORÇO HORIZONTAL_VIGAU_Modelp	**1201133_2025_05**				4	
5	Orelhas para lashing_ASS_M	**1201133_2025_16_A4**				12	
6	Orelha_Lashing_Modelado_M	**1201133_2025_03**				20	
7	BASE TRAVAO	**1201133_2025_07**				4	
8	tubo_Lashing_MODELO_O_sistema inferio model oO	**1201133_2025_04**				4	
9	Travão regulável 3	**1201133_2025_15_A3**				1	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título: 1201133_2025_17_A5_b)

Número: 1201133_2025_17_A5_c)

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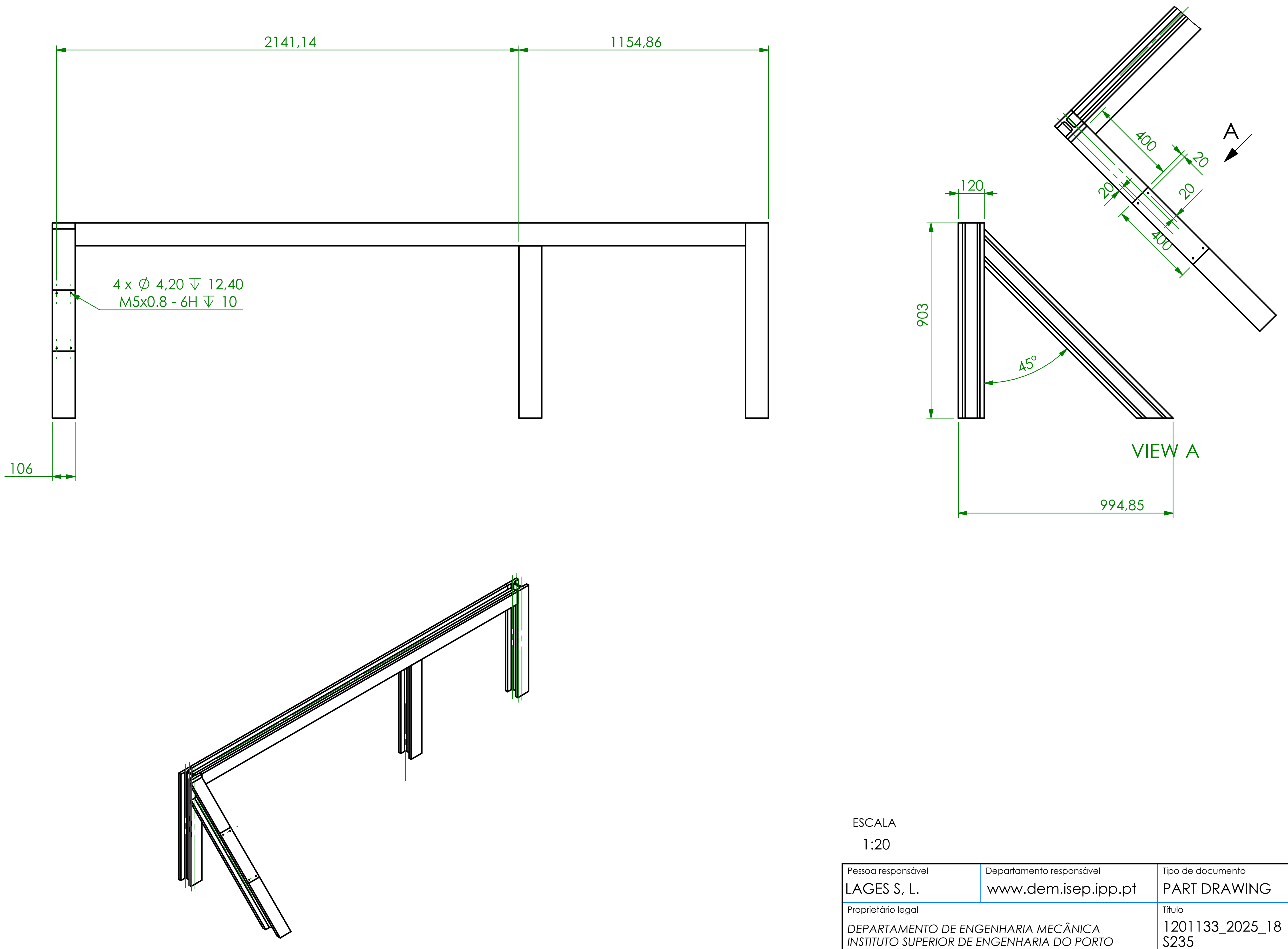

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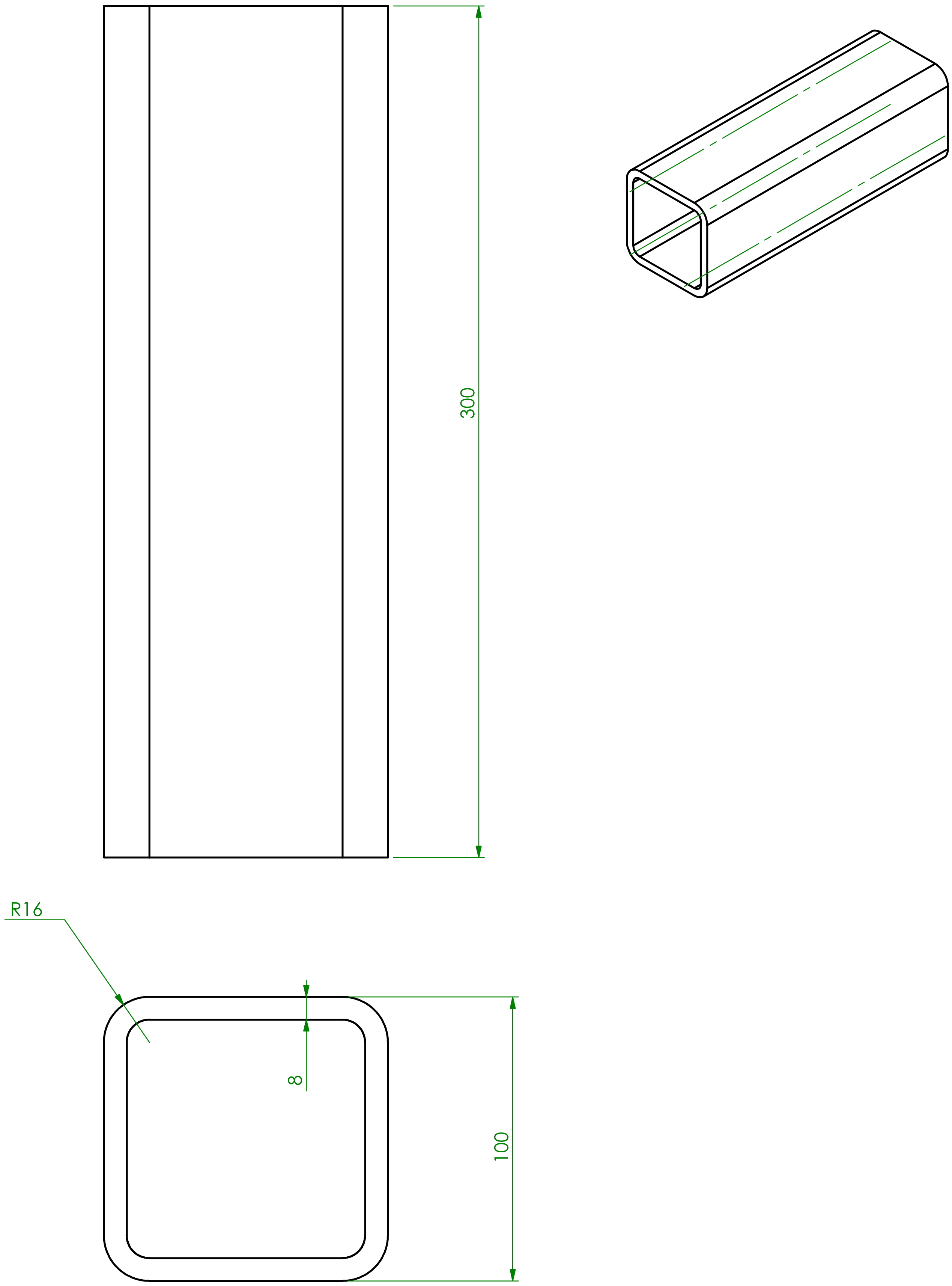

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título

1201133_2025_19
S235

Número

1201133_2025_19

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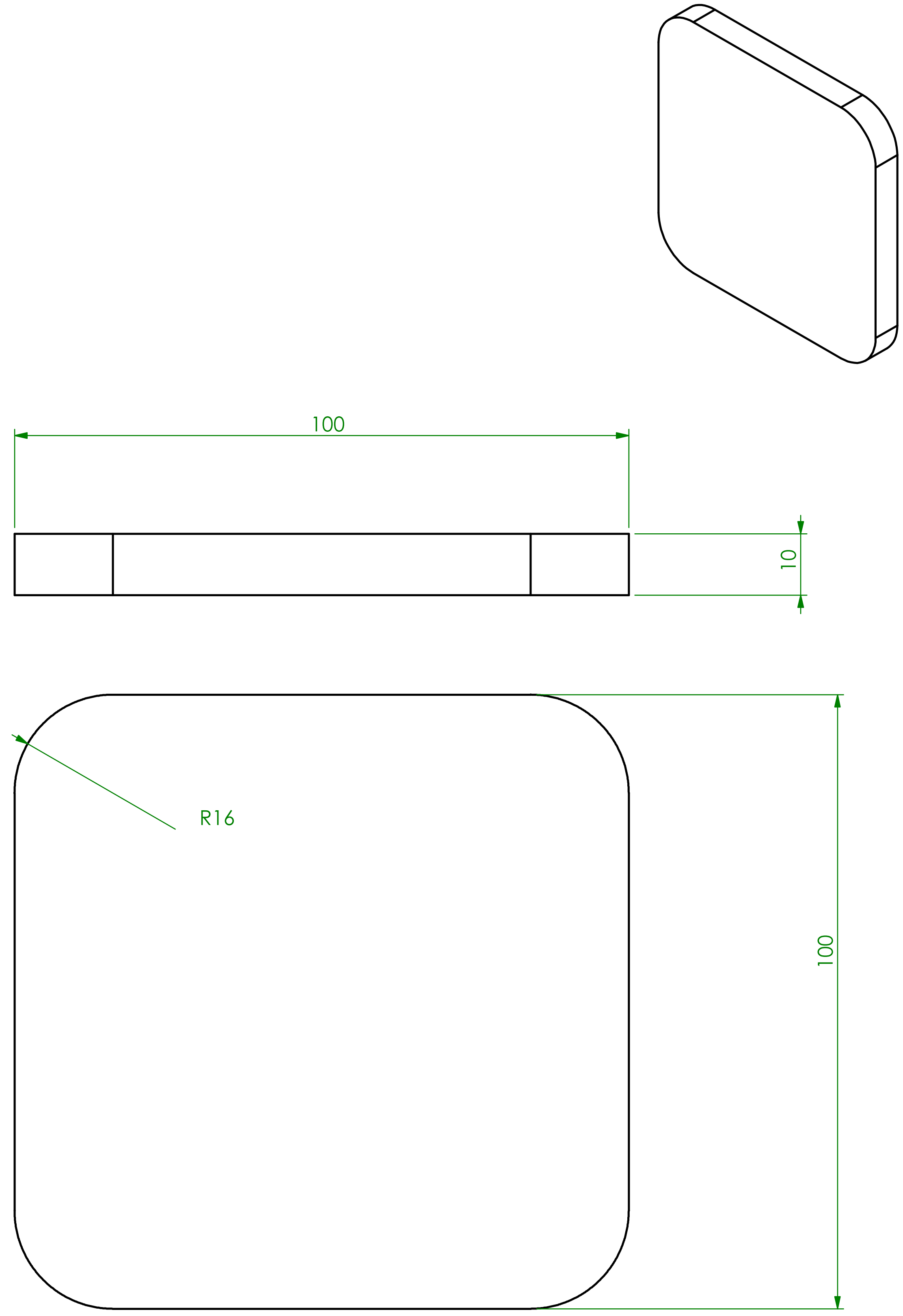

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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Proprietário legal	Título	Número
DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto	1201133_2025_20 S235	1201133_2025_20

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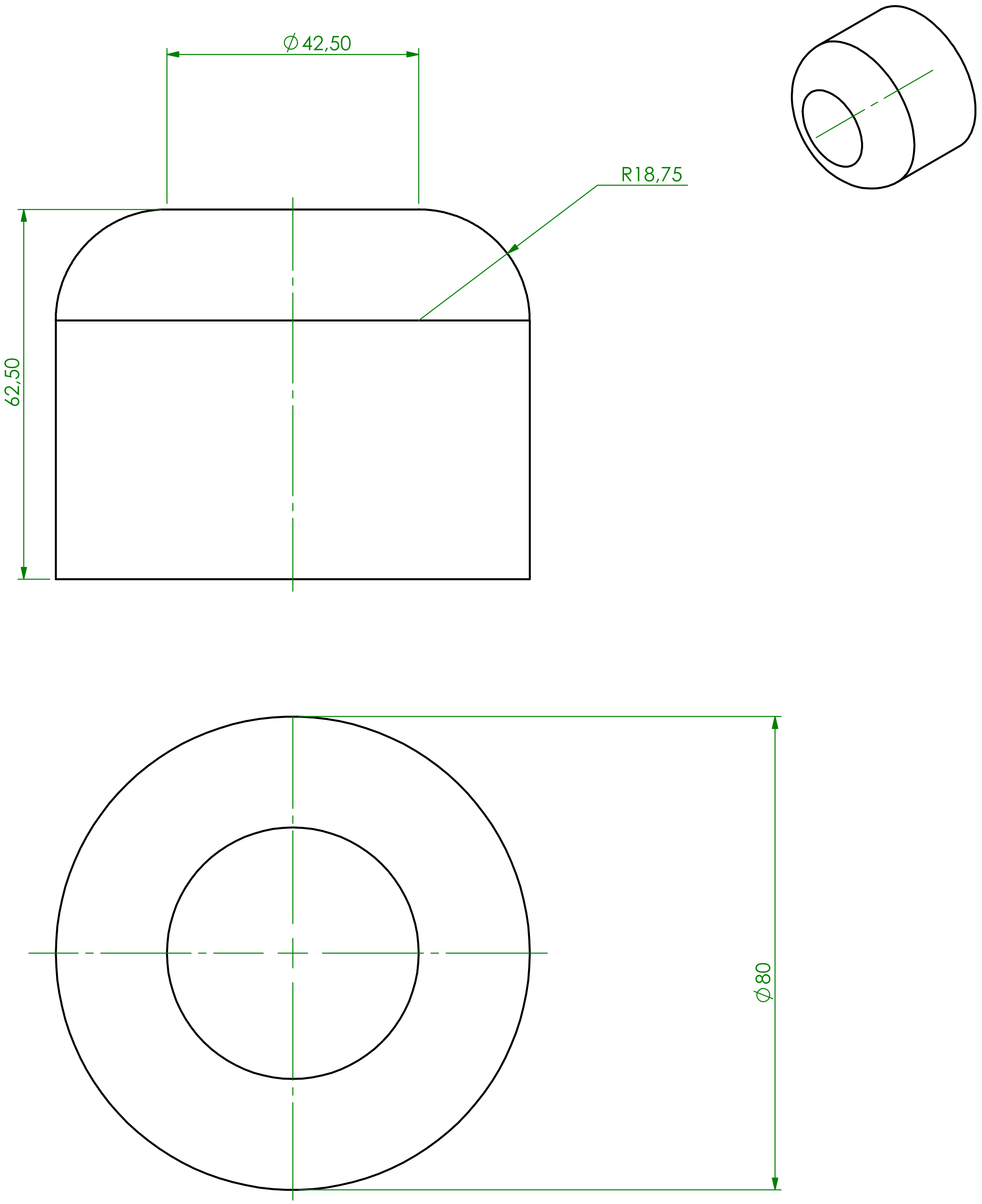

