Metal for Additive Manufacturing Applied in a Maritime Solution

Design and optimization of a Rolling Furler

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Abstract

Additive manufacturing (AM) is an innovative manufacturing process, which is still in the process of research and expansion in the business sector due to its high costs. This thesis aims to design and optimise a rolling furler benefitting from the additive manufacturing process and a swivel carbine, used for climbing, to reduce its complexity and its cost.

The design consisted in taking advantage of Design for Additive Manufacturing (DfAM). Specifically, two optimization methods for reducing redundant material have been employed in this thesis, lattice structures and topology optimization. Additionally, the redesign of the different components has also been considered the need to merge some parts to reduce the printing process and minimise the material used. This has been achieved by reducing the initial number of components from 7 to 5.

These optimizations reduced the weight of the final prototype by 39,22% with respect to its initial model, with a final weight of 471 g. Also, an economic analysis was conducted, determining a final cost estimation for the Stainless Steel printing for the rolling furler of 977,60€. Nevertheless, in further studies, the economic feasibility of the prototype could be extended by determining a commercialization plan for large-scale production.

The printed components were manufactured in PrintSharp 250 by Prima Additive in Stainless Steel 316L. And as a result, the designed rolling furler is ready to be finished printed and tested on a conventional boat. However, before testing it in a sailboat, further mechanical tests should be conducted to determine its mechanical properties and behaviour under different stresses.

Language: English
Key Words: Additive Manufacturing, DfAM, Lattices structures, Topology Optimization, Furler

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Glossary

Acronyms

3D	Three Dimension
3DP	Three-dimensional printing
ABS	Butadiene styrene
AM	Additive Manufacturing
BJ	Binder Jetting
CAD	Computer-Aided Desing
CNC	Computer Numerical Control
CT	Computer Tomography
DC	Diamond Cubic
DED	Direct Energy Deposition
DfAM	Design for Additive Manufacturing
FCC	Face-centered cubic cell
ME	Material Extrusion
MfAM	Metal for Additive Manufacturing
MJ	Material Jetting
MRI	Magnetic Resonance Imaging
PA	Polyamide
PBF	Powder Bed Fusion
PLA	Polylactic acid
SL	Sheet Lamination
STEP	Standard for the Exchange of Product Data
STL	Stereolithography
TO	Topology optimization
VP	Vat Photopolymerization

Units

€	Euros
g	Gram
mm	Millimeters

1 Introduction

Vaasa, a city situated on the west coast of Finland, has a long history in the maritime sector. The city's port serves the country's import and export needs, and the region is well-known for its shipbuilding and repair facilities. In addition, the city is also home to important leading research institutions and industries focusing on sustainable shipping, demonstrating its dedication to the maritime sector.

The maritime industry has played a significant role in human development for centuries, facilitating global trade and providing leisure and recreational activities. The sector is dynamic, always looking for innovative ways to satisfy the evolving needs and demands of users (International Maritime Organization, 2015). One of the critical components in a sailing vessel is the furler, which allows sailors to quickly and easily furl or unfurl their sails. This process is essential to ensure optimum sailing performance and safety for the crew in various weather conditions (Sailing Britican, 2023).

A furler consists of a rotating drum and a length of line or cable that is wrapped around the drum. When the line is pulled, the sail is rolled up around the drum, reducing its surface area and making it easier to control in high winds (Colgate, 2015).

Therefore, this thesis aims to investigate the design and optimization of a furler, that is going to be used in a private conventional ship, taking advantage of additive manufacturing. The study will also evaluate the potential benefits of additive manufacturing in terms of flexibility, customization, and sustainability. In recent decades, there has been a growing trend towards additive manufacturing, which involves building 3D objects from digital models using successive layers of material (Madeleine, 2023).

Unlike traditional manufacturing methods, which involve cutting away material to create a product, additive manufacturing builds up material to create the final prototype (Formlabs, 2023a). This technology has changed the way of thinking about design, production, and supply chains, and has the potential to increase efficiency and improve sustainability (Despeisse and Ford, 2015). So, this thesis aims to explore the potential of additive manufacturing in the maritime sector and its impact on the performance of the furler.

1.1 Aim and objectives

This thesis aims to design and print a rolling furler prototype taking advantage of an advanced manufacturing process, Additive Manufacturing, using a swivel carabine (used for climbing) to reduce its cost. The furler will be used in a functional ship to allow the sailor to quickly and easily furl or unfurl the sail around the stay.

To achieve the aim of this thesis, objectives have been established as follows:

- Design and optimize a furler with a CAD software taking advantage of topology optimization and lattice structures.
- Merge together some parts of the furler taking advantage of the Part Consolidation process, to reduce the number of printing parts.
- Assembly of the swivel carbine without using mechanical joints.
- Print a final prototype in Stainless Steel 316L, with the PrintSharp 250 machine by Prima Additive.

The thesis has been commissioned to the Metal Additive Manufacturing Laboratory of the University of Vaasa. A laboratory that is equipped with a Powder Bed Fusion machine, a PrintSharp 250 machine by Prima Additive, and some other machines suitable for the post-processing of the parts.

1.2 Document structure

Section 2 presents the information obtained to understand both the Additive Manufacturing process and what a rolling furler is. Then, in section 3 the methodology is presented together with the planning for developing the project in section 4. Subsequently, in section 5 the whole process of design and optimisation of the rolling furler is shown. Section 6 explains how the designed furler is assembled and how it works. And, in Section 7 the printing process is detailed both for plastic and metal. Also, a study of the economic viability of the furler has been carried out in section 8.

Section 9 summarises the results obtained in the thesis, which are discussed in section 10. And finally, in section 11, the work is concluded.

2 Study background

This project has been commissioned to the Additive Manufacturing laboratory of the University of Vaasa. The development of this project requires the 3D design of the different components that constitute a furler, using additive manufacturing, an advanced manufacturing process.

It is very interesting to become acquainted with this process, as it is not yet widely used in the industry. However, the trend for research and development for its use is continuously growing, as Additive Manufacturing can overcome some of the limitations of traditional manufacturing methods.

Not only the way of manufacturing is innovative, but also the design process for it takes advantage of CAD software, leaving behind 2D designs and allowing prototypes to be created digitally in 3D.

To understand the thesis' fundamental concepts, in this section, a study background is done. Specifically, it provides an overview of what a furler is and the different types of furlers that are available nowadays (Section 2.3). In addition, the Additive Manufacturing process (Section 2.1) and its design (Section 2.2) also will be studied, as the final prototype will be processed in Additive Manufacturing.

2.1 Additive manufacturing

Additive Manufacturing (AM), also known as industrial three-dimensional printing (3DP), is a process used to build physical objects from digital 3D-model data, such as Computer-Aided Design (CAD) files, by successive addition of material (Kermavnar et al, 2021).

Additive manufacturing enables the production of items with precise geometric shapes using CAD software or through Reverse Engineering (RE), which approaches using different scanning techniques, e.g., 3D scanning, Computer Tomography (CT) scanning and Magnetic Resonance Imaging (MRI).

Then, the information from a computer-aided design (CAD) file is converted to a stereolithography (STL) file, in which the pieces are "cut in slices" containing the information for each layer. The method of creating an STL file mainly involves converting the continuous geometry contained in a CAD file into a header, a set of small triangles, or a triplet list of coordinates for x, y, and z, as well as the normal vector for the triangles (Wong and Hernandez, 2012). Multiple layers are built in the X-Y direction on top of one another in this freeform layer-wise fabrication to produce the Z or third dimension. (Bandyopadhyay and Bose, 2020).

According to the Welding Institute (2023a), this method can produce an end product, as opposed to traditional manufacturing which often requires a part to be made by joining separate components or using different techniques to remove excess material.

While traditional manufacturing processes necessarily require a thorough and in-depth analysis of the geometry of the part to determine the order in which different characteristics may be generated, what tools and processes may be used, and what additional fixtures may be required to complete the part, additive manufacturing (AM) provides a substantial quantity of design freedom (Gibson et al. 2015).

AM is mostly used for producing quick prototypes, but it is also used for tooling applications and small-scale series production (Gardan, 2015). However, AM is much more than a process that can be used to make personalized novel items or prototypes. With new developments in AM, we live in an age that is on the cusp of industrialized rapid manufacturing tasking over as a process to mass produce products and make it economically feasible to design and create new ones in a timely fashion. Also, AM overcomes the limitations of localised engineering and emerges on a global scale by enabling individuals to participate in the design process from almost any place.

Due to their favourable mechanical characteristics, metals are the most often used materials in 3D printing in the engineering field. As a result, the 3D printing industry looks for innovative methods for manufacturing metallic parts that can substitute those made in a more traditional manner (Dilberoglu et al., 2017), this is known as Metal for Additive Manufacturing (MfAM). Aluminum, titanium, stainless steel, and other materials have recently been used as the primary components in the AM processes used to manufacture many metallic components.

Thanks to the increased product quality, AM is being employed in a variety of industries, including aerospace, biomedicine, and manufacturing (Pant et al., 2021). Although there are some questions about its applications for mass production, the industry is increasingly using AM as a consequence of current technological advancements (Dilberoglu et al., 2017).

2.1.1 Additive manufacturing processes

According to the International Standard ISO/ASTM 52900 (2015), AM technologies can be classified into seven categories: Binder Jetting (BJ), Directed Energy Deposition (DED), Material Extrusion (ME), Material Jetting (MJ), Powder Bed Fusion (PBF), Sheet Lamination (SL), and Vat Photopolymerization (VP). In Figure 1, a schematic of the most common AM techniques is shown.

