Examensarbete

HÖGSKOLAN I SKÖVDE

SURFACE TREATMENT METHODS FOR METAL COMPONENTS TRAYS AND FRAMES

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Abstract

The proper selection of materials and surface treatment is critical in ensuring the strength, durability, and safety of metal structures in various environments. Therefore, this project is being developed in collaboration with Aurobay Company to explore and provide insights into the most suitable material and surface treatment method for a frame.

The first step of the project entailed extensive research into typical materials, surface treatments, and types of corrosion that commonly occur in the automotive industry. It was discovered that the appropriate combination of materials and surface treatments can significantly enhance the durability and performance of metal structures. Following the research phase, the appropriate material for the frame was selected using Ansys Granta software, taking into consideration factors, such as, mechanical strength, corrosion resistance, ductility, toughness, weldability, density, and price of the materials.

Continuing with the project, the next step was to select the most suitable surface treatment method for the material based on various factors, for instance, the environmental conditions of the structure's application, performance requirements, cost, and availability of the treatment. Furthermore, simulations of the frame were conducted using Solidworks software to evaluate the performance of the selected material under different environmental conditions. The simulation results were then compared to determine if the material selected was appropriate for the frame's intended purpose.

The final step of the project involved an analysis of the sustainability and circularity of the frame. This included considerations of energy consumption, CO_2 emissions, availability of raw materials, transport, and the potential for material reuse.

Certification

This thesis has been submitted by Alaitz Egaña Azkargorta and Josu Najera Bernabeu to the University of Skövde as a requirement for the degree of Bachelor of Science in Production/Mechanical Engineering.

The undersigned certifies that all the material in this thesis that is not our own has been properly acknowledged using accepted referencing practices and, further, that the thesis includes no material for which we have previously received academic credit.

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Table of Contents

ABSTRACT .... **I**

CERTIFICATION .... **II**

ACKNOWLEDGEMENTS .... **III**

INTRODUCTION **1**

1.1 BACKGROUND 1
1.2 PROBLEM STATEMENT 2
1.3 AIM AND OBJECTIVES 2
1.4 OVERVIEW 3
1.5 LIMITATIONS 3

THEORETICAL FRAME OF REFERENCE **4**

2.1 DEVELOPMENT OF THE AUTOMOTIVE INDUSTRY 4
2.2 IMPORTANCE OF CHASSIS DESIGN 4
2.2.1 Joining Methods *7*
2.2.2 Material Selection *7*
2.2.3 Surface Treatments *7*
2.3 MATERIALS WITHIN THE AUTOMOTIVE INDUSTRY 8
2.4 CORROSION 10
2.4.1 Corrosion in automotive industry *13*
2.5 SURFACE TREATMENTS WITHIN THE AUTOMOTIVE INDUSTRY 14
2.6 SUSTAINABILITY 19

LITERATURE REVIEW **20**

METHODOLOGY **22**

IMPLEMENTATION **24**

5.1 MATERIAL SELECTION 24
5.2 SIMULATIONS 28
5.2.1 Boundary Conditions *28*
5.2.2 Mesh *29*
5.2.3 Materials *30*
5.3 SUSTAINABILITY 31
5.3.1 Social impact *31*
5.3.2 Economic impact *31*
5.3.3 Environmental impact *32*

RESULTS AND DISCUSSION **39**

6.1 MATERIAL SELECTION 39
6.1.1 Magnesium *39*
6.1.2 Cast iron *40*
6.1.3 Stainless Steel *40*
6.1.4 Aluminium *41*
6.1.5 Material Selected *42*
6.2 THERMAL TREATMENT 43
6.3 FRAME'S STATIC ANALYSIS 45
6.3.1 Principal stress *45*
6.3.2 Deformation *47*
6.4 SURFACE PREPARATION AND THE JOINING 49
6.4.1 Joining methods *50*
6.5 SURFACE TREATMENT 51
6.6 SUSTAINABILITY 52
6.6.1 The manufacturing cost *52*
6.6.2 The environmental impact *53*

CONCLUSIONS 55

FUTURE WORK 58

BIBLIOGRAPHY 59

APPENDICES 65

APPENDIX A: WORK BREAKDOWN AND TIME PLAN 65
APPENDIX B: CMT/CMT+P 66
APPENDIX C: ADHESIVE JOINING (HYSOL 9492 EPOXY) 66
APPENDIX D: ALUMINIUM ALLOY SERIES 68
APPENDIX E: TYPES OF ANODIZING 70
APPENDIX F: BILL OF MATERIALS 73
APPENDIX G: DIFFERENT 6XXX ALUMINIUM ALLOYS 74
APPENDIX H: ALUMINIUM TEMPER DESIGNATION SYSTEM 78
APPENDIX I: DIFFERENT THERMAL TREATMENTS SIMULATIONS 79
APPENDIX J: DATA COLLECTED FOR THE LIFE CYCLE ASSESSMENT 81

List of Figures

FIGURE 1: LADDER FRAME (CHANGAROTH, 2019) 5
FIGURE 2: MULTI-TUBULAR FRAME (BORIA, GIANNONI, & GIAMBÓ, 2015) 5
FIGURE 3: TRUSS FRAME (BASKARA SETHUPATHI, CHANDRADASS, SHARMA, BANTWAL BALIGA, & SHARMA) .. 6
FIGURE 4: MONOCOQUE FRAME (GUDMUNDSSON, 2014) 6
FIGURE 5: MATERIALS USED FOR MANUFACTURING CAR PARTS (HOVORUN, BERLADIR, PEREVA, RUDENKO, & MARTYNOV, 2017) 8
FIGURE 6: UNIFORM CORROSION, FERROUS ALLOY (S. TAIT, 2018) 10
FIGURE 7: UNIFORM CORROSION, ALUMINIUM ALLOY (ALUMECO GROUP) 10
FIGURE 8: PITTING CORROSION, FERROUS ALLOY (WILEY , 2018) 11
FIGURE 9: PITTING CORROSION, ALUMINIUM ALLOY (VELLING, 2020) 11
FIGURE 10: CREVICE CORROSION, FERROUS ALLOY (STEELFAB, 2021) 11
FIGURE 11: CREVICE CORROSION, ALUMINIUM ALLOY (JUHL) 11
FIGURE 12: GALVANIC CORROSION, FERROUS ALLOY (HARKIN, 2017) 12
FIGURE 13: GALVANIC CORROSION, ALUMINIUM ALLOY (VU) 12
FIGURE 14: STRESS CORROSION, FERROUS ALLOY (FINCHEN PARSONS, 2001) 12
FIGURE 15: STRESS COSSORION, ALUMINIUM ALLOY (VELLING, 2020) 12
FIGURE 16: WHITE CORROSION, FERROUS ALLOY (DEY, 2022) 13
FIGURE 17: WHITE CORROSION, ALUMINIUM ALLOY (ALL METALS FABRICATION, 2022) 13
FIGURE 18: VENN DIAGRAM FOR SUSTAINABLE DEVELOPMENT (SADIKU, OLALEYE, & MUSA, 2019) 19
FIGURE 19: METHODOLOGY CHART 22
FIGURE 20: CHART OF LIMITS APPLIED IN MATERIAL SELECTION FOR FRAMES 25
FIGURE 21: CHART OF PRICE PER KG APPLIED IN MATERIAL SELECTION FROM FRAMES 25
FIGURE 22: GRAPH OF STIFFNESS-TO-WEIGHT RATIO 26
FIGURE 23: GRAPH OF STRENGTH-TO-WEIGHT RATIO 26
FIGURE 24: GRAPH OF STRENGTH-TO-PRICE RATIO 27
FIGURE 25: BOUNDARY CONDITIONS OF THE FASTENINGS OF THE FRAME 28
FIGURE 26: SURFACE IN CONTACT WITH THE ENGINE 29
FIGURE 27: GRAVITY FORCE 29
FIGURE 28: THE FRAME MESHED 30
FIGURE 29: MESH CONVERGENCE 30
FIGURE 30: PROCESS FLOW CHART 33
FIGURE 31: END-OF-LIFE ALTERNATIVES AND THEIR OUTPUT (BERNTSSON & DIMGARD, 2022) 35
FIGURE 32: ENERGY CONSUMPTION AND CO2 EMISSIONS DEPENDING ON THE TRANSPORT (BERNTSSON & DIMGARD, 2022) 37
FIGURE 33: TRANSPORT CONSUMPTION AND EMISSIONS 38
FIGURE 34: AL 6082 T6, PRINCIPAL STRESS 45
FIGURE 35: AL 6082 -T6, DEFORMATION 45

FIGURE 36: PRINCIPAL TENSION, ALUMINIUM......46
FIGURE 37: PRINCIPAL TENSION, 108 STAINLESS STEEL......46
FIGURE 38: STRESS SINGULARITY REGION, ALUMINIUM......47
FIGURE 39: DEFORMATION, ALUMINIUM......48
FIGURE 40: DEFORMATION, 108 STAINLESS STEEL......48
FIGURE 41: ENERGY CONSUMPTION OF EACH PROCESS (APPENDIX J)......53
FIGURE 42: CO_2 EMISSIONS FOR EACH PROCESS (APPENDIX J)......54
FIGURE 43: FIRST GANTT DIAGRAM......65
FIGURE 44: FINAL GANTT DIAGRAM......65
FIGURE 45: PRINCIPAL STRESS, AL 6082-0......79
FIGURE 46: PRINCIPAL STRESS, AL 6082-T4......79
FIGURE 47: PRINCIPAL STRESS, AL 6082-T6......79
FIGURE 48: PRINCIPAL STRESS, AL 6082-T651......79
FIGURE 49: DEFORMATION, AL 6082-0......80
FIGURE 50: DEFORMATION, AL 6082-T4......80
FIGURE 51: DEFORMATION, AL 6082-T6......80
FIGURE 52: DEFORMATION, AL 6082-T651......80

List of Tables

TABLE 1: CORROSION TYPES AND THEIR CHARACTERISTICS 10
TABLE 2: TYPE OF SURFACE TREATMENTS AND THEIR CHARACTERISTICS 14
TABLE 3: SUBPROCESSES FOR THE PRODUCT'S LIFE CYCLE 33
TABLE 4: INPUTS AND OUTPUTS OF THE ANODIZING 34
TABLE 5: END-OF-LIFE POSSIBILITIES OF AL 6082-T6 35
TABLE 6: RECYCLING PROPERTIES OF AL 6082-T6 36
TABLE 7: TYPICAL THERMAL TREATMENTS FOR AL 6082 43
TABLE 8: PRINCIPAL STRESS AND DEFORMATION SUFFERED BY A AL 6082-T6 FRAME 45
TABLE 9: MANUFACTURING COST OF A FRAME 52
TABLE 10: ENERGY CONSUMPTION AND CO_2 EMISSIONS OF THE RECYCLING PROCESS OF THE FRAME 54
TABLE 11: NAMING OF ALUMINIUM ALLOYS (SHANGHAI ZHENGSHANG INDUSTRIAL CO, 2021) 68
TABLE 12: TYPES OF ANODIZING IN DETAIL 70
TABLE 13: BILL OF MATERIALS 73
TABLE 14: CHEMICAL COMPOSITION OF AL 6061 (CHRISTY, MURUGAN, & KUMAR, 2010) 74
TABLE 15: MECHANICAL PROPERTIES OF 6001 ALLOY (AALCO METALS LTD, 2018) 74
TABLE 16: CHEMICAL COMPOSITION OF AL 6063 (THYSSENKRUPP MATERIALS (UK) LTD, 2016) 75
TABLE 17: MECHANICAL PROPERTIES OF 6063 ALLOY (AALCO METALS LTD, 2018) 75
TABLE 18: CHEMICAL COMPOSITION OF AL 6005 76
TABLE 19: MECHANICAL PROPERTIES OF 6005 ALLOY (AALCO METALS LTD, 2018) 76
TABLE 20: CHEMICAL COMPOSITION OF AL 6082 (HIGH GRADE METALS, 2022) 77
TABLE 21: MECHANICAL PROPERTIES OF 6082 ALLOY (SMITH METAL, 2022) 77
TABLE 22: THE BASIC TEMPER DESIGNATIONS (GENCULU) (KOCH, 2020) 78
TABLE 23: PRINCIPAL STRESS SUFFERED BY THE FRAME WITH DIFFERENT THERMAL TREATMENTS 79
TABLE 24: DEFORMATION SUFFERED BY THE FRAME WITH DIFFERENT THERMAL TREATMENTS 80
TABLE 25: DATA COLLECTED FROM MATERIAL EXTRACTION 81
TABLE 26: DATA COLLECTED FOR ADDITIONAL PROCESSES 82
TABLE 27: TOTAL SUM OF ADDITIONAL PROCESSES 84
TABLE 28: DATA COLLECTED FROM COATING PROCESS 84
TABLE 29: DATA COLLECTED FROM WELDING PROCESS 85
TABLE 30: DATA COLLECTED FROM RECYCLING PROCESS 85

Chapter 1

Introduction

1.1 Background

Since ancient times, frames have provided structural support for a broad range of endeavours, from transportation to architecture. In contemporary engineering, frames are structures created to support loads by resisting bending and distortion.

The development of frames in engineering dates back to the late 18^{th} century, with the construction of the iron framed Coalbrookdale Bridge in the UK in 1779 (G. Slamon, E. Johnson, & A. Malhas, 1996). This was one of the earliest applications of iron as a structural material, which transformed the building sector by enabling the creation of larger and more intricate buildings.

With the invention of new materials and production methods in the 20^{th} century, the usage of frames in engineering continued to evolve. The development of composite materials made of aluminium and carbon fibre in the 1970s and 1980s considerably increased the design options for frames, enabling stronger, lighter, and more energy-efficient constructions (Zhang, Lin, Vaidya, & Wang, 2023).

Nowadays, frames are employed in a broad variety of applications, including bridges, buildings, cars, bikes, and other vehicles. It is critical for engineers and designers to conduct study in this field since the choice of materials and surface treatments for frames has a significant impact on the general effectiveness, toughness, and safety of these structures.

Last but not least, mention that this project is performed at Aurobay, to develop and produce world-class powertrain solutions for a global market, with a heritage from Volvo Cars and Geely. In the footsteps of vehicles getting electrified new businesses have become interesting for Aurobay (Aurobay, 2022). The tray for batteries and frames for range extenders are the two new components to Aurobay which are great of interests. These structures could be part of the bodywork of the vehicle or stand-alone which demand a high-quality surface treatment and resistance to corrosion properties.

1.2 Problem Statement

Aurobay company is interested in expanding its knowledge on vehicle frames material and surface treatment in order to improve material performance. Therefore, pre-defined aluminium frames and boxes will be evaluated as initial step in this thesis work. In addition, a suitable material and surface treatment method will be defined. Apart from that, the sustainability of the whole process will be analysed by calculating the cost and the environmental impact of the manufacturing process.

1.3 Aim and Objectives

The main objective of this project is to identify the most suitable material and surface treatment method for a specific part of a vehicle frame. In addition, the manufacturing of the part will also be evaluated, including the estimation of its production cost and the environmental impact during its manufacturing and service life. It is crucial that this frame is capable of withstanding all types of environmental conditions worldwide, ensuring optimal performance and safety.

The current status of the frame is that is still under development and not yet in production. Besides, the initial material selection for the frame is aluminium, with different options for pipes and brackets/plates. To achieve the functional goals of the frame, a CAD geometry will be designed with specific objectives in mind, which include but are not limited to:

1. Is there a more suitable material for the frame than the selected aluminium? If so, which one? The material can be aluminium, steel or a composite (carbon fibre). When defining the material, the physical characteristics that the frame needs to fulfil its function are to be considered.

2. Is it necessary to improve the corrosion resistance of the frame by applying any surface treatment? If so, which treatment (chemical or thermal treatment) would be the most appropriate method for the chosen material? The possible corrosion risk will be analysed considering different environmental operating conditions using SolidWorks software.

3. What is the cost of manufacturing the structure? What is the total environmental impact (kg CO_2 emitted) of the structure during its manufacture and lifetime? In order to calculate the total cost of manufacture and the total environmental impact of the structure, it is necessary to take into account where it will be manufactured, the possible material transports during manufacture, the lifetime of the structure and the possible repairs or maintenance required during its lifetime.

1.4 Overview

In the following chapters, the material selection and surface treatment selection for a frame will be described. In *Chapter 2*, the theoretical framework will introduce and define the different aspects that are going to be treated along the thesis. The literature review will be exposed in *Chapter 3*. The methodology used will be detailed in *Chapter 4*. Besides, *Chapter 5* will describe the implementation process: from theory to the 3D model simulation results. The results of the research will be in *Chapter 6*. Last but not least, conclusions of the whole project will be discussed in *Chapter 7*.

1.5 Limitations

There are two clear limitations in this project:

- Lack of knowledge in this field. Due to the limited amount of previously available knowledge, the same factor that makes this endeavour intriguing also serves as a constraint.

- The inability to demonstrate our discoveries experimentally and practically. The greatest obstacle to providing convincing results is the lack of access to frames made with different materials and surface treatment for comparing the results with theoretical study.

Chapter 2

Theoretical Frame of Reference

2.1 Development of the Automotive Industry

The automotive industry has undergone a significant evolution since its beginning in the late 19^{th} century. The first automobiles were expensive and reserved for the wealthy elite, but Henry Ford introduced mass production techniques in 1908 with the Model T (Ford Motor Company, 2022), making cars more affordable and popularizing them as a means of transportation for the middle class.

Throughout the 20^{th} century, the industry introduced various technological innovations, including the internal combustion engine, automatic transmission, anti-lock braking systems, airbags, power steering, and more. Nevertheless, it was not until 1960s that this industry started globalizing. (Adams, 2019)

In recent decades, there has been a focus on energy efficiency and reducing emissions, leading to the development of hybrid and electric cars. Therefore, the industry is concentrating on the development of batteries and lighter materials for vehicles. (Zhang & Xu, 2022) Last but not least, mention that the industry is also developing automated and autonomous driving technologies which promise to improve safety, reduce traffic congestion, and make driving more efficient.

2.2 Importance of chassis design

Automotive chassis is a frame just like skeletal on which supports all the components that forms the vehicle, such as, engine, tires, axle assemblies, brakes, steering. Not only gives strength and rigidity to the assembly under different conditions, but it also keeps electrical systems and moving parts away from dust, dirt, and moisture. In addition, frames provide strength as well as flexibility to the automobile (Moreno, Milena, Florez, & Julieth, 2014).