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Proprietário legal		Título	Número			
DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		1201133_2025_21 S235	1201133_2025_21			
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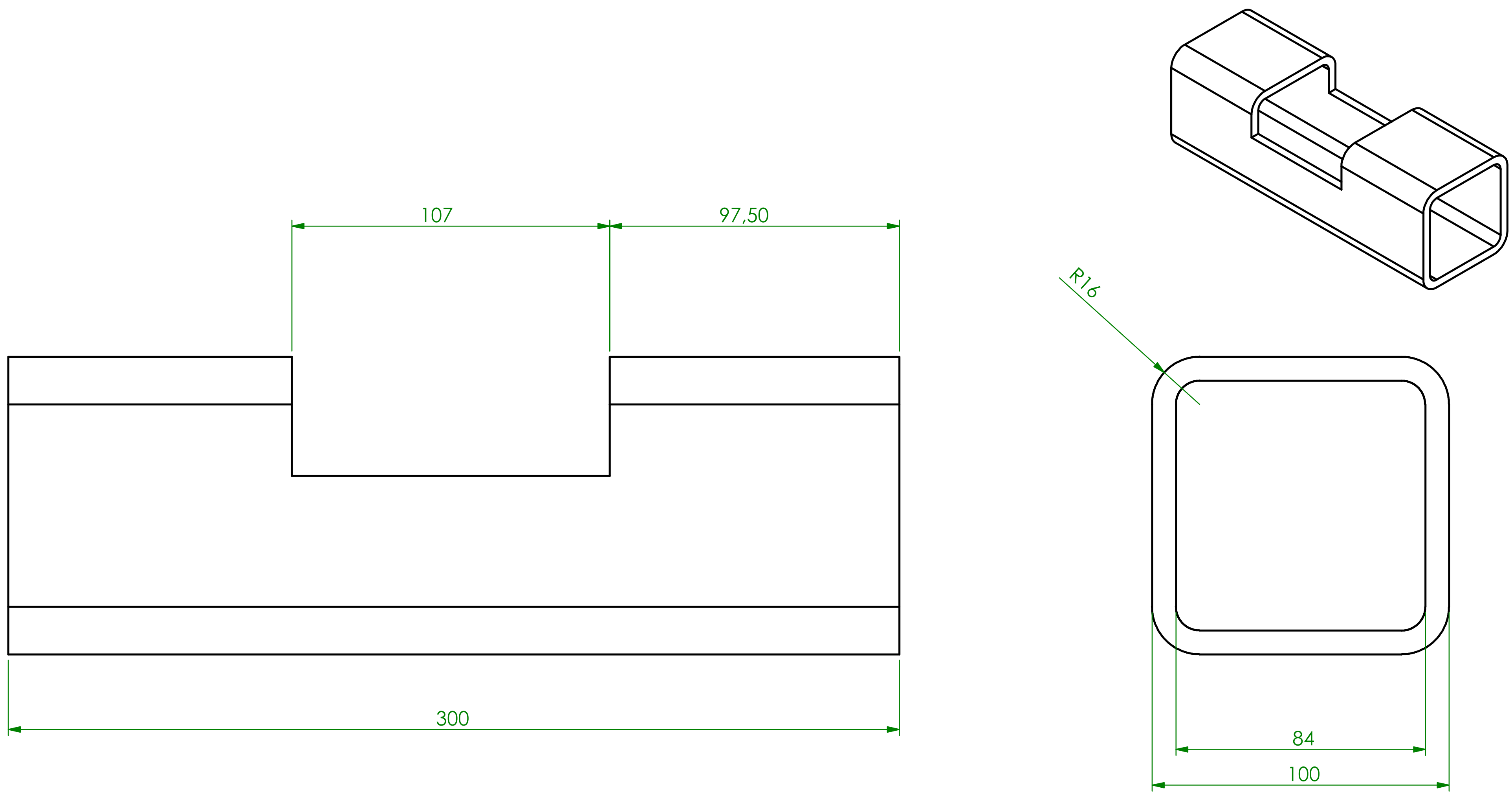

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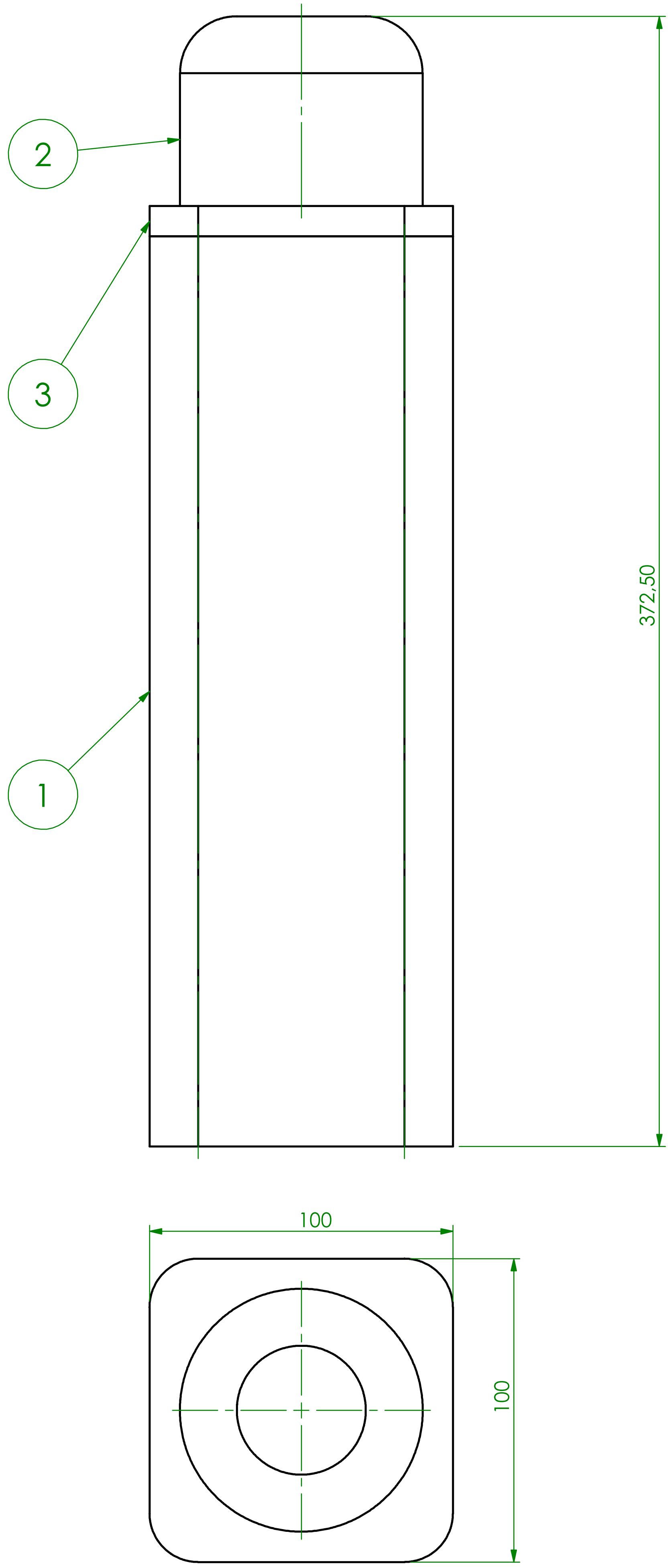
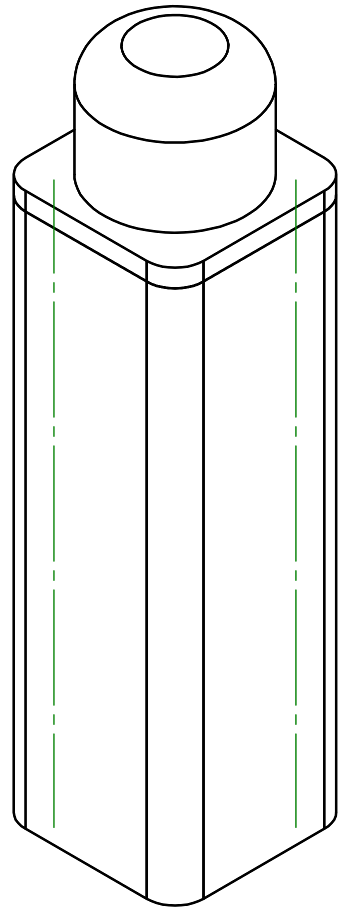
Proprietário legal *DEPARTAMENTO DE ENGENHARIA MECÂNICA* *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		Título 1201133_2025_22 S235	Número 1201133_2025_22 Revisão / Data de edição / Lingua: PT / Folha: 1/1





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2	Taco para empilhamento	**1201133_2025_21**				1	
3	tampa sistema empilhamento_Modelo_E	**1201133_2025_20**				1	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
LAGES S, L.	www.dem.isep.ipp.pt	ASSEMBLY DRAWING	FINISHED

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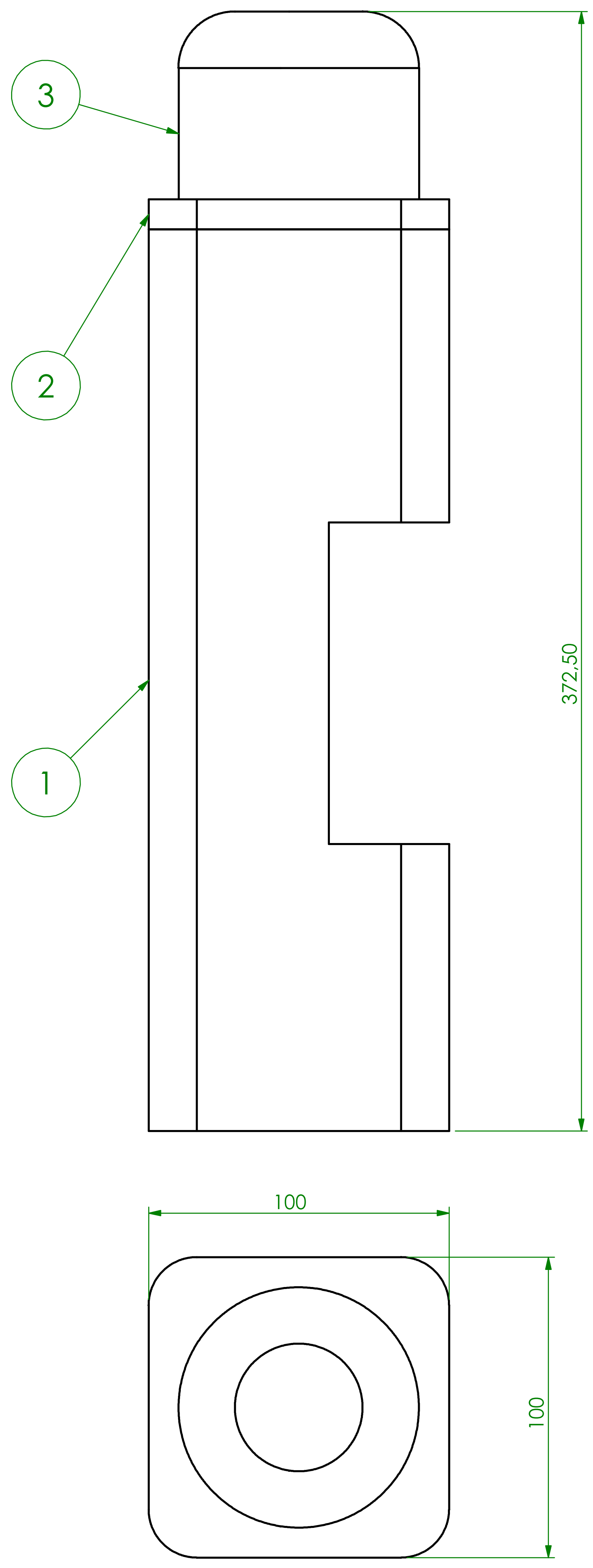
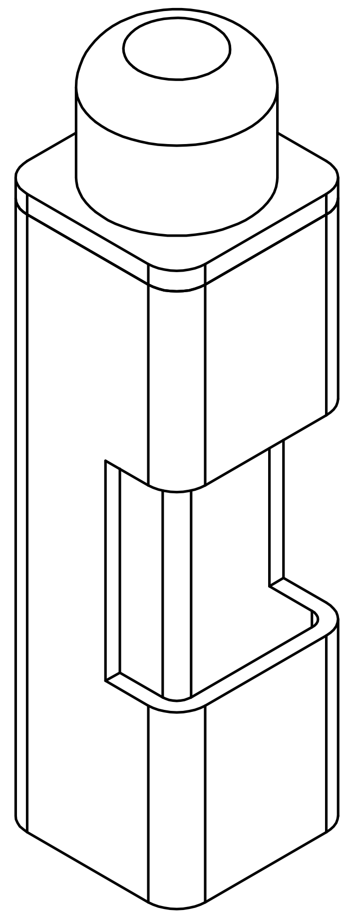
DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título: 1201133_2025_23_A6

Número: 1201133_2025_23_A6

Revisão	Data de edição	Língua	Folha
		PT	1/1





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2	tampa sistema empilhamento_Modelo_E	1201133_2025_20				1	
3	Taco para empilhamento	1201133_2025_21				1	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título: 1201133_2025_24_A7

Número: 1201133_2025_24_A7

Revisão	Data de edição	Língua	Folha
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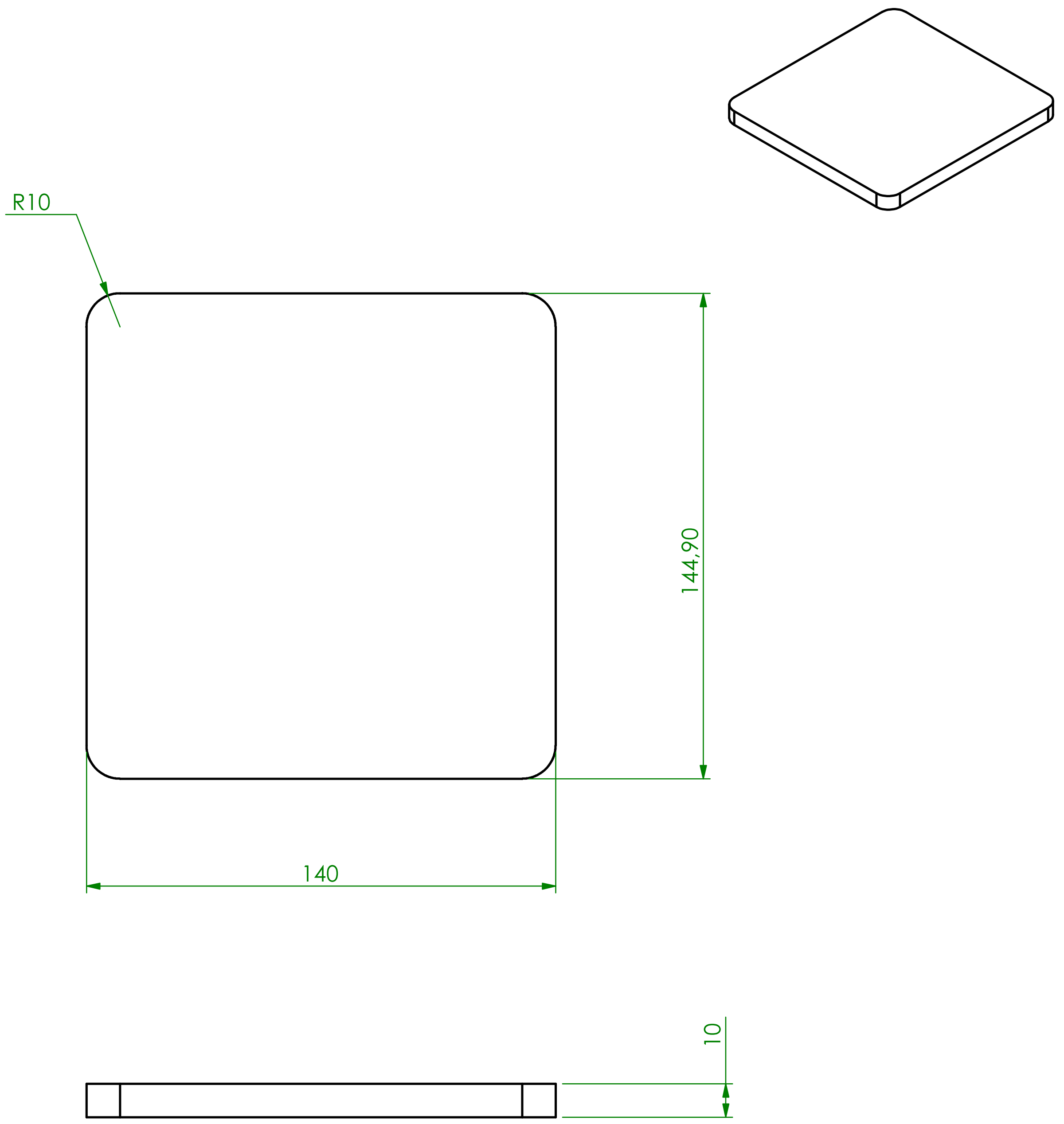

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
LAGES S, L.	www.dem.isep.ipp.pt	PART DRAWING	FINISHED

Proprietário legal	Título	Número			
DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto	1201133_2025_25 S235	1201133_2025_25			
		Revisão	Data de edição	Lingua	Folha
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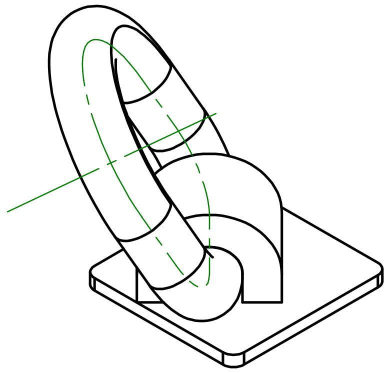