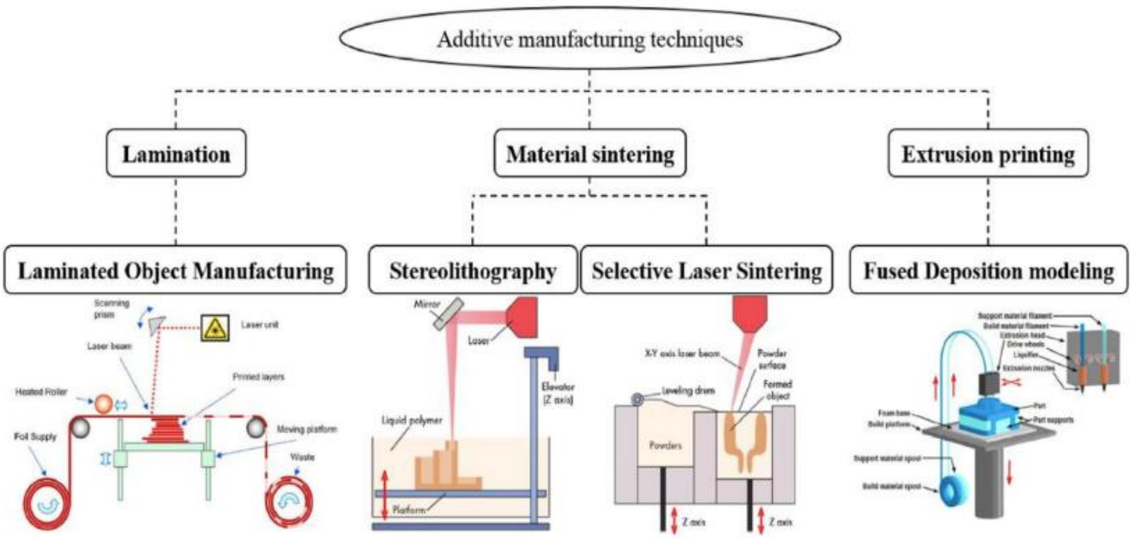


Figure 1. Schematic of various additive manufacturing techniques (Harding et al., 2023).

The selection to use AM technology for a specific application is determined by the choice of material, cost, post-processing requirements, requirements of surface finish and dimensional accuracy, the possibility of sterilization, fabrication speed, and resolution (Imsirovic and Kumnova, 2017).

Binder Jetting (BJ)

The binder jet technique consists of the deposition of a liquid adhesive binder on thin layers of powdered material to form a two-dimensional pattern on a layer (Ziaee and Crane, 2019). Powdered materials are ceramic or metallic based.

According to Schwaar (2023) during the BJ printing process, the printhead with inkjet nozzles moves over the build platform depositing binder droplets, that bond the powder particles together. When a layer is finished, the powder bed descends, allowing new powder to cover the print area. Then, the process is repeated until the whole part is completed.

Binder jetting is different from other additive manufacturing techniques since it does not require heat to fuse the materials, a wide range of materials can be used and allows colour printing (Jason, 2022).

Directed Energy Deposition (DED)

Powder or wire is fed into a melt pool which has been generated on the surface of the part where it adheres to the underlying part or layers by using an energy source. Essentially, this is a form of automated build-up welding (Jason, 2022).

The heat input can be a laser, electron beam, or plasma arc and the material feedstock is usually metal powder or wire. Powders result in lower deposition efficiency compared with metal wires as only a part of the total powder would be melted and bonded to the substrate (Sing et al., 2020).

One of the main advantages described by The Welding Institute (2023b) is that DED includes the ability to control the grain structure, allowing the process to be used for the repair of high-quality functional parts. This process also enables the creation of components with hybrid structures using various materials with differing compositions (Jason, 2022).

Material Extrusion (ME)

This is a thermal extrusion process, using a heated extrusion nozzle to soften or melt the material, usually plastic, supplied in the form of wire. Once melted, the material passes through an extrusion nozzle that deposits the material, which cools to solidify and form the final part geometry (Bikas et al., 2015).

During this process, the material is softened to a viscous fluid or near-fluid state so it can be applied to a build table or existing printed model layer. The material should be sufficiently melted to flex and bond with surrounding (cooler) materials but not so liquid that it flows away from the application point. The extruded material then rapidly cools and solidifies so that the next layer can be applied on top of it (Team Xometry, 2022).

Material Jetting (MJ)

Material Jetting consists of the dispense of droplets of a photosensitive material that is solidified under ultraviolet (UV) light, building layer-by-layer a part (Yap et al., 2017). Printing creates high-dimensional accurate parts with a very smooth surface (Kauppila, 2022).

According to a Protolabs company, Hubs (2023), the most commonly used materials in MJ are thermoset photopolymers that come in a liquid form. However, a wide range of materials (such as ABS-like, rubber-like and fully transparent materials) and multi-material printing are available in Material Jetting.

Some recent materials developments have expanded the use of MJ for biocompatible dental molds, rapid factory tooling, and industrial jigs and fixtures (Kauppila, 2022).

Sheet Lamination (SL)

In the Sheet lamination process sheets of different possible materials are stacked and laminated together to fabricate an object. Adhesives/ chemistry (paper/plastics), ultrasonic welding, or brazing (metals) are all possible laminating methods (Jason, 2022).

Sheet lamination can use a variety of materials such as paper, polymer, and metal. However, each of these materials requires a unique method to bind the sheets of material together (Siemens, 2022). In the paper-based lamination process, papers are glued together layer by layer using heat and pressure to activate a layer of activated adhesive that is pre-applied and then, precisely cut to the designed geometry to make the intended shape of the final object (Zhang and Liou, 2021). For some polymers, the same application of heat and pressure is used for melting the sheets together. For metals, instead of melting or sintering, the sheets are bound together with ultrasonic vibrations under pressure (Siemens, 2022).

Vat Photopolymerization (VP)

Vat polymerization is an additive manufacturing process that uses a vat, or container, filled with photosensitive liquid resin and a light source to create solid objects with excellent surface finishes (The Welding Institute, 2023b).

The build platform lowers from the top of the tank filled with liquid polymer (Learn, 2021). Liquid resin is selectively cured using an ultraviolet light source according to the pattern specified in the 3D CAD data file. Then, an ultraviolet (UV) light, typically from a laser or projector, selectively cures liquid resin according to the pattern defined in the 3D CAD data file, causing a chemical reaction called photopolymerization within the resin (Fast Radius, 2022b).

The photopolymer's molecules bond together to form a solid, and the build platform moves away from the light source to allow additional layers to be built on top of the previous ones. After the part is fully formed, the resin is drained and the part is removed (Carbon3d, 2022).

Powder Bed Fusion (PBF)

Powdered Bed Fusion is a printing method that consists of joining powdered material point by point using an energy resource, such as a laser or electron beam (Hendrixson, 2022). The powder surrounding the consolidated part acts as support material for overhanging features (Jason, 2022).

The powder particles are fused through one of the four fusion mechanisms: solid-state sintering, chemically induced sintering, liquid-phase sintering, or full melting (Stavropoulos and Foteinopoulos, 2018).

Most PBF parts will require post-processing to achieve the desired surface finish quality (Protolabs, 2020).

2.1.2 Advantages and disadvantages of AM

Additive manufacturing has been a game-changer in the industry of manufacturing. It allows products to be created layer by layer instead of traditional subtractive manufacturing methods that remove material from a larger piece. This method has led to a wide range of advantages including increased speed of production, customization, and reduced waste. However, like any technology, there are also disadvantages such as high initial costs, limited material options, and varying levels of product quality.

Unlike traditional manufacturing processes, which entail the removal of material or formative shaping or moulding processes, additive manufacturing techniques utilise the addition of material to entirely build an object from scratch. So, AM allows for complex and unique designs to be produced that would not be possible with traditional manufacturing methods (Alfonso, 2020). Giving the designer the freedom to design everything with only restrictions about the size, as the design has to fit in the machine.

Moreover, comparing AM with other traditional manufacturing processes, even other digitally driven manufacturing technologies such as computer-controlled “CNC” machining, additive manufacturing produces less material waste as it only uses the exact amount required for each part. However, this could depend on the part design and alternative manufacturing methods (Wong and Hernandez, 2012).

Due to the freedom in design that AM allows, designs can be optimised, e.g. by topology optimisation and lattice structures, to considerably reduce their weight and in turn the material required (Bandyopadhyay and Bose, 2020). This makes AM a much more environmentally friendly manufacturing process, being more energy efficient than conventional manufacturing processes and producing very little waste. This reduced environmental impact is a major advantage of additive manufacturing and should be considered before choosing the manufacturing process (May, 2022).

However, products produced using additive manufacturing often have low-quality surface finishes, which can be unappealing to customers and not suitable for all applications (Rouf et al., 2022).

Another important parameter to consider is batch size. Smaller production runs tend to be more suitable for additive manufacturing (Dam, 2022). Being not efficient for large-scale production.

Furthermore, Additive manufacturing equipment can be expensive, making the initial investment for companies quite high.

Additive manufacturing is experiencing significant growth in recent years. It is a great time for companies to embrace it, join the digital transformation and implement Industry 4.0 technologies to help improve their processes (Ramírez, 2023).

To sum up, additive manufacturing has many advantages that have revolutionized the manufacturing industry. However, it is important to balance these benefits the drawbacks to determine whether it is the appropriate manufacturing method for any specific company.

2.2 Designing for Additive Manufacturing

Design for Additive Manufacturing (DfAM) is the art, science and skill to design for manufacturability using 3D printers. In contrast to traditional manufacturing, this additive design process enables engineers to create production parts with more complex designs while reducing weight and material. It is an important reversal of conventional thinking about design (Torosian, 2023).

It is the process of adjusting a design to make it faster and cheaper to produce. By ensuring that the 3D printer is used efficiently, it is possible to enhance yield and reduce time and costs while creating a production process employing optimal design for additive manufacturing processes (Markforged, 2023).

The definition of design from an engineering perspective is the application of scientific principles, mathematics, and creativity to envision a structure, machine, system, or artefact that performs a predefined function (Mital et al, 2014).

In the past, 3D printing was considered a tool only for rapid prototyping or as an alternative method to create spare components without materially affecting the geometry (AMFG, 2021). Today, additive manufacturing has developed to the point that it can now be utilised to create essential components that meet even the most stringent engineering specifications. It is only possible to reach this degree of maturity by utilising the technology's fundamental advantages (Bournias, 2022).

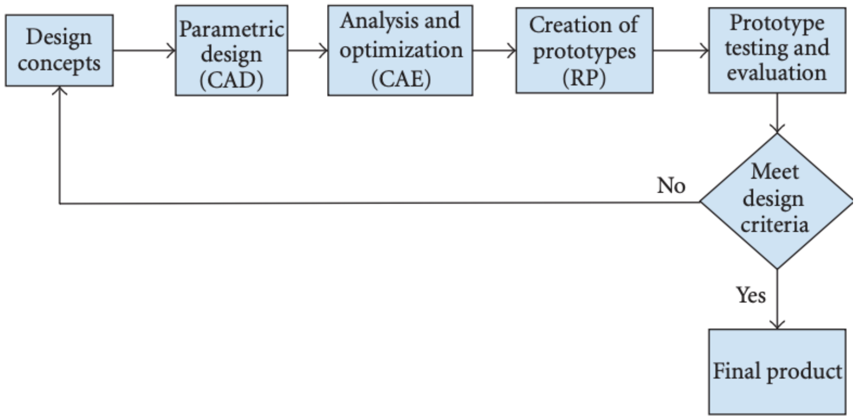


Figure 2. Product design cycle (Wong & Hernandez, 2012)

Product design is the process of identifying a market opportunity, defining the problem, developing a suitable solution for the problem and validating the solution with real users (Babich, 2018). The general process for designing a product is shown in Figure 2. It consists of a design concept that comes first and then the idea is developed. It is realized with the usage of different software, and finally, if the design criteria are met, the final product is obtained.