Depending on their functionality there are different types of chassis, for example, multi-tubular, ladder, monocoque and truss. Over time, chassis have evolved, lightening their weight while maintaining the rigidity of the structure. The stability required is determined by the type of vehicle for which the chassis is designed. Among the various types of chassis, the main ones are:

- **Ladder frames**

Ladder type is one of the oldest forms of automotive chassis these are still used in most of the SUVs today. As the *Figure 1* shows, it consists of two lateral beams of tubular section, which are joined by transverse or diagonal reinforcements, sometimes with both types of joints in the chassis, increasing the torsional rigidity of the assembly and allowing the fixing of the components. The ladder chassis is characterised by its durability, ease of construction, resistance in the event of accidents and easy access to the components attached to it. Nevertheless, its disadvantages are the lack of torsional stiffness and the considerable weight due to the type of steel required for its construction. (Moreno, Milena, Florez, & Julieth, 2014)

Figure 1: Ladder frame (Changaroth, 2019)

- **Multi-tubular frames**

A structure called a "multi-tubular space frame" is made of tubes with diverse cross sections and supports various vehicle components while also safeguarding the passengers. See *Figure 2*. It has better structural rigidity than the ladder chassis, access to components is difficult but is highly dependent on design. Moreover, it requires a significant diameter in the pipes used for its construction, and the welds to be applied in the joints must be accurately calculated, their durability is determined according to the weight, taking into account that the bending loads in the welded joints are critical points of resistance. (Moreno, Milena, Florez, & Julieth, 2014)

Figure 2: Multi-tubular frame (Boria, Giannoni, & Giambó, 2015)

- **Truss frames**

A truss is a triangular structure made up of bars joined together by joints (nodes), the purpose of which is to support the loads acting on its plane. See *Figure 3*. By replacing the joints with spherical plain bearings, torsion can be eliminated in all members by torsion in all members by making the loads affecting them tensile or compressive (axial loads) only. The frame is structurally very efficient, with superior torsional and bending stiffness. Ideally it is designed as a rectangular box with diagonals on all sides, but due to the difficulty of construction of the design, in practice it is made by starting from three or more sub-frames to achieve its construction. It has acceptable impact resistance, as loads are progressively absorbed by each structural member. (Moreno, Milena, Florez, & Julieth, 2014)

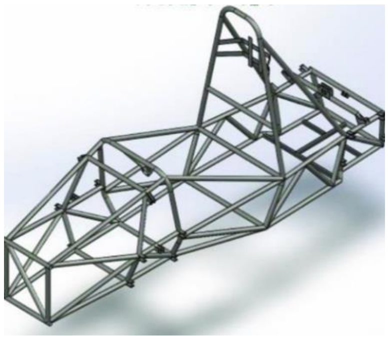


Figure 3: Truss frame (Baskara Sethupathi, Chandradass, Sharma, Bantwal Baliga, & Sharma)

- **Monocoque frame**

Structurally more efficient than the truss type chassis, its principle of operation consists of the principle is the absorption of loads by the skin of the structure. This is a frame made by joining thin sheets together using supporting bulkheads that allow the transmission of loads to the skin. (Moreno, Milena, Florez, & Julieth, 2014). The determining factors for the chassis design are the accessibility of components and the required rigidity of the vehicle. Lastly, mention that nowadays, most automobiles employ steel-plated monocoque chassis because they are economical and well-suited for automated manufacture (Singh, Soni, & Singh, 2014). *Figure 4* shows this kind of frame.

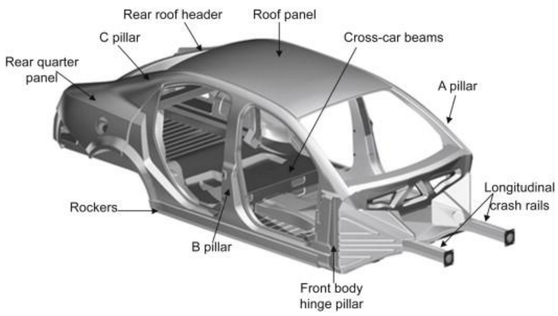


Figure 4: Monocoque frame (Gudmundsson, 2014)

2.2.1 Joining Methods

Typical joining methods in automotive manufacturing are spot welding, adhesive joining, laser assembly welding, electric arc welding, and MIG welding. It is important to choose an appropriate joining method, which will meet the requirements and the costs will not be high (Rzasinsk & Kochanski, 2018).

Spot welding and clinching are other two commonly used methods in automotive industry (Crolla, 2009).

Finally, screws, clips, hooks, rivets, and plugs are used in different applications: Special screws are developed for aluminium plates, FDS screws, for lightweight structures, by piercing and extrusion forming threads leaving the excessive material acting as a nut (Lundqvist & Thomas, 2017).

2.2.2 Material Selection

A good material selection is important in the automotive industry. For that, these are the main requirements that materials must have for the manufacture of automobile parts (Hovorun, Berladir, Pererva, Rudenko, & Martynov, 2017):

- High strength
- Energy intensity (ability to absorb impact energy when collision)
- Manufacturability (the possibility of manufacturing parts of a complex form with a minimum number of operations).
- Minimum car body weight.
- Corrosion resistance.
- Maintainability.

2.2.3 Surface Treatments

Automobile industry is progressively focusing on surface improvement engineering solutions to reduce wear, friction, and corrosion for engine interiors and powertrain parts. Besides, new surface solutions are also applied for interior and exterior parts. Surface enhancement engineering entails altering a material's surface via additive methods including thermal spray, PVD, plasma enhanced CVD, and thermochemical heat treatment like nitriding or nitrocarburizing. (Abadias, et al., 2016)

2.3 Materials within the Automotive Industry

In the 1960s and 1970s, as a result of research efforts, high strength steels were divided into several groups due to the lack of adequate forming techniques for the new vehicle designs; HSS, conventional high strength steels, low carbon steels, and other groups with similar metallurgical and physical characteristics: AHSS advanced high strength steels, IF, modern interstitial free steels for stamping complex features, and TWIP, twinning induced plasticity, and L-IP, lightweight steels with induced plasticity (Mallick, 2010).

Low carbon steel is being replaced in vehicles by lightweight alloys, such as aluminium and magnesium, and polymer matrix composites due to improvements in weight reduction, safety, durability, processing, joining, recycling, and cost (Mallick, 2010).

In order to reduce the structural weight of goods, low density materials are increasingly employed in the construction, automotive, and aerospace industries. This may lead to significant fuel savings, a smaller carbon footprint for transportation, and makes it easier to manipulate specifics in applications for construction applications (Monteiro, Buso, & Silva, 2012).

In addition, as less material is needed to produce consumer items, the low material density promotes the conservation of natural resources.

Upon analysis of *Figure 5*, it is evident that over half of the parts are produced using cast iron and steel, constituting 55% of the materials used. Plastics and aluminium alloys are the next most commonly used materials, comprising 11% and 9% of the materials, respectively. Rubber and glass are responsible for 7% and 3%, respectively, while the share of non-ferrous alloys (magnesium, titanium, copper, and zinc) does not surpass 1%. It should be noted that other materials, make up the remaining 14% of the total materials used.

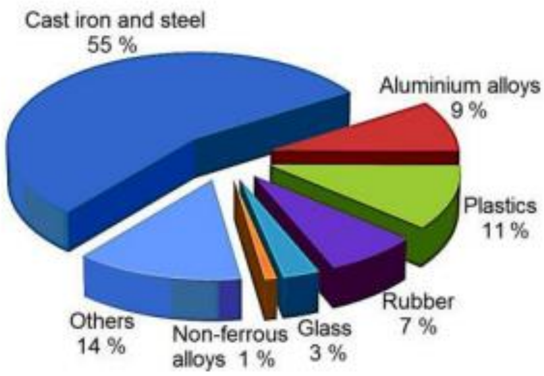


Figure 5: Materials used for manufacturing car parts (Hovorun, Berladir, Pererva, Rudenko, & Martynov, 2017)

Historically, all critical automotive parts are made of steel or other metal alloys. Steel has excellent strength and reliability, nevertheless, is prone to corrosion and parts manufactured from it vary in mass by a reasonable amount.

Nowadays, owing to the application of the most recent scientific advancements, polymer composites exhibit significantly higher hardness and strength than traditional steel. Synthetic fibres are woven together to provide a sturdy reinforcing frame that equally distributes the weight across the component's full surface. Moreover, carbon fibre components weigh nearly three times less than steel-like components (Hovorun, Berladir, Pererva, Rudenko, & Martynov, 2017).

2.4 Corrosion

Corrosion is the consumption or dissolution of a material (metal, ceramic, or polymer) by chemical or electrochemical interactions with its surroundings. In addition, there is a significant economic cost to society from corrosion and corrosion prevention, which account for around 5.0% of the gross national product of any country. (Palankeezhe Balan, 2018) The following table shows different types of corrosion, their characteristics, and their appearance in ferrous and aluminium alloys:

Table 1: Corrosion types and their characteristics

CORROSION TYPE	**DEFINITION**	**PREVENTION**	**FIGURE (Ferrous alloys)**	**FIGURE (Aluminium alloys)**
UNIFORM	Uniform corrosion is a type of corrosion that occurs uniformly over the surface of a metal, causing a gradual loss of material when it is exposed to a corrosive environment, such as exposure to saltwater, acid rain or other chemical agents. (Kumar & Singh, 2021)	Use of corrosion surface protection measures, such as, painting, coating, anodizing, plating, cladding and cathodic protection. Use of a corrosion-resistant metal. Lastly, regular maintenance and cleaning. (Nimmo & Hinds, 2003)	 *Figure 6: Uniform corrosion, ferrous alloy (S. Tait, 2018)*	 *Figure 7: Uniform corrosion, aluminium alloy (Alumeco Group)*

PITTING	It is a form of extremely localized attack that results in the formation of a pit leading to perforation in the metal. Is typically caused by exposure to aggressive chemicals, such as chloride ions or sulphur compounds. (Palankeezhe Balan, 2018)	Use of protective coatings, cathodic protection, and careful selection of materials for specific applications. (Palankeezhe Balan, 2018)	 *Figure 8: Pitting corrosion, ferrous alloy (Wiley , 2018)*	 *Figure 9: Pitting corrosion, aluminium alloy (Velling, 2020)*
CREVICE	Crevice corrosion is a type of localized corrosion that occurs in narrow gaps between two surfaces when metal surfaces are exposed to corrosive environment. It often occurs when there is a difference in oxygen concentration between the inside and outside of the crevice. (Kumar & Singh, 2021)	Reduction of crevices in the design of the structure. Improve drainage, seal edges, or keep crevices as open as possible in order to avoid the entrance of moisture. Using materials that are resistant to crevice corrosion or coatings or inhibitors to protect the metal surface. (Rashidi, Alavi-Soltani, & Asmatulu, 2007)	 *Figure 10: Crevice corrosion, ferrous alloy (Steelfab, 2021)*	 *Figure 11: Crevice corrosion, aluminium alloy (Juhl)*

GALVANIC / SELECTIVE CORROSION	Galvanic corrosion often referred to as bimetallic corrosion or dissimilar metal corrosion occurs in galvanic couples where the active one corrodes in the presence of an electrolyte, such as, saltwater, or acidic solution. This happens because the two metals have different electrochemical potentials, which creates a voltage difference between them. (Zhang X. G., 2011)	Using metals with similar electrochemical potentials, isolating the metals with a non-conductive material, or using sacrificial anodes. (Palankeezhe Balan, 2018)	 *Figure 12: Galvanic corrosion, ferrous alloy (Harkin, 2017)*	 *Figure 13: Galvanic corrosion, aluminium alloy (Vu)*
STRESS	Stress corrosion cracking (SCC) refers to failure under simultaneous presence of a corrosive medium and tensile stress. It is a phenomenon that occurs when a material experiences both mechanical stress and corrosion simultaneously, leading to cracking and failure of the material. (Kumar & Singh, 2021)	Careful consideration of both the material and the environment. Use protective coating or inhibitors. Do regular maintenance. (Parkins, 2012)	 *Figure 14: Stress corrosion, ferrous alloy (Finchen Parsons, 2001)*	 *Figure 15: Stress cossorion, aluminium alloy (Velling, 2020)*

WHITE	White corrosion is normally formed when the metal is exposed to oxygen and hydrogen in certain environments. It is often caused by the exposure of the zinc to humid environments. This appears as a white chalky substance in the surface of the metal. This rust can easily appear on galvanized metals that are in contact with water, due to the zinc that contains those surfaces. White corrosion damages the appearance and makes the coating useless becoming the metal prone to corrosion attack. (Dey, 2022)	Avoid exposure to water, applying a waterproof covering in the surface. Allowing the zinc to form stable oxides prior to exposure to moisture. To use passivation chemicals to prevent the oxidation of the zinc. Avoid exposing the cold zinc material to a warm environment. (Dey, 2022)	 *Figure 16: White corrosion, ferrous alloy (Dey, 2022)*	 *Figure 17: White corrosion, aluminium alloy (All Metals Fabrication, 2022)*

2.4.1 Corrosion in automotive industry

Corrosion is a significant issue in the automotive industry because vehicles are often exposed to harsh environmental conditions, including moisture, salt, and chemicals, which can lead to corrosion of various components. It may occur in many different areas of a car, such as the body, frame, suspension components, brake lines, fuel lines, and exhaust system. (Kumar & Singh, 2021) It is important to use corrosion-resistant materials, coatings, sealants, and regular maintenance to avoid it so that it does not weaken the structural integrity, brakes, and fuel leaks. (Huang, Xu, Zhao, & Chen, 2019)

2.5 Surface treatments within the Automotive Industry

As there has been mentioned above, surface treatments are an important aspect of automotive manufacturing and maintenance, as they can improve the performance, durability, and appearance of automotive parts and components. Some common surface treatments used in the automotive industry include:

Table 2: Type of surface treatments and their characteristics

TYPE OF SURFACE TREATMENT	DEFINITION	MATERIALS	ADVANTAGES	DISADVANTAGES
ELECTROPLATING	Electroplating is a process that consists of depositing a thin layer of metal onto a conductive surface by hydrolysis. It consists of transferring the desired metal coating from an anode to a cathode. (BYJU'S, 2023)	Any materials, from metals to non-conductive materials such as plastic or wood. (Form Labs, 2023)	++ Improves the durability, the conductivity, and the function of the object. + Increases the hardness or lubrication of the object. (Aspiring Youths, 2023)	- Very expensive and complex. -- It can cause hazardous environmental impact. --- The thickness of the electroplated layer is limited and can result in defects such as cracks. (Aspiring Youths, 2023)

ANODIZING	Is an electrochemical process that consists of creating naturally an oxide layer on the surface of a metal. There are three types of anodizing: Chromic Acid Anodizing (Type I), Sulfuric Acid Anodizing (Type II), and Hard coat anodizing (Type III). In the *Appendix E: Types of Anodizing* can be found explained the three types of anodizing. (Fast Radius, 2021)	Commonly used on aluminium, but also in titanium and magnesium. (HUBS, 2023)	+++ Higher corrosion resistance. ++ Improved wear resistance. ++ Better adhesion for paints and other coatings. + Creation of decorative finishes with different colours and textures. (HUBS, 2023)	- Cannot be used on Stainless steel. - Environmental risk. - Limitation in colour selection. -- Hard to replicate consistency between batches. -- An expensive solution for small quantities. (Phos, 2023) (Keymark Corporation, 2023)
POWDER COATING	Powder coating is a dry finishing process that consists of the application of a dry, free-flowing, thermoplastic or thermoset powder to a surface. Powder coating uses an electrostatically charged mixture of finely ground particles of pigment and resin that are adhered to the surface of the material. (Ronquillo, 2023)	Metals, plastics, glass, and medium density fibreboard (MDF). (Ronquillo, 2023)	+ A wide range of surface finishes and textures. +++ A layer of protection against corrosion. + Economic. (Ronquillo, 2023)	-- The coating breaks down exposed to UV rays. - High startup costs - Less control over smoothness. - Not possible to obtain different colours. (Performance Coating, 2020)

PASSIVATION	Passivation is a chemical surface treatment that consists of creating a thin and protective layer on the surface of the metal. (Best Technology, 2023)	Applied to corrosion-resistant alloys: Stainless steel, titanium, and aluminium. (Best Technology, 2023)	+++ Improves the corrosion resistance of the metal. (Best Technology, 2023)	-- Not suitable for welded parts. - Not suitable for Stainless Steel alloys with low chromium and nickel content. - The temperature and type of acid must be adjusted for specific steel alloy. - It does not alter the appearance of the part. (Marlin Wire, 2020)
GALVANIZATION	Galvanization is a surface treatment that prevents corrosion applying a protective zinc coating to iron or steel. There are two types: hot dip galvanizing and electro-galvanizing. (Ye, 2021)	Iron or Steel. (Ye, 2021)	+++ Excellent corrosion resistance + Provides a decorative finish. + Provides the chance to be painted to the metal. (National Material, 2019)	--- Easy to flake and peel off, which rusts the metal. -- Very hard and tough surfaces, so they are not suitable for applications requiring flexibility and are difficult to weld. - A qualified person is needed.

				- Only used for low quality products. (Mechanical Education, 2023)
CHROMATE COATING	Are formed on metal surfaces as a result of the chemical attack that occurs when a metal is immersed in or sprayed with an aqueous solution of chromic acid, chromium salts. The chemical attack facilitates the dissolution of some surface metal and the formation of a protective film containing complex chromium compounds. (L. Hagans, 1994)	Magnesium, copper, silver, tin, zinc, aluminium, and steel alloys. (Fredericks)	+++ High corrosion protection. ++ Improves electrical conductivity. + Provides decorative finish to the surface. ++ Improves adhesion to other coatings or paints. (Fredericks)	-- Harmful for the environment. -- Toxic process that may cause health problems. - More expensive than anodizing or plating. (Omari, Penafiel, & McIndoe, 2020)
PLASMA ELECTROLYTIC OXIDATION (PEO)	Plasma electrolytic oxidation (PEO) is a promising novel electrochemical surface treatment technique that can produce a thick, hard, and dense ceramic-like coating. PEO employs environmentally friendly weak alkaline as well as acidic electrolytes	Aluminium, titanium, magnesium, and other lightweight alloy substrates. (Sikdar, V. Menezes,	++ Stronger final product. + Simple pre-treatment. ++ Environmentally friendly process. (Austin, 2020)	- High temperature and pressure are needed. - Great amount of power is consumed.

	in which the oxide coatings are formed under the application of high electric voltages. (Sikdar, V. Menezes, Maccione, Jacob, & L. Menezes, 2021)	Maccione, Jacob, & L. Menezes, 2021)		- Continuous replacement of electrolytes. - Expensive process. (Austin, 2020)
NATURAL OXIDATION	Metal corrosion is also known as metal oxidation. This happens when an ionic chemical reaction occurs on a metal's surface while oxygen is present. This oxidation layer can form protective layer over time. Not all oxidation forms rust. (Tampa Steel, 2022)	Aluminium, Stainless steel, Copper, Titanium, Molybdenum and Magnesium. (Jansen, Kashchiev, & Erdem-Senatalar, 1994)	+++ Protects the metal from further corrosion. + Can give decorative properties to the metal. (Corrosionpedia, 2018)	-- The oxide layer may take time to form. --- The oxide layer may react with different environments. --The oxide layer may lead to irregular surface. Thus, to remove the surface quality, must be removed. (Lissmac, 2023)

2.6 Sustainability

Sustainability can be defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs". For a system, product, or industrial construction to be considered sustainable it must be (Trueba Muñoz, 2009):

- Equitable between social needs and economic profitability.
- Economically and environmentally viable.
- Liveable, to respond to social and environmental needs.