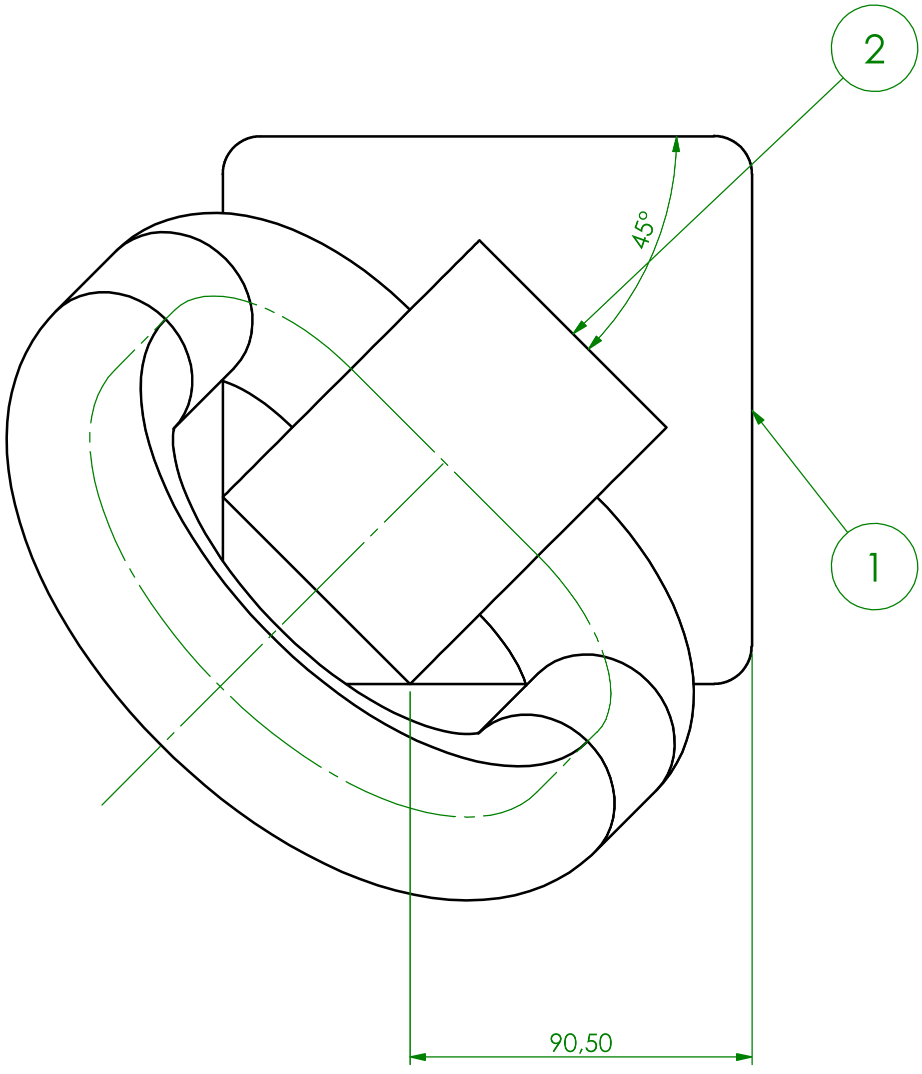

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1:2	2	Conjunto olhal modelado_MODELK	buy	THIELE TWN 019			1	

Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
LAGES S, L.	www.dem.isep.ipp.pt	ASSEMBLY DRAWING	FINISHED

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Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título: 1201133_2025_26_A8

Número: 1201133_2025_26_A8

Revisão	Data de edição	Lingua	Folha
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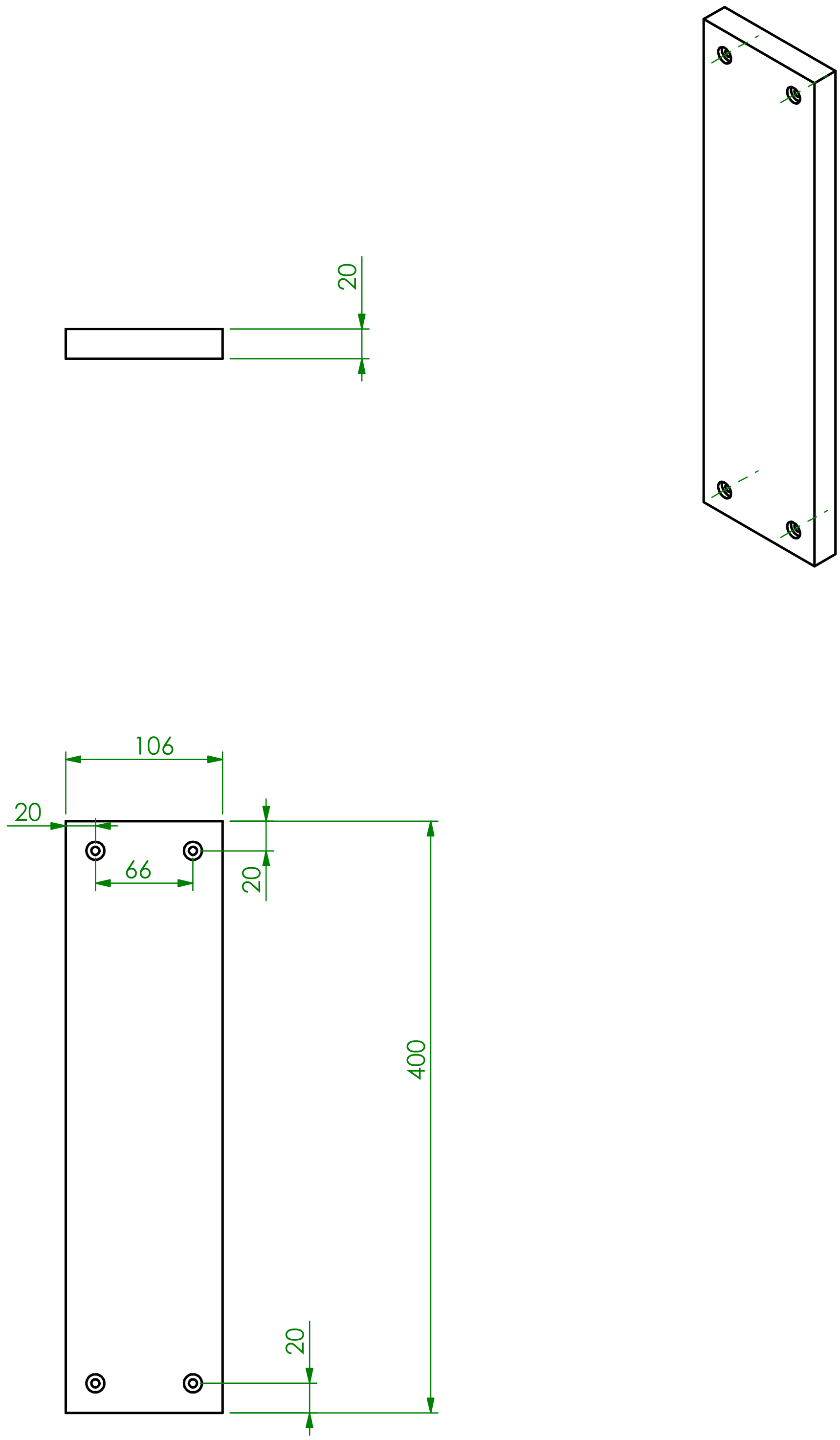

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Revisão	Data de edição	Lingua	Folha
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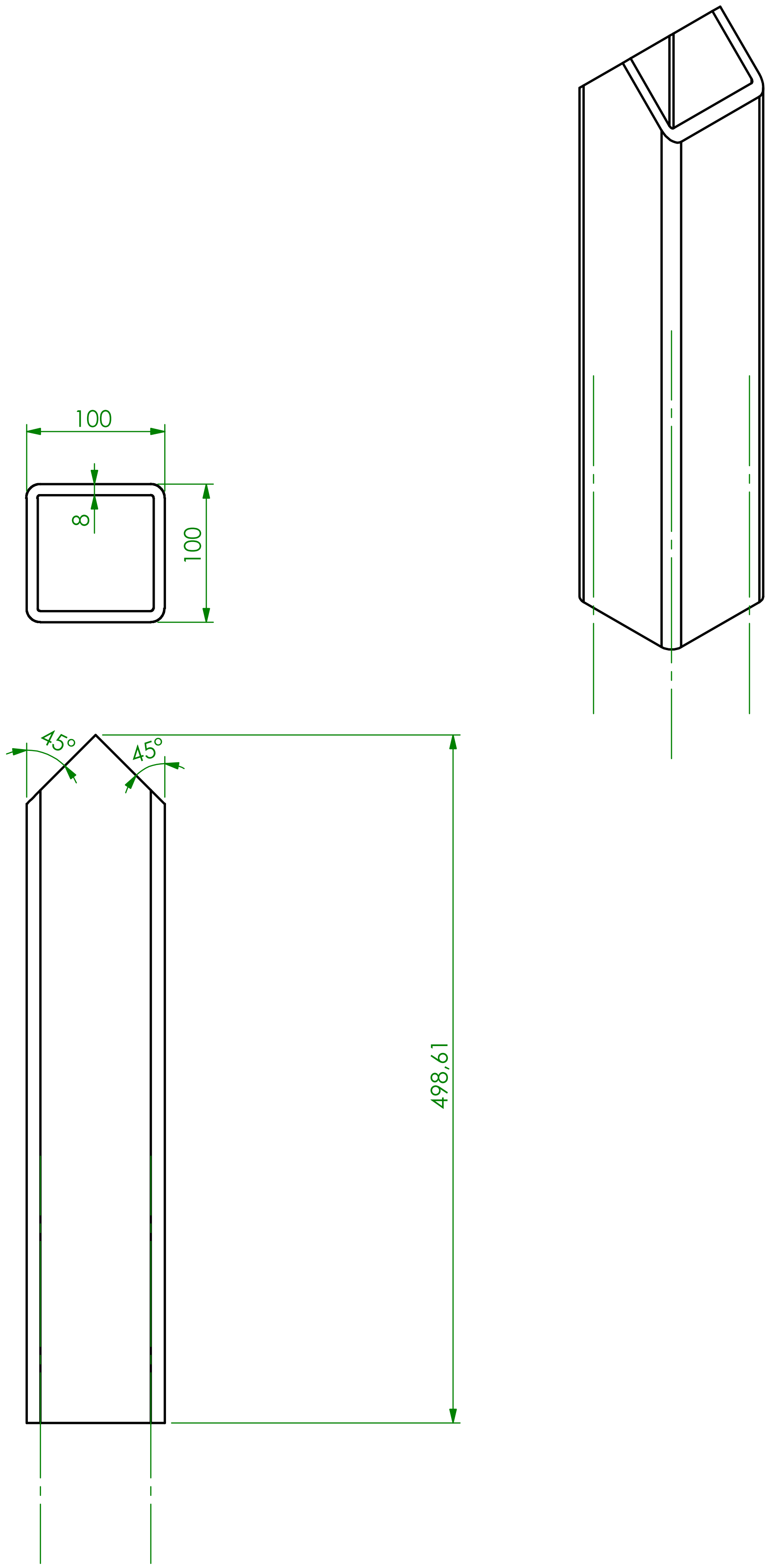

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DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*	1201133_2025_28 S235	1201133_2025_28

Revisão	Data de edição	Lingua	Folha
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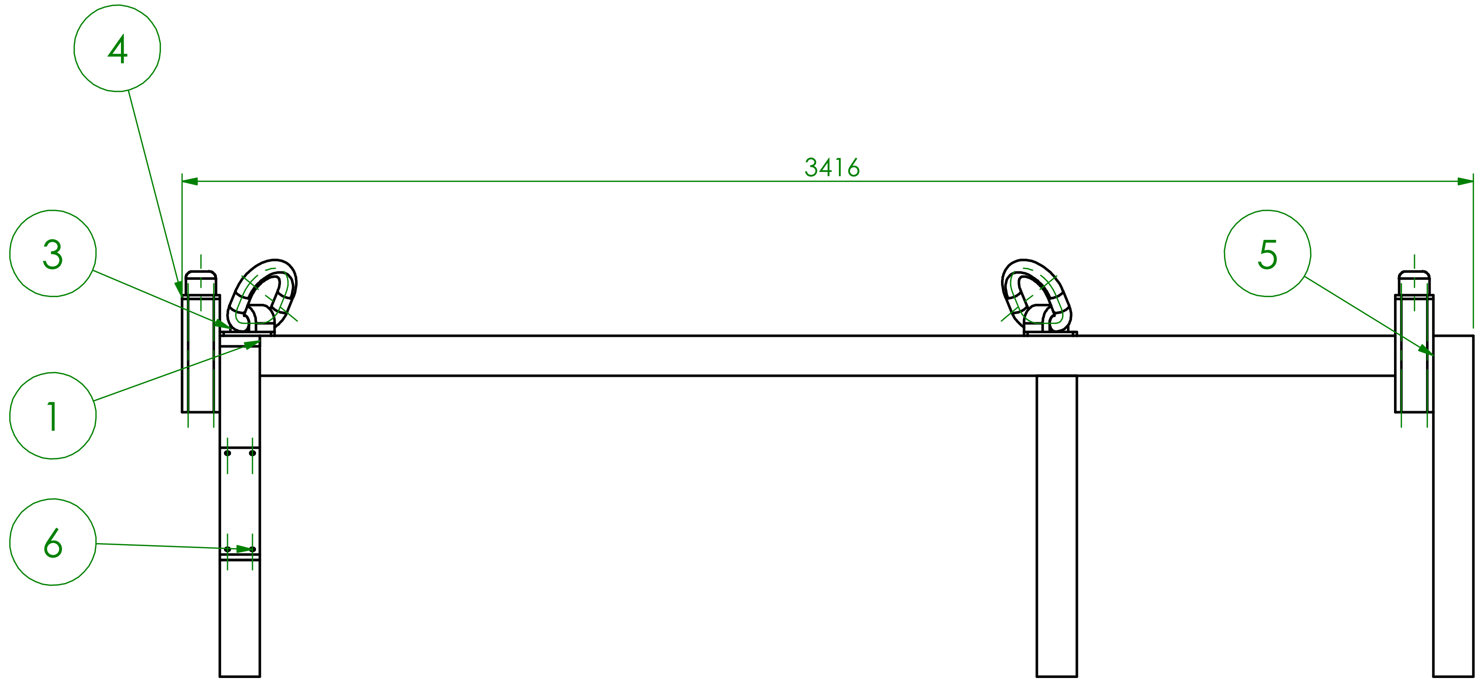

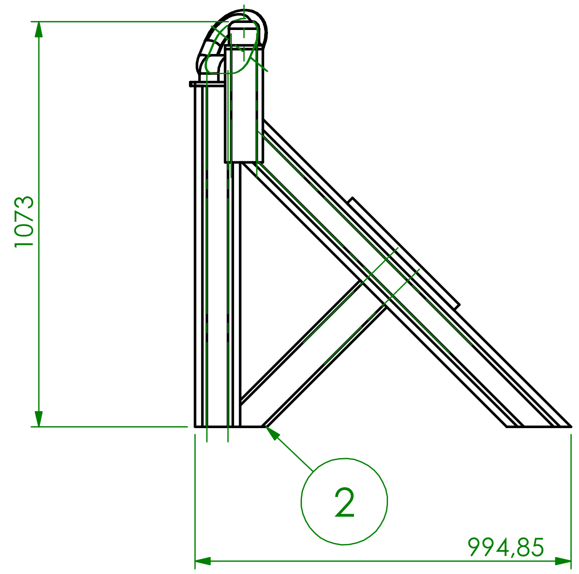

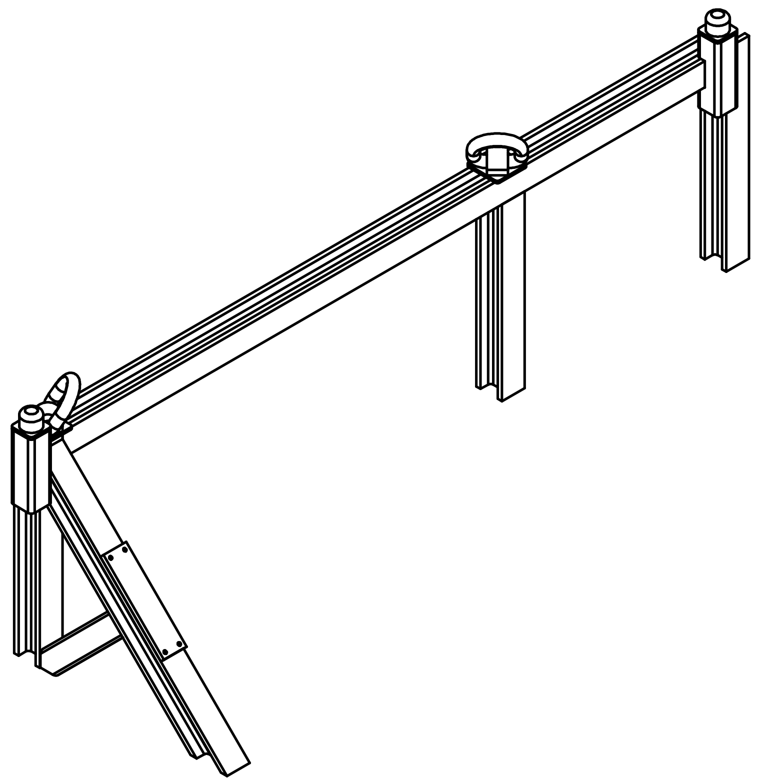

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Pos.	Name	Drawing. Nº	Material	Description	Type	Qty.	CL
1	Apoio_maior_Diametro_Q	1201133_2025_18				1	
2	TUBO SQUARE 100x100x8_nuniforme	1201133_2025_28				1	
3	Conjunto olhal_K	1201133_2025_26_A8				2	
4	Sistema de empilhamkento model O superior_3	1201133_2025_23_A6				1	
5	Sistema de empilhamkento model O superior_2	1201133_2025_24_A7				1	
6	BORRACHA SUPORTE MAIOR	1201133_2025_27				1	

Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto	1201133_2025_29_A9	1201133_2025_29_A9

Revisão	Data de edição	Lingua	Folha
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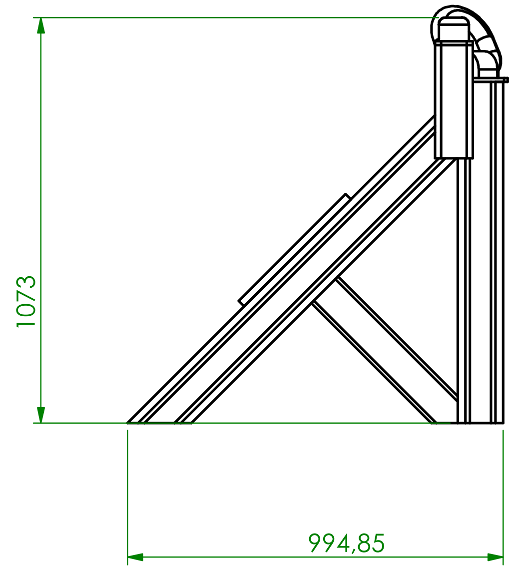

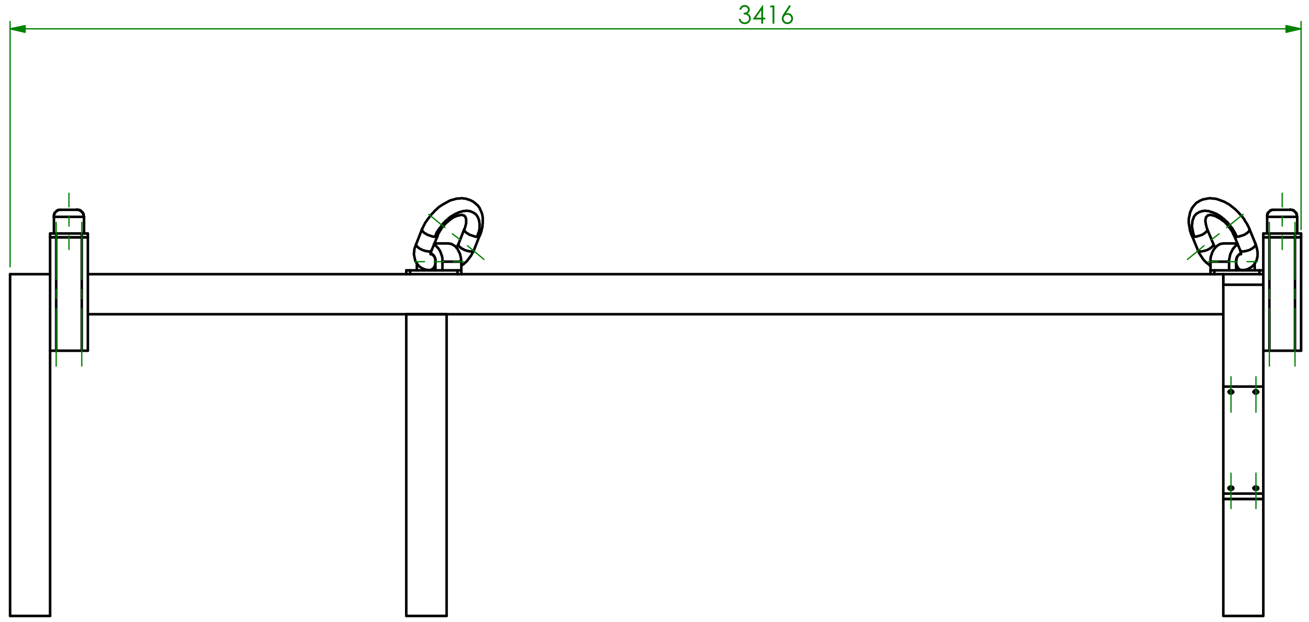

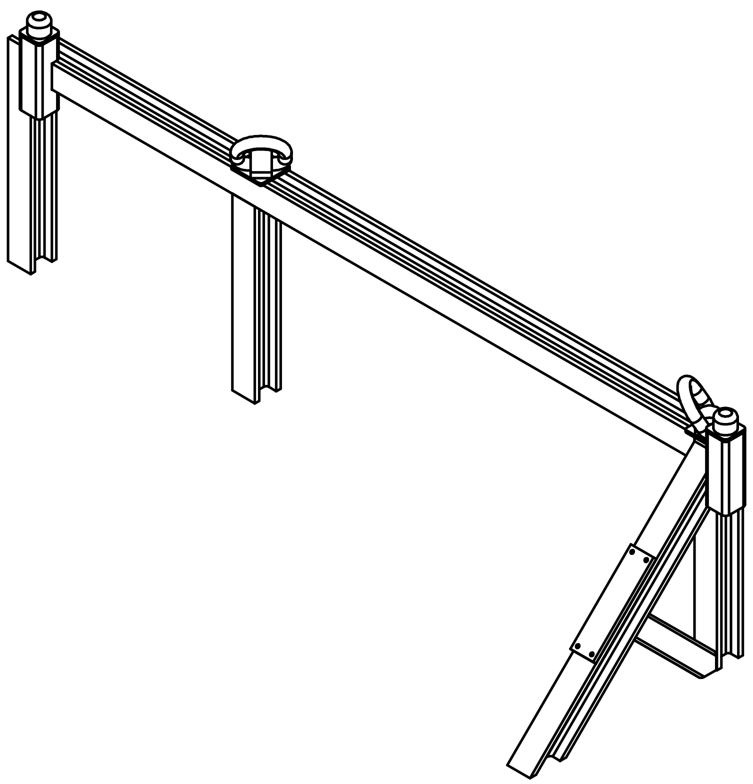

Pos.	Name	Drawing. Nº	Material	Description	Type	Qty.	CL
1	TUBO SQUARE 100x100x8_nuniforme	1201133_2025_28				1	
2	Apoio_maior_Diametro_Esq_H	1201133_2025_18 ESQ				1	
3	Conjunto olhal_K	1201133_2025_26_A8				2	
4	Sistema de empilhamkento model O superior_3	1201133_2025_23_A6				1	
5	Sistema de empilhamkento model O superior_2	1201133_2025_24_A7				1	
6	BORRACHA SUPORTE MAIOR	1201133_2025_27				1	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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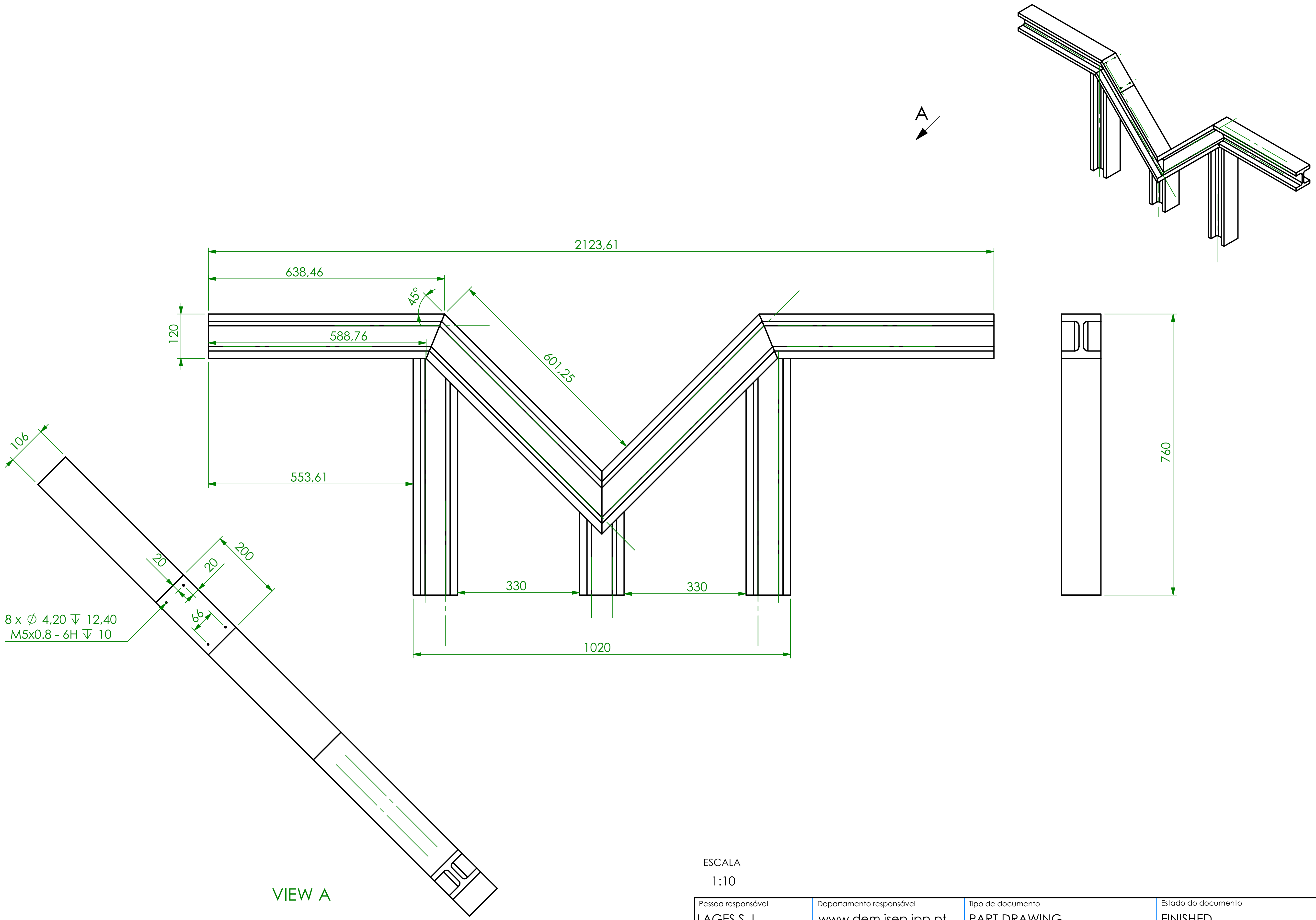
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título
1201133_2025_30_A10

Número
1201133_2025_30_A10

Revisão	Data de edição	Lingua	Folha
		PT	1/1



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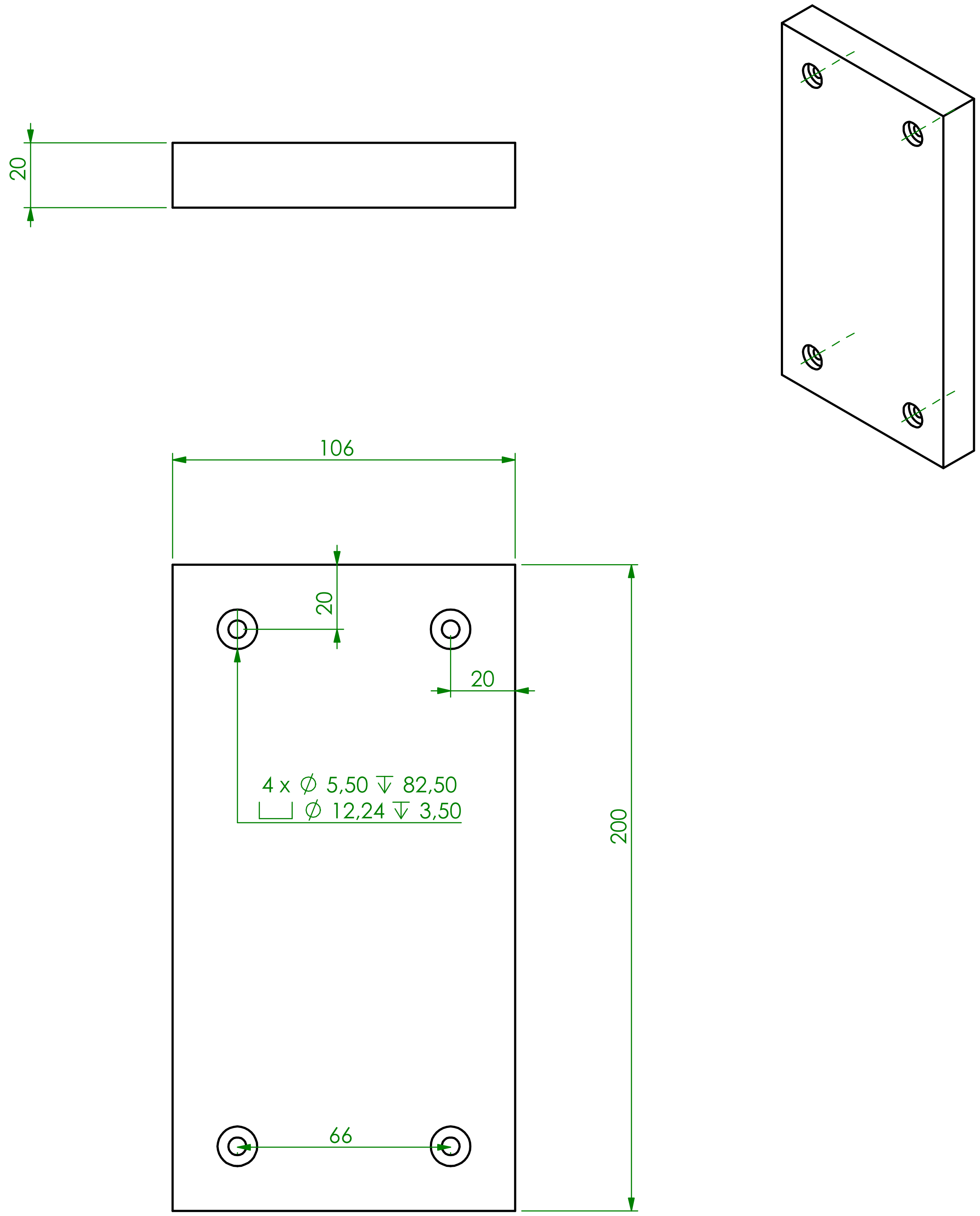
Proprietário legal		Título	Número
DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto		1201133_2025_31 S235	1201133_2025_31
			Revisão / Data de edição / Lingua: PT / Folha: 1/1