According to Barnes (2022), DfAM is an integrated process that begins with the concept stage and ends with the installed part. The complete value chain must be taken into consideration, including the features required for the installation and maintenance of the fielded component. DfAM focuses more on design and how to change, or modify, designs for additive manufacturing (AM).

DfAM involves more than simply adapting an existing design to be produced using additive manufacturing. Without the manufacturing limitations of conventional processes like injection moulding or CNC machining, it is about recreating the part, optimizing it, and improving it (Gaget, 2020).

2.2.1 Materials for Additive Manufacturing

There is a wide range of materials that can be used in additive manufacturing to create objects with diverse properties, performances, and functionalities (Shi et al., 2021). For the material to function effectively in the specified application, it must display acceptable service properties (Bourell et al, 2017). Also, the material's choice depends on the additive manufacturing process that is going to be employed, as the seven AM processes cover the use of different materials (Loughborough University, 2014).

Table 1 lists the different materials that are currently commercialized and used for each AM process.

Table 1. Current commercial materials for each AM process

	Amorphous	Semi-crystalline	Thermoset	Material extrusion	Vat polymerization	Material jetting	Powder bed fusion	Binder jetting	Sheet lamination	Directed energy deposition
ABS [Acryonitrile Butadiene Styrene]	X			X						
Polycarbonate	X			X						
PC/ABS Blend	X			X						
PLA [Polylactic Acid]	X			X						
Polyetherimide (PEI)]	X			X						
Acrylics			X		X	X				
Acrylates			X		X	X				
Epoxies			X		X	X				
Polyamide (Nylon) 11 and 12		X					X			
Neat		X					X			
Glass filled		X					X			
Carbon filled		X					X			
Metal (Al) filled		X					X			
Polymer bound	X	X		X						
Polystyrene	X						X			
Polypropylene		X					X			
Polyester ("Flex")							X			
Polyetheretherkeytone (PEEK)		X		X			X			
Thermoplastic polyurethane (Elastomer)				X			X			
Chocolate		X		X						
Paper									X	
Aluminum alloys							X	X	X	X
Co–Cr alloys							X	X		X
Gold							X			
Nickel alloys							X	X		X
Silver							X			
Stainless steel							X	X	X	X
Titanium, commercial purity							X	X	X	X
Ti–6Al–4V							X	X	X	X
Tool steel							X	X		X

(Shi et al, 2021).

In this chapter, the most commonly used materials in additive manufacturing are discussed.

Polymers

Polymers are one of the most frequently used materials in AM due to their low cost, ease of processing, and availability. Polymers can be classified into thermoplastics and thermosets, where thermoplastics are extensively used in AM (Riedl and Rudolph, 2021). The more common types of thermoplastics include polylactic acid (PLA), butadiene styrene

(ABS), polyamide (PA), and other specialty, high-performance materials (Picard et al., 2020).

PLA is the chosen material for a first draft for the furler before printing it in metal, since it is a low-cost material, it can be printed at low temperatures, and it does not require a heated bed.

Metals

High-strength, corrosion resistance, and thermal conductivity objects are produced using metal-based additive manufacturing technologies including selective laser melting (SLM) and electron beam melting (EBM) (Biserova-Tahchieva et al., 2023). The most used metals in AM include stainless steel, titanium, cobalt-chrome, and aluminium. Stainless steel is widely used in the automotive and maritime industry due to its resistance to corrosion and wear. Titanium is commonly used in the biomedical industry due to its biocompatibility, low weight, and high strength. Cobalt-chrome is used in the dental industry due to its biocompatibility, strength, and hardness. And, due to its lightweight, resistance to corrosion and high strength, aluminium is specially used in the aerospace industry.

Ceramics

Ceramics are used in AM due to their unique properties such as wear resistance, high hardness, low thermal expansion, and high electrical insulation. Although in the additive manufacturing sector, ceramics are not as well known as polymers and metals (Alicia, 2022a), zirconia, aluminium, and silica are also popular materials in the dental and biomedical industry, the semiconductor industry and the automotive (Vigilancer, 2020).

This thesis is going to be focused on the resources that are available in the Technobothnia laboratory. The printing machine used, PrintSharp 250 by Prima Additive, is based on the Bed Fusion Laser technology and takes advantage of the properties that metals can provide to the prototypes. Specifically, the printing is performed with Stainless steel 316L. The Standard Specification for Additive Manufacturing for Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion is regulated by the standard F3184-16 (ASTM, 2017).

Stainless Steel 316L is an ideal material for the maritime industry due to and thus its high corrosion resistance, durability and low maintenance (Forth, 2022).

Stainless steel grade 316L is an austenitic stainless steel with molybdenum content, known to be the most widely used stainless steel on the market. As stainless steel, 316L steel has a longevity that meets the requirements of sustainable construction (SSF, 2021).

The material is provided to the laboratory by Oerlikon Mteco, a Belgian company. MetcoAdd 316L-A is an austenitic steel powder with chemistry similar to EN 1.4404 and UNS S316603. In Table 2, general information about the Stainless Steel 316L powder by Oerlikon is shown. And also, the catalogue for it can be found in Appendix 1.

Table 2. General Information about Stainless Steel 316L powder by Oerlikon.

Product information	
Suitable for Service Environment	Corrosive Gas Corrosive Liquid
Nominal Chemistry	Fe 18Cr 12Ni 2Mo 0.02C
Manufacture	Gas atomized (Nitrogen)
Apparent Density	>4 g/cm^3 (typical)
Classification	Alloy, Iron base
Liquidus Temperature (º C)	1448 ± 10 °C / 2638.4 ± 18 °F
Solidus Temperature (º C)	1390 ± 10 °C / 2534 ± 18 °F
Process	Laser Powder Bed Fusion (PBF-LB) Electron Beam Powder Bed Fusion (PBF-EB) Directed Energy Deposition (DED)

(Adapted from: www.addimen.com)

Moreover, it is remarkable that AM parts are typically post-processed in some way to optimize the microstructure, reduce porosity, finish surfaces, minimize roughness, and achieve geometric tolerance for the most demanding service applications (Jithinraj et al., 2022). Especially, for stainless steel it is not necessarily, post-processed via machining, grinding, electrical discharge machining (EDM), polishing, and so forth to achieve the desired surface finish and critical dimensions (ASTM, 2017).

2.2.2 Computer-Aided Design (CAD)

Computer-Aided Design (CAD) is a technology to aid in design processes by using computer-based software (Chai, 2020). Nowadays CAD software is fundamental for engineering design. Moreover, this type of software has an important role in the development of this thesis, as it is the tool that will allow the design of the prototype of the furler.

CAD is utilized to improve design quality and amount of detail, increase productivity, optimise and streamline the designer's workflow, improve documentation communications, and frequently contribute to a production design database. CAD software outputs come in the form of electronic files, which are then used accordingly for manufacturing processes.

The immense capabilities of the different machines AM cause the real constraint in the manufacturing process to be the design. One key factor that makes AM so innovative is that it can create a ready-to-use part from a CAD file. Almost any part that can be theorised, can now be produced in a digital version due to the advancements in CAD that have made it possible to create almost anything. This CAD file can then be converted to an STL file and made on an AM machine. With the advent of additive manufacturing technology, engineers now have a design flexibility that was previously unavailable in prototyping on paper.

For this project, the CAD software used for the design of the prototype is Creo parametric 5.0.6.0, a 3D modelling software. This has been chosen, as previous knowledge about it was acquired in the subject 'Graphic Expression 2', taught at the University of Lleida. Thus, the licence is owned by the University of Lleida.

2.2.3 Part Consolidation

Part consolidation is the redesign and rethinking of an assembled component into fewer, more complex parts that may be manufactured as a single unit without the need for assembly (Schwaar and Newton, 2022).

This concept has been used for many years in traditional manufacturing methods and is known to speed up assembly, enhance functionality, and reduce material waste. It is acknowledged that when compared to a traditional multi-piece assembly, consolidation of

AM parts can improve structural performance (Liu, 2016). Thus, it is widely recognized as one of the major motivations for utilizing AM technology (Yang et al., 2019).

Usually, thinking in terms of combining two parts is insufficient. The likelihood of higher savings increases with the number of elements being integrated. If elements are fastened after assembly, consolidation may be possible (Protolabs, 2023).

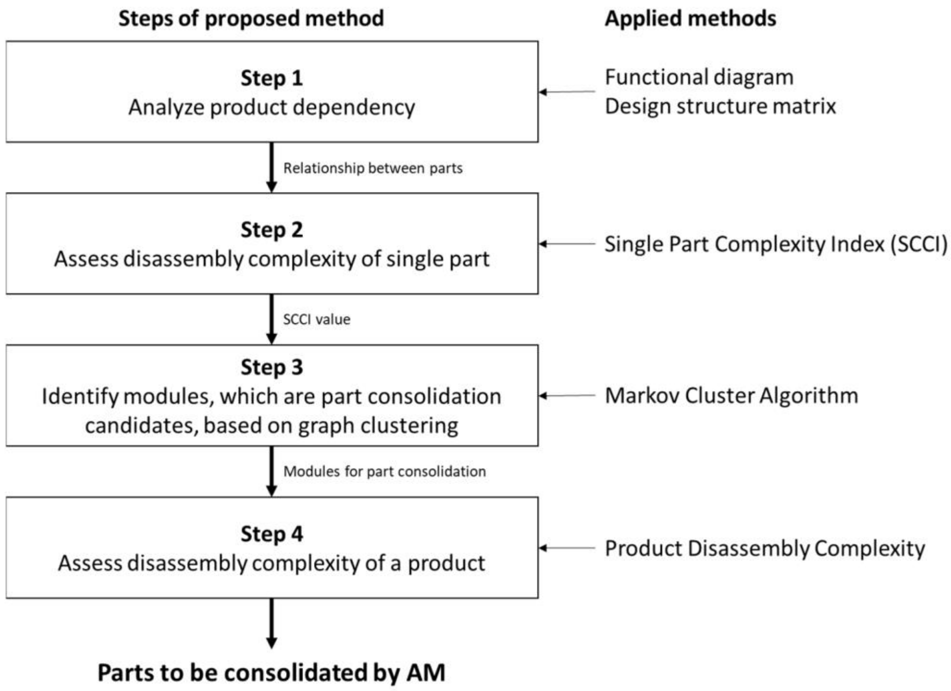


Figure 3. Overview of the proposed design method (Kim and Moon, 2020).