Figure 18: Venn diagram for sustainable development (Sadiku, Olaleye, & Musa, 2019)

- **Social sustainability**

In this case, defining a suitable material and surface treatment method for a specific automotive frame will make institutions/companies on an engineering sphere gain and widen knowledge about materials and surface treatment methods, having a beneficial impact on society.

- **Economic sustainability**

This project has the key of reducing cost in the manufacturing process of a frame, therefore, it is important to select the cheapest and most affordable material and surface treatment method but at the same time suitable one that fulfils the aim of the structure.

- **Environmental sustainability**

This project wants to promote an environmental sustainability through energy saving, availability of raw materials, recycling materials, waste reduction; thus, achieving the most environmentally friendly manufacturing process possible. For that, a life cycle assessment will be done.

Chapter 3

Literature Review

For this thesis, many different references have been used in order to have a good understanding of the diverse types of materials used in automotive industry. Besides, other references have been used to understand different types of corrosion that affect frames and surface treatment methods to avoid this fatal problem.

To start with, Forero Moreno, Daniela Milena, Angela Julieth, and Pinzon Florez (Moreno, Milena, Florez, & Julieth, 2014) provides information about the importance of a good frame design in order to fulfil its aims: give strength and rigidity to the assembly and protect the parts from dust, dirty and moisture. As mentioned, there are many types of frames, but according to Singh, Soni, and Singh (Singh, Soni, & Singh, 2014), nowadays, monocoque frame is the most used in the automotive industry, because it provides good accessibility of components and the required rigidity of the vehicle.

Good joining method is vital for manufacturing a frame, therefore, according to the article written by Rzasinsk and Kochanski (Rzasinsk & Kochanski, 2018), there are many joining methods, but between them, the best ones are adhesive joining and CMT/CMT+P. Besides, screws, clips, hooks, rivets, and plugs are also other joining method that are used in automotive industry to join different parts, such as, aluminium plates and lightweight structures. This information is provided by Lundqvist and Thomas (Lundqvist & Thomas, 2017).

The scope of this thesis work is to find a suitable material for a frame and Hovorun, Berladir, Pererva, Rudenko, and Martynov (Hovorun, Berladir, Pererva, Rudenko, & Martynov, 2017) give the requirements that needs to fullfil any material in order to make a good material selection. Go to *2.2.2 Material Selection* to see the properties and characteristics that any material must have. Besides, these writers provide that the 55 % of material used in automotive industry are the cast iron and steel. Nevertheless, with the advancement of the technology, new materials like carbon or glass fibre, are gaining momentum. This is because they provide same or better material properties with lower density.

Selecting a good surface treatment method is another important objective for this thesis work. This selection will be made considering the corrosion. Palankeezhe Balan (Palankeezhe Balan, 2018) provides information about corrosion, giving examples of different types. Each one can occur depending on different factors, such as, metal microstructure, environmental conditions, stresses… It is important to avoid or prevent this problem, because as Huang, Xu, Zhao and

Chen (Huang, Xu, Zhao, & Chen, 2019) stated, it decreases the strength of the structure, increase the cost due to maintenance, decreases the fuel efficiency and so on… A good way to prevent the corrosion is using coating methods, for example, electroplating, anodizing, powder coating, passivation, galvanization. Not only prevents corrosion, but also improve the performance, durability, and appearance of automotive parts and components.

Last but not least, as the environmental impact is crucial for this thesis work, a life cycle assessment will be made following the steps represented in this thesis work: Development of a process for environmental life cycle investigations conducted by Eric Berntsson and ALBIN Dimgard. (Berntsson & Dimgard, 2022)

Chapter 4

Methodology

To achieve the project goals in a time effective way, the main work has been divided into five steps: Gathering information, material selection, surface treatment selection, simulations, and sustainability. For that, a chart will be used (*Figure 19*). Although gathering information is the first step must be followed to conduct this thesis work, material selection and surface treatment selection can be made simultaneously. However, it is crucial to acknowledge that certain surface treatments may not be compatible with specific materials. Lastly, the following steps are simulations and sustainability.

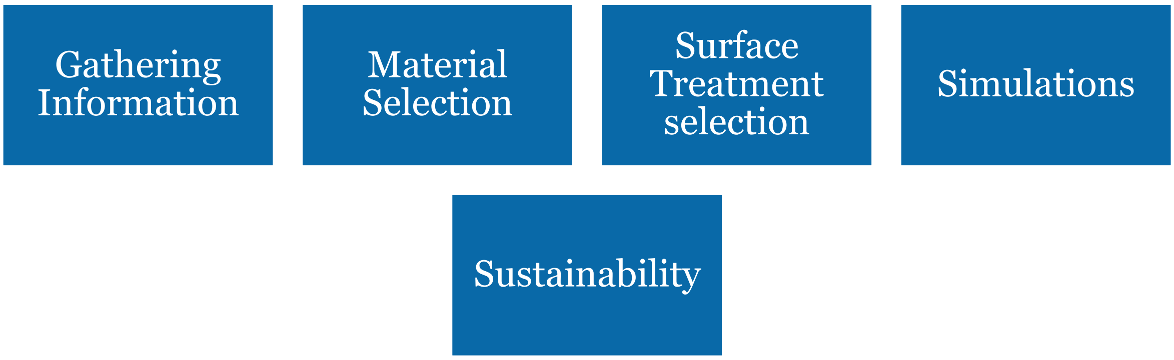


Figure 19: Methodology chart

- **Gathering Information**

  Gathering information is one of the most important parts in this thesis work in order to know nowadays which material is commonly used in automotive industry and, which surface treatments are normally used. Besides, it is vital to investigate types of corrosion that may manifest in metal frames.

- **Material Selection**

  The selection of the most appropriate material is a crucial step in achieving the desired characteristics of the frame. To accomplish this, the Ansys Granta software will be employed, which is a powerful tool for material selection and analysis.

- **Surface Treatment Selection**

  If deemed necessary, the next step would be to theoretically select the surface treatment. Mention that most materials do not need any surface treatment to deal with corrosion and other many factors.

- **Simulations**

  Precise CAD models of the frame is created. The model is subjected to Finite Element Analysis to look at design in terms of corrosion resistant. This part is important to obtain valuable results.

- **Sustainability**

  Sustainability in engineering refers to an approach that seeks to develop projects, processes and systems that are socially fair, economically viable and environmentally responsible in the long term. According to the total manufacturing cost, is crucial to determine the new frame's entire production cost. Besides, reducing the carbon footprint, ensuring that any company is in compliance with regulations and avoiding penalties or fines, lead to cost savings by using resources more efficiently, reducing waste, and improving energy efficiency. To calculate both cost and the impact different software's will be used: SolidWorks and Life Cycle Assessment.

Last but not least, *Chapter 6* will cover the results from the analysis of the solution. *Chapter 7* will explain the conclusions, discussing the results obtained, and finally, *Chapter 8* will construct a collection of potential future work.

Chapter 5

Implementation

5.1 Material Selection

Material selection is a very important part of engineering processes as far as the design of systems is concerned. Generally, effective material selection process implies selecting materials with optimal costs with good performance that meets the component designed service life. Based on the above material requirements and materials indices, a search was carried out using the Ansys Granta software Level 3 to select suitable materials for frames.

Materials selected at the end of each process must possess certain characteristics that meets the following criteria:

- High resistance to corrosion. Internal and external different environments specify.
- Low density which makes lighter the vehicle.
- High young modulus to withstand vibration from the engine or other components.
- High fracture toughness to resist crack propagation from an existing crack.
- High stiffness to resist changes in shape of the pipes when forces are applied.
- High weldability in order to be easier to join each frame parts.

Figure 20 presents the criteria for limits applied in the material selection for frames. These limits are the following:

- Maximum service temperature of 100 °C. (Since the service temperature considered for a typical automotive frame structure is about 100 °C and above, a minimum temperature of 100 °C was set to filter off materials whose service temperature is below this value.)
- A minimum value of 15 Mpa·$m^{0.5}$ of fracture toughness was set. (Fracture toughness is one of the most important factors that determine the longevity of the exhaust system under such severe condition. Therefore, a minimum value of it was set to filter off materials with fracture toughness below this value.)
- Good or excellent weldability.

- Good or excellent water (salt) resistance.
- Good or excellent organic solvents resistance.

These limits remove materials that do not have the characteristics mentioned above. From 4243 materials, 920 are still good to frame applications.

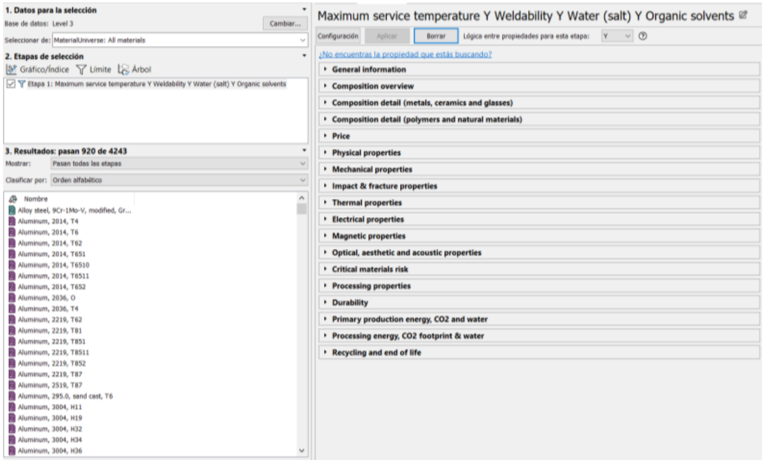


Figure 20: Chart of Limits applied in material selection for frames.

Following the material selection process, it is crucial to take into account not only the mechanical properties of the materials but also their cost. In this project, a limit was defined based on the price per kilogram, which was set at 2 €/kg. *Figure 21* illustrates the materials that are available within this price range. Out of the initial 920 materials, the list has been reduced to 224. The cheapest material is coated steel (galvanized), while the most expensive is stainless steel (UNS S44627). The aluminium (5086 H111) and stainless steel (AISI 430) fall in the middle range of the affordability and are therefore viable options.

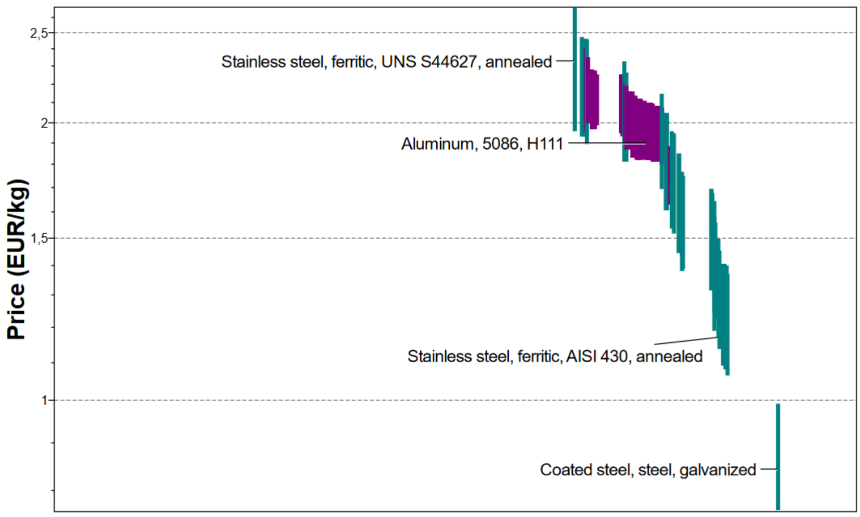


Figure 21: Chart of price per kg applied in material selection from frames.

The relationship between the Young's modulus (GPa) and density of the materials was analysed and presented in the *Figure 22*. In this application, it is crucial to have a material with high stiffness-to-weight ratio to provide the required stiffness for the frame minimizing its weight. Four material families were identified to meet the defined limits for affordability and stiffness requirements: Different aluminium, stainless steel, magnesium, and Cast iron. It was observed that Cast iron has the lowest stiffness-to-weight ratio, whereas aluminium and stainless steel have the highest ratio.

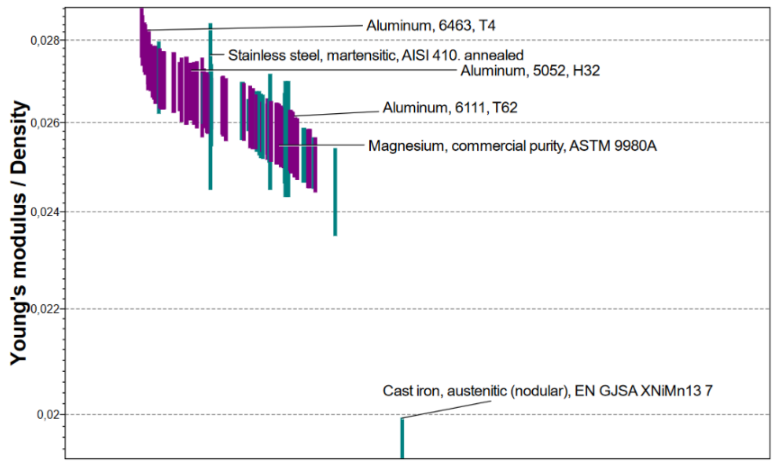


Figure 22: Graph of stiffness-to-weight ratio

As shown in the *Figure 23*, the relationship between density and tensile strength is plotted. For this application, it is crucial to choose a material with high strength-to-weight ratio to ensure the structural integrity and safety of the frame under loading. It can be observed that materials, such as, aluminium, and stainless steel have the higher strength-to-weight ratio. This implies that these materials will withstand higher loads for a given weight. On the other hand, magnesium and cast iron have lower strength-to-weight ratio.

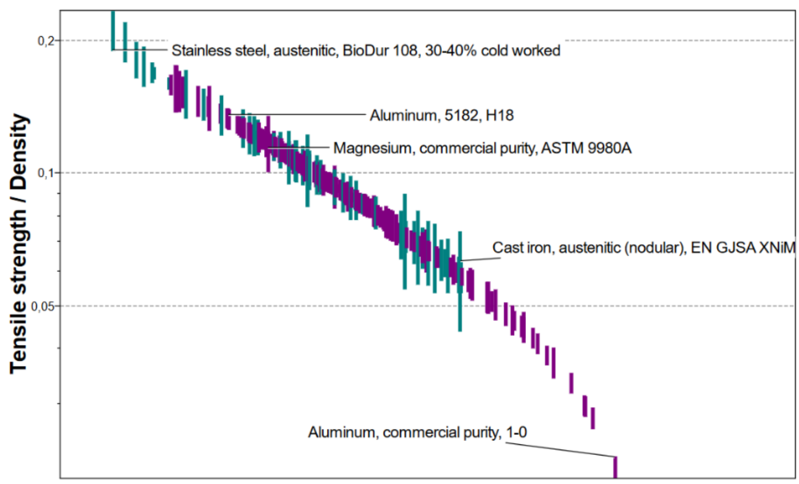


Figure 23: Graph of strength-to-weight ratio

In continuation of the material selection process, *Figure 24* illustrates the comparison between the tensile strength and price. In this case, it is important to select a material having hight strength-to-cost ratio as it indicates that a material or structure offers greater strength or load-carrying capacity for a given cost. The graph shows that stainless steel is the most suitable material due to its high tensile strength and low price, as it has the highest strength-to-price ratio. Nevertheless, magnesium, cast iron and aluminium alloys has the lowest ratio.

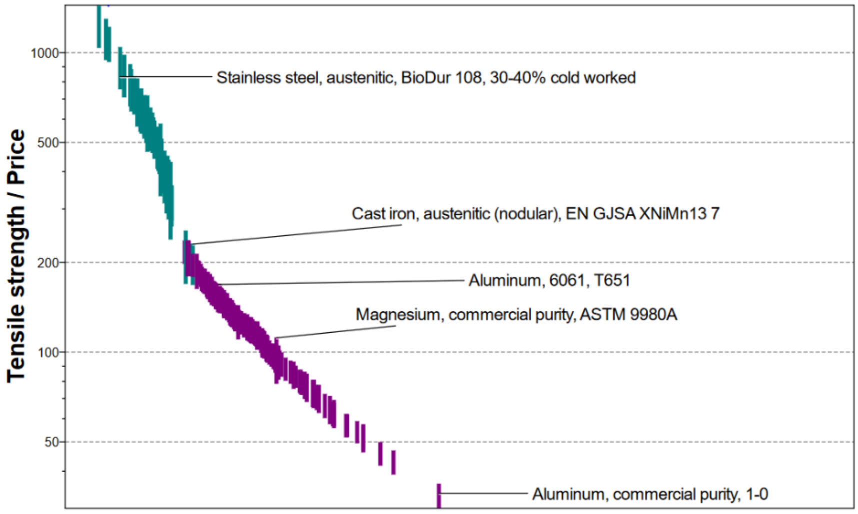


Figure 24: Graph of strength-to-price ratio

5.2 Simulations

Simulations are of great importance for the selection and justification of material selection and surface treatment methods and to identify the regions most susceptible to corrosion and stress corrosion cracking. Thus, it is possible to identify, from which part of the frame is more prone to initiate corrosion. As previously mentioned, the frames under study are still in the development stage and have not yet been produced. This lack of physical frame makes it impossible to conduct practical and experimental analysis. Nevertheless, SolidWorks software was used to perform simulations that aimed to assess the behaviour of the frames under various environmental conditions and to compare the obtained results. Thus, the designs of the frames were tested and validated using the software visualization and simulation tools. Lastly, mention that these simulations are done in order to obtain areas of high stresses.