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Proprietário legal		Título	Número			
DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		1201133_2025_32 PVC-CAW SIMONA	1201133_2025_32			
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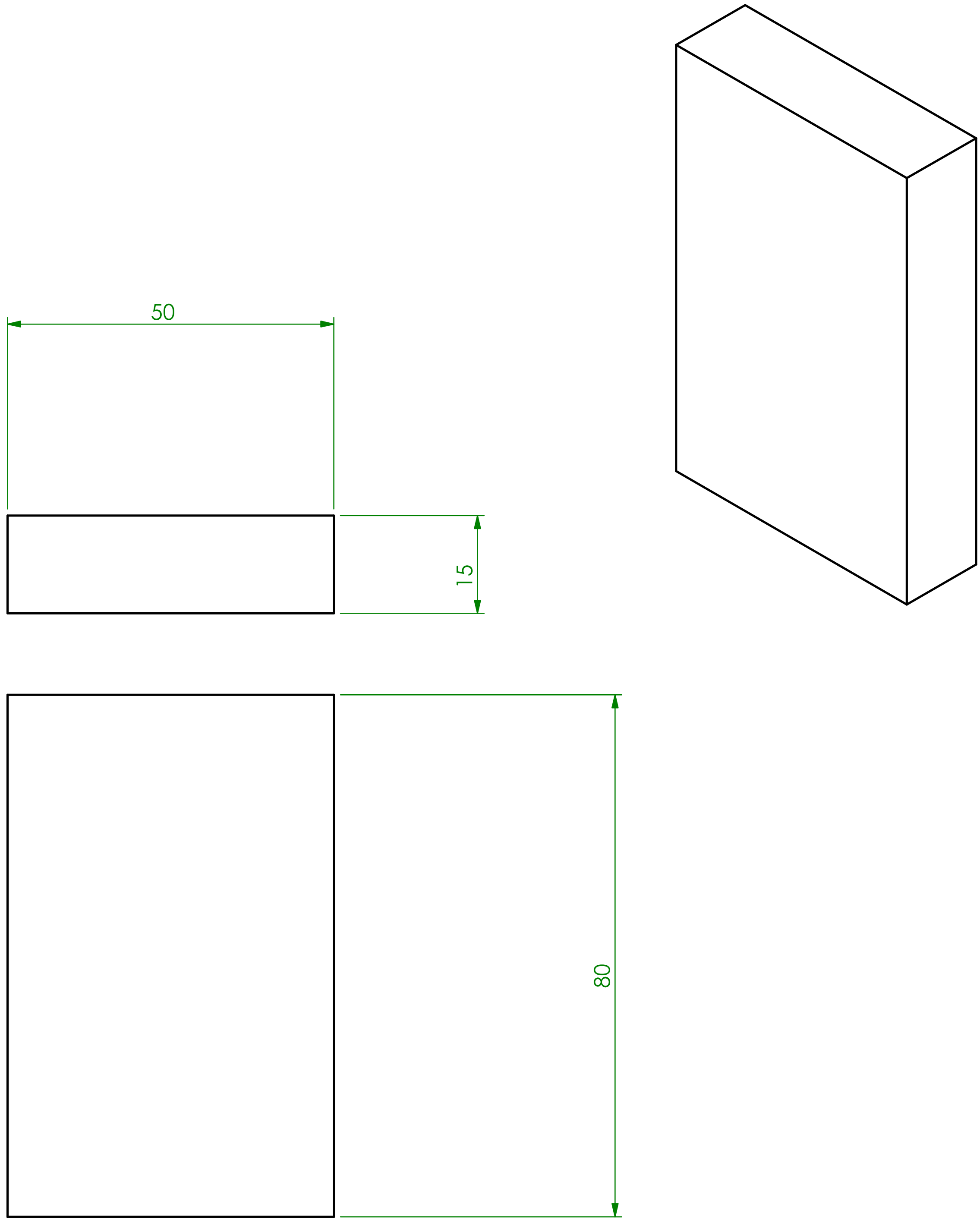

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento			
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Proprietário legal		Título	Número			
DEPARTAMENTO DE ENGENHARIA MECÂNICA *INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO* *Rua Dr. António Bernardino de Almeida, 431* *4200-072 Porto*		1201133_2025_33 S235	1201133_2025_33			
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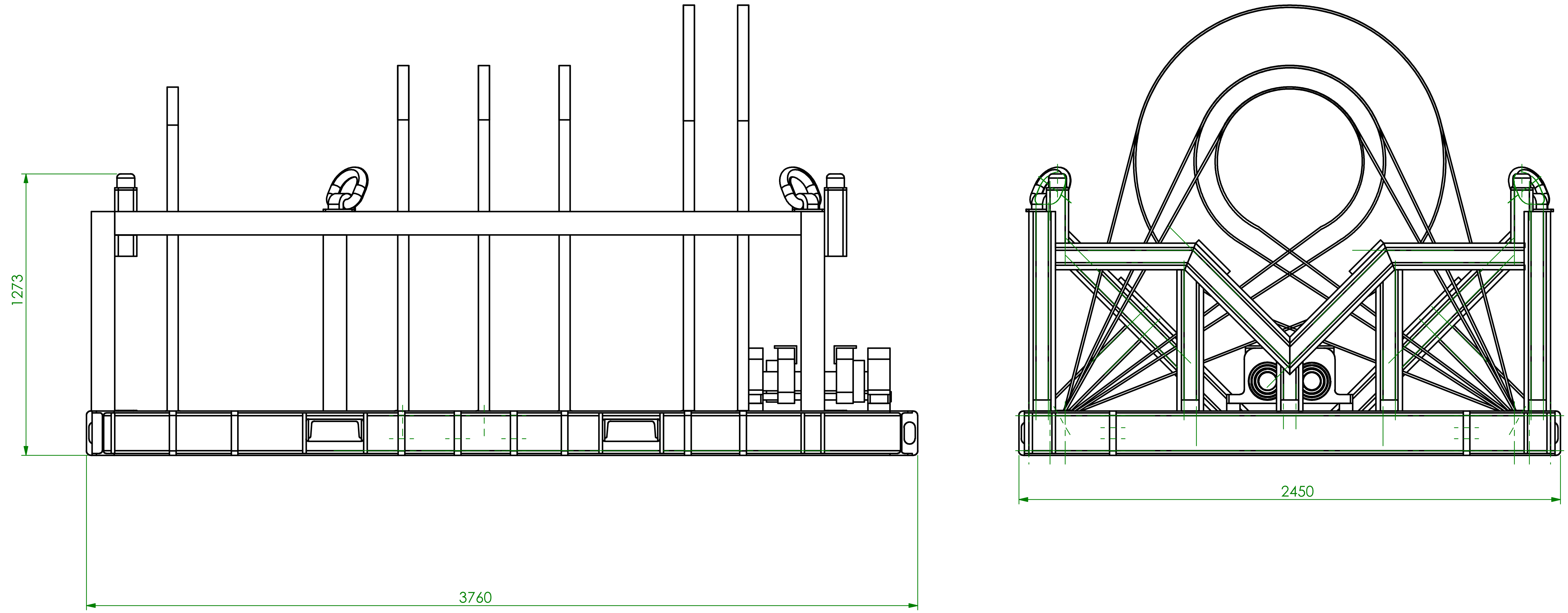
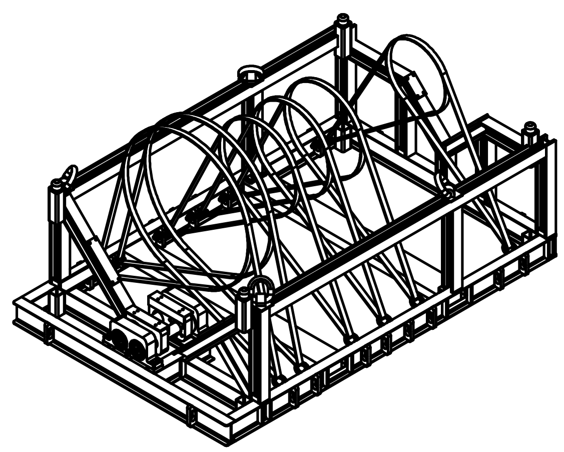
					PT	1/1





All welds shall be full strength and shall not be less than 0.7x the thickness of
the thinnest material being welded. All welds shall be free from porosity, slag
and splatter. Unless otherwise stated, all welds shall be continous.
Welders shall be qualified in accordance with ISO 9606-1:2012.
All welds shall be made according to ISO 5817:2023, level D acceptance
criteria

SURFACE TREATMENT
All bolts, nuts and washers shall be zinc plated as per EN ISO 4042:2018
except otherwise stated.

PAINTING GENERAL
degreasing or sand blasting
RAL: 5012

DIMENSIONAL TOLERANCES
General dimensional tolerances unless otherwise stated according to:

Linear	Diagonal	Uprightness
0–500 mm: ±1.0 mm	0–1000 mm: ≤2 mm	≤100 mm: <1.0 mm
501–1000 mm: ±1.5 mm	1001–2000 mm: ≤3 mm	100–200 mm: <1.5 mm
1001–2000 mm: ±2.0 mm	2001–3000 mm: ≤4 mm	200–300 mm: <2.0 mm
2001–4000 mm: ±2.5 mm	3001–4000 mm: ≤5 mm	300 mm: <2.5 mm
4001–6000 mm: ±3.0 mm	4001– : ≤7 mm	

General tolerance for angles (if not specified on the drawing): ±1°
General tolerance for machined parts according to ISO 2768-1 medium.
◇ = Important dimensions for the functionality of the rack (key dimensions).

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1:20

Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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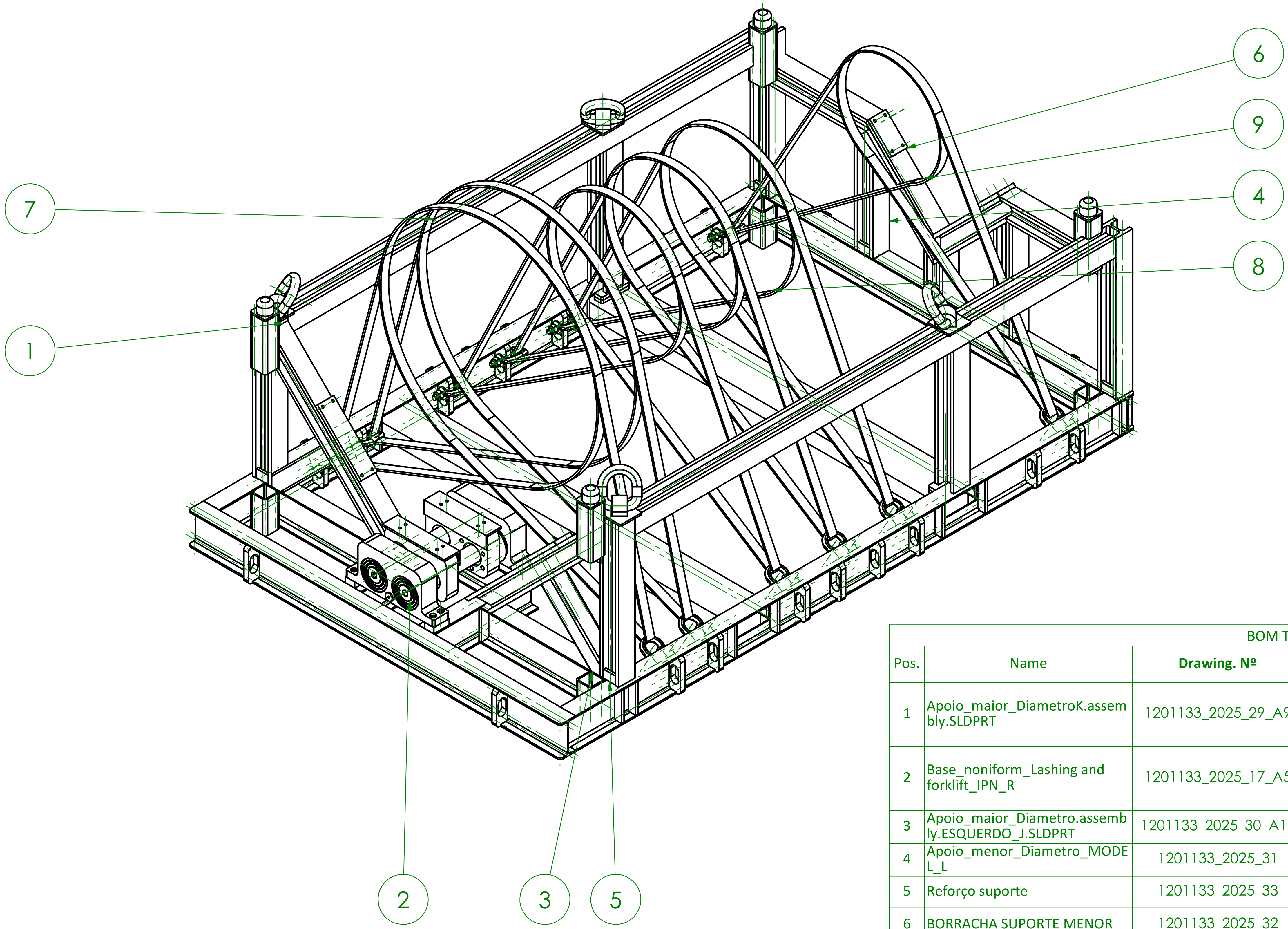
Proprietário legal		Título	Número
DEPARTAMENTO DE ENGENHARIA MECÂNICA INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO Rua Dr. António Bernardino de Almeida, 431 4200-072 Porto		1201133_2025_34_A11_a)	1201133_2025_34_A11
			Revisão / Data de edição / Lingua: PT / Folha: 1/1



BOM Table							
Pos.	Name	**Drawing. Nº**	Material	Description	Tipo	Qty.	CL
1	Apoio_maior_DiametroK.assembly.SLDPRT	1201133_2025_29_A9				1	
2	Base_noniform_Lashing and forklift_IPN_R	1201133_2025_17_A5				1	
3	Apoio_maior_Diametro.assembly.ESQUERDO_J.SLDPRT	1201133_2025_30_A10				1	
4	Apoio_menor_Diametro_MODEL_L	1201133_2025_31				1	
5	Reforço suporte	1201133_2025_33				14	
6	BORRACHA SUPORTE MENOR	1201133_2025_32				2	
7	Cinta_1	**buy**	Cordlash HDB12N 6 t or similar (5 meters)			4	
8	Cinta_2	**buy**	Cordlash HDB12N 6 t or similar (3.5 meters)			6	
9	Cinta_3	**buy**	Cordlash HDB12N 6 t or similar (3.5 meters)			2	

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Pessoa responsável	Departamento responsável	Tipo de documento	Estado do documento
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DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto

Título: 1201133_2025_34_A11_b)

Número: 1201133_2025_34_A11

Revisão	Data de edição	Lingua	Folha
		PT	1/1

Annex A

Trade name: **SIMONA® PVC-CAW**
Date of printing: 11.06.2025

Revision: 21.06.2023

	SIMONA® PVC-CAW
Data sheet update	21.06.2023
Moulding compound extruded	PVC-U,EDP,074-05-T33
Extruded to moulding compound standard	DIN EN ISO 21306, Teil 1
Density, g/cm³, DIN EN ISO 1183	1.44
Tensile modulus of elasticity, MPa, DIN EN ISO 527	3,300
Yield stress, MPa, DIN EN ISO 527	58
Elongation at yield, % , DIN EN ISO 527	4
Impact strength, kJ/m², DIN EN ISO 179	-
Notched impact strength Charpy, kJ/m², DIN EN ISO 179-1eA	4
Dielectric strength, kV/mm , DIN IEC 60243-1	39
Shore hardness D (15 s), DIN EN ISO 868	82
Mean coefficient of linear thermal expansion, K^{-1} , ISO 11359-2	0,8 x 10^{-4}
Vicat B, °C , DIN EN ISO 306	74
Surface resistivity, Ohm , DIN EN 61340	≥ 10^{13}
Temperature range, °C	0 to +60
Fire behaviour DIN 4102	DIN 4102, B1 low flammability, 1 to 4 mm
Fire behaviour DIN EN 13501-1	DIN EN 13501, B – s3, d0, 1 to 10 mm
Fire behaviour UL 94	UL 94 V-0, up from 1 mm
Note	Contrary to the figures listed above, the following specifications shall apply to round rods made of PVC-U: Density in accordance with DIN EN ISO 1183: >= 1.37 g/cm³. Notched impact strength in accordance with DIN EN ISO 179: >= 2 kJ/m²

	SIMONA® PVC-CAW
Physiological safety in accordance with BfR (German Federal Institute for risk valuation)	no
Fire behaviour BS 476	BS 476 class 1 for 3 mm
Fire behaviour BS 476	BS 476 class 1 for 3 mm

All specifications are deemed to be approximate values in respect of the specific material and may vary depending on the processing methods used. In general, data specified applies to average values measured on extruded sheets with a thickness of 4 mm. In the case of sheets manufactured by means of pressing, testing is generally performed on sheets with a thickness of 20 mm. Deviations from the values specified are possible if the sheets in this thickness are not available. In the case of backed sheets, all technical specifications relate to the non-backed base sheets. Information presented herein is not necessarily applicable to other products (e.g. pipes, solid rods) of the same material or products that have undergone downstream processing. Suitability of materials for a specific field of application must be assessed by the party responsible for processing or the end-user. All technical specifications presented herein are designed merely to provide assistance in terms of project planning. They do not constitute a guarantee of specific properties or qualities. All technical specifications and temperature ranges were determined in short-term tests and therefore cannot be used for design work for permanent, long-term use that requires long-term properties. For further information, please contact our Technical Service Centre at tsc@simona.de.