As shown in Figure 3, for consolidating, some previous steps have to be done. It is important to analyse the structure of the design and the product dependency between the parts that are considered to be consolidated.

Part consolidation has several benefits in Additive Manufacturing. As parts consolidation results in less number of components to be used, it effectively reduces the supply chain and improves production efficiency as the demand decreases. Also, by lowering the cost of supplies, these supply chain reductions can boost a company's profits (Sydney, 2022). Moreover, consolidated assemblies remove the necessity for parts to be assembled with pinning, bolts, welding, or other methods (Jones and Ice, 2021).

Combining parts can lead to improved functionality. By integrating parts, an engineer can create more intricate and complex structures that can perform a greater number of functions, as product complexity limitations are reduced by AM (Liu, 2016). In addition, the instances of part failure decrease when the part has been manufactured as a single unit rather than assembled separately.

The engineering components manufactured by AM in many cases have better performance because it enables geometries that cannot be made with conventional manufacturing. Some of the interesting advantages in improving product performance for AM applications include high strength-to-weight ratio, heat transfer, fluid flow, and energy absorption (Gao et al., 2015). And, manufacturing fewer parts also reduces the potential for tolerance stack and alignment issues (Jones and Ice, 2021).

Reducing the number of parts in a design can save time and money, and these are the best and most evident benefits of consolidating parts with AM. The cost of assembly will be lower if there are fewer pieces required for assembly. By eliminating assembly from the equation, potential cost-driving facts such as quality control and inventory management will be reduced. Also, part consolidation can reduce material waste. With fewer parts, there are fewer materials needed, leading to less waste and lower production costs.

Despite the benefits, there are also some limitations to part consolidation in additive manufacturing. Firstly, incorporating more functions into a single part can lead to increased complexity and difficulty in production. As the complexity of a part increases, more design, production, and testing time may be required. This can make part consolidation impractical for some applications. Also, in some specific designs, each part can require different materials or properties that may not be suitable for consolidation.

Part consolidation, as an alternative to assembly design (Yang et al., 2019), is an effective technique to improve functionality, reduce production time and costs, and decrease material waste in additive manufacturing. It offers a significant opportunity for designers and manufacturers to push the limits of what is possible, creating complex and customized parts with multiple functions. However, to decide whether part consolidation is appropriate, it is required a careful analysis of the design, functionality, and assembly requirements of a product.

2.2.4 Topology optimization

Topology optimization (TO) is a mathematical method that, by satisfying predetermined constraints and minimising a predetermined cost function, spatially optimises the distribution of material within a specific domain (Rosinha et al., 2015). TO reduces weight or addresses design issues like lowering resonance or thermal stress by removing redundant material from areas that do not need to carry substantial loads. This maximises the performance and efficiency of the design (Formlabs, 2023b).

In recent years, topology optimization has become increasingly popular in the field of additive manufacturing (AM) as it is well-suited to the design freedom that AM offers. Because, unlike other types of optimisations, topological optimisation offers a new concept of structural design focused on those applications where component weight is crucial (Catec, 2019).

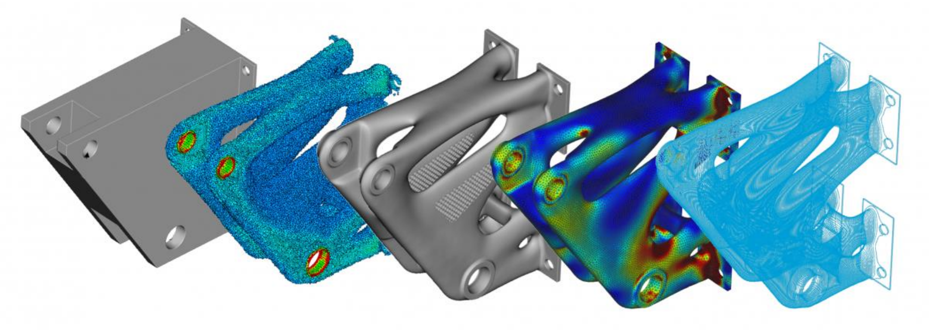


Figure 4 .Topology optimization process (Source: https://ntopology.com).

The Topological optimization process begins with the creation of a 3D model in the draft phase, in which different loads or forces are applied to the part. Afterwards, the software is responsible for calculating all the applied stresses.

At this level, the part can be cut in order to remove the parts not subjected to the forces. The final geometry, which meets the mechanical and design requirements, can finally be obtained after smoothing the part. In this way, topological optimisation meets the need for mass reduction and increases the part's mechanical strength (Lucía C, 2020). An example of this process is represented in Figure 4.

Conventional topology optimization employs finite element analysis to assess the effectiveness of the design and generate structures that meet the following goals:

- Reduced stiffness-to-weight ratio
- Better strain energy to weight ratio
- Reduced material volume to safety factor ratio
- Natural frequency to weight ratio.

Support structure reduction, which may be the most researched subject in the area of AM limited TO, is of great interest to end users in the industry as it offers some of the most obvious and immediate advantages in terms of reducing wasteful material and reducing print time (Sabiston and Kim, 2018).

Overall, topology optimization for AM enables designers to create parts and products that are optimized for specific applications, resulting in lighter, stronger, and more efficient structures that can be produced with additive manufacturing technologies.

2.2.5 Lattices

Lattices in additive manufacturing refer to complex structures made up of repeating patterns of interconnected frameworks or struts that form a three-dimensional network (Fast Radius, 2022a). For these structures, the most fundamental requirement is that they must be self-supporting (Hussein et al., 2013).

Mass can be reduced through lattices without compromising stress or displacement. These can be used on products including porous implants, energy-absorbing machinery, thermal insulation, and lightweight structural panels (McClintock, 2020).

Lattices can be used in the design of various manufacturing applications such as medical, aeronautical and automobile industries as it comprises enhancing features (Wang et al., 2018). In comparison to conventional structures and solid materials, lattice structures have many advantages. They are known for their unique properties, such as high strength-to-weight ratio, energy absorption, and excellent thermal insulation (Tao and Leu, 2016). Also, lattices have been found to have a wide variety of applications in AM, including the creation of lightweight parts, the design of custom implants, and the optimization of mechanical properties.

The simplest repeating structure in a lattice is the unit cell. The type of lattice is defined by the unit cell structure. A cell map is used to arrange unit cells in space to form a lattice. Cell maps can be square, round, spherical, curved to fit between two faces, or any combination of these (Bournias,2022). And the size, shape, and connectivity of the unit cell can influence the strength, stiffness, and ductility of the material (Plocher and Panesar, 2020).

There are a variety of techniques to create lattices and a wide variety of lattice structures (Bournias, 2022). Figure 4 shows all the different types of lattices that are available in nTopology, the software that is used in this thesis for the design of the rolling furler.

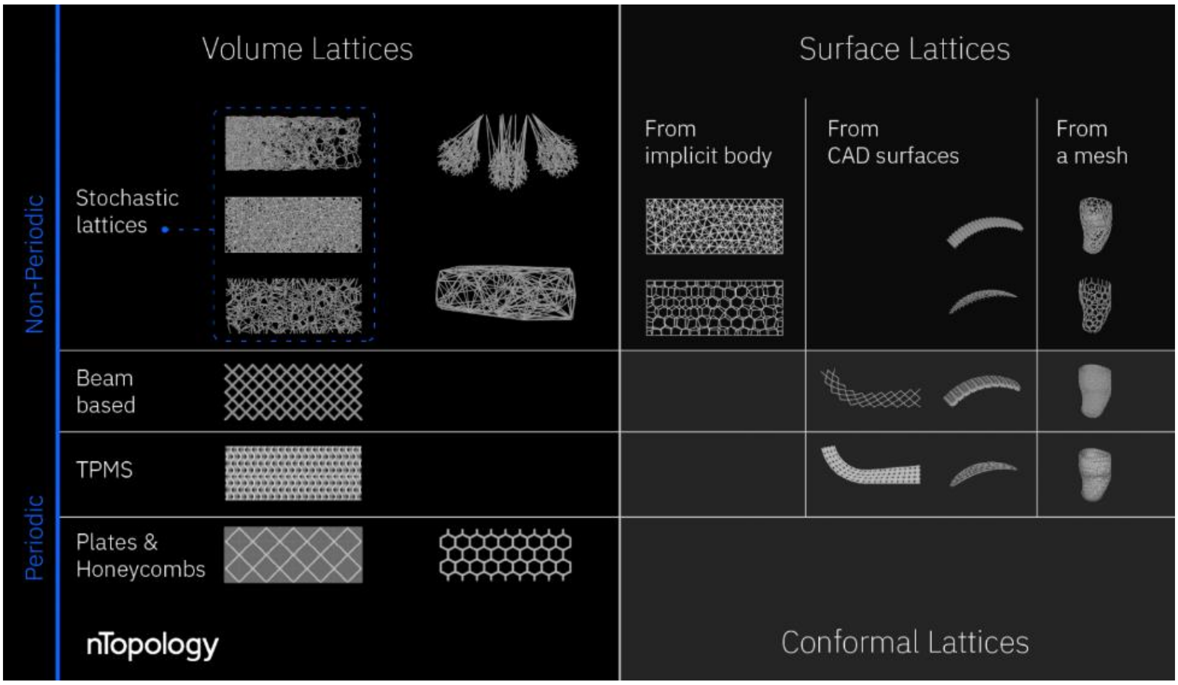


Figure 5. Types of Lattices according to nTopology (Source: www.ntop.com.)

According to Figure 5, lattice structures can be divided to be periodic and non-periodic, or stochastic, from their layout patterns. The main difference between both is that periodic lattices are trimmed to the design space and non-periodic are conformed to it. Lattices can also be classified as volume or surface lattices, depending if these are applied to the body or only to the surface.

Unit cell design

The smallest component of the whole lattice structure is the unit cell (Plessis et al., 2018). Consequently, the design of the unit cell has a significant effect on the properties of a lattice structure, including mechanical response, specific surface area, stiffness, pore size, and other characteristics. Furthermore, when designing unit cells, the formability of lattice structures should be considered (Chen et al., 2021).