5.2.1 Boundary Conditions

To start with the simulations, first the boundary conditions, critical forces, and the most extreme environmental conditions has been specified:

Boundary conditions, also known as constraints, are essential factors to consider in the simulation process. They represent the surfaces that are joined to the chassis without suffering any deformation. These constraints are critical in determining the behaviour of the frame under different conditions. One of these fastened surfaces can be observed in *Figure 25*:

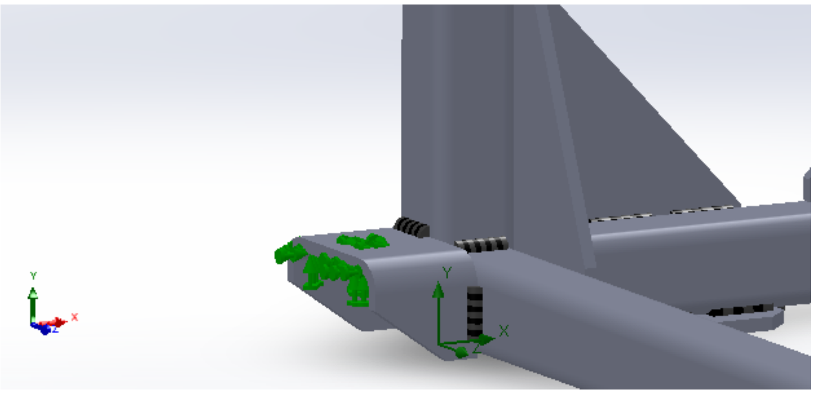


Figure 25: Boundary conditions of the fastenings of the frame

Based on the available information, the forces that the frame must endure have been estimated and located in different surfaces of the frame, as represented in *Figure 26*. However, since the frame is not yet manufactured, the exact forces cannot be determined. It is important to note that the estimated forces are based on assumptions and may not represent the real forces that the frame will be subjected to. Nonetheless, these assumptions serve as a starting point for the simulation studies to evaluate the behaviour of the frame under different loads and environmental conditions.

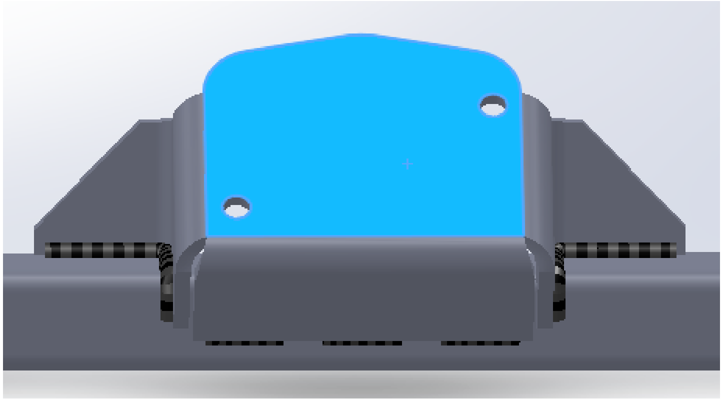


Figure 26: Surface in contact with the engine

In accordance with the laws of physics, the weight of the component applies a force in the same direction as gravity, which is downward with a constant acceleration of 9.81 m/s². This force is normal to the ground and is depicted in *Figure 27*. This information is necessary for the simulations to accurately model the behaviour of the frame under the specified conditions.

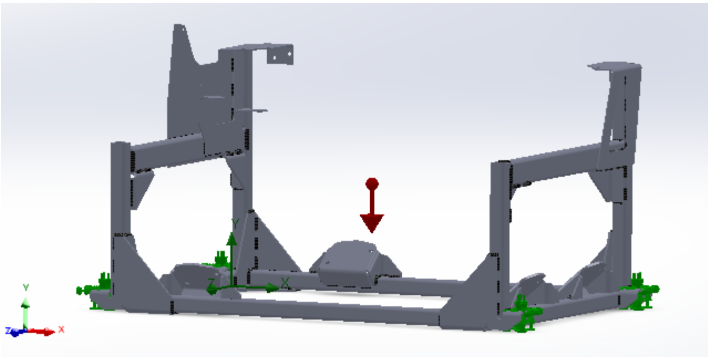


Figure 27: Gravity force

Additionally, the frame experiences two other forces in different surfaces, but due to their relatively small magnitudes, they have been neglected in this simulation.

5.2.2 Mesh

In the scope of this analysis, a mesh comprising 502699 elements has been generated for the frame model. To achieve this, an approximate element size of 1 mm has been defined for the general region of the model. Nevertheless, in specific areas where the required level of precision was relatively lower, an approximate element sizes up to 33 mm has been employed, as dictated by the design specifications. The mesh employed in this analysis is a Solid Mesh constructed based on combined curvature.

This mesh can be seen in the *Figure 28*:

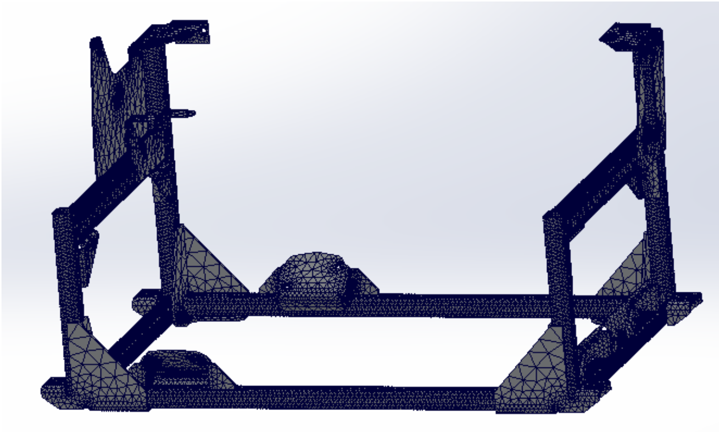


Figure 28: The frame meshed

To determine the optimal mesh configuration with the highest level of accuracy, various mesh sizes were systematically tested and evaluated. The mesh size was iteratively adjusted until the obtained results reached a stated of stability. The convergence of the mesh is illustrated in *Figure 29*, which showcases the graph depicting changes in maximum stress experienced by the frame as a function of the mesh variations. The highlighted portion in the figure corresponds to the specific mesh utilized for this analysis.

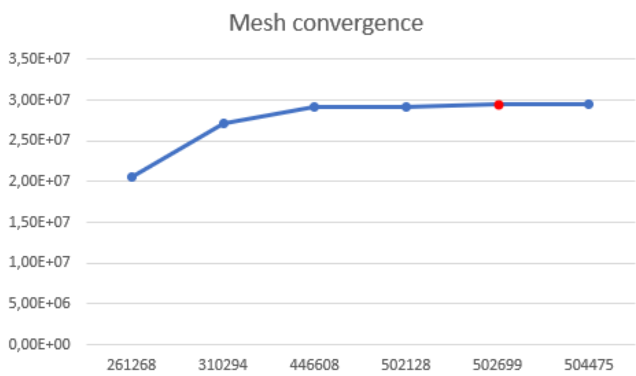


Figure 29: Mesh convergence

5.2.3 Materials

In accordance with the preliminary material selection made by Aurobay, aluminium Al 6082-T6 was chosen as the initial material for the simulations. Subsequently, simulations were conducted using other materials, such as, 108 Stainless steel, galvanized steel, and turned steel, which were obtained from the Granta analysis. It is worth mentioning that the results obtained from the steel simulations were quite similar. This is because the mechanical properties of the different steels are very similar. Ultimately, a comparison between the various simulation results will be performed to determine the most appropriate material for the frame.

5.3 Sustainability

In the following lines can be seen how the social, economic, and environmental impact of this frame would be calculated and concluded.

5.3.1 Social impact

As mentioned in section *2.6 Sustainability,* this project can provide valuable insights for various industries by presenting a detailed analysis of different materials and surface treatment methods. The economic and environmental impact of this project can serve as a reference for readers, highlighting the significance of these factors in today's society and different sectors, including automotive industry. Additionally, the readers will be able to learn from this project about the process of calculating the economic and environmental impact of an automotive product. Therefore, this thesis work can be beneficial for professionals and researchers in the field of automotive engineering and related industries.

5.3.2 Economic impact

In the *2.6 Sustainability* section, it has been highlighted that selecting the most cost-effective material and manufacturing process is crucial for the sustainability of the project. Therefore, it is important to calculate the manufacturing cost of the frame to identify areas where cost can be reduced.

The total manufacturing cost is the sum of all costs during the production of a product or service to convert raw materials into a finished product. This way, the manufacturing cost of a frame depends on several characteristics of that frame and its manufacturing process. This costs that are directly related to the production, are called direct costs: (Indeed, 2023) (Lee, 2022)

- Material costs: The cost of all materials used during the production process. Such as raw materials.
- Labour costs: The salaries of employees involved in the production.
- Overhead costs: The service costs, utility expenses, rent payments and equipment costs.

However, there are other costs that are not directly connected to the production but are necessary to keep the business running. These costs are called indirect costs and sometimes is not possible to classify them into a specific product's cost of production. (Indeed, 2023) (Lee, 2022)

- Utilities and office supplies: The cost of facilities and utilities related to the physical space or building used in the company.
- Marketing: The cost of promoting the product.
- Administrative: The cost related to administrative functions such as legal services.

One efficient way of reducing the production costs is to identify, report and control the indirect production overhead costs. (Lee, 2022)

5.3.3 Environmental impact

In this section, a determination of the frame climate impact is done by performing a life cycle assessment (LCA), which is a method to investigate the environmental aspects of a product during its complete life cycle, from raw material extraction, through all life cycle stages, to the final disposal. This analysis will be held based on the standardised ISO 14040-series Life Cycle Assessment (LCA) method.

Step 1, pre-analysis

A natural way to state the foundation for the study is to define the goal. Additionally, the study's scope and boundaries need to be defined. Furthermore, a table that combines a Process Flow Chart and the product's Bill of Materials is created.

- Goal: The aim of this analysis is to calculate the environmental impact of manufacturing the frame, from the raw material extraction to the product end of life.
- Scope and boundaries: The study will only include inputs of energy and outputs of CO_2 emissions, other inputs and outputs will be neglected. The product is a component for a vehicle and as it has low weight the influence on the vehicle use will not be included. Besides, allocation will primarily be made by mass. Lastly, in this case different geographical scenarios will be calculated in other to see the transport impact, although, the whole product will be fabricated in EU, specifically in Sweden.
- Functional unit: one component in a vehicle that is driven 200 000 km.
- Bill of materials: This can be found in the *Appendix F: Bill of materials*.

- Process flow chart:

The following figure represents the process flow chart with the main processes and known subprocesses for the product's life cycle.

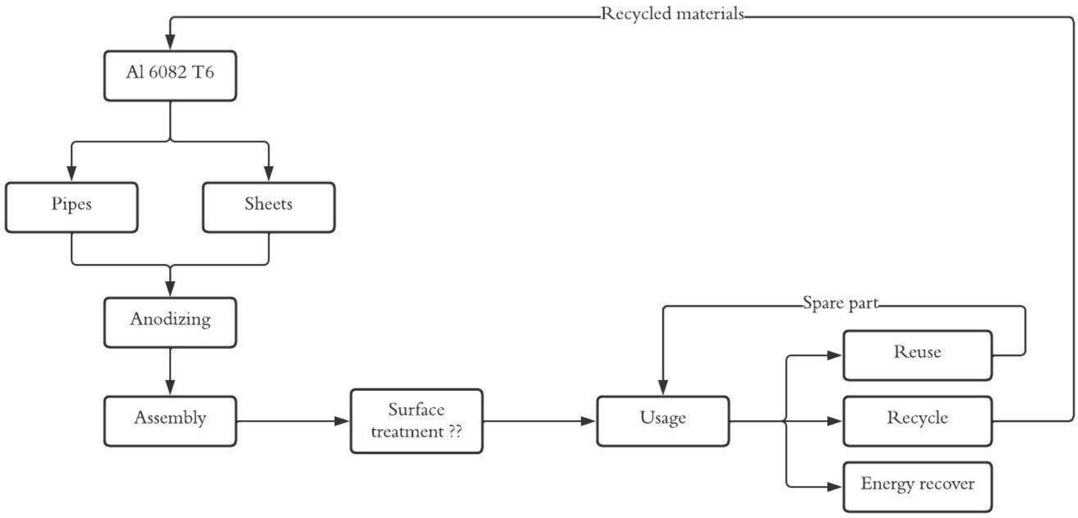


Figure 30: Process flow chart

Table 3: Subprocesses for the product's life cycle

Material Processing		**Component manufacturing**			**Surface treatment application**		**Assembly manufacturing**				**Use**	**End-of-life**		
Material extraction	Transport	Cold impact extrusion	Sheet rolling	Transport	Anodizing	Transport	Assembly	Transport	Assembly vehicle	Transport	User	Reuse	Recycling	Energy recovery

- A Life Cycle Eco Data Table is created from the Process Flow Chart and the Bill of Materials. When the data collection is conducted, the data values are documented in the table's cell corresponding to the examined process and component or components. Further, while the study is conducted additional processes or components are easily added to the table.

Step 2, Data collection, Raw materials

The raw material data is collected from Granta's Life Cycle Assessment database EduPack.

Step 3, Data collection, Additional processes

The Process Flow Chart most likely describes additional processes, i.e., other processes than those concerning raw materials, use phase, End of Life, and transports. The additional processes
vary between different analyses and are spread through the complete life cycle of the product, in this case, these processes are, extrusion, rolling, welding, and coating. The additional processes data is collected from Granta's LCA database EduPack.

Inputs and outputs that are assessed for the anodizing process, each related to 1 m^2 of aluminium treated, are summarized in the following table (*Table 4*):

Table 4: Inputs and outputs of the anodizing

	Value
Energy consumption	3 MJ/m^2
CO_2 emissions	3 kg/m^2

Step 4, Data collection, Use Phase

This step will not be considered because the product analysed has a low impact on the vehicles total mass, less than 1‰. Besides, this product does not require maintenance during its lifespan.

Step 5, Data collection, End-of-Life

The End-of-Life phase of a product refers to the withdrawal of a product from the market because it does not work as intended and is replaced by a new version. Thus, after a product is retired from the market, many things can be done with it. These different End-of-Life solutions have a significant influence on the environmental impact of the product. In the *Figure 31*, different End-of-Life alternatives and their outputs can be seen:

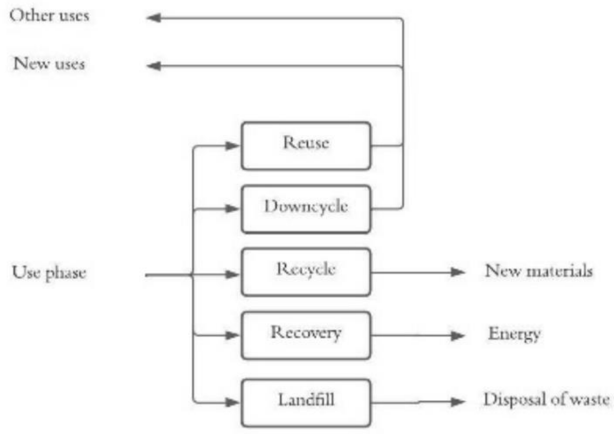


Figure 31: End-of-Life alternatives and their output (Berntsson & Dimgard, 2022)

The European Commission requires firstly to encourage the reuse of vehicle components that are suitable for reuse, secondly to recycle and finally to recover energy from the components. However, the anodizing process can protect the aluminium component by extending its lifetime and allowing it to be reused before recycling. Apart from that, anodized aluminium is as recyclable as traditional aluminium. However, in the first case, some strong acids and alkaline solutions must be used to remove the anodized layer. But, if this process is done properly, it is an environmentally friendly process. (Aotco, 2018)

Different ways of end-of-life of the Al 6082-T6 are represented in the following table:

Table 5: End-of-life possibilities of Al 6082-T6

End of life option	Description	Environmental burden	Possibility
Reuse	Extension of product life.	LOWEST	YES
Recycle	Reprocessing of material into primary supply chain.	↓	YES
Downcycle	Reprocessing into a lower grade material.		YES
Combustion	Recovery of the calorific content of the material.		NO
Landfill	Disposal of material.	HIGHEST	YES

According to the recycle of the Al 6082-T6 however, its properties and possibilities are represented in the following table (*Table 6*):

Table 6: Recycling properties of Al 6082-T6

	Description	**Value**
Energy consumption	The energy required to recycle 1 kg of the material.	31.6 - 34.9 MJ/kg
CO_2 footprint	The CO_2 mass of greenhouse gases in kg, produced and released into the atmosphere because of recycling one kg of the material.	2.48 - 2.74 kg/kg
Recycle fraction in current supply	The percentage of recycled and downcycled material in total worldwide supply of the material.	42.8 - 47.3 %

However, it is important to note that if the recycling process is not conducted properly and cleanly, the recycled aluminium may contain high levels of impurities, particularly iron. This can result in a reduction of the corrosion resistance, formability, and ductility of the metal, as well as increasing its susceptibility to pitting corrosion. The effects of the impurities are not solely due to differences in alloy compositions but are also a result of the production method and heat treatment history of the recycled aluminium. (Hydro Extrusions, 2021)

Step 6, Data collection, Transports

This step refers to the transportation of materials and components between different processes within the manufacturing plant. It excludes transportation within the use phase of the final product.

In this step, it is necessary to assume the transport routes and different kinds of vehicles used for the transport. Once this is defined, the equations *(1)* and *(2)* are used to calculate estimations of the Total energy usage and Total CO_2 emissions for the transport. In these equations m represents the component's mass and DST represents the transported distance. (Berntsson & Dimgard, 2022)

$$Total\ energy\ usage = m \cdot DST \cdot Energy\ consumption \tag{1}$$

$$Total\ CO_2\ emissions = m \cdot DST \cdot CO_2\ emissions \tag{2}$$

In the manufacturing of the frame, it is important to consider the transportation of the raw materials to the plant. This transportation process can have a significant impact on both energy and the CO_2 emissions of the overall manufacturing process. Therefore, it is crucial to select the most efficient mode of transport in terms of energy consumption and environmental impact. Once the raw materials are transported to the plant, all the manufacturing process are carried out in-house, helping to minimize the need for additional transportation. *Figure 32* displays the energy consumption and CO_2 emissions for different modes of transport:

Transport type	Energy consumption MJ/(kg·km)	CO_2 emissions kg/(kg·km)
55 tonne truck (8 axle)	7,10E-04	5,10E-05
40 tonne truck (6 axle)	8,20E-04	5,90E-05
32 tonne truck (4 axle)	9,40E-04	6,80E-05
26 tonne truck (3 axle)	1,10E-03	7,90E-05
14 tonne truck (2 axle)	1,50E-03	1,10E-04
Light goods	2,20E-03	1,60E-04
Train	3,50E-04	2,50E-05
Ferry, ocean	1,80E-04	1,30E-05
Ferry, coastal	2,70E-04	1,90E-05
Ferry, river	4,00E-04	2,90E-05

Figure 32: Energy consumption and CO2 emissions depending on the transport (Berntsson & Dimgard, 2022)

It has been established that the frame for the project under analysis will be manufactured in Europe, specifically in Sweden. However, the origin of the raw materials used in the manufacturing process is yet to be determined. To address this uncertainty, an evaluation of the energy consumption and CO_2 emissions arising from various transportation options was conducted. The study considered different possible origins of the raw materials, as defined by the respective suppliers and relevant distances. The equations *(1)* and *(2)* and the *Figure 32* were employed in the analysis. The results of the evaluation provide insight into the potential energy-efficient and eco-friendly transportation options suitable for the project.