SAFETY DATA SHEET

Conforms to Regulation (EC) No. 1907/2006 (REACH), Annex II, as amended by Commission Regulation (EU) 2015/830

SECTION 1: Identification of the substance/mixture and of the company/ undertaking

1.1 Product identifier

Product identifier	:	2025000205093
Product name	:	AE30015501220 TEODUR AP RAL 5012 LIGHT BLUE MATT SMOOTH
Product type	:	Powder.
Other means of identification	:	Not available.
Date of issue	:	30 March 2020
Version	:	3
Date of previous issue	:	22 January 2020

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses	:	Powder coating for industrial use.
Uses advised against	:	For industrial use only by trained professionals. Not for sale to or use by consumers.

1.3 Details of the supplier of the safety data sheet

Axalta Coating Systems Germany GmbH & Co. KG
Christbusch 25
DE 42285 Wuppertal
+49 (0)202 529-0

e-mail address of person responsible for this SDS : sds-competence@axalta.com

National contact

Axalta Powder Coating Systems UK Ltd.
Whessoe Road
GB Darlington, County Durham. DL3 0XH
+44 (0)1325 355371

1.4 Emergency telephone number

Supplier

+(44)-870-8200418

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

Product definition : Mixture

Classification according to Regulation (EC) No. 1272/2008 [CLP/GHS]

Aquatic Chronic 3, H412

The product is classified as hazardous according to Regulation (EC) 1272/2008 as amended.

See Section 16 for the full text of the H statements declared above.

See Section 11 for more detailed information on health effects and symptoms.

2.2 Label elements

Hazard pictograms : Not applicable.

Signal word : No signal word.

Hazard statements : H412 - Harmful to aquatic life with long lasting effects.

Precautionary statements

Prevention : P273 - Avoid release to the environment.

Response : Not applicable.

Storage : Not applicable.

Disposal : P501 - Dispose of contents and container in accordance with all local, regional, national and international regulations.

Supplemental label elements : Not applicable.

Annex XVII - Restrictions on the manufacture, placing on the market and use of certain dangerous substances, mixtures and articles : Not applicable.

2.3 Other hazards

Product meets the criteria for PBT or vPvB according to Regulation (EC) No. 1907/2006, Annex XIII : This mixture does not contain any substances that are assessed to be a PBT or a vPvB.

Other hazards which do not result in classification : May form explosible dust-air mixture if dispersed.

SECTION 3: Composition/information on ingredients

3.2 Mixtures : Mixture

Product/ingredient name	Identifiers	%	Regulation (EC) No. 1272/2008 [CLP]	Type
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	REACH #: 01-2119977073-34 CAS: 26741-53-7	≤1	Aquatic Chronic 1, H410 (M=1)	[1]

SECTION 3: Composition/information on ingredients

			See Section 16 for the full text of the H statements declared above.	

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment, are PBTs, vPvBs or Substances of equivalent concern, or have been assigned a workplace exposure limit and hence require reporting in this section.

Type

[1] Substance classified with a physical, health or environmental hazard
[2] Substance with a workplace exposure limit
[3] Substance meets the criteria for PBT according to Regulation (EC) No. 1907/2006, Annex XIII
[4] Substance meets the criteria for vPvB according to Regulation (EC) No. 1907/2006, Annex XIII
[5] Substance of equivalent concern
[6] Additional disclosure due to company policy

Occupational exposure limits, if available, are listed in Section 8.

SECTION 4: First aid measures

4.1 Description of first aid measures

General : In all cases of doubt, or when symptoms persist, seek medical attention. Never give anything by mouth to an unconscious person. If unconscious, place in recovery position and seek medical advice.

Eye contact : Remove contact lenses, irrigate copiously with clean, fresh water, holding the eyelids apart for at least 10 minutes and seek immediate medical advice.

Inhalation : Remove to fresh air. Keep person warm and at rest. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel.

Skin contact : Remove contaminated clothing and shoes. Wash skin thoroughly with soap and water or use recognised skin cleanser. Do NOT use solvents or thinners.

Ingestion : If swallowed, seek medical advice immediately and show the container or label. Keep person warm and at rest. Do NOT induce vomiting.

Protection of first-aiders : No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

4.2 Most important symptoms and effects, both acute and delayed

There are no data available on the mixture itself. The mixture has been assessed following the conventional method of the CLP Regulation (EC) No 1272/2008 and is classified for toxicological properties accordingly. See Sections 2 and 3 for details.

This takes into account, where known, delayed and immediate effects and also chronic effects of components from short-term and long-term exposure by oral, inhalation and dermal routes of exposure and eye contact.
Coating powders can cause localised skin irritation in folds of the skin or under tight clothing.

4.3 Indication of any immediate medical attention and special treatment needed

Notes to physician : In case of inhalation of decomposition products in a fire, symptoms may be delayed. The exposed person may need to be kept under medical surveillance for 48 hours.

Specific treatments : No specific treatment.

SECTION 4: First aid measures

See toxicological information (Section 11)

SECTION 5: Firefighting measures

5.1 Extinguishing media

Suitable extinguishing media	:	Recommended: alcohol-resistant foam, CO_2 blanket, water spray or mist.
Unsuitable extinguishing media	:	Do not use water jet. Do not use inert gas under high pressure (e.g. CO2).

5.2 Special hazards arising from the substance or mixture

Hazards from the substance or mixture	:	Fire will produce dense black smoke. Exposure to decomposition products may cause a health hazard.
Hazardous combustion products	:	Decomposition products may include the following materials: carbon monoxide, carbon dioxide, smoke, oxides of nitrogen.

5.3 Advice for firefighters

Special protective actions for fire-fighters	:	Cool closed containers exposed to fire with water. Do not release runoff from fire to drains or watercourses.
Special protective equipment for fire-fighters	:	Appropriate breathing apparatus may be required.

SECTION 6: Accidental release measures

6.1 Personal precautions, protective equipment and emergency procedures

For non-emergency personnel	:	Exclude sources of ignition and ventilate the area. Avoid breathing dust. Refer to protective measures listed in sections 7 and 8.
For emergency responders	:	If specialised clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".

6.2 Environmental precautions	:	Do not allow to enter drains or watercourses. If the product contaminates lakes, rivers, or sewers, inform the appropriate authorities in accordance with local regulations.
6.3 Methods and material for containment and cleaning up	:	Contain and collect spillage with an electrically protected vacuum cleaner or by wet-brushing and place in container for disposal according to local regulations (see section 13). Do not use a dry brush as dust clouds or static can be created.
6.4 Reference to other sections	:	See Section 1 for emergency contact information. See Section 8 for information on appropriate personal protective equipment. See Section 13 for additional waste treatment information.

SECTION 7: Handling and storage

The information in this section contains generic advice and guidance. The list of Identified Uses in Section 1 should be consulted for any available use-specific information provided in the Exposure Scenario(s).

Advice should be taken from a competent occupational health practitioner on the assessment of employees with skin or respiratory complaints before the individual is exposed to the uncured product.

7.1 Precautions for safe handling : Precautions should be taken to prevent the formation of dusts in concentrations above flammable, explosive or occupational exposure limits.
Electrical equipment and lighting should be protected to appropriate standards to prevent dust coming into contact with hot surfaces, sparks or other ignition sources.
Mixture may charge electrostatically: always use earthing leads when transferring from one container to another.
Operators should wear antistatic footwear and clothing and floors should be of the conducting type.
Keep away from heat, sparks and flame.
Avoid contact with skin and eyes. Avoid the inhalation of dust, particulates, spray or mist arising from the application of this mixture. Avoid inhalation of dust from sanding.
Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed.
Put on appropriate personal protective equipment (see Section 8).
Always keep in containers made from the same material as the original one.
Comply with the health and safety at work laws.
Do not allow to enter drains or watercourses.

7.2 Conditions for safe storage, including any incompatibilities

Store in accordance with local regulations.

Additional information on storage conditions

Observe label precautions. Store in a dry, cool and well-ventilated area. Keep away from heat and direct sunlight. Keep container tightly closed.
Keep away from sources of ignition. No smoking. Prevent unauthorised access. Containers that have been opened must be carefully resealed and kept upright to prevent leakage.

7.3 Specific end use(s)

Recommendations : Not available.

Industrial sector specific solutions : Not available.

SECTION 8: Exposure controls/personal protection

The information in this section contains generic advice and guidance. Information is provided based on typical anticipated uses of the product. Additional measures might be required for bulk handling or other uses that could significantly increase worker exposure or environmental releases.

8.1 Control parameters

Occupational exposure limits

No exposure limit value known.

SECTION 8: Exposure controls/personal protection

Recommended monitoring procedures : If this product contains ingredients with exposure limits, personal, workplace atmosphere or biological monitoring may be required to determine the effectiveness of the ventilation or other control measures and/or the necessity to use respiratory protective equipment. Reference should be made to monitoring standards, such as the following: European Standard EN 689 (Workplace atmospheres - Guidance for the assessment of exposure by inhalation to chemical agents for comparison with limit values and measurement strategy) European Standard EN 14042 (Workplace atmospheres - Guide for the application and use of procedures for the assessment of exposure to chemical and biological agents) European Standard EN 482 (Workplace atmospheres - General requirements for the performance of procedures for the measurement of chemical agents) Reference to national guidance documents for methods for the determination of hazardous substances will also be required.

DNELs/DMELs

Product/ingredient name	Type	Exposure	Value	Population	Effects
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	DNEL	Long term Oral	0.275 mg/kg bw/day	General population	Systemic
	DNEL	Long term Dermal	0.275 mg/kg bw/day	General population	Systemic
	DNEL	Long term Dermal	0.55 mg/kg bw/day	Workers	Systemic

PNECs

No PNECs available

8.2 Exposure controls

Appropriate engineering controls : Avoid breathing dust. Where reasonably practicable, this should be achieved by the use of local exhaust ventilation and good general extraction. If these are not sufficient to maintain exposure to dusts below the OEL, suitable respiratory protection must be worn.

Individual protection measures

Hygiene measures : Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.

Eye/face protection : Safety eyewear should be used when there is a likelihood of exposure.

Skin protection

Body protection : Personnel should wear protective clothing. Care should be taken in the selection of protective clothing to ensure that inflammation and irritation of the skin at the neck and wrists through contact with the powder are avoided.

Other skin protection : Appropriate footwear and any additional skin protection measures should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

SECTION 8: Exposure controls/personal protection

Respiratory protection	: If workers are exposed to concentrations above the exposure limit, they must use appropriate, certified respirators. Dry sanding, flame cutting and/or welding of the dry paint film will give rise to dust and/or hazardous fumes. Wet sanding/flatting should be used wherever possible. If exposure cannot be avoided by the provision of local exhaust ventilation, suitable respiratory protective equipment should be used.
Environmental exposure controls	: Do not allow to enter drains or watercourses.

SECTION 9: Physical and chemical properties

9.1 Information on basic physical and chemical properties

Appearance

Physical state	: Solid.
Colour	: Blue.
Odour	: Not available.
Odour threshold	: Not available.
pH	: Not applicable.
Melting point/freezing point	: Not available.
Initial boiling point and boiling range	: Not applicable.
Flash point	: Closed cup: Not applicable. [Product does not sustain combustion.]
Evaporation rate	: Not available.
Flammability (solid, gas)	: Not available.
Lower and upper explosive (flammable) limits	: Lower: 40 g/m³
Vapour pressure	: Not available.
Vapour density	: Not available.
Relative density	: 1.568 g/cm³
Solubility(ies)	: Partially soluble in the following materials: cold water.
Partition coefficient: n-octanol/ water	: Not available.
Auto-ignition temperature	: Not available.
Decomposition temperature	: Not applicable.
Viscosity	: Not available.
Explosive properties	: Not available.
Oxidising properties	: Not available.
Weight volatiles	: 0 % (w/w)
VOC content	: 0 % (w/w)

9.2 Other information

Solubility in water	: Not available.

room temperature (=20°C)

SECTION 10: Stability and reactivity

10.1 Reactivity : No specific test data related to reactivity available for this product or its ingredients.

10.2 Chemical stability : Stable under recommended storage and handling conditions (see Section 7).

10.3 Possibility of hazardous reactions : Under normal conditions of storage and use, hazardous reactions will not occur.

10.4 Conditions to avoid : When exposed to high temperatures may produce hazardous decomposition products.

10.5 Incompatible materials : Not applicable.

10.6 Hazardous decomposition products : Decomposition products may include the following materials: carbon monoxide, carbon dioxide, smoke, oxides of nitrogen.

Not applicable

SECTION 11: Toxicological information

11.1 Information on toxicological effects

There are no data available on the mixture itself. The mixture has been assessed following the conventional method of the CLP Regulation (EC) No 1272/2008 and is classified for toxicological properties accordingly. See Sections 2 and 3 for details.

This takes into account, where known, delayed and immediate effects and also chronic effects of components from short-term and long-term exposure by oral, inhalation and dermal routes of exposure and eye contact.
Coating powders can cause localised skin irritation in folds of the skin or under tight clothing.

Acute toxicity

Product/ingredient name	Result	Species	Dose	Exposure
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	LD50 Oral	Rat	5580 mg/kg	-

Conclusion/Summary : Not available.

Acute toxicity estimates

Product/ingredient name	Oral (mg/kg)	Dermal (mg/kg)	Inhalation (gases) (ppm)	Inhalation (vapours) (mg/l)	Inhalation (dusts and mists) (mg/l)
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	5580	N/A	N/A	N/A	N/A

Irritation/Corrosion

SECTION 11: Toxicological information

Product/ingredient name	Result	Species	Score	Exposure	Observation
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	Skin - Severe irritant	Rabbit	-	0.5 Grams	-

Conclusion/Summary : Not available.

Sensitisation

Conclusion/Summary : Not available.

Mutagenicity

Conclusion/Summary : Not available.

Carcinogenicity

Conclusion/Summary : Not available.

Reproductive toxicity

Conclusion/Summary : Not available.

Teratogenicity

Conclusion/Summary : Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Not available.

Aspiration hazard

Not available.

Other information : Not available.

SECTION 12: Ecological information

12.1 Toxicity

There are no data available on the mixture itself.
Coating powder residues should not be allowed to enter drains or watercourses or be deposited where they could affect ground or surface waters.

The mixture has been assessed following the summation method of the CLP Regulation (EC) No 1272/2008 and is classified for eco-toxicological properties accordingly. See Sections 2 and 3 for details.

Product/ingredient name	Result	Species	Exposure
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	LC50 70.7 mg/l	Fish	96 hours
	NOEC 0.1 mg/l	Daphnia	21 days

Conclusion/Summary : Not available.

12.2 Persistence and degradability

SECTION 12: Ecological information

Product/ingredient name	Test	Result	Dose	Inoculum
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	OECD 301 B	9 % - 28 days	-	-

Conclusion/Summary : Not available.

Product/ingredient name	Aquatic half-life	Photolysis	Biodegradability
BIS(2,4-DI-T-BUTYLPHENYL) PENTAERYTHRITOL DIPHOSPHITE	-	-	Not readily

12.3 Bioaccumulative potential

Not available.

12.4 Mobility in soil

Soil/water partition coefficient (K_{OC}) : Not available.

Mobility : Not available.

12.5 Results of PBT and vPvB assessment

This mixture does not contain any substances that are assessed to be a PBT or a vPvB.

12.6 Other adverse effects : No known significant effects or critical hazards.

SECTION 13: Disposal considerations

The information in this section contains generic advice and guidance. The list of Identified Uses in Section 1 should be consulted for any available use-specific information provided in the Exposure Scenario(s).

13.1 Waste treatment methods

Product

Methods of disposal : The generation of waste should be avoided or minimised wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction.

Hazardous waste : Within the present knowledge of the supplier, this product is not regarded as hazardous waste, as defined by EU Directive 2008/98/EC.

Disposal considerations : Do not allow to enter drains or watercourses.
Dispose of according to all federal, state and local applicable regulations.
If this product is mixed with other wastes, the original waste product code may no longer apply and the appropriate code should be assigned.
For further information, contact your local waste authority.

European waste catalogue (EWC)

SECTION 13: Disposal considerations

The European Waste Catalogue classification of this product, when disposed of as waste, is:

Waste code	Waste designation
08 02 01	waste coating powders

Packaging

Methods of disposal : The generation of waste should be avoided or minimised wherever possible. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible.

Disposal considerations : Using information provided in this safety data sheet, advice should be obtained from the relevant waste authority on the classification of empty containers.
Empty containers must be scrapped or reconditioned.
Dispose of containers contaminated by the product in accordance with local or national legal provisions.

Type of packaging	European waste catalogue (EWC)	
CEPE Paint Guidelines	15 01 10*	packaging containing residues of or contaminated by hazardous substances

Special precautions : This material and its container must be disposed of in a safe way. Care should be taken when handling emptied containers that have not been cleaned or rinsed out. Empty containers or liners may retain some product residues. Avoid dispersal of spilt material and runoff and contact with soil, waterways, drains and sewers.