Pattern design

The lattice structures are made up of unit cells that are repeated in three dimensions. The final configuration of lattice structures is determined by the organization of unit cells, which is known as pattern design. The pattern design can be direct or conformal:

- **Direct patterning**

The unit cells in direct patterning are typically designed as cubic elements and are simply repeated in lattice structures, making it very simple and convenient (Shao and Chen, 2014). The unit cells are apparently simply repeated in a 3D space, regardless of the lattice structure that will be constructed. This approach is appropriate for designing lattice structures manufactured with AM technologies.

- **Conformal patterning**

In order to stiffen or strengthen the required structure, conformal pattering maintains the integrity of the unit cell, which is seen to be a better strategy because it can distribute the load uniformly across the entire structure (Tao and Leu, 2016).

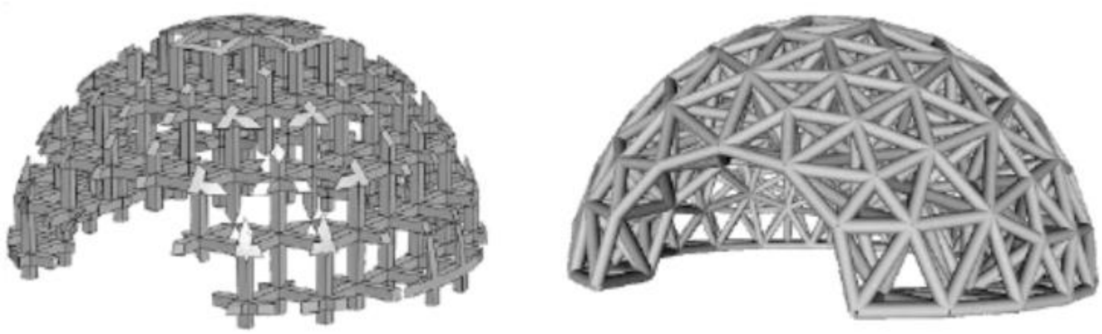


Figure 6. a) Direct patterning. b) Conformal patterning (Tao and Leu, 2016).

The above properties can be appreciated in Figure 6. As it shows an example of the same body with lattices of direct patterning (a) and conformal patterning (b).

According to Wang et al. (2018), many studies have been developed to demonstrate that periodic lattices perform better than stochastic ones. However, when the feature sizes of lattice structures, also known as mesostructures, are comparable to the length scale of the global structure, these could show quite different mechanical behaviour (Deshpande et al., 2001).

Factors including material composition, laser power, and layer thickness during fabrication can affect the mechanical properties of metallic lattice structures made using additive manufacturing.

Additionally, the mechanical properties of the structure could also be affected by the unit cell's orientation in relation to the direction of loading (Xu et al., 2016). For example, isotropic structures have similar properties in all directions, whereas unidirectional structures tend to be stronger in the direction of the load.

Porosities of metallic lattice structures also have a significant influence on their mechanical properties because it determines the relative density of lattice structures. The presence of it can significantly affect the mechanical properties (Zhang et al., 2022). However, the increased relative density of the lattice structure would also result as an increased consumption of material and the increased weight of the final products, opposite to the concept of lightweight.

2.2.6 Overhang

Overhang features are portions of the printed part that extend out horizontally or at an angle from the vertical axis of the part. The layer-by-layer approach of additive manufacturing can result in overhang features that require additional support structures to ensure successful fabrication. These features can create challenges during the printing process, as they require additional support structures to hold up the overhanging portion of the part during printing.

The design of support structures for overhang features is an important consideration in additive manufacturing. Inadequate support structures can lead to deformation or collapse of the overhanging portion of the part, resulting in a failed print (O’Neill, 2023). On the other hand, excessive support structures can lead to increased print time and material usage, as well as difficulty in removing the support structures after printing (Chakravorty, 2023).

There are two general rules about support structures in additive manufacturing: the 45° rule and the 5mm rule (Alicia, 2022b). Regarding the first one, if an overhang of the part is inclined at an angle of less than 45 degrees to the vertical, then you can print that overhang without using supports. And on the other hand, the 5 mm rule explains that when a bridge (space between two parallel points of the part) is less than 5 mm long, supports are not required either.

Figure 7. Examples of support generation structures (Source: https://www.hubs.com/).

Figure 7 shows an illustrated example to better understand the generation of support structures of different models of letters Y, H and T. The arms of the letter Y can be printed with a 3D printer without generating any support structures, as these are less than 45º. However, letters H and T require support since the overhang is 90º. If the centre bridge of letter H were under 5mm, it is printable without support or sagging.

These rules must also be considered in the creation of lattice structures since these structures are interesting as self-supported and if this does not require additional supports that can modify its internal structure.

Another approach to minimizing overhang features in additive manufacturing is to redesign the part itself to avoid or minimize the need for overhang features. This can be achieved through the use of chamfers, fillets, or other design features that eliminate the need for support structures (Williams, 2022).

Overall, the design and optimization of support structures for overhang features is an important consideration in additive manufacturing. By carefully considering the design of the overhang features and the support structures needed to fabricate them, designers can ensure successful printing while minimizing material usage and print time.

2.3 Furling systems

Roller furling is a system for reefing or unrolling a sail around a turning pole or an extrusion with grooves for handling lines. The sail can be easily deployed or stowed simply by turning a handle or pulling a line, which rotates the furler and rolls the sail in or out. Roller furling systems are commonly used on cruising boats and make sailing much easier and safer, especially for single-handed sailors who need to manage their sails from the cockpit (Wade, 2021).

Figure 8. Ship which uses a furler for reefing and unrolling the sail (Source: www.offshoresailing.com).

A furler is a device used to roll or furl a sail, making it easier to handle and adjust. It consists of a rotating drum and a length of line or cable that is wrapped around the drum. When the line is pulled, the sail is rolled up around the drum, reducing its surface area and making it easier to control in high winds.

Furling systems can be used for different types of sails, such as jibs, genoas, and even mainsails (Get my boat, 2018). And they are designed to make sail handling more efficient, reduce the need for crew to handle sails on deck, and increase safety especially in changing weather conditions.

2.3.1 Advantages and disadvantages

Like every device, the use of furlers on boats has both advantages and disadvantages. These are set out below.

Firstly, furling systems make sail handling easier and more efficient, especially for single-handed or short-handed sailors. Also, these systems allow sails to be reefed quickly and easily, which can be helpful in changing wind conditions.

However, this furling systems usually are expensive devices, which can cost more than traditional sail handling systems, particularly for larger boats and high-end systems with features like motorized furling. Furling systems can also require accurate maintenance and care to ensure that they remain functional and reliable. Moreover, these systems may not be suitable for all types of sails or sailboat designs, especially for racing sailors who may require maximum performance and sail shape control.

As with any sailing equipment, the advantages and disadvantages of furling systems depend on the individual sailing needs and preferences, as well as the specific features of the system that is chosen.

2.3.2 Types of furlers

There are many types of furlers, which can be divided into three main categories according to Fastiggi (2017). The characteristics and particularities of each type are detailed below.

Head Swivel Furlers

The most common roller furling system in use today is the head swivel furling. It is durable, simple to maintain, and simple to use. The headsail halyard is integrated into the typical furling system, which mounts just aft of the head stay (Burden, 2019).

Two spindles are used in head swivel furling systems: one drum at deck level and one smaller spindle just above the headsail. It makes use of ball bearings for easy rotation and weather resistance in general. The sail itself fastens with hanks to a wire halyard, which is connected to the drum at the system's base. A line attached to an eyelet on the deck leading to the cockpit is used to rotate the drum (Wade, 2021). The sailor pulls on the furling line to furl the sail by turning the furling drum and winding up the sail.

They are designed to be used with jibs and genoas and work by attaching to the head of the sail and rotating it around the forestay.

Internal Halyard Furlers

Internal halyard furlars are devices that are mounted inside the mast and are used with a halyard (the line used to hoist the sail) that runs through a slot in the center of the furler.

This technology is unique in that it uses an existing forestay to be installed. The spindle drum used in the bottom-up furling method is where the forestay runs through. Despite the fact that the drum in this system is larger than in other systems, the deck is easier to move around because of the drum's placement on the forestay. The spindle drum mechanism of the internal halyard model is really placed further than the wire luff and the head swivel (TopRik, 2023).

The advantages of it are the reduced head swivel, and the ability to use the halyard for spinnaker raising. However, it has some disadvantages such as the difficulty adjusting halyard tension for sail control, compression on the forestay can make furling difficult in high winds, and sail changes can be challenging (Fastiggi, 2017).

Wire Luff Furlers

Wire luff furling systems are freuquently use on smaller boats and coastal cruising. And it is very similar to the heat swivel system, however, this kind of systems are more affordable. They are designed to wrappe up the sail around a long wire luff, that is the section of the sail that runs along the forestay.

Just aft of the forestay, it has a large rotating drum that is mounted to a chainplate. Additionally, it makes use of a swivel that connects to a regular halyard, enabling you to keep using your current headsail rigging.

Wire luff furlers are popular because they are relatively simple, reliable, and offer good sail shape control. They are also easy to install and maintain. However, wire luff furlers can also have some limitations. Due to their potential weight and lack of flexibility compared to other furling systems., their use can be limited in certain sailboat designs or applications. Moreover, these require a certain amount of tension on the wire luff to operate properly, which can be challenging to achieve in certain wind and sea conditions.

2.3.3 Examples of furlers currently for sale

A small-scale research of the current market for furlers has been carried out to analyse the furlers that are available for sale nowadays and its prices. Next, some models with a similar performance to the prototype to be designed had been chosen. However, they had been created with other manufacturing methods.

Table 3. Furlers on sale (Source: Author's own).

Profurl NEX V2 Flying Sail Furler	**Selden CX Furling Kit**
 Price: 938,04€ Website: jimmygreen.com	 Price: 1021,96€ Source: jimmygreen.com
Plastimo 609S Turnbuckle Jig Reefing	**Selden GX Asymmetric Spinnaker Top Down Furler**
 Price: 676,99 € Source: www.tradeinn.com	 Price: 969,00€ Source: www.bluemarinestore.com

(Source: Author's own).

3 Methodology

This thesis is focused on the creation of a rolling furler design, taking advantage of the AM process, while meeting the requirements for it and keeping a good aesthetic design. The rolling furler is designed using a low-cost off-the-shelf component, a swivel carabine (used for climbing), allowing independent rotation of the lower part, which is anchored to the sailboat, and the upper part, which is anchored to the sail, permitting it to furl or un-furl depending on the direction of the rotation.

For meeting the final design, several stages are going to be followed to achieve the thesis' objectives. Starting with a literature review for collecting background information and introducing the AM process and the available furlers in the market. Then, the development of the design of the furler consists of the CAD design. The design will be lately lightweight and finally, some parts are optimized taking advantage of Topology Optimization.