The present figure (*Figure 33*) illustrates that the transportation of materials from Europe to the desired location via a small truck result in higher energy consumption and CO_2 emissions when compared to shipping materials from North America. Nevertheless, it has been observed that when the same distance is covered by a larger truck in Europe, the energy consumption and CO_2 are halved. Additionally, it is noted that transporting materials from Asia by ship leads to higher energy consumption and CO_2 emissions when compared to all other available options.

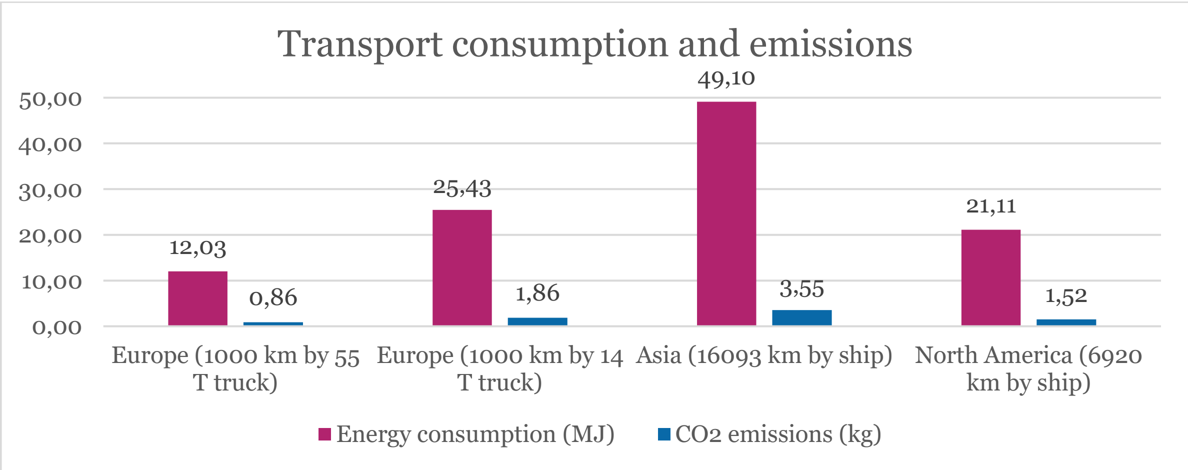


Figure 33: Transport consumption and emissions

To proceed with the present analysis, a raw material supplier based in Europe has been identified, and the transportation of the raw materials has been proposed to be undertaken by a large truck for a maximum distance of 1000 km. This approach has been applied in *6.6.2 The environmental impact* section. The aforementioned approach serves a foundational element of this thesis work, enabling a comprehensive evaluation of the logistics strategies that could be employed to improve the transportation of raw materials.

Chapter 6

Results and Discussion

This chapter will represent the results of the project, from the material selection to sustainability. Moreover, these results will also be discussed.

6.1 Material Selection

Fundamentally, a study of the different parts of the automobile with respect to the structure reveals that it is exposed to various stresses and physical environments that must be accounted for by the choice of material, as well as the design. The frame is exposed to different forces and vibrations that require the materials used in processing the parts to be hard as well as flexible and light. Additionally, different environmental conditions, such as, extreme temperatures, humidity and salt environment need to be considered because this could bring the parts to be corroded.

As in the *5.1 Material Selection* section is reflected, different limits and graphs with different material properties have been obtained in order to make a good material selection. Once all the analysis has been finished four material groups have been obtained as the most suitable material for frames, however, one material will be selected that satisfied the aim of the frame. The four materials are, magnesium, cast iron, stainless steel and aluminium.

6.1.1 Magnesium

In the material selection process, it was found that the magnesium is not a suitable material for the frame due to its poor properties. Although it has low density (lower than 2000 kg/m^3), which is advantageous in reducing the weight of the vehicle, its young modulus, yield strength, tensile strength and fatigue strength are not high enough to withstand the forces that the frame experiences and it can crack and fracture more easily under repeated loads. As illustrated in the *Figure 22*, *Figure 23*, and *Figure 24*, it has low stiffness-to-weight, strength-to-weight, and strength-to-cost ratios. This material has also poor corrosion resistance because it oxidizes easily in presence of water or humid air. Is a relatively difficult material to work with, making it more challenging and expensive to manufacture large parts with it. Additionally, magnesium is one of the most expensive materials, with a price per kg located above the limit of 2 €/kg set for affordability, as shown in *Figure 21*. Therefore, magnesium was eliminated from the material options for the frame. (Dong, et al., 2022)

6.1.2 Cast iron

As mentioned earlier, the material selection process involved the rejection of certain materials due to their unsuitability for the project. Cast iron is one such material that was deemed unsuitable for use. Despite having the same density as stainless steel, cast iron has poorer properties, with a density between 7000 kg/m^3 and 8000 kg/m^3. Therefore, it was decided that stainless steel would be a better choice, despite its higher density. Furthermore, cast iron was removed from the list of suitable materials due to its low stiffness-to-weight and strength-to-weight ratio, making it more likely to crack and fail under tension, brittle nature, being more likely to fracture than bend or deform under stress, poor weldability as it is difficult to weld, and high cost compared to other options, as indicated in *Figure 21*, where it is listed above the maximum price of 2 €/kg. (Ghasemi, Elmquist, Svensson, König, & Jarfors, 2016) (Ghasemi & Elmquist, Cast iron and self-lubricating behaviour of graphite under abrasive wear conditions, 2014)

6.1.3 Stainless Steel

Considering the various types of stainless-steel materials available (Austenitic, Ferritic and Martensitic), the most important applicable stainless-steel materials on automotive industry are the Ferritic and Austenitic stainless steel:

The most common one used in the automotive industry between the three of them is Austenitic stainless steel. Austenitic stainless steel is a non-magnetic alloy that contains high levels of chromium and nickel. The role of the nickel is to stabilize austenite phase, improves mechanical properties fabrications and welding characteristics. Addition of nickel to steel can result in movement of the eutectoid point to the left and increase the critical range of temperatures. Chromium is usually combined with nickel to achieved required ductility and toughness offered by nickel and the hardness and wear resistance provided by chromium. This type of steel is highly resistant to corrosion and can withstand high temperatures, making it ideal for exhaust systems, catalytic converters, and foul tanks. (Ikpe Aniekan , Orhorhoro Ejiroghene, & Gobir, 2017)

Ferritic stainless steel, on the other hand, is a magnetic alloy that is also corrosion-resistant but has lower levels of nickel, making it less ductile and not well-suited for structural applications. Besides, this is not as heat resistant as the austenitic. Typical applications in automotive industry are trim or decorative pieces.

To finish with stainless steel, martensitic is a hard, string and magnetic alloy that often used in applications that require high strength and wear resistance, such as, engine components. Nevertheless, is not as corrosion resistant, ductile, and tough as austenitic stainless steel.

Based on the analysis and comparison of various materials, it can be concluded that the most suitable material for an automotive frame is austenitic stainless steel. Despite its good material properties, such as, high yield strength and tensile strength, its high density and cost may pose as drawbacks. With a density close to 8000 kg/m^3 and a price higher than 2 €/kg (as shown in *Figure 21*), it may not be the most cost-effective option, but it does provide the required stiffness and strength-to-weight (as illustrated in the *Figure 22* and *Figure 23*) to withstand the forces experienced by the frame in automotive applications minimizing the weight. Therefore, considering all the factors, austenitic stainless steel can be considered as the optimal choice for this particular application.

6.1.4 Aluminium

Aluminium is the best material for structural components in automotive industry, not only for the low density, also because of the properties and low cost it provides. Apart from that, when the material is in contact with the air, it is coated with a very thin, adherent oxide layer that protects it and gives resistance to corrosion, therefore, is a self-resistant material. Aluminium alloys are divided into 8 different series, depending on the composition of the alloy. Properties of each group are represented in the *Appendix D: Aluminium alloy series*. According to the table, the most used aluminium alloys for structural applications are the 6xxx series and the 7xxx series. (Jarfors, Ghasemi, Awe, & Jammula, 2021)

The 6xxx series aluminium alloys are a family of alloys that primarily contain magnesium and silicon as their major alloying elements and are commonly used in structural applications due to their high strength-to-weight ratio, plasticity, capacity for crucial shape forming along with their ease for joining and good corrosion resistance. Besides, it is increasingly focused for versatile applications such as design of armour structures, rocket, missile casing, light-weight defence vehicle, cars, and marine structures. The 7xxx series, however, contain zinc as their major alloying element, along with copper and magnesium. They are known for their high strength and toughness and are commonly used in applications that require high strength-to-weight ratio, such as aerospace, military, and high-performance sports equipment. Moreover, compared to the 6xxx series alloys they are generally less weldable and machinable. (Mukhopadhyay, 2012)

In summary, the 6xxx series aluminium alloys are deemed the most suitable for structural applications such as an automotive frame. This is due to their favourable strength-to-weight ratio, good corrosion resistance and ease of fabrication. On the other hand, the 7xxx series alloys may present challenges in terms of welding and could be more prone to stress corrosion cracking. Therefore, the 6xxx series alloy are preferred for the intended purpose.

6.1.5 Material Selected

In this section the material will be selected between the aluminium and stainless steel.

To start with, mention that the choice between the aluminium and stainless steel as the most suitable material for the aim of the frame depends on the specific requirements and constraints. Aluminium, on the one hand, is lightweight with high strength-to-weight ratio and good corrosion resistance. Stainless steel, on the other hand, has excellent corrosion resistance, is stronger and more durable than aluminium, and is suitable for harsh environments and high strength applications.

In overall, stainless steel is ideal if strength, durability, and resistance to corrosion or wear are needed, while aluminium is appropriate for weight-sensitive applications where cost is a consideration. For this project, the selection of the optimal material for the frame is crucial to achieve the desired outcomes of weight reduction, good corrosion resistance, and affordability. After analysing the different material groups and their respective alloys, it has been determined that aluminium is the most suitable material for this purpose. However, it is essential to identify the specific aluminium alloy that best fits the requirements of this project:

The aluminium 6xxx series composed four most common ones are: 6061, 6063, 6005 and 6082. In the Appendix G: Different 6xxx aluminium alloys section, these four 6xxx aluminiums properties, composition and application are represented in order to compare them and select the best suitable one for the frame. In this section, the material will be selected comparing 6061, 6063, 6005 and 6082 aluminium alloys.

Between the four aluminium alloys, two of them are typically used in structural applications, specifically, Al 6061 and Al 6082. The 6061 alloy is precipitation-hardenable, and it has good corrosion resistance, however, Al 6082 it has the highest strength, with a tensile strength of around 310 MPa and a yield strength of around 275 MPa, amongst various 6xxx grade alloys with proper heat treatment.

In consideration of the importance of strength and durability for the structural application, the 6082 aluminium alloy may be the better choice. However, if ease of fabrication and machinability are the key factors, then the 6061 aluminium alloy may be preferred. Despite both materials being suitable for the purpose of the frame, the Al 6082 will be selected as the most appropriate material due to its higher strength, durability and corrosion resistance.

6.2 Thermal treatment

Once the aluminium alloy is defined, a heat treatment is commonly applied to achieve specific mechanical, physical and chemical properties that are necessary in a wide range of applications. Heat treatments help to increase the strength, ductility, and toughness of the aluminium by precipitation hardening. (Baily, 2004) However, as some aluminium alloys do not achieve significant strength improvement by heating or cooling, heat treatments are not applicable for all aluminium alloys. This way, the aluminium alloys that can be strengthen by heat treatment followed by precipitation hardening are 2xxx, 6xxx, 7xxx and 8xxx aluminium series. (L&L Special Furnace, 2018) On the contrary, aluminium alloys that are not heat treatable, 1xxx, 3xxx, 4xxx and 5xxx series, are normally strengthened by strain hardening and sometimes by aging. (Howard, 2007)

First, it is important to know that the heat treatments of aluminium are quite different from steel's (L&L Special Furnace, 2018). Aluminium alloys normally have a temper designation in their name that describes the specific thermal and mechanical treatments that have been undertaken. This designation is normally used with heat-treatable alloys and more information about it can be found in the *Appendix H: Aluminium Temper Designation System*. (Genculu) (Koch, 2020).

The following table (*Table 7*) presents some typical thermal treatments used for aluminium 6082 alloys:

Table 7: Typical thermal treatments for Al 6082

NAME	DESCRIPTION	BENEFITS
O	Annealed. Soft material. (Aalco Metals Ltd, 2019)	• Low strength • High ductility
T4	Solution heat-treated and naturally aged to substantially stable condition. (Aalco Metals Ltd, 2018)	• Moderate strength • Good formability

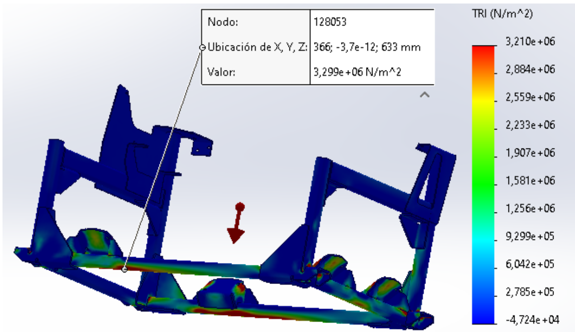
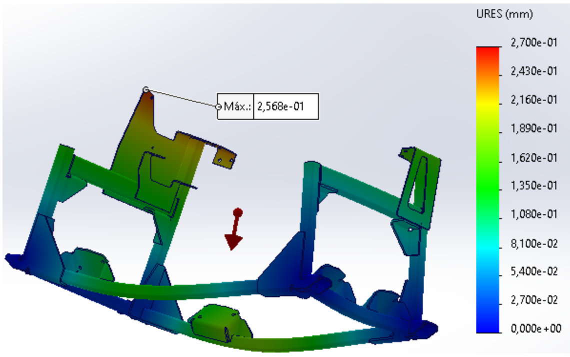
T6	Solution heat-treated and artificially aged. (Aalco Metals Ltd, 2019)	• High strength • Good toughness • Lower formability than T4 and T5
T651	Solution heat-treated, stress relieved by stretching and the artificially aged. (Aalco Metals Ltd, 2019) (Cnclathing JunYing, 2020)	• Similar T6 properties • Better machinability than T6 • Dimensionally more stable than T6

In the Appendix I: Different thermal treatments simulations, results of four different static simulations with the same aluminium alloy (Al 6082) but with four mostly used thermal treatments are represented. In these simulations, principal stress and the deformation suffered by the frame have been analysed.

Based on the analysis of the simulation results, it can be observed that the principal stress and deformation values obtained for the four materials are quite similar. This can be seen in *Figure 34*, which displays the principal stress distribution for each materials, and in *Figure 35*, which illustrates the deformation experienced by the frame. It is nothing that the maximum stress and deformation values for the four materials are located in the same point, regardless the material selected. This is due to the fact that although different thermal treatments were applied to the steel materials, the aluminium alloy used in all cases remained the same, resulting in the same young's modulus for all materials.

Following with the results of the simulations, it can be concluded that the maximum load that the frame can endure before starting to deform plastically or fracture under compression or tension would be different for each material. The elastic limit, compressive strength, and tensile strength are higher for some materials compared to others, resulting in a higher maximum load the frame can bear before failure. Thus, the Al 6082-T6, with the highest values for these three properties, is the most suitable material for this application. The principal stress and deformation suffered by the Al 6082-T6 frame can be found in the table below (*Table 8*).

Table 8: Principal Stress and Deformation suffered by a Al 6082-T6 frame

Principal stress	Deformation
 *Figure 34: Al 6082 T6, Principal stress*	 *Figure 35: Al 6082 -T6, Deformation*

6.3 Frame's static analysis

After defining the boundary conditions and the frame's material in *5.2 Simulations* section, some results about Principal stresses and deformation have been obtained:

6.3.1 Principal stress

The Principal stress analysis of both the aluminium and 108 stainless steel frames has been conducted, and the results are represented in the *Figure 36* and in *Figure 37*, respectively. Upon careful examination of these figures, in can be concluded that the stress distribution across both frames is comparable. The results indicate that the regions exhibiting the highest stress concentration coincide in both frames, as depicted by the red areas in the figures. However, it is noteworthy that the steel frame experiences higher stress levels compared to the aluminium frame, primarily owing to the inherent material properties of the two materials. These regions experiencing tensile stress are particularly vulnerable to fatigue, as well as corrosion and stress corrosion cracking, as outlined in the *Table 1*.