SECTION 14: Transport information

	ADR/RID	ADN	IMDG	IATA
14.1 UN number	Not regulated.	9005	Not regulated.	Not regulated.
14.2 UN proper shipping name	-	ENVIRONMENTALLY HAZARDOUS SUBSTANCE, SOLID, N.O.S.	-	-
14.3 Transport hazard class(es)	-	9	-	-
14.4 Packing group	-	-	-	-
14.5 Environmental hazards	No.	Yes.	No.	No.

Additional information

ADN : The product is only regulated as a dangerous good when transported in tank vessels.

14.6 Special precautions for user : **Transport within user's premises:** always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.

SECTION 14: Transport information

14.7 Transport in bulk according to Annex II of Marpol and the IBC Code : Not applicable.

The actual shipping description for this product may vary based several factors including, but not limited to, the volume of material, size of the container, mode of transport and use of exemptions or exceptions found in the applicable regulations. The information provided in Section 14 is one possible shipping description for this product. Consult your shipping specialist or supplier for appropriate assignment information.

SECTION 15: Regulatory information

15.1 Safety, health and environmental regulations/legislation specific for the substance or mixture

EU Regulation (EC) No. 1907/2006 (REACH)

Annex XIV - List of substances subject to authorisation

Annex XIV

None of the components are listed.

Substances of very high concern

None of the components are listed.

Annex XVII - Restrictions on the manufacture, placing on the market and use of certain dangerous substances, mixtures and articles : Not applicable.

Other EU regulations

Seveso Directive

This product is not controlled under the Seveso Directive.

National regulations

Industrial use : The information contained in this safety data sheet does not constitute the user’s own assessment of workplace risks, as required by other health and safety legislation. The provisions of the national health and safety at work regulations apply to the use of this product at work.

15.2 Chemical safety assessment : No Chemical Safety Assessment has been carried out.

SECTION 16: Other information

CEPE code : 3

Not available.

Indicates information that has changed from previously issued version.

Abbreviations and acronyms : ATE = Acute Toxicity Estimate
CLP = Classification, Labelling and Packaging Regulation [Regulation (EC) No. 1272/2008]
DMEL = Derived Minimal Effect Level
DNEL = Derived No Effect Level
EUH statement = CLP-specific Hazard statement
N/A = Not available
PBT = Persistent, Bioaccumulative and Toxic
PNEC = Predicted No Effect Concentration
RRN = REACH Registration Number
vPvB = Very Persistent and Very Bioaccumulative

Procedure used to derive the classification according to Regulation (EC) No. 1272/2008 [CLP/GHS]

Classification	Justification
Aquatic Chronic 3, H412	Calculation method

Full text of abbreviated H statements

H410 H412	Very toxic to aquatic life with long lasting effects. Harmful to aquatic life with long lasting effects.

Full text of classifications [CLP/GHS]

Aquatic Chronic 1, H410 Aquatic Chronic 3, H412	LONG-TERM (CHRONIC) AQUATIC HAZARD - Category 1 LONG-TERM (CHRONIC) AQUATIC HAZARD - Category 3

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Date of previous issue : 22 January 2020

Version : 3

Notice to reader

This product is intended for industrial use only.

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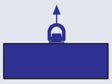
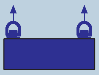
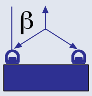
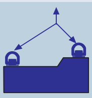
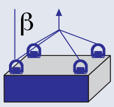
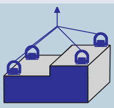
SECTION 16: Other information

Annex B

Working Load Limits for Lifting Points, Weld-on Type

Application	Inclination Angle β	No. of Legs	TWN 0119 Lifting Point								TWN 0124 Lifting Point with Fixing Spring							
																		
			Working Load Limit [t max.]															
		Marking	1,12	2	3,15	5,3	8	15	31,5	50			1,12	2	3,15	5,3		
	0°	1	1,12	2	3,15	5,3	8	15	31,5	50			1,12	2	3,15	5,3		
	0°	2	2,24	4	6,3	10,6	16	30	63	100			2,24	4	6,3	10,6		
	90°	1	1,12	2	3,15	5,3	8	15	31,5	50			1,12	2	3,15	5,3		
	90°	2	2,24	4	6,3	10,6	16	30	63	100			2,24	4	6,3	10,6		
	0-45°	2	1,6	2,8	4,25	7,5	11,2	21,2	45	71			1,6	2,8	4,25	7,5		
	45-60°	2	1,12	2	3,15	5,3	8	15	31,5	50			1,12	2	3,15	5,3		
	unbalanced	2	1,12	2	3,15	5,3	8	15	31,5	50			1,12	2	3,15	5,3		
	0-45°	3+4	2,36	4,25	6,7	11,2	17	31,5	67	106			2,36	4,25	6,7	11,2		
	45-60°	3+4	1,7	3	4,75	8	11,8	22,4	47,5	75			1,7	3	4,75	8		
	unbalanced	3+4	1,12	2	3,15	5,3	8	15	31,5	50			1,12	2	3,15	5,3		

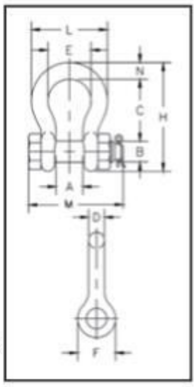
Annex C

Crosby

SHACKLES

G-2130 / S-2130

- Working Load Limit and Grade 6 permanently shown on every shackle.
- Forged, Quenched & Tempered, with alloy bolts.
- Hot-dip galvanized (G) or self colored (S). 85, 120, and 150-metric ton shackles are all hot-dip galvanized bows and the bolts are Dimetcoted® and painted red.
- Sizes 3/8 and below are mechanically galvanized.
- Fatigue rated to 20,000 cycles at 1-1/2 times the Working Load Limit (1/3t - 55t).
- Approved for use at -40° F (-40° C) to 400° F (204° C).
- Meets or exceeds all requirements of ASME B30.26.
- Shackles 85 metric tons and larger are individually proof tested to 2.0 times the working load limit.
- Type Approval certification in accordance with ABS 2016 Steel Vessel Rules ABS Guide for Certification of Lifting Appliances available. Certificates available when requested at time of order and may include additional charges.
- 3.1 Certification as standard available for charpy and statistical proof test from 3.25t up to 25 tons to DNV 2.7-1 and EN13889.
- Crosby 3.25t through 25t G-2130OC anchor shackles are type approved to DNV Certification Notes 2.7-1-Offshore Containers. These Crosby shackles are statistical proof and impact tested to 31 ft-lb (42 Joules) min. avg. at -4° F (-20° C). The tests are conducted by Crosby and 3.1 test certification is available upon request.
- All other 2130 shackles can meet charpy requirements of 31 ft-lb (42 Joules) avg at -4° F (-20° C) when requested at time of order.
- Meets the performance requirements of Federal Specification RR-C-271H, Type IVA, Grade A, Class 3, except for those provisions required of the contractor.
- Look for the Red Pin®... the mark of genuine Crosby quality.



G-2130 / S-2130 Bolt Type Anchor Shackles

Nominal Size (in)	Working Load Limit (t)	Stock No.			Weight Each (lb)	Dimensions (in)										Tolerance (+/- in)	
		G-2130	S-2130	G-2130OC		A	B	C	D	E	F	H	L	M	N	C	A
3/16	0.33 ‡	1019464	-	-	.06	.38	.25	.88	.19	.60	.56	1.47	.98	1.29	.19	.06	.06
1/4	0.5	1019466	-	-	.11	.47	.31	1.13	.25	.78	.61	1.84	1.28	1.56	.25	.06	.06
5/16	0.75	1019468	-	-	.22	.53	.38	1.22	.31	.84	.75	2.09	1.47	1.82	.31	.06	.06
3/8	1	1019470	-	-	.33	.66	.44	1.44	.38	1.03	.91	2.49	1.78	2.17	.38	.13	.06
7/16	1.5	1019471	-	-	.49	.75	.50	1.69	.44	1.16	1.06	2.91	2.03	2.51	.44	.13	.06
1/2	2	1019472	1019481	-	.79	.81	.64	1.88	.50	1.31	1.19	3.28	2.31	2.80	.50	.13	.06
5/8	3.25	1019490	1019506	1262013	1.68	1.06	.77	2.38	.63	1.69	1.50	4.19	2.94	3.56	.69	.13	.06
3/4	4.75	1019515	1019524	1262022	2.72	1.25	.89	2.81	.75	2.00	1.81	4.97	3.50	4.15	.81	.25	.06
7/8	6.5	1019533	1019542	1262031	3.95	1.44	1.02	3.31	.88	2.28	2.09	5.83	4.03	4.82	.97	.25	.06
1	8.5	1019551	1019560	1262040	5.66	1.69	1.15	3.75	1.00	2.69	2.38	6.56	4.69	5.39	1.06	.25	.06
1-1/8	9.5	1019579	1019588	1262059	8.27	1.81	1.25	4.25	1.13	2.91	2.69	7.47	5.16	5.90	1.25	.25	.06
1-1/4	12	1019597	1019604	1262068	11.71	2.03	1.40	4.69	1.29	3.25	3.00	8.25	5.75	6.69	1.38	.25	.06
1-3/8	13.5	1019613	1019622	1262077	15.83	2.25	1.53	5.25	1.42	3.63	3.31	9.16	6.38	7.21	1.50	.25	.13
1-1/2	17	1019631	1019640	1262086	19.00	2.38	1.66	5.75	1.53	3.88	3.63	10.00	6.88	7.73	1.62	.25	.13
1-3/4	25	1019659	1019668	1262095	33.91	2.88	2.04	7.00	1.84	5.00	4.19	12.34	8.80	9.68	2.25	.25	.13
2	35	1019677	1019686	-	52.25	3.25	2.30	7.75	2.08	5.75	4.81	13.68	10.15	10.81	2.40	.25	.13
2-1/2	55	1019695	1019702	-	98.25	4.13	2.80	10.50	2.71	7.25	5.69	17.90	12.75	13.58	3.13	.25	.25
3	† 85	1019711	-	-	154	5.00	3.30	13.00	3.12	7.88	6.50	21.50	14.62	15.13	3.62	.25	.25
3-1/2	† 120 ‡	1019739	-	-	265	5.25	3.76	14.63	3.62	9.00	8.00	24.88	17.02	17.00	4.38	.25	.25
4	† 150 ‡	1019757	-	-	338	5.50	4.26	14.50	4.00	10.00	9.00	25.68	18.00	17.75	4.56	.25	.25

6:1 Design Factor. Maximum Proof Load is 2 times the Working Load Limit. For Working Load Limit reduction due to side loading applications, see Warnings & Applications..
† Individually Proof Tested with certification. ‡ Furnished with eye bolts for handling.

Load Rated · Fatigue Rated · TA · QUIC-CHECK · Q&T · MAXTOUGH · CE

APPLICATION AND WARNING INFORMATION SECTION 17

CORDSTRAP
LASHING

Cordstrap lashing, known as Cordlash®, is the most effective way to secure cargo for international shipping wherever it may be, on any transport unit – containers, flat racks, railcars or ships.

Cordstrap's polyester one-way lashings have many advantages over conventional securing products such as steel straps, chains or wood blocking and bracing. Cordlash® eliminates incidents and damage to your cargo.

Strong, reliable and safe, Cordlash® complies fully with the latest rules and regulations. Ensuring that your responsibilities as a shipper are met and that your cargo passes through controls in the logistics chain quickly and without any hold up. Arriving at its destination safely and in perfect condition.

OPTIMAL SECURITY

Made of high tenacity polyester yarn to ensure maximum strength, Cordlash® has many advantages over conventional products. It ensures that your cargo arrives at its destination in the same condition as when dispatched.

SAFE

Cordstrap's woven lashing solutions are non-abrasive and safe for both operator and cargo. Optimized lashing and buckle combinations maintain securing function for dynamic and static loads during the most severe transport conditions.

FULLY CERTIFIED

The quality and performance of our lashing is undisputed as it complies with the latest national and global regulations. It is GL certified, AAR approved and CTU Code compliant.

EXPERT SUPPORT

Cordstrap Lashing is fully supported by training and implementation from local cargo securing experts enabling efficiency, standardization and consistency in how your cargo is secured.

ASSOCIATION OF AMERICAN RAILROADS

GL

CORDSTRAP LASHING SOLUTIONS SPECIFICATIONS

COMPOSITE SOLUTIONS

SYSTEM BREAKING STRENGTH*	STRAP TYPE	BUCKLE TYPE	WIDTH	SUITABLE TENSIONERS
2600 daN – 5720 lbf	CC 105/230	CB 10	32 mm / 1.1/4"	CT 40 (Manual) CBT 35 (Battery) CT 35 PN (Pneumatic)
2600 daN – 5720 lbf	CC 105/230 UF	CB 10	32 mm / 1.1/4"	CT 40 (Manual) CBT 35 (Battery) CT 35 PN (Pneumatic)

WOVEN SOLUTIONS

SYSTEM BREAKING STRENGTH*	STRAP TYPE	BUCKLE TYPE	WIDTH	SUITABLE TENSIONERS
3000 daN – 6600 lbf	Cordlash® 105	HDB 10C	32 mm / 1.1/4"	CT 40 (Manual) CBT 35 (Battery) CT 35 PN (Pneumatic)
4000 daN – 8800 lbf	Cordlash® 105	HDB 10N Dynablock® 10	32 mm / 1.1/4"	CT 40 (Manual) CBT 35 (Battery) CT 35 PN (Pneumatic)
5000 daN – 11000 lbf	Cordlash® 150	HDB 12C	40 mm / 1.5/8"	CT 40 (Manual) CRT 50 (Manual) CT 40 PN (Pneumatic)
6000 daN – 13200 lbf	Cordlash® 150	HDB 12N Dynablock® 12 -150	40 mm / 1.5/8"	CT 40 (Manual) CRT 50 (Manual) CT 40 PN (Pneumatic)
7500 daN – 16500 lbf	Cordlash® 200	HDB 12C	40 mm / 1.5/8"	CRT 50 (Manual) CT 40 PN (Pneumatic)
8500 daN – 18700 lbf	Cordlash® 200	HDB 12N Dynablock® 12 - 200	40 mm / 1.5/8"	CRT 50 (Manual) CT 40 PN (Pneumatic)
10000 daN – 22000 lbf	Cordlash® 750	HDB 15N	50 mm / 2"	CRT 50 (Manual) CT 50 PN (Pneumatic)
12000 daN – 26400 lbf	Cordlash® 750	Dynablock® 15	50 mm / 2"	CRT 50 (Manual) CT 50 PN (Pneumatic)
20000 daN – 44000 lbf	Cordlash® 1500	Dynablock® 20	60 mm / 2.3/8"	CRT 60 (Manual) CT 60 PN (Pneumatic)

All Cordstrap Composite and Woven solutions have been witness tested by Germanischer Lloyd
For more information about Cordstrap's Container Solutions or Dynamic Cargo Solutions get in touch with one of our Cargo Protection Experts

*System breaking strength is the total system strength based on the use with recommended Cordstrap buckle type.

Annex D

Specification Sheet Online:
https://www.thomsonlinear.com/en/product/20332F

Thomson Customer Support:
https://www.thomsonlinear.com/en/support/global-customer-service-call

THOMSON
Linear Motion. Optimized.™
A REGAL REXNORD BRAND

20332F

Screw Acme Nut

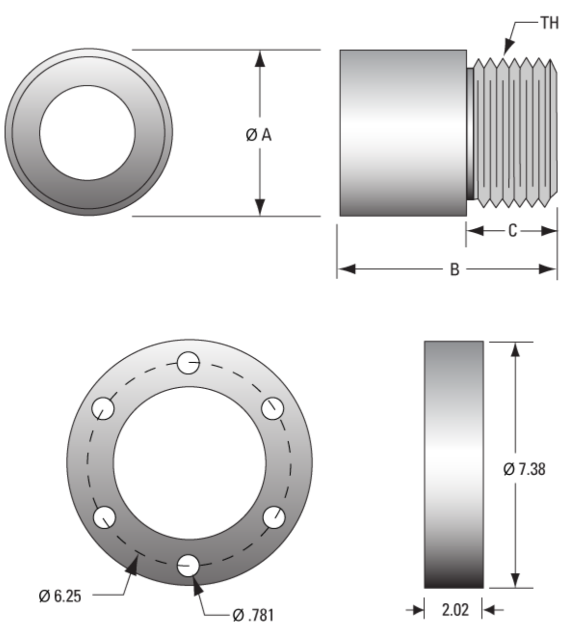
Bronze Nut with Flanged Nut, Acme, Externally Threaded, 3.375 in dia. X 1.5 in Lead, Right Hand

- With mounting flange installed on bronze nut
- Centralized thread form for smooth, no-wedging performance
- High quality bronze material for superior load capacity and wear resistance

*Lead times may increase with higher quantities. Lead time displayed in business days.