After having the final design of the rolling furler, different tests were held in PLA (Plastic), as it is much cheaper, and when everything worked well, then the final product was printed in Stainless Steel 316L (Metal).

As it is a multi-part product, the assembly and the operation are also analyzed and detailed, so anyone can understand its usage.

Finally, to conclude the project, economic feasibility will be studied, as one of the main disadvantages of AM is the high cost of production.

Bellow, the different stages are found with a brief explanation of their development.

- **CAD Design**

The design of the different components is carried out on the basis of a first proposal that needs to be improved, as it is a simple model, which does not consider important parameters for the design and the different parts don't fit. Furthermore, it does not consider the different methodologies to take advantage of additive manufacturing.

The only restriction for the furler design proposal is to use a swivel carabine, to take advantage of its rotational operation. Therefore, the first step of the design is to take the different measurements of the furler and determine its size.

The different parts are designed independently with the 3D modelling software Creo Parametric 5.0.6.0 CAD (www.ptc.com). For the creation of these, not only different designs have been made to determine which one could be the most suitable both functionally and aesthetically, but also improvements have been done to these to obtain a good final result suitable for printing on a 3D printer for metal (Metal for Additive Manufacturing).

An additional issue related to this Creo Parametric is that the files are properly generated in a PRT format. However, in order to be able to work later with other software, specifically Altair Inspire and nTopology, the files should be exported in STEP, a common file format used for modelling and 3D printing, an ISO standard interchange format. Exporting these files directly with Creo leads to low-quality files. Thus, for this transition, an additional online free software is used, OnShape (www.onshape.com/en/).

- **Topology Optimization**

Topological optimisation has been used to optimise and reduce the material required for one of the components in order to obtain an organic design. This optimisation has been carried out with the Altair Inspire 2022.2 software (altair.com/inspire).

- **Lightweight with lattices structures**

For the 3D printing process, one of the main objectives is to make designs as light as possible in order to reduce the weight and the cost of the product and optimize the use of the material. For this reason, after the design of the components, it has been determined to use lattice structures to the solid parts, making an optimal casting. These lattices have been designed with nTopology (https://www.ntop.com/), an engineering design software built for additive manufacturing.

Lattice structures can not only be used to reduce the weight of designs but are also used to aesthetically decorate smooth surfaces.

The lattices used in this thesis are both volumetric and surface lattices (see section 5.4). For each part of the furler, the type of lattices has been determined considering its purpose of it and considering the design for additive manufacturing principles (detailed in section 2.2).

- **Operation and Assembly**

The furler is a product made up of different parts which must be assembled to operate properly. Due to the importance of correct assembly, this will be detailed by means of an assembly instructions manual where the operation of this is also described.

Moreover, the furler is a very specific mechanism used only in the maritime sector. For this particularity, it is necessary to describe in detail its correct functionality.

- **Printing**

Firstly, to be able to print, the parts must be exported as an STL (Standard Triangle Language) file. Once the design is in STL format, each printer has its own software or specific software to control I then proceed to print. And in turn, depending on the type of material with which you want to print the process may slightly vary. For this project, two materials will be used for printing. Firstly, the first prototype is held in PLA (plastic) as a first draft and the final prototype is printed with Stainless Steel 316L (metal).

Next, the different parts for printing are placed in the relevant software. The software used for plastic is Ultimaker Cura (ultimaker.com) for the Ultimaker S3 printer and the software for metal is EPHatch for the PrintSharp 250 by Prima Additive printing machine. These both display a simulation of the printer bed with which the printing is going to be carried out, and then the different properties with which it is desired to print are defined.

Once all the parameters are defined and the parts are placed in the desired position, these are then sliced, converting the 3D model file into a machine language that can be recognized by the printer.

Finally, the file is uploaded to the printer and the printing begins.

- **Study of the economic feasibility**

Metal for Additive Manufacturing (MfAM) is a rather innovative manufacturing process, which is not yet widely applied in the industry partly due to its high cost. For this reason, a study of the economic feasibility of printing a furler in Stainless steel will be undertaken, determining its costs and comparing it with the furlers currently available on the market.

To develop all these tasks and achieve the aim and objectives, these have been organized following the strategies described in the Project Management course taught at Novia UAS, exposed in the following chapter (section 4).

4 Project Management

In this section, a planning of the project has been made taking into account the tasks to be carried out as described in the methodology section (section 3).

To carry out this planning, the first step was to define the deliverables of the thesis and to determine specific tasks for each of them using the Work Breakdown Structure (WBS) planning tool. And finally, the schedule is set in section 4.2.

4.1 WBS

A project is visually, hierarchically, and deliverable-focused disassembled using a work breakdown structure (WBS). It is a useful diagram for project managers since it enables them to deconstruct the scope of their projects and see all the tasks necessary to finish them. (Organ and Bottorf, 2023)

According to Work Breakdown Structure website (2023), breaking work down into smaller jobs is a typical productivity method used to make the work more manageable and approachable. This tool is called the Work Breakdown Structure (WBS).

The development of WBS started first of all to determine the 4 deliverables, it consist of considering the main stages of the projects. Then, according to the methodology the task to develop each deliverable are set. In Figure 9, the WBS can be seen.

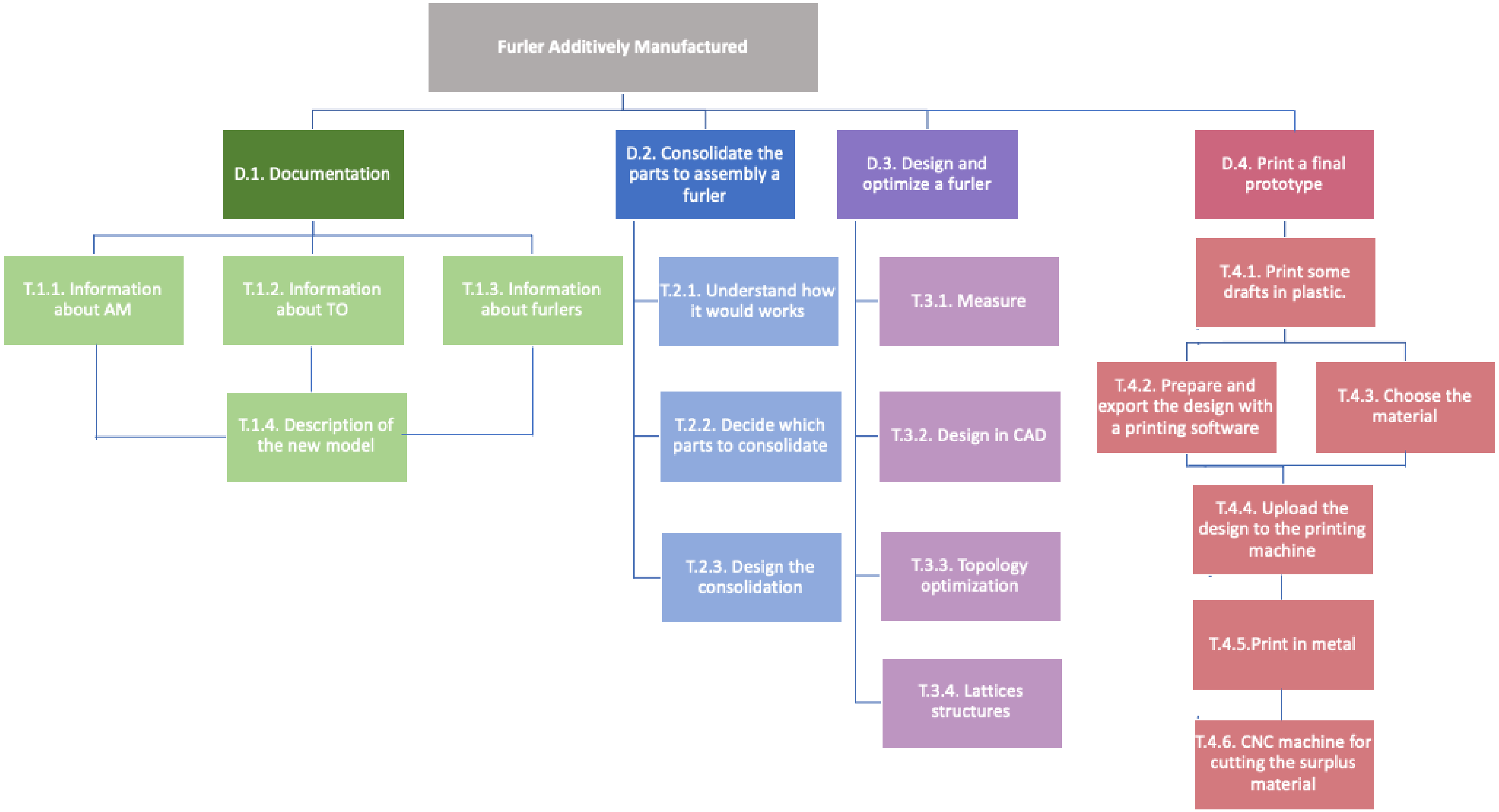


Figure 9. Work Breakdown Structure (Source: Author's own).

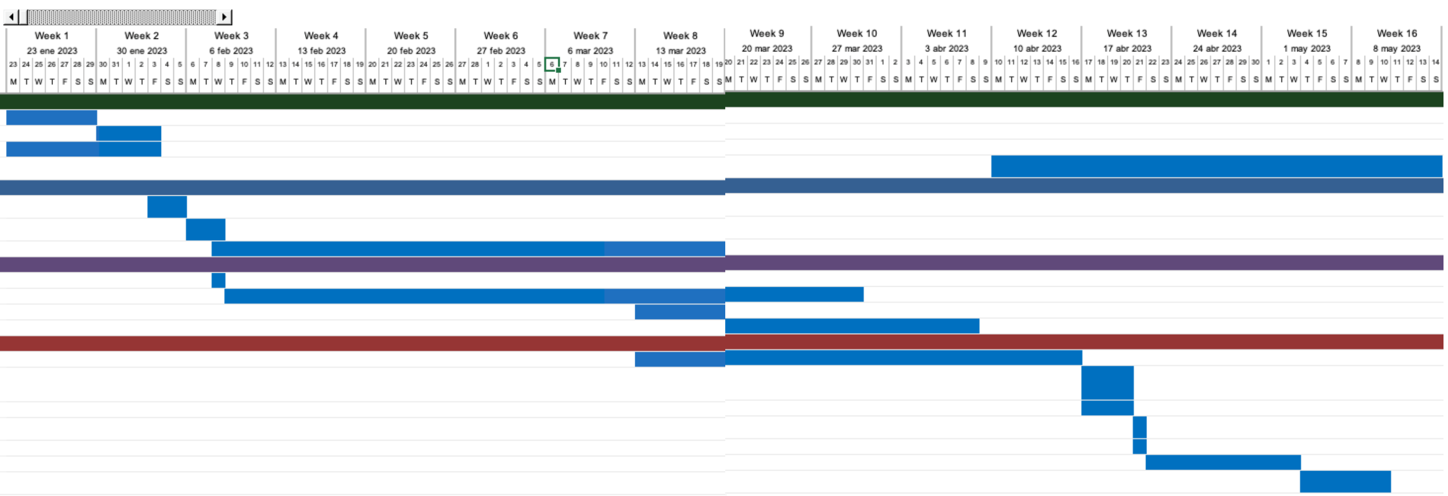
4.2 Schedule

Having a good schedule and interlocking the activities with the aim of optimising the available resources (time, personnel and material) effectively and efficiently for each deliverable is the main point. Furthermore, it also gives the possibility of having a clearer perspective of what has been done, and what needs to be done, monitoring the deadlines, perceive greater reliability towards the customer. To set the schedule, the Gantt Diagram tool has been used.