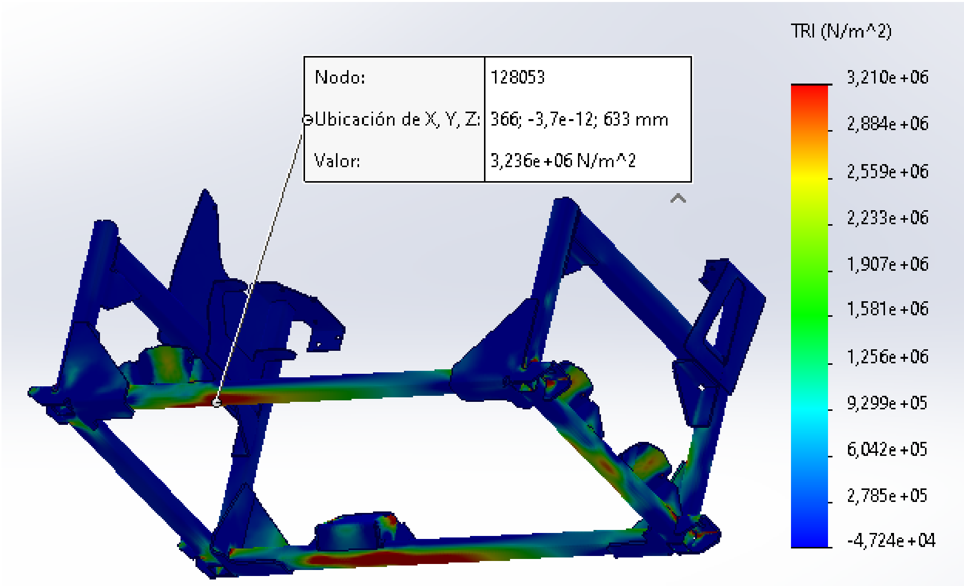


Figure 36: Principal tension, Aluminium

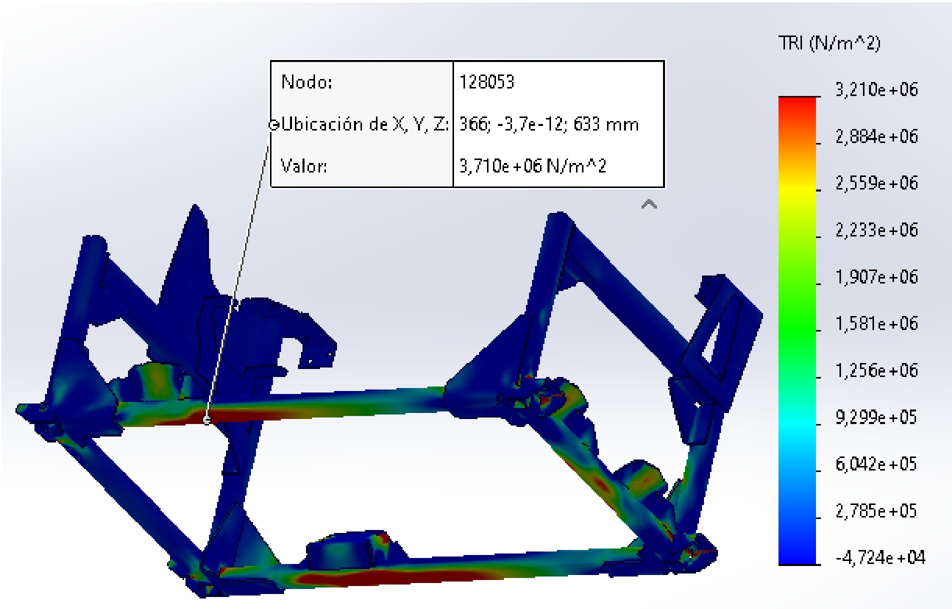


Figure 37: Principal tension, 108 Stainless Steel

The analysis of the acquired results reveals that not all regions exhibiting high stress levels are accurate. An instance of this discrepancy can be observed in *Figure 38*, which displays the region identified as having the maximum stress experienced by the frame. Nevertheless, it should be noted that this result is erroneous and can be attributed to a phenomenon known as stress singularity. Stress singularities emerge in simulations involving sharp corners or specific geometries due to mathematical simplifications employed during the analysis.

Consequently, the maximum stress values derived from these simulations cannot be deemed reliable. Lastly, to determine if stress concentrations manifest around stress singularity, it becomes necessary to analyse the surrounding region encompassing these points.

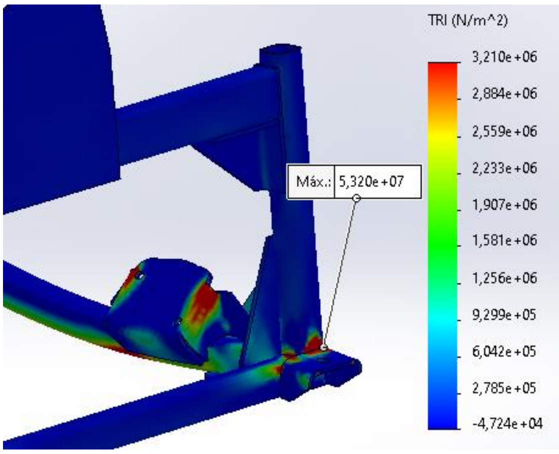


Figure 38: Stress singularity region, Aluminium

6.3.2 Deformation

This section focuses on the deformation analysis of two different materials: the aluminium and the 108 stainless steel. *Figure 39* shows the deformation of the aluminium frame, which highlights the areas where the frame is most susceptible to deformation. The results of the analysis reveal that the horizontal long tubes are the most deformed areas of the frame. *Figure 40*, on the other hand, illustrates the deformation suffered by the steel. The analysis indicates that the deformation distribution is not uniform, with the region around the welds being the most deformed.

Upon analysing both figures, it can be concluded that the aluminium frame undergoes more deformation than the steel frame, and the deformation is proportional in both cases. Furthermore, the regions affected the most and the least are the same for both materials, as represented by the red and blue zones, respectively.

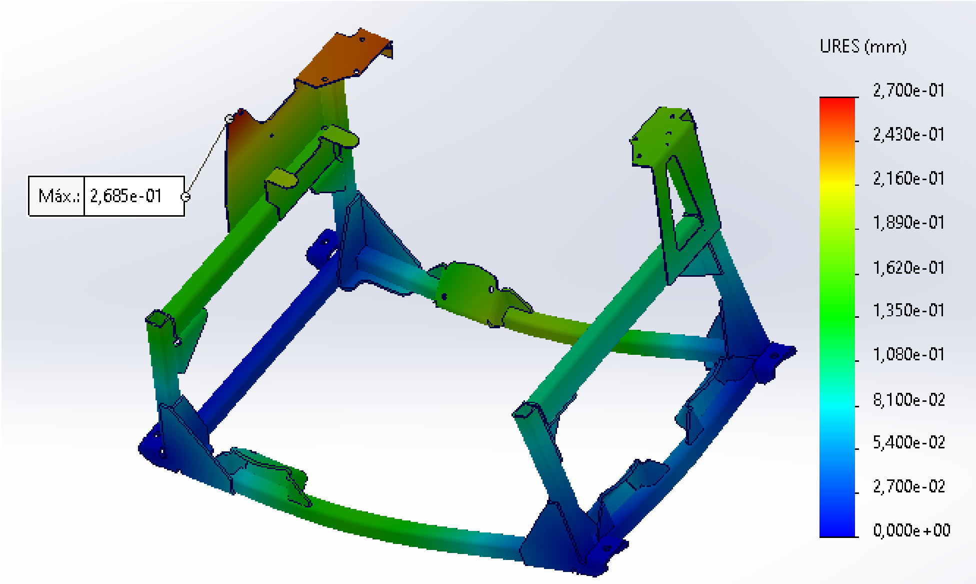


Figure 39: Deformation, Aluminium

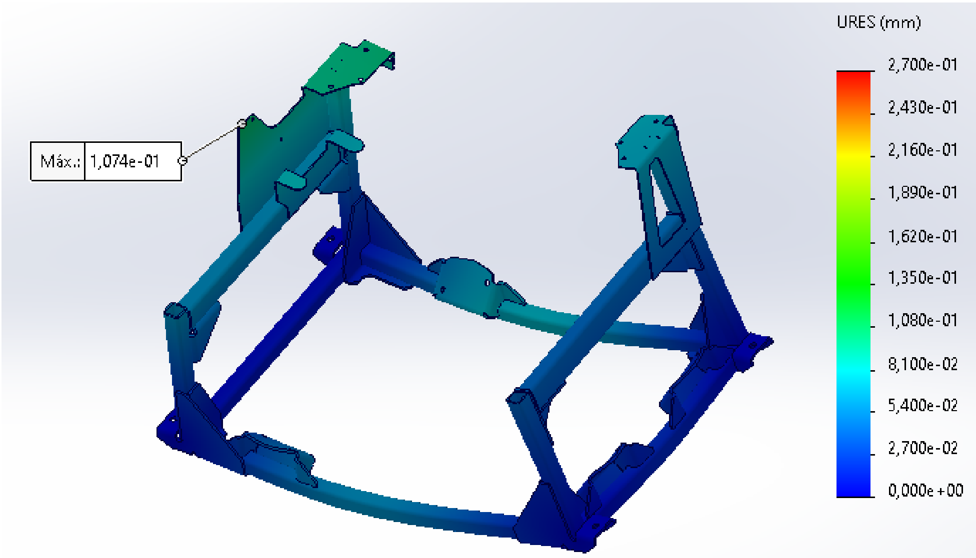


Figure 40: Deformation, 108 Stainless Steel

Consequently, based on the findings of the study, it is now feasible to pinpoint the region of the frame where tensile and contraction deformation will occur. Furthermore, the section that is most susceptible to stress corrosion cracking can also be identified (as shown in *Table 1*). As a result, both *Figure 39* and *Figure 40* highlight that the long horizontal tubes experience the greatest amount of tensile deformation and are more susceptible to corrosion.

6.4 Surface preparation and the joining

Depending on the specific environmental conditions and application requirements, the specific surface treatments and the order of their application may vary. Moreover, it is important to apply the surface treatments before the joining process to remove the contaminants and oxide layer that can inhibit adhesion and compromise the strength and durability of the joint. However, in order to improve the joining and avoid corrosion, the following general process can be followed: (AR Powder Coating, 2021) (Sabau, Liu, Weibel, Groll, & Geoghegan, 2017) (Dro´zdziel-Jurkiewicz & Bienia´s, 2022)

1. **Degreasing**: The aluminium surface must be cleaned to remove any residual oil, grease, dirt, and grime. For that, pressure or solvent cleaners can be used.

2. **Surface preparation**: The aluminium surface must be prepared depending on the specific joining method is going to use. This way, for adhesive joining abrasive cleaning may apply to prepare the surface. But in the case of welding, chemical cleaning may be more appropriate.

    a. **Abrasive cleaning:** This is done to remove oxide layers or surface soils that may interfere with the adhesion from the materials surface. Apart from that, it also serves to create a roughened surface and with it, better adhesion between surfaces. Grinding, bristle blasting and sanding are some forms of abrasive cleaning. This step would be normally applied if the joining would be done by adhesive joining.

    b. **Chemical cleaning:** This is used to remove organic soils, machining coolants, lubricants and to dissolve the oxide layer that may be in interfere with the adhesion of the surfaces. For that the surface is immersed in an acid cleaner. This step would be normally applied if a welding joining would be done.

3. **Surface treatment:** Depending on the specific requirements of the application and the joining method is going to be used, the surface treatment applied may vary. These surface treatments can improve corrosion and joining resistance. In the *Table 2* can be found different surface treatments that be applied.

4. **Joining:** After the surface treatment, the components would be joined with the joining method predefined. Before the joining, a primer could be applied to improve the joining. This primer may differ depending on the joining method used.

5. **Post-treatment cleaning:** After the joining, the joint areas must be cleaned. With this cleaning, any adhesive, welding or joining materials that may cause corrosion must be cleaned.

6. **Surface treatment**: Finally, after the joining, the joint areas may require an additional surface treatment to ensure moisture or corrosion penetration. This surface treatment would vary depending on the joining method used.

6.4.1 Joining methods

Some frame joining methods may react with the materials and surface treatments, affecting and degrading the properties obtained. As all joining methods are different, the corrosion affects the joints differently depending on the joining used. In this case, the joining methods more prone to use are CMT/CMT+P and Adhesive joining (Hysol 9492 Epoxy). In the *Appendix B: CMT/CMT+P* and *Appendix C: Adhesive joining (Hysol 9492 Epoxy)* these joining methods are explained. This way it is analysed how the galvanic and selective corrosion affects in these joints:

Galvanic corrosion is very unlikely to occur in CMT/CMT+P or Adhesive bonded joints if the two joined aluminium are of the same alloy and have a similar microstructure and composition. This is because, as adhesives fill the crevices, they ensure galvanic separation. However, in adhesive joining, the adhesives can act as an electrolyte creating electrochemical cells between surfaces. And if the aluminium surfaces have different composition or microstructure or if impurities are present, local galvanic cells can be created. As in CMT/CMT+P the joining material is a metal, no electrolytic cells are created, so galvanic corrosion is very unlikely to occur. (Hydro Extrusions, 2021)

According to selective corrosion, both CMT/CMT+P and Adhesive joining are more prone to selective corrosion than galvanic corrosion. This can occur if some areas of the aluminium are more susceptible to corrosion due to surface differences or the presence of impurities on the surface. (Hydro Extrusions, 2021)

Thus, to ensure corrosion resistance, cleanliness, wetting and adhesion of the joining, surface treatments are necessary. (Hydro Extrusions, 2021)

6.5 Surface treatment

In this thesis work, the main objective is to select an appropriate surface treatment method for the structure. As demonstrated in the *6.4 Surface preparation and the joining* section, the application of a surface treatment prior to joining can enhance the corrosion resistance and the joining resistance. After considering various options, it was concluded that anodizing is a suitable surface treatment method for this purpose. *Appendix E: Types of Anodizing* shows that there are three types of anodizing available, and the *Table 12* explains these three types of anodizing in detail.

Nevertheless, for this application, Type II anodizing (Sulfuric Acid Anodizing) has been found to be the most suitable. The reason for this preference is that Type II anodizing creates a thicker anodized coating than Type I anodizing, resulting in a harder and improved corrosion and wear resistance coating. Furthermore, Type II anodizing is easier to waste treatment and provides a greater variety of colours than Type I anodizing. While Type III anodizing creates a thicker and harder coating than Type II, it is also more expensive and complex, and for this application, an extremely hard coating may not be necessary. Additionally, Type II anodizing is relatively environmentally friendly compared to Type I and III anodizing. As a result, Type II anodizing has been found to be the most suitable treatment for this application.

Finally, as presented *6.4 Surface preparation and the joining* section, it is worth noting that in certain cases, a surface treatment can be applied after the joining process. However, given the absence of practical or experimental testing regarding the corrosion resistance of the frame, it is not currently possible to determine whether a surface treatment is necessary after the joining. Consequently, it is recommended that future work should incorporate an experimental analysis of the corrosion resistance of the frame, involving the application of a Type II anodizing treatment prior to joining. If this analysis reveals that the frame is not sufficiently corrosion-resistant, powder coating has been identified as a viable treatment option that can be applied post-anodizing and joining. The key characteristics of this surface treatment method are outlined in *Table 12*. (Ghasemi, Elmquist, Ghassema, Salomonsson, & Jarfors, 2018) (Wollmann, Pintaude, & Ghasemi, 2020)

6.6 Sustainability

In this section the results obtained will be represented after making the life cycle assessment.

6.6.1 The manufacturing cost

The *5.3.2 Economic impact* section highlights that reducing the indirect costs of manufacturing is the most effective means to decrease the overall cost of a product.

However, in the present case, calculating the manufacturing cost with precision is challenging, and therefore, only the direct costs of producing the project have been taken into account. Costs associated with the transport of materials, maintenance of equipment, employee salaries, machining, welding, joining processes, and the quantity of frames manufactured have been excluded from the analysis. As a result, the following table (*Table 9*) presents the material cost and surface treatment costs for one frame only. This information has been taken from Granta and (John, 2023):

Table 9: Manufacturing cost of a frame

CATEGORY	WHAT	QUANTITY	COST	TOTAL COST / Frame
Material cost	Aluminium 6082 – T6	0.00635 m^3	5270 €/m^3	33.465 €
Overhead costs	Equipment costs: Anodizing costs	3.0194 m^2	1128.4 €/m^2	3407.098 €
				3440.563 €

The cost of the anodizing process of €/m^2 mentioned in the *Table 9* represents only the average cost of type II anodizing, and is subject to variability depending on various factors such as the thickness of the coating and the number of frames produced. This way can be observed that the cost of surface treatment for a frame is 100 times greater than the cost of the materials used in its production.

6.6.2 The environmental impact

In this section, the analysis of the results obtained in the study will be presented. The study includes two different graphs that show the energy consumption in MJ and CO_2 emissions in kg. These two parameters have been calculated for different processes, including material extraction, bar extrusion, sheet rolling, welding of the structure, coating of each component, and recycling of the whole structure. The purpose of this analysis is to evaluate the environmental impact of the manufacturing process of the frame and identify potential areas for the improvement in terms of energy and resource efficiency.

The analysis of energy consumption in the studied processes reveals that the material extraction process presents the highest energy consumption, as shown in *Figure 41*Figure 1. Specifically, this process consumes 3428.67 MJ, representing 78% of the total energy consumption. Recycling the product follows the previous activity, being the second highest energy-consuming process, accounting for 13% of the total energy consumption with a value of 589.46 MJ. On the other hand, the coating process presents the lowest energy consumption among the studied processes. This is due to the fact that no high amount of energy is required for surface coating. The amount of energy needed for this process is 9.06 MJ, representing 0% of the total energy consumption. These results highlight the importance of considering the energy consumption associated with each process in order to identify areas for energy optimization and reduction in future works.

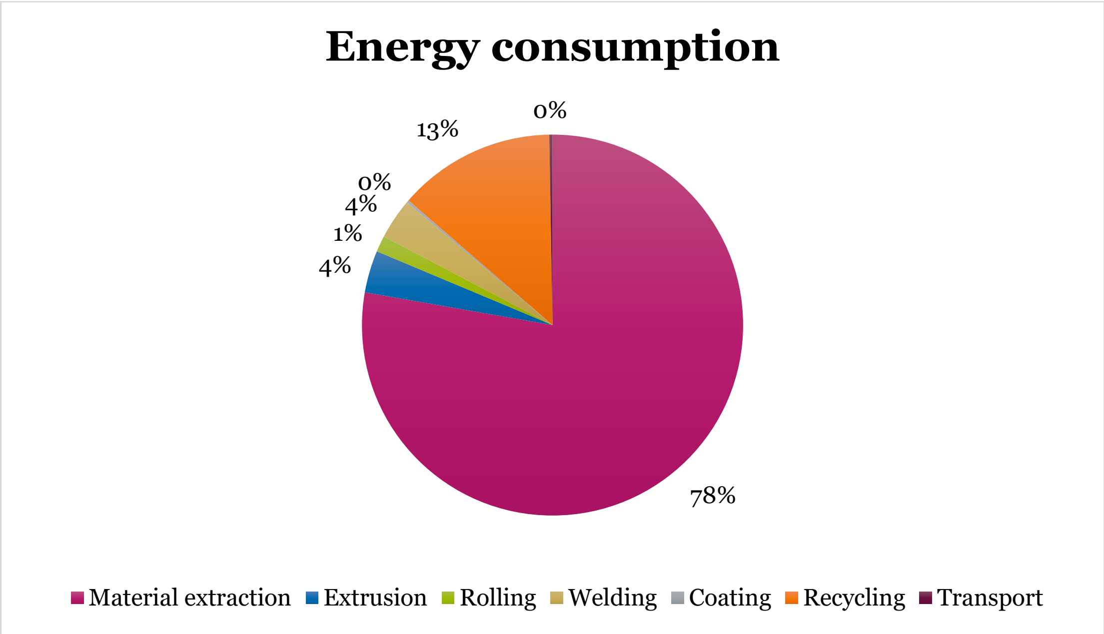


Figure 41: Energy consumption of each process (Appendix J)

Lastly, nowadays there is a worrisome problem with climate change, therefore, it is crucial to analyse the CO_2 emissions as it allows the development of sustainable processes that reduce greenhouse gas emissions and mitigate climate change. As such, this aspect was also considered in this study. As illustrated in *Figure 42*, material extraction was found to emit the highest amount of CO_2, accounting for 59% of the total emissions, with a value of 244.91 kg. Following this, the welding process of the frame resulted in the second highest amount of emissions, with a value of 101.34 kg, representing 24% of the total emissions.