†The price shown here is the North American List Price for general reference only. Please Contact Thomson for actual net price and current delivery schedule which will vary with geographic region, quantity ordered and distribution channel. Estimated costs for shipping, packaging and import taxes/duty are not included in this list price. Please contact Thomson Customer Support for more information.

Dimensions



Dimension	Value
A	4.50 in (114.3 mm)
B Max	4.50 in (114.3 mm)
C	2.00 in (50.8 mm)
TH	3.625-12

Dimension	Value

Specifications

Specifications	Value
Screw Diameter	3.375 in (85.73 mm)
Lead	1.500 in (38.10 mm)
Nut Mounting Style	Threaded
Nut Material	Bronze
Max Axial Backlash	0.0200 in (0.508 mm)
Efficiency	34%
Max Temperature	350 °F (176.7 °C)
Weight	11.62 lbs (5.27 kg)
Nut Length	4.50 in (114.30 mm)
Nut Body Diameter	4.50 in (114.30 mm)
Threaded Display Length	0.00 in

Performance

Performance	Value
Max Dynamic Load	60,000.0 lbf (266,893.3 N)

Related Products

13332

Acme Screw, 4140 Alloy, 3.375 in dia. X 1.5 in Lead, Right Hand, Black Oxide Coated

https://www.thomsonlinear.com/en/product/13332

70740

Circular mounting flange, Carbon Steel

https://www.thomsonlinear.com/en/product/70740

Specification Sheet Online:
https://www.thomsonlinear.com/en/product/13332

Thomson Customer Support:
https://www.thomsonlinear.com/en/support/global-customer-service-call

THOMSON Linear Motion. Optimized.™
A REGAL REXNORD BRAND

13332

Acme Screw

Acme Screw, 4140 Alloy, 3.375 in dia. X 1.5 in Lead, Right Hand, Black Oxide Coated

- Rolled acme screws are cost effective and stocked for quick delivery
- Made from high quality 4140 steel with black oxide coating to resist corrosion
- Low friction, minimum wear, long life, and clean operation

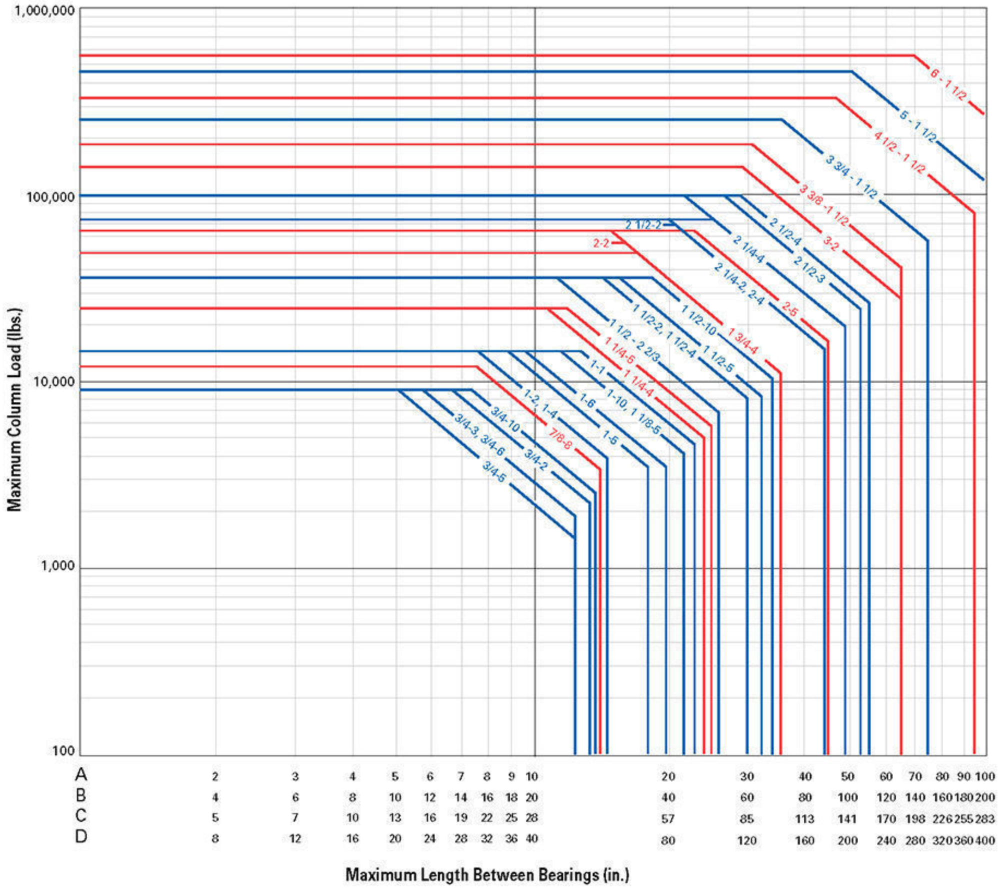
*Lead times may increase with higher quantities. Lead time displayed in business days.

†The price shown here is the North American List Price for general reference only. Please Contact Thomson for actual net price and current delivery schedule which will vary with geographic region, quantity ordered and distribution channel. Estimated costs for shipping, packaging and import taxes/duty are not included in this list price. Please contact Thomson Customer Support for more information.

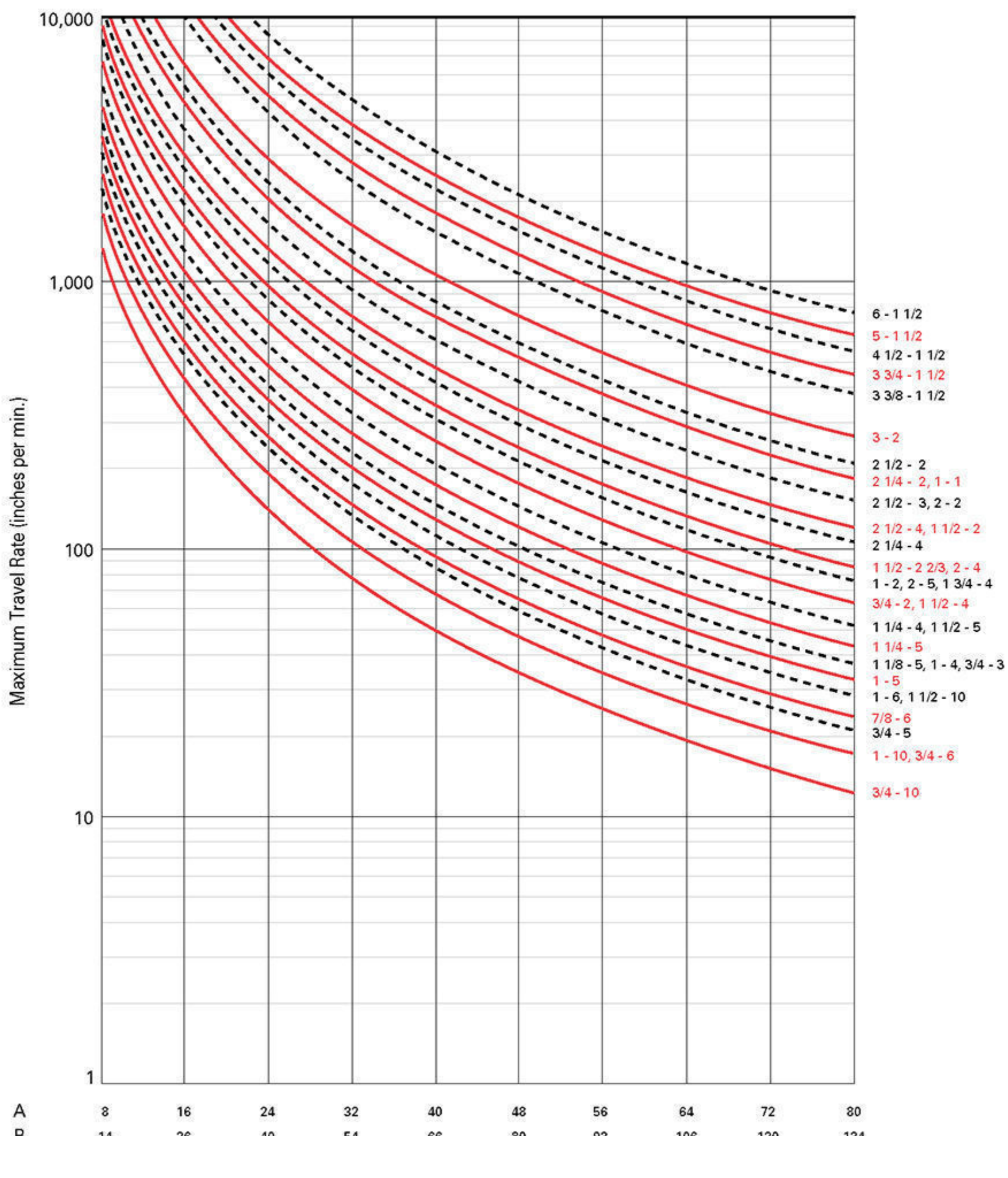
Specifications

Specifications	Value
Screw Part Number	332-RA/00X/00X/12.00/00000/S
Screw Thread Form	2C
Screw Diameter	3.375 in (85.73 mm)
Lead	1.500 in (38.10 mm)
Lead Accuracy	0.0006 in/in (0.0006 mm/mm)
Screw Straightness	0.010 in/ft (258 µm/300mm)
Screw Material	4140 Alloy
Screw Coating	Black Oxide Coated
Max Temperature	350 °F (176.7 °C)
Weight	0.00
Screw Length	144.00 in (3,657.6 mm)
Screw Display Length	144.00 in
Screw Length (Ls)	144.00 in (3,657.6 mm)
Threaded Length	144 in (3,657.6 mm)
Threaded Display Length	144.00 in

Performance



1,000,000
100,000
10,000
1,000
100
Maximum Column Load (lbs.)
6 - 1 1/2
5 - 1 1/2
4 1/2 - 1 1/2
3 3/4 - 1 1/2
3 3/8 -1 1/2
3-2
2 1/2-2
2 1/2-4
2 1/2-3
2 1/4-4
2-2
2 1/4-2, 2-4
2-5
1 1/2-10
1 3/4-4
1 1/2-2, 1 1/2-4
1 1/2-5
1 1/2 - 2 2/3
1 1/4-5
1 1/4-4
1-1
1-6
1-10, 1 1/8-5
1-5
1-2
1-4
7/8-6
3/4-10
3/4-3, 3/4-6
3/4-2
3/4-5
A 2 3 4 5 6 7 8 9 10 20 30 40 50 60 70 80 90 100
B 4 6 8 10 12 14 16 18 20 40 60 80 100 120 140 160 180 200
C 5 7 10 13 16 19 22 25 28 57 85 113 141 170 198 226 255 283
D 8 12 16 20 24 28 32 36 40 80 120 160 200 240 280 320 360 400
Maximum Length Between Bearings (in.)



10,000
1,000
100
10
1
Maximum Travel Rate (inches per min.)
6 - 1 1/2
5 - 1 1/2
4 1/2 - 1 1/2
3 3/4 - 1 1/2
3 3/8 - 1 1/2
3 - 2
2 1/2 - 2
2 1/4 - 2, 1 - 1
2 1/2 - 3, 2 - 2
2 1/2 - 4, 1 1/2 - 2
2 1/4 - 4
1 1/2 - 2 2/3, 2 - 4
1 - 2, 2 - 5, 1 3/4 - 4
3/4 - 2, 1 1/2 - 4
1 1/4 - 4, 1 1/2 - 5
1 1/4 - 5
1 1/8 - 5, 1 - 4, 3/4 - 3
1 - 5
1 - 6, 1 1/2 - 10
7/8 - 6
3/4 - 5
1 - 10, 3/4 - 6
3/4 - 10
A 8 16 24 32 40 48 56 64 72 80

B	14	26	40	54	66	80	93	106	120	134
C	16	32	49	65	81	97	113	130	146	162
D	19	40	60	80	99	119	139	159	179	198

Related Products

20332

Bronze Nut, Acme, Externally Threaded, 3.375 in dia. X 1.5 in Lead, Right Hand

https://www.thomsonlinear.com/en/product/20332

20332F

Bronze Nut with Flanged Nut, Acme, Externally Threaded, 3.375 in dia. X 1.5 in Lead, Right Hand

https://www.thomsonlinear.com/en/product/20332F

SKF

Image may differ from product. See technical specification for details.

6316 2RSJEM

Rolamento rígido de esferas

Os rolamentos rígidos de esferas de uma carreira são o tipo de rolamento mais usado e são particularmente versáteis. Eles possuem baixo atrito e são otimizados para baixo ruído e baixa vibração, o que permite uma alta velocidade de rotação. Eles podem suportar cargas radiais e axiais em ambas as direções, são fáceis de montar e requerem menos manutenção do que muitos outros tipos de rolamentos.

- Modelo simples, versátil e robusto
- Baixo atrito
- Capacidade de alta velocidade
- Suporta cargas radiais e axiais em ambas as direções
- Requer pouca manutenção

Visão geral

Dimensões

Diâmetro do furo	80 mm
Diâmetro externo	170 mm
Largura	39 mm

Desempenho

Classificação de carga dinâmica básica	130 kN
Classificação de carga estática básica	86.5 kN
Velocidade-limite	2 600 r/min
Classe de desempenho SKF	SKF Explorer

Propriedades

Rasgos de entrada	Sem
Número de carreiras	1
Recurso de fixação, anel externo do rolamento	Nenhum
Tipo de furo	Cilíndrico
Gaiola	Metal laminado
Arranjo pareado	Não
Folga interna radial	C3
Material, rolamento	Aço para rolamentos
Revestimento	Sem
Vedação	Vedação em ambos os lados
Tipo de vedação	Contato
Lubrificante	Graxa
Recurso de relubrificação	Sem

Logística

Peso líquido do produto	3.64 kg
Código eClass	23-05-08-01
Código UNSPSC	31171504

Mais informações

Detalhes do produto

- Rolamentos rígidos de uma carreira de esferas
- Rolamentos rígidos de esferas de aço inoxidável
- Rolamentos rígidos de uma carreira de esferas com rasgos de entrada
- Rolamentos rígidos de duas carreiras de esferas
- Especificações gerais do rolamento
- Cargas
- Limites de temperatura
- Velocidade permitida
- Sistema de designação

Informações de engenharia

- Princípios da seleção de rolamentos
- Conhecimentos gerais sobre rolamentos
- Processo de seleção de rolamentos
- Interfaces do rolamento
- Tolerâncias de assento para condições padrão
- Seleção de folga interna
- Lubrificação
- Vedação, montagem e desmontagem
- Falha do rolamento e como evitá-la

Ferramentas

- SKF Product Select (Seleção de produtos SKF)
- SimPro Quick
- Engineering Calculator
- LubeSelect para graxas SKF
- Ferramenta para seleção de aquecedor

SKF

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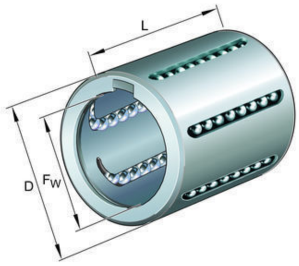
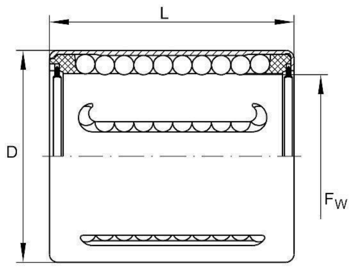


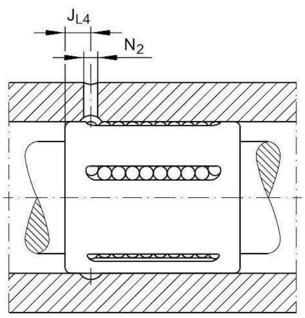
KH30-PP

Rolamento de esferas linear

Rolamentos lineares com lubrificação inicial, vedado em ambos os lados, relubrificável

Informação técnica





Variante do seu produto atual

Size code	30	
Seal	PP	Sealed

Dimensões principais e dados de desempenho

F_w	30 mm	Diâmetro do eixo
D	40 mm	Diâmetro exterior
L	50 mm	Comprimento
C_{min}	3.300 N	Capacidade de carga din.
$C_{0\ min}$	2.700 N	Capacidade de carga est.
C_{max}	3.300 N	Capacidade de carga din.
$C_{0\ max}$	3.100 N	Capacidade de carga est.
≈m	94,7 g	Peso

dimensões de conexão

J_{L4}	8 mm
N_2	2,5 mm

The data sheet only contains an overview of the technical data of the selected product. Please refer to the additional documentation for this product. For further information, please use the following link on our website: Contact form