The created Gantt Chart for the project was designed with an Excel Template from Vertex42 (www.vertex42.com) and it can be seen in Figure 10. The use of this diagram has made it possible to keep track of the status of all tasks in the project.

The diagram shows that the entire project lasted 80 working days (16 weeks), with an average of 5 hours of dedication per day, which gives a total of 400 hours of dedication to the project.

Also, analyzing the Gantt Chart, it can be seen that most of the tasks have dependencies and cannot be started until the previous one is finished.



WBS	TASK	LEAD	START	END	DAYS	% DONE	WORK DAYS
1	**Documentation**			-			-
1.1	Information about AM		lun 1/23/23	dom 1/29/23	7	0%	4
1.2	Information about TO		lun 1/30/23	vie 2/03/23	5	0%	4
1.3	Information aobut furlers		lun 1/23/23	vie 2/03/23	12	0%	4
1.4	Description of the new model		lun 4/10/23	dom 5/14/23	35	0%	25
2	**Consolidate the parts to ensamble a furler**			-			-
2.1	Understand how it would works		vie 2/03/23	dom 2/05/23	3	0%	1
2.2	Decide which parts to consolidate		lun 2/06/23	mié 2/08/23	3	0%	3
2.3	Design the consolidation		mié 2/08/23	dom 3/19/23	40	0%	23
3	**Design and optimize a furler**			-			-
3.1	Measure		mié 2/08/23	mié 2/08/23	1	0%	1
3.2	Design in CAD		jue 2/09/23	jue 3/30/23	50	0%	36
3.3	Topology optimization		lun 3/13/23	dom 3/19/23	7	0%	5
3.4	Lattice structure		lun 3/20/23	sáb 4/08/23	20	0%	15
4	**Print a final prototype in metal**			-			-
4.1	Print some drafts in plastic		lun 3/13/23	dom 4/16/23	35	0%	25
4.2	Prepare and export the design whith a printing software		lun 4/17/23	jue 4/20/23	4	0%	4
4.3	Choose the material		lun 4/17/23	jue 4/20/23	4	0%	4
4.4	Upload the design to the printing machine		vie 4/21/23	vie 4/21/23	1	0%	1
4.4	Feed the machine		vie 4/21/23	vie 4/21/23	1	0%	1
4.5	Print		sáb 4/22/23	mié 5/03/23	12	0%	8
4.6	CMC machine for cutting the surplus material		jue 5/04/23	mié 5/10/23	7	0%	5

Figure 10. Gantt Diagram (Source:Autho's own).

5 Design and Optimization

This section describes the whole design process of the different parts of the rolling furler, including the different software used for each part of the process. Specifically, in section 5.1, the required measurements are specified and justified. Subsequently, in Section 5.2the design process of the parts is carried out with CAD software. Then, the application of the optimisation methods topology optimization (Section 5.3) and lightweight with lattice structures (Section 5.4). And finally, Section 5.5 specifies the preparation of the parts to be printed.

5.1 Description of the swivel carbine

The design of the furler is based on an initial idea proposed to the Additive Manufacturing lab. This design consists of a simple mechanism due to the usage of a swivel carbine to make it easier to work and reduce its costs.

A swivel carbine is a 360° friction-free rotating device with two buckles connected with sealed ball bearings. Its swivel design has a breaking strength of 30kN. The lower part can rotate independently from the upper one.

This device can be found on Amazon and its cost is 20,04€ (Source: https://www.amazon.com/).

Figure 11. Swivel carbine (Source: Author's own).

The lower part of the swivel carbine is anchored to the boat, while the upper part is attached to the mast of the sail, allowing the rotation of it and thus, furling or unfurling the sail.

Measurements of the swivel carbine were taken with a caliper so that the design could be considering this.

5.2 CAD Design

This section presents the design process of the different components. The Creo Parametrics CAD software has been used for the design. This section does not include the material optimisations, as these are presented in the following sections.

5.2.1 Bottom support

The lower support initially consisted of two parts, a base and the walls. Between them, no connection system had yet been developed and they were independent of each other. In addition to these parts, the swivel carbine also had to be attached.

Firstly, Figure 12 shows the evolution of the design of the lower part. Initially, it was solid and had a hole specifically for the swivel carbine (a). Subsequently, a locking system was developed to limit the movement of the swivel carbine, which consists of using an auxiliary part (see section 5.2.2). For this reason, the hole was adjusted to fit this auxiliar part (b). And finally, as it is a solid body, it was decided to lighten it by using a lattice structure (c).

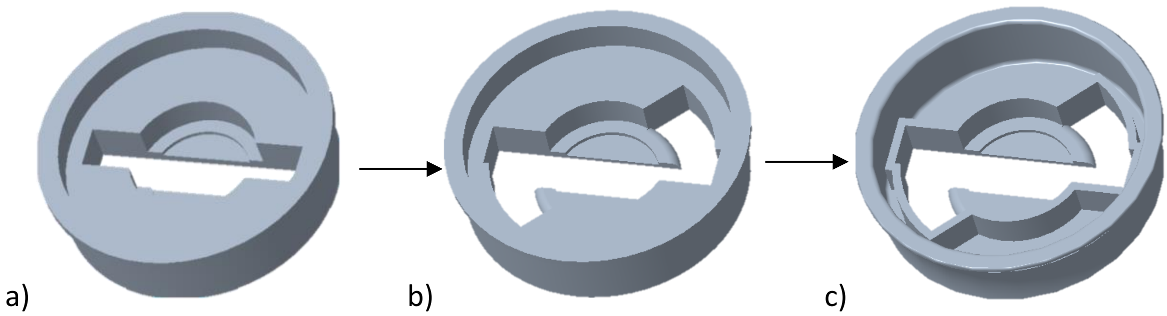
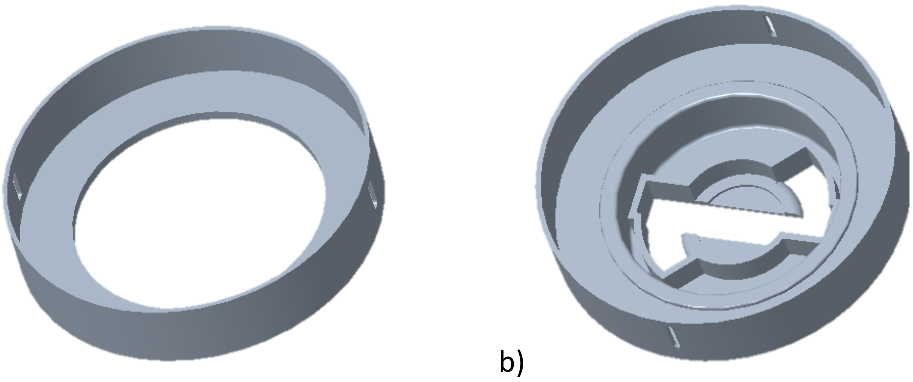


Figure 12. Support component. a) Initial component. b) Modifications to fit the auxiliary component. C) Shell. (Source: Author's own)

In order to use lattice structures, the desired part must be "cut off" and then put back together again after creating them. The lattice designing process is specified in section 5.4.

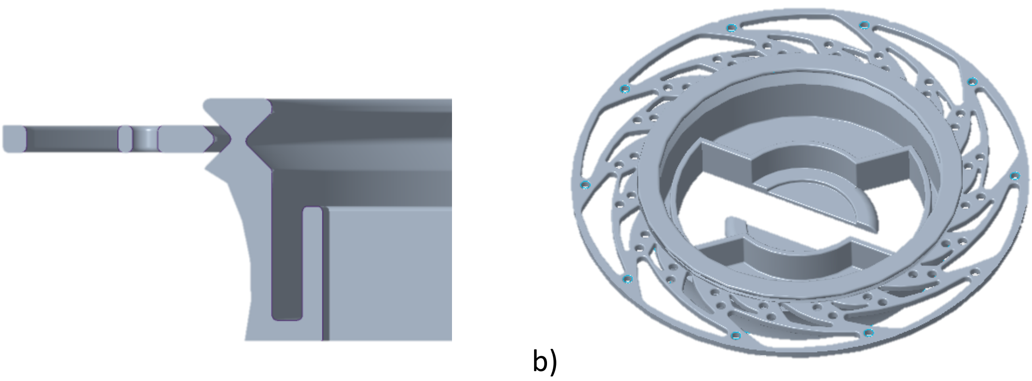
As mentioned above, this is not the only part that makes up the bottom support, there are also the walls (Figure 13. a). So, these two parts are merged together to obtain the result shown in Figure 13. b).



a) b)

Figure 13. a) Walls of the support component. b) Merge of the bottom and the walls. (Source: Author's own)

These two parts must rotate independently of each other. So, to be able to assemble these two pieces, it has been decided to make a direct connection between the two parts by printing them together. To be able to perform this printing, the rules of overhanging have been considered, to avoid the generation of support between them, as they could hinder the rotation. In the design of this joint, a space of 1.25 mm has been left between both parts, enough to ensure the rotation, with an angle of 45º of inclination. The design of this joint is shown in Figure 14. a).



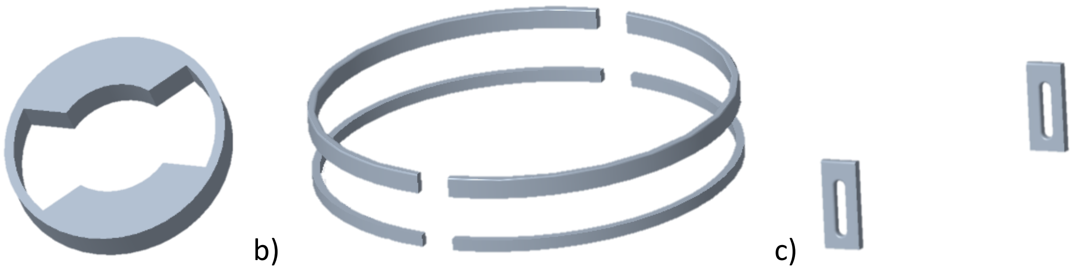
a) b)

Figure 14. Bottom support joint a) Section View. b) General view (Source: Author's own).

Figure 14. b) shows the new design of this component. Following the decision to print this joint together, support will be generated under the horizontal part of the wall part.

Therefore, the material has been considerably reduced there by means of a design appropriate for a furler, and in addition, it has been decided to use surface lattices to reduce the weight of the walls.

Bellow, in Figure 15 the various components that have been separated from the initial design to reduce their weight with lattices are shown.



a) b) c)

Figure 15. Parts to merge. a) Body for volume lattices. b) Walls. c) Part of the walls. (Source: Author's own)

Finally, all parts are put together, even the lattice bodies (designed in section 5.4), with the help of the Magics software (see section 5.5), and the final design shown in Figure 16 is obtained for the bottom support component.

Figure 16. Final design for the bottom support component (Source: Author's own).

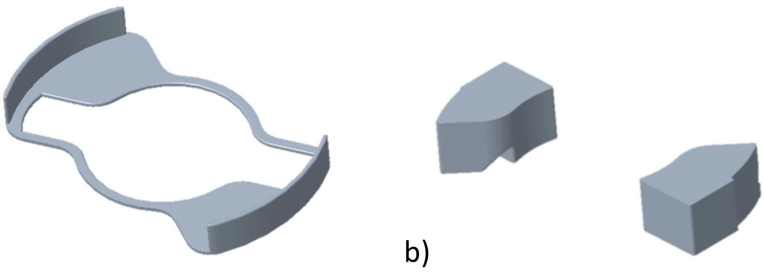
In this redesigned component, both a mounting system for joining the swivel carbine to the swivel carbine and a solution for joining the bracket to the walls is proposed. Merging the two components and going from having 2 components to 1 (Part Consolidation).

5.2.2 Auxiliar component

An auxiliary part has been designed, as mentioned above, to be able to lock the swivel carbine to the bottom support, fitting the three parts together perfectly. The result of this piece can be seen in Figure 17.

Figure 17. First design of the auxiliar component (Source: Author's own).

For the solid parts of this piece, lattice structures are used, which in this case will not be visible, as they are only internal lattices. To be able to do this, the parts are separated as shown in Figure 18, where the upper part (a) is independent of the lattice part (b).



a) b)

Figure 18. Separation for lattice structures. a) Upper part. b) Lattices part. (Source: Author's own)

Finally, these two parts are merged, as shown in Figure 19, resulting in the final design for the auxiliary component.

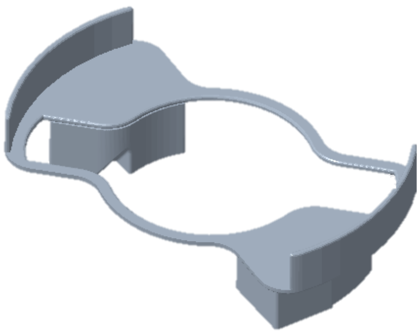


Figure 19. Final design for the auxiliar component (Source: Author's own).

This part is indispensable for the correct functioning of the furler as it fits two of the most important parts, the bottom support with the swivel carbine. However, to understand better its operation, the assembly of it is more detailed in the following section 6.1.

5.2.3 Top disc

The main requirements for the design of the disc are that it fits inside the walls of the bottom support, i.e. its diameter is slightly smaller, and that there is a recess for the swivel carbine.

For this, three possible designs were made, as shown in Figure 20. The first (Figure 20. a).) was a simple and visually unappealing design. Next, a more artistic design was done (Figure 20. b.). And finally, a last design was obtained, which was considered more suitable for a furler (Figure 19. c).

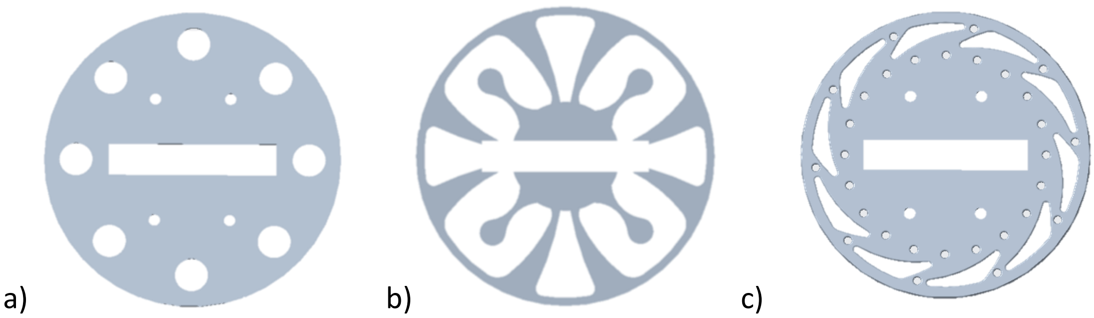


Figure 20. Top disc. a) First design. b) Second design. c) Third design. (Source: Author's own)

Later, an attempt was made to reduce some more material from the central part of the chosen disc and a visually appealing geometry was chosen, which allowed the design of the inner layers of the furler to be seen (Figure 21. a). And it was also decided to add surface lattices to a part of it (Figure 21. b).

a)

b)

Figure 21. a) Final design without surface lattices. b) Body for surface lattices. (Source: Author's own)

Figure 22 shows the final result for the design of the top disc, after joining the surface lattices part.

Figure 22. Final design for the top disc (Source: Author's own).

The design of this disc affects the design of the lower disc, as the same disc will be used, because they are similar. This is important to keep in mind in order to get a visually good result of the furler.

5.2.4 Bottom disc

The lower disc is the first disc that is placed on top of the swivel carabiner and around which the rope is wound to produce a rotating movement when tensioned.

Initially, this was composed of three parts, the base disc and two additional parts to allow the winding of the rope. So, in order to make a single print of these, it was decided to put them together, reducing the number of parts from 3 to 1, resulting in Figure 23.

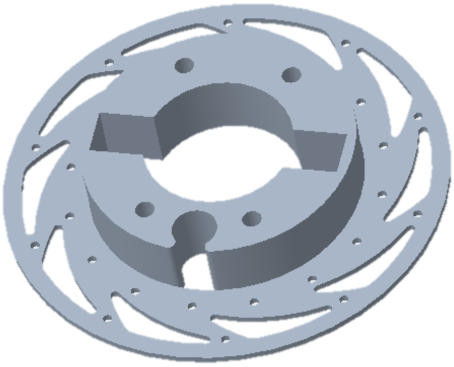
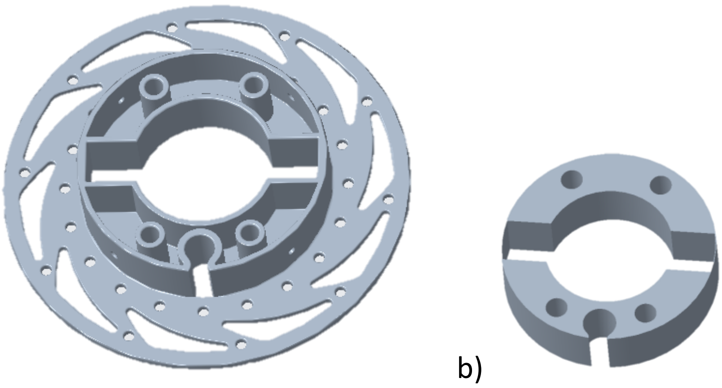


Figure 23. Merge parts of the bottom disc (Source: Author's own).

As before, there is also a large solid part in this component, so lattice structures will similarly be used to empty it. To do this, the part to be optimised (Figure 24. b) is separated from the remaining part (Figure 24. a).



a) b)

Figure 24. a) Final design without lattices. b) Body for volume lattices. (Source: Author's own)

Finally, Figure 25 shows the final result for the bottom disc design.

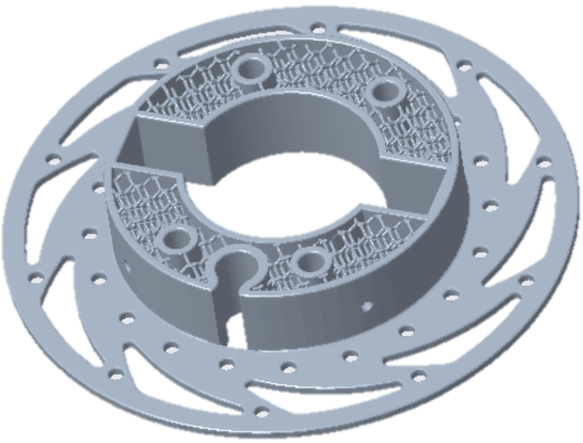


Figure 25. Final design of the bottom disc (Source: Author's own).

5.2.5 Cover

The functionality of the cover is only to prevent the free vertical movement of the discs. It is bolted to the discs with M4 x 20 screws.

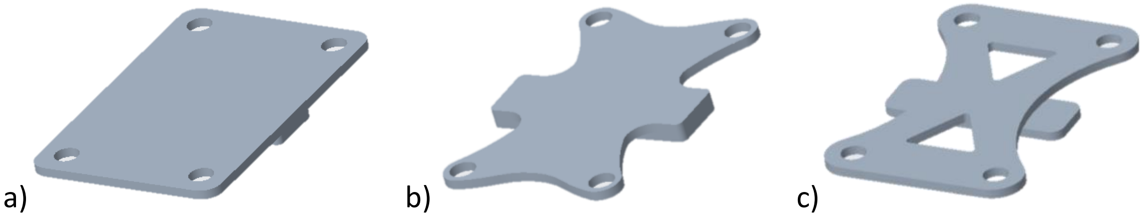


Figure 26. Cover component. a) Initial component. b) First modifications. c) Second modification. (Source: Author's own)

The initial design consisted of a plain plate as shown in Figure 26 a). Later, two new designs were created with some modifications (Figure 