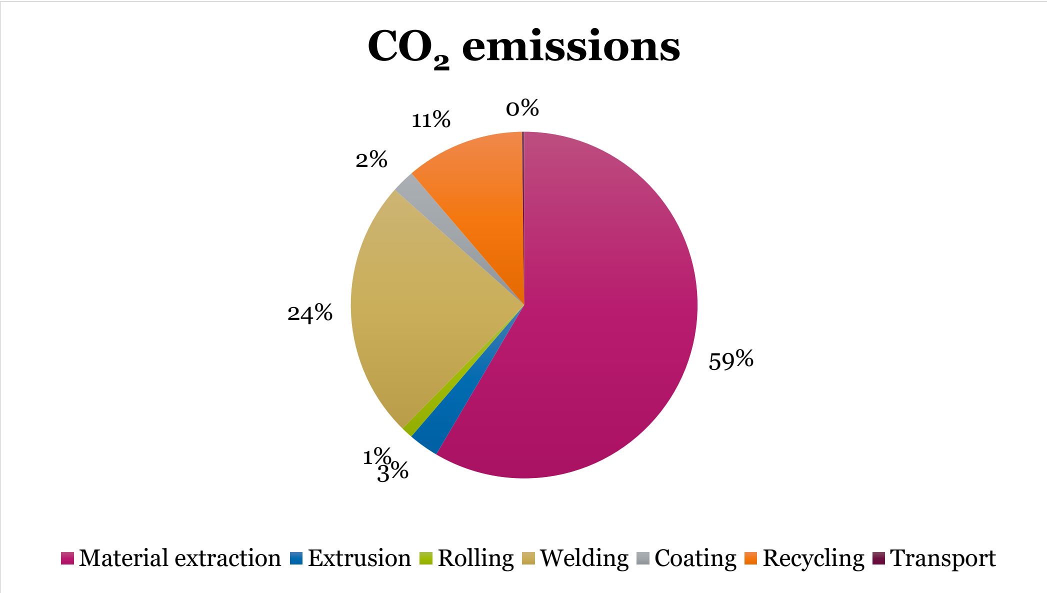


Figure 42: CO_2 emissions for each process (Appendix J)

On the other hand, there are two processes that produces the lowest emissions, which accounts for only 1% and 0% of the total CO_2 emissions. The first one is the rolling process, which has a value of 4.57 kg and represents de 1% of the total emissions. The second one, however, is the transport, with a value of 1.67 kg, accounting the 0%. It is worth mentioning that the results obtained highlight the need for more sustainable approaches to these processes in order to reduce their environmental impact.

Table 10: Energy consumption and CO_2 emissions of the recycling process of the frame

	Consumption / Emissions data	**Value**
Energy consumption	31.6 - 34.9 MJ/kg	533.7 - 589.5 MJ
CO_2 footprint	2.48 - 2.74 kg/kg	41.9 – 46.3 kg CO_2

Chapter 7

Conclusions

The following objectives were set in *1.3 Aim and Objectives* section to try to answer the research question, here is discussed to what extent the objectives were met.

First, it must be noted that selecting the most suitable material for the frame is the key of this thesis work. After thorough research and analysis, it can be concluded that there is no better material than Al 6082 T6 for this particular application. This alloy is widely used in high duty applications, such as, in aerospace, transportation and marine industries. Some of its key characteristics are listed below and mention that most of the information has been obtained from Ansys Granta Edupack 2022 Al 6082 T6 database:

- It provides high strength between 295 and 344 MPa which makes ideal for applications that require high-strength-to-weight ratio.
- Low density between 2670 and 2730 kg/m^3 in order to reduce the weight of the structure leading to savings in fuel and increasing efficiency in aerospace and transportation industries, increasing durability because lighter structures undergoes lower stress on their support structures, easier to handle and transport and increasing safety.
- Good workability and machinability because it is acceptable for different processes, such as, metal cold forming, metal hot forming, press forming, deep drawing, sheet rolling and also because although it has high strength it gives the opportunity to create parts with complex shapes and tight tolerances.
- Good corrosion resistance particularly in presence of seawater and other harsh environmental conditions.
- Good weldability. Preheating is not required, post weld treatment, however, is required.
- Heat treatment is applied in order to increase strength, hardness and surface properties.
- It is known where the frame is more prone to corrosion by knowing where the frame will undergo the greatest stresses and tensile deformation. This information is known

by making static simulations of the frame and resulting on the stresses and tensile and contraction deformation that will undergo.

In overall, Al 6082 T6 is the most suitable material compared with steel, cast iron, magnesium, and other aluminium alloys.

Second, in the context of this thesis work it has been identified that improving the corrosion resistance of the structure is a critical factor that needs to be addressed. Based on the analysis carried out, it has been concluded that applying a surface treatment method is important to achieve this objective. Therefore, the selected surface treatment for this purpose is a chemical treatment, specifically, anodizing type II or also known as sulphuric anodizing treatment. Information about the selected treatment:

- Improves the corrosion resistance by creating a thicker and more durable oxide layer on the surface of the aluminium, providing an excellent corrosion resistance and other environmental factors, for instance, humidity, salt spray and extreme temperatures.
- Improves the wear resistance that makes the material be less likely to scratch, chip or face over time. More suitable for outdoor applications.
- Improves the joining resistance that makes to increase the strength and durability of the joining of the frame.
- Improve the aesthetic by providing satin or matte finishes making more appealing to costumers.
- Electrical insulation. As it creates an insulating layer, it can prevent electrical conductivity and reduce the risk of electrical shock or damage.
- Environmentally friendly because there is no use of hazardous or harmful chemicals.

Mention that this surface treatment must be applied before the joining.

The third and final conclusion of this study highlights the importance of sustainability in the in the project, especially in light of the current global issues (lack of raw materials, lack of water, climate change…). The environmental impact analysis has demonstrated that material extraction has the most significant impact on the environment. As a result, it is necessary to use recycled materials to minimize the need for extraction of virgin material and create a more environmentally friendly manufacturing process. This approach will significantly reduce energy consumption and carbon emissions.

Furthermore, it is crucial to consider the economic impact of the project to ensure if it is affordable and not expensive to produce the frame. Nevertheless, the economic analysis in this study is not real enough, as it only considers the cost of the material and surface treatment. Therefore, it is necessary to conduct further research to determine the cost of other factors in the manufacturing process. The results show that surface treatment accounts for 99% of the total cost, highlighting the need to investigate more cost-effective options.

Chapter 8

Future Work

Due to the limitations of this study and the inability to demonstrate the findings experimentally and practically, further research in this field is necessary. Thus, the areas that require future investigations can be identified as follows.

- Further work in the field includes conducting a practical salt spray test on the Al 6082-T6 frame that has undergone Anodized Type II or Sulphuric Acid anodization to determine its resistance to corrosion.
- A further analysis is required to investigate the changes in surface treatment properties of the frame over time and in different environmental conditions. This study can provide insight into the long-term durability and effectiveness of the chosen method, as well as identify any potential weaknesses or areas for improvement.
- The potential use of recycled AL 6082-T6 material for the frame must be analysed in order to determine its suitability and effectiveness. This analysis should include a comprehensive study of physical properties and resistance of the recycled material in comparison to the virgin material, and whether it is possible to use the recycled material without compromising the frame's performance.
- Calculate the actual total manufacturing cost of the frame, considering all the direct and indirect costs associated with its production. This should include costs such as material procurement, tooling, labour, energy, waste disposal, and other costs associated with the manufacturing process. By accurately calculating these costs, we can assess the economic feasibility of the project and identify areas where cost reductions can be made.
- A comprehensive analysis must be conducted in order to evaluate the potential use of composite or biodegradable materials for the frame. This should include an assessment of the physical properties and characteristics required for the frame to fulfil its function, as well as comparative study of the properties of potential materials.
- Perform functional analysis of the frame. This systematic process should help to identify and define the functions and requirements of the frame to determine the most appropriate material and surface treatment properties.

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Appendices

In this section can be found some appendices that does not fit in the main text:

Appendix A: Work Breakdown and Time Plan

In *Figure* 43, the initial time plan (Gantt chart) for the project is presented. This schedule is divided into different phases based on the planes development and research process. To better differentiate each phase, each main objective defined in the graph is highlighted in a different colour. Furthermore, deliveries/presentations and meeting are also presented in different colours.

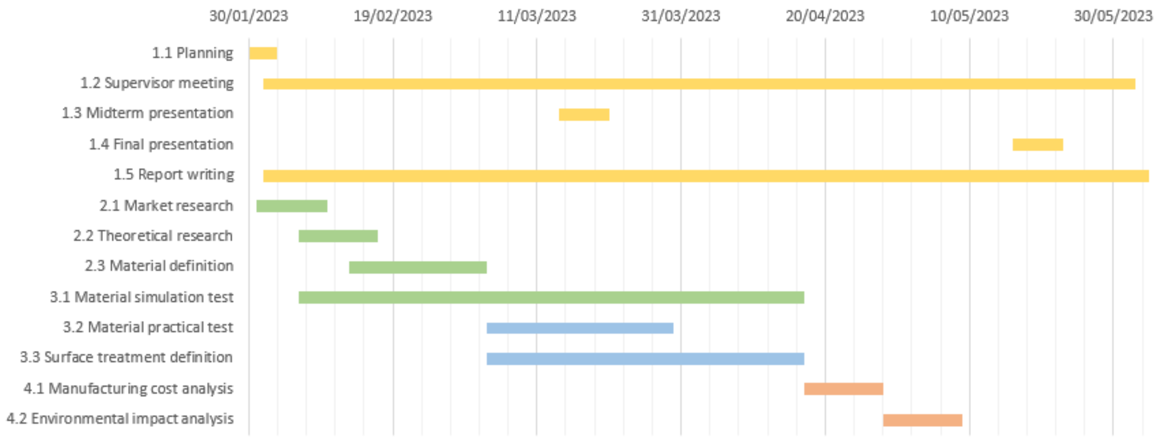


Figure 43: First Gantt Diagram

However, the project did not fully follow the original plan. Therefore, in *Figure* 44, a revised time plan (Gantt chart) is presented, showing how the project was actually executed.

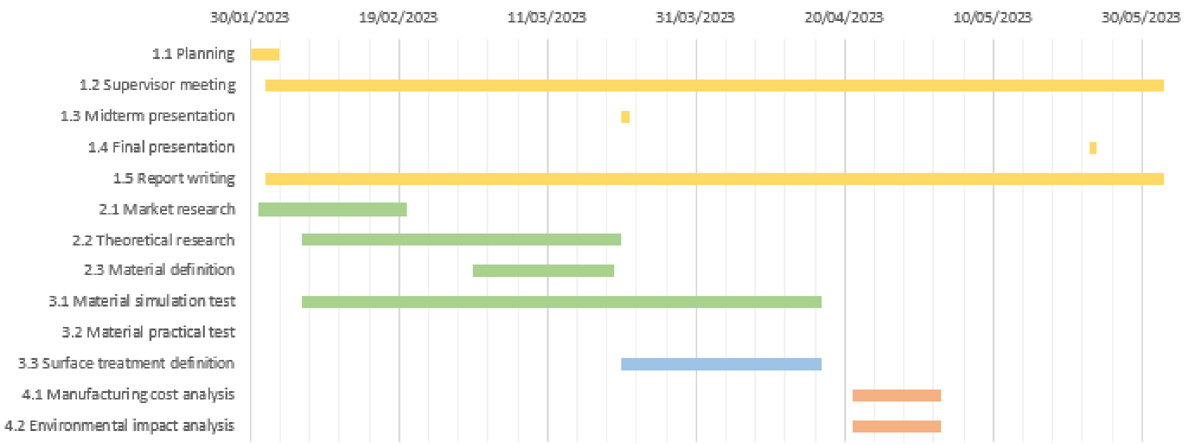


Figure 44: Final Gantt Diagram

Comparing both time plans, several clear changes can be observed: Firstly, the Market and Theoretical research phase took longer than planned. However, the Surface Treatment Definition phase was completed in less time than anticipated. Additionally, although some Material Practical Tests were initially planned, they could not be executed due to the unavailability of the frames. Furthermore, the Manufacturing Cost and Environmental Impact Analysis were carried out concurrently and completed ahead of schedule. Finally, as scheduled, there was enough time to finalize the report, conclusions, and future work.

Appendix B: CMT/CMT+P

Cold Metal Transfer (CMT) and Cold Metal Transfer Plus Pulse (CMT+P) welding methods are modified MIG welding process based on short-circuiting transfer process developed by Fronius.

CMT is a Gas Metal Arc Welding (GMAW) process that provides controlled method of material deposition and low thermal input by incorporating an innovative wire feed system coupled with high-speed digital control. (Selvi, Vishvaksenan, & Rajasekar, 2017)

CMT+P is an innovative CMT welding process with additional pulse technology. Thus, the heat input can be more easily adjusted and better controlled, reducing the risk of spatter during this welding process. (Pang, Hu, Shen, Wang, & Liang, 2016)

Due to the low heat input in both processes, they allow joining dissimilar metals with a low risk of spatter. Furthermore, these processes can be used for thin and delicate components in all welding positions. (Ramlab, 2023)

However, these processes are limited to thin materials and require a high skills level. In addition, the equipment is expensive compared to other welding techniques and is not suitable for welding materials requiring high levels of heat input. (Mason, 2022)

Appendix C: Adhesive joining (Hysol 9492 Epoxy)

Adhesive bonding is a joining method used to join two or more surfaces using an adhesive material. This process offers the possibility of bonding a wide range of materials but is limited by the strength of the bond and the applicable service conditions.

This joining method reduces corrosion and material fatigue, and prevents heat distortion, warping and weakening. It also allows the use of dissimilar materials and increases rigidity. Finally, this method reduces weight, saves costs and improves the appearance of the frame. (Taylor, 2015)

This bonding method has some limitations; the adhesive needs a curing time before bonding two materials together. Depending on the type of adhesive, the resistance to temperature and different environmental conditions may be different. The surface of the components must be cleaned and prepared to achieve good adhesion. And, as adhesives are chemical compounds, it is necessary to avoid human exposure to them during the application process. (McCoy Mart, 2022)

The adhesive used in this joining method include epoxies, polyurethanes, and acrylics. In this case, the adhesive selected is Hysol 9492 Epoxy.

Appendix D: Aluminium alloy series

In the following table (*Table 11*), different aluminium alloy series are represented:

Table 11: Naming of aluminium alloys (Shanghai Zhengshang Industrial Co, 2021)

Alloy series	Alloy	Properties	Applications
1xxx	Pure	Low strength, excellent thermal/electrical conduction, and corrosion resistance, highly reflective.	Fuel filters, electrical conductors, radiator tubing, lighting reflectors, decorative components.
2xxx	Cu	High strength, relatively low corrosion resistance, good elevated temperature strength.	Aircraft skin, aircraft fittings and wheels, ballistic armour, forged and machined components.
3xxx	Mn	Medium strength, good formability, good corrosion resistance.	Storage tanks, beverage tanks, home appliances, heat exchangers, pressure vessels, siding, gutters.
4xxx	Si	High castability, high machinability, high fluidity, low ductility.	Variety of castings, including large castings, filler metals (2xxx, 3xxx, 5xxx and 7xxx used for castings).
5xxx	Mg	Medium strength, good formability, excellent marine corrosion resistance.	Interior automotive, appliance trim, pressure vessels, armour plate, marine and cryogenic components.

6xxx	Mg, Si	Med-high strength, good corrosion resistance, easily extruded.	Exterior automotive, automotive profiles, railcars, piping, marine, screws stock, doors, and windows.
7xxx	Zn	Very high strength, prone to stress corrosion, poor corrosion resistance.	Aircraft construction, truck trailers, railcars, armour plate, ski poles, tennis rackets.
8xxx	Li	Very high strength, low density.	Aircraft and aerospace structures, foil, heat exchanger fin stock.

Appendix E: Types of Anodizing

In the table below (*Table 12*) can be found the three different types of anodizing:

Table 12: Types of anodizing in detail

TYPE OF SURFACE TREATMENT	DEFINITION	MATERIALS	ADVANTAGES	DISADVANTAGES
CHROMIC ACID ANODIZING (TYPE I)	A type of anodizing that uses chromic acid as the electrolyte. This process produces the thinnest oxide layer compared with other anodizing methods. (Xometry, 2022)	Aluminium and aluminium alloys. (Xometry, 2022)	+++ Increases abrasion and corrosion resistance. ++ Improved adhesion. + Good for tight tolerance parts. ++ Good bonding with adhesives. + Non-conductive. ++ Good for welded parts and assemblies. + Can be black dyed. (Anoplate, 2015)	-- Thinner oxide layer compared with other anodizing. - Limitation in decorative finish. -- Environmental risk. (Sheasby & Pinner, 2002)

SULFURIC ACID ANODIZING (TYPE II)	A type of anodizing that uses sulfuric acid as the electrolyte. This method is the most common anodizing method and creates a thin and porous layer in the metal surface. (Xometry, 2022)	Aluminium and aluminium alloys. (Xometry, 2022)	+++ Good corrosion and abrasion resistance. ++ Improves adhesion of coatings and adhesives. + Cheaper that other anodizing. ++ Harder than chromic anodize. + Great variety of colours. ++ Easier waste treatment than chromic anodize. ++ Shorter plating time to reach specified thickness. ++ Environmentally friendlier than other types of anodizing. (Aotco, 2023)	-- The created layer is porous. - Environmental risk. (Sheasby & Pinner, 2002)
HARD ANODIZING (TYPE III)	A type of anodizing that uses a sulfuric acid-based electrolyte. Parts of the base material become fully integrated with the coating, which results in an extremely high bonding strength of the	Aluminium, aluminium alloys, magnesium, and titanium.	+++ Increases abrasion and corrosion resistance. +++ Higher durability and resistance. + Good heat distribution. + Non-sticky properties.	- Expensive -- Can be heavy. -- Can warp.

	anodic layers. With this type of anodizing a thicker and denser layer compared to sulfuric anodize layer is obtained. (Aalberts, 2022)	(Xometry, 2023)	+ Non-conductive. (Aspiring Youths, 2023)	- The thicker oxide layer can cause increased part size. - Environmental risk. (Aspiring Youths, 2023) (Sheasby & Pinner, 2002)

Appendix F: Bill of materials

In the following table (*Table 13*) can be found the bill of parts of the frame. The material, quantity, and weight of that part:

Table 13: Bill of materials

Part number	Title	Material	Quantity	Weight (kg/each)
1	Pipes I	Al 6082 T6	2	0.88
2	Pipes II	Al 6082 T6	2	0.83
3	Pipes III	Al 6082 T6	2	1.4
4	Pipes IV	Al 6082 T6	2	1.11
5	Pipes V	Al 6082 T6	2	0.58
6	Sheet I	Al 6082 T6	1	0.16
7	Sheet II	Al 6082 T6	4	0.45
8	Sheet III	Al 6082 T6	4	0.23
9	Sheet IV	Al 6082 T6	4	0.75
10	Sheet V	Al 6082 T6	1	1.02
11	Sheet VI	Al 6082 T6	1	0.39
		SUM	25	16.89 (total frame)

Appendix G: Different 6xxx aluminium alloys

There are many 6xxx aluminium alloys, but the most common ones are the following:

6061 Aluminium alloy

6061 aluminium was the first alloy to demonstrate acceptable levels of resistance to stress and corrosion. It is widely used in numerous engineering applications including transport and construction where superior mechanical properties such as tensile strength, hardness etc., are essentially required. Its superior corrosion resistance makes it a suitable candidate material for marine structural applications. (Christy, Murugan, & Kumar, 2010) In the following table, Table 1*Table 14*, the composition of this aluminium is represented.

Table 14: Chemical composition of Al 6061 (Christy, Murugan, & Kumar, 2010)

Element	Mg	Fe	Si	Cu	Mn	V	Ti	Al
Weight (%)	1.08	0.17	0.63	0.32	0.52	0.01	0.02	Reminder

Table 15: Mechanical properties of 6001 alloy (Aalco Metals Ltd, 2018)

Mechanical Properties	Metric
Ultimate Tensile Strength	310 MPa
Tensile Yield Strength	276 MPa
Shear Strength	207 MPa
Fatigue Strength	96.5 MPa
Modulus of Elasticity	68.9 GPa
Shear Modulus	26 GPa

6063 Aluminium alloy

Aluminium alloy 6063 is a medium strength alloy commonly referred to as an architectural alloy. It is normally used in intricate extrusions. It has a good surface finish, high corrosion resistance, is suited to welding and can be easily anodised. Most commonly available as T6 temper, in the T4 condition it has good formability. This material is used for architectural applications, shop fittings, irrigation tubing, balustrading, window frames, extrusions, and doors. (thyssenkrupp Materials (UK) Ltd, 2016) In the following table, Table 1*Table 16*, the composition of this aluminium is shown.

Table 16: Chemical composition of Al 6063 (thyssenkrupp Materials (UK) Ltd, 2016)

Element	**Mn**	**Fe**	**Mg**	**Si**	**Zn**	**Ti**	**Cr**	**Cu**	**Al**
Weight (%)	0 – 0.1	0 – 0.35	0.45 – 0.9	0.2 – 0.6	0 – 0.1	0 – 0.1	0 – 0.1	0 – 0.1	Balance

Table 17: Mechanical properties of 6063 alloy (Aalco Metals Ltd, 2018)

Mechanical Properties	**Metric**
Ultimate Tensile Strength	130 MPa
Tensile Yield Strength	54 MPa
Shear Strength	75.6 MPa
Fatigue Strength	59.4 MPa
Modulus of Elasticity	70.6 GPa
Shear Modulus	26.6 GPa

6005 Aluminium alloy

Alloy 6005/6005A has properties similar to those of alloys 6106 and 6082 and can sometimes be used interchangeably with them, but 6005/6005A has better extrusion characteristics.

The chemical compositions of 6005 and 6005A are different. Alloy 6005 contains significantly higher amounts of silicon, which reduces the melting temperature and improves its extrudability. Alloy 6005A, nevertheless, differs from 6005 in manganese and chromium content. The additional chromium in 6005A reduces stress corrosion susceptibility and improves toughness, while the extra manganese improves strength as well as extrudability. Alloy 6005 is similar to alloy 6061. When produced to a -T5 temper, it has the same minimum tensile and yield strength as 6061-T6 and better machinability and strength properties than 6063-T6. Alloy 6005A may also replace 6061 due to its better extrudability and surface appearance. (Hydro, 2023)

Table 18: Chemical composition of Al 6005

Element	**Mn**	**Fe**	**Mg**	**Si**	**Zn**	**Ti**	**Cr**	**Cu**	**Al**
Weight (%)	0.5 max	0.35 max	0.4 – 0.7	0.5 – 0.9	0.2 max	0.1 max	0.1 max	0.3 max	Remainder

Table 19: Mechanical properties of 6005 alloy (Aalco Metals Ltd, 2018)

Mechanical Properties	**Metric**
Ultimate Tensile Strength	198 MPa
Tensile Yield Strength	122 MPa
Shear Strength	-
Fatigue Strength	97 MPa
Modulus of Elasticity	71 GPa
Shear Modulus	28.4 GPa

6082 Aluminium alloy

Aluminium alloy 6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Is also known as a structural alloy. In plate form, Aluminium alloy 6082 is the alloy most commonly used for machining. As a relatively new alloy, the higher strength of Aluminium alloy 6082 has seen it replace 6061 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy. The tighter chemical band ensures more consistent anodising between batches. (High Grade Metals, 2022)

In the T6 and T651 temper, Aluminium alloy 6082 machines well and produces tight coils of swarf when chip breakers are used. (High Grade Metals, 2022) In the following table, *Table 20*, the composition of this aluminium is shown.

Table 20: Chemical composition of Al 6082 (High Grade Metals, 2022)

Element	**Mn**	**Fe**	**Mg**	**Si**	**Zn**	**Ti**	**Cr**	**Cu**	**Al**
Weight (%)	0.4 – 1	0 – 0.5	0.6 – 1.2	0.7 – 1.3	0 – 0.2	0 – 0.1	0 – 0.25	0 – 0.1	Balance

Table 21: Mechanical properties of 6082 alloy (Smith Metal, 2022)

Mechanical Properties	**Metric**
Ultimate Tensile Strength	260 MPa
Tensile Yield Strength	134 MPa
Shear Strength	170 MPa
Fatigue Strength	96.4 MPa
Modulus of Elasticity	70 GPa
Shear Modulus	26 GPa

Appendix H: Aluminium Temper Designation System

The aluminium tempering designation is a series of letter and numbers used to indicate the specific type of thermal and mechanical treatment to which the aluminium alloy has been subjected. The temper designation is placed after the aluminium alloy designation. The most used temper designations are shown in the table below:

Table 22: The Basic Temper Designations (Genculu) (Koch, 2020)

LETTER	MEANING	DESCRIPTION
F	As fabricated	No special control over thermal or strain hardening conditions of the product is employed. They are used for shaping, finishing or other thermal processes.
O	Annealed	The product is heated to achieve the lowest strength condition. To maximize workability or increase toughness and ductility.
H	Strain Hardened	Products are strengthened by cold working. The “H” is followed by two or more digits that indicates the basic operation.
W	Solution Heat-Treated	After solution heat treating, these alloys age naturally and spontaneously.
T	Thermally Treated	Products that have been heat-treated followed by quenching and aging. The “T” is followed by one or more digits that indicates the basic operation.

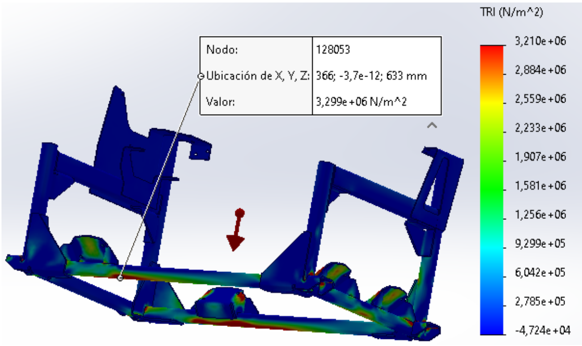
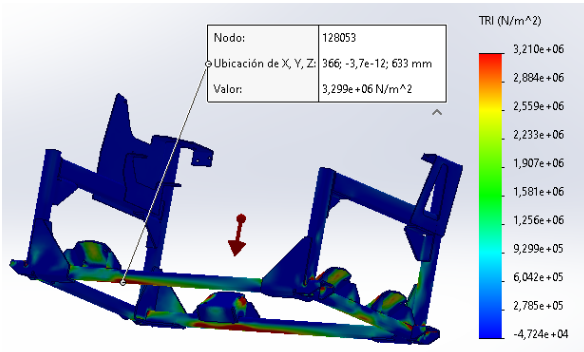
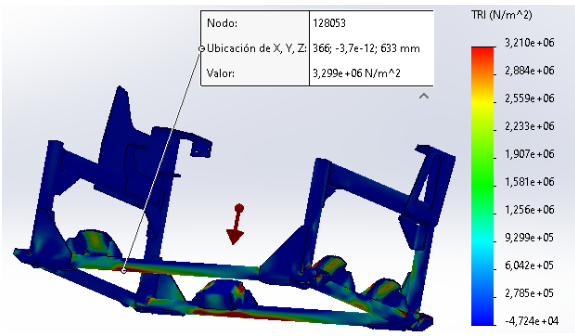
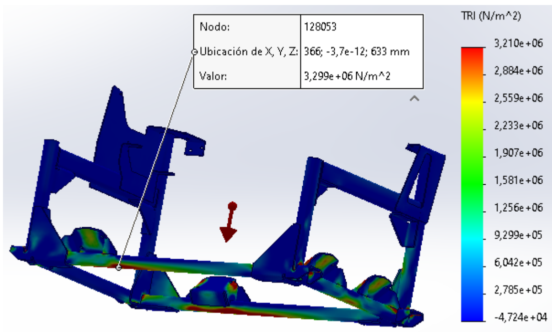
- Quenching: Tempering is a heat treatment consisting of the rapid cooling of a part by immersion in fluids to achieve certain material properties. (Metal Supermarkets, 2019)
- Aging: Ageing is a process used on solution heat-treated metal alloys to ensure that the materials do not revert to their original configuration after a certain period of time. This process can be artificially or naturally induced. (AZO Materials, 2013)

Appendix I: Different thermal treatments simulations

In these simulations have been analysed how different thermal treatments affects in the stress and deformation suffered by the frame. For that, have been analysed the same frame with same boundary conditions and aluminium alloy (Al 6082) but with four different thermal treatments (-0, -T4, T-6 and -T651). Material properties information for the simulation have been taken from several sources: (Xometry, 2022) (Aalco Metals Ltd, 2019).

In the following table (*Table 23*) can be seen the Principal stress suffered by the Al 6082 with different thermal treatments.

Table 23: Principal Stress suffered by the frame with different thermal treatments

Al 6082-0	**Al 6082-T4**
 *Figure 45: Principal Stress, Al 6082-0*	 *Figure 46: Principal Stress, Al 6082-T4*
Al 6082-T6	**Al 6082-T651**
 *Figure 47: Principal Stress, Al 6082-T6*	 *Figure 48: Principal Stress, Al 6082-T651*

In the following table (*Table 24*) can be seen the deformation suffered by the Al 6082 with four different thermal treatments (-0, -T4, -T6 and -T651).

Table 24: Deformation suffered by the frame with different thermal treatments

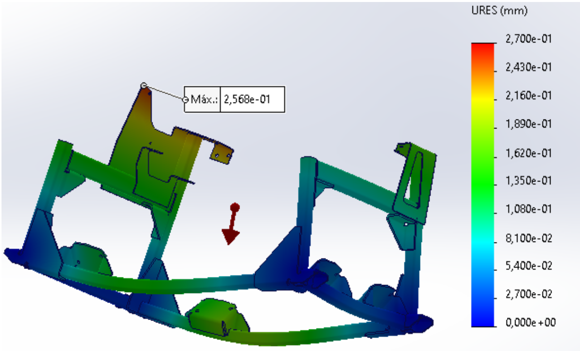
<table>
<tr><th>Al 6082-0</th><th>Al 6082-T4</th></tr>
<tr><td>

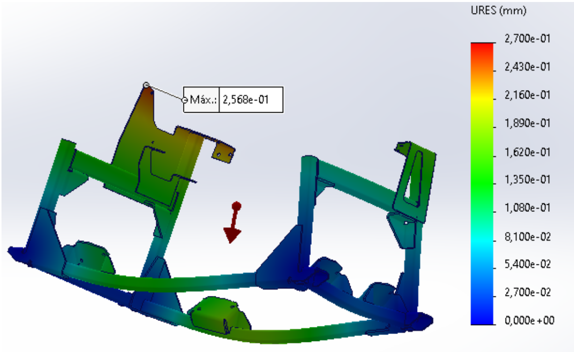
Figure 49: Deformation, Al 6082-0</td><td>

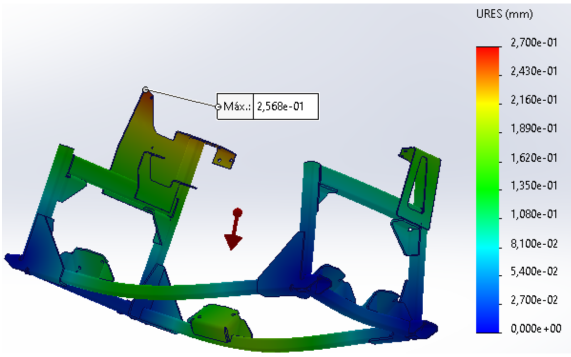
Figure 50: Deformation, Al 6082-T4</td></tr>
<tr><th>Al 6082-T6</th><th>Al 6082-T651</th></tr>
<tr><td>

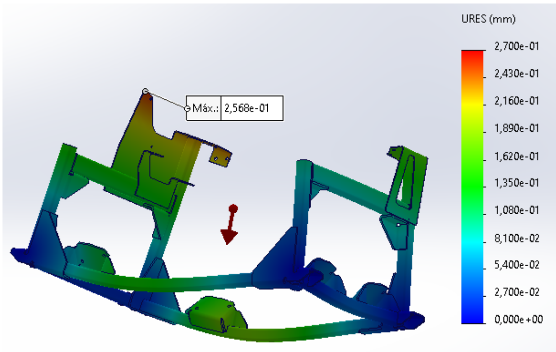
Figure 51: Deformation, Al 6082-T6</td><td>

Figure 52: Deformation, Al 6082-T651</td></tr>
</table>

Appendix J: Data collected for the life cycle assessment

In this section different tables are represented with data collected for making the life cycle assessment:

Table 25: Data collected from material extraction

BILL OF MATERIALS					MATERIAL PROCESSING				
Title	Material	Weight (kg)	Flow	Unit	Material extraction/production		SUM		
					Min	Max	Min	Max	Unit
Raw material	Al 6082 T6	16,89	Energy	MJ/kg	184	203	3107,76	3428,67	MJ
			CO_2	kg/kg	13,1	14,5	221,259	244,905	kg

Table 26: Data collected for additional processes

BILL OF MATERIALS								COMPONENT MANUFACTURING					
Part	Title	Material	Weight (kg)	Quantity	Total Weight (kg)	Flow	Unit	Extrusion		Rolling		SUM	
								Min	Max	Min	Max	Min	Max
1	Pipe I	Al 6082 T6	0,88	2	1,76	Energy	MJ/kg	14,8	16,4			26,04	28,86
						CO2	kg/kg	1,11	1,23			1,95	2,16
2	Pipe II	Al 6082 T6	0,83	2	1,66	Energy	MJ/kg	14,8	16,4			24,56	27,22
						CO2	kg/kg	1,11	1,23			1,84	2,04
3	Pipe III	Al 6082 T6	0,58	2	1,16	Energy	MJ/kg	14,8	16,4			17,16	19,02
						CO2	kg/kg	1,11	1,23			1,28	1,42
4	Pipe IV	Al 6082 T6	1,4	2	2,8	Energy	MJ/kg	14,8	16,4			41,44	45,92
						CO2	kg/kg	1,11	1,23			3,10	3,44
5	Pipe V	Al 6082 T6	1,11	2	2,22	Energy	MJ/kg	14,8	16,4			32,85	36,40

						CO_2	kg/kg	1,11	1,23			2,46	2,730
6	Sheet I	Al 6082 T6	0,16	1	0,16	Energy	MJ/kg			7,56	8,36	1,20	1,33
						CO_2	kg/kg			0,56	0,62	0,09	0,10
7	Sheet II	Al 6082 T6	0,45	4	1,8	Energy	MJ/kg			7,56	8,36	13,60	15,04
						CO_2	kg/kg			0,56	0,62	1,02	1,12
8	Sheet III	Al 6082 T6	0,23	4	0,92	Energy	MJ/kg			7,56	8,36	6,95	7,69
						CO_2	kg/kg			0,567	0,627	0,52	0,57
9	Sheet IV	Al 6082 T6	1,02	1	1,02	Energy	MJ/kg			7,56	8,36	7,71	8,52
						CO_2	kg/kg			0,567	0,627	0,57	0,63
10	Sheet V	Al 6082 T6	0,39	1	0,39	Energy	MJ/kg			7,56	8,36	2,94	3,26
						CO_2	kg/kg			0,567	0,627	0,22	0,24
11	Sheet VI	Al 6082 T6	0,75	4	3	Energy	MJ/kg			7,56	8,36	22,68	25,08
						CO_2	kg/kg			0,567	0,627	1,701	1,88

Table 27: Total sum of additional processes

	TOTAL EXTRUSION		**TOTAL ROLLING**		**UNIT**
	Min	Max	Min	Max	
Energy Consumption	142,08	157,44	55,11	60,94	MJ
CO_2 emissions	10,66	11,81	4,13	4,57	kg

Table 28: Data collected from coating process

	Value	**Unit**	**m^2**	**SUM**	**UNIT**
Energy consumption	3	kWh/m^2	3,02	9,06	MJ
CO_2 emissions	3	kg/kg	3,02	9,06	kg

Table 29: Data collected from welding process

	Min	Max	Total weight (kg)	Min sum	Max sum	Unit
Energy consumption	7	9	16,89	118,23	152,01	MJ
CO_2 emissions	5	6	16,89	84,45	101,34	kg

Table 30: Data collected from recycling process

	Min	Max	Total weight (kg)	Min sum	Max sum	Unit
Energy consumption	31,6	34,9	16,89	533,72	589,46	MJ
CO_2 emissions	2,48	2,74	16,89	41,88	46,27	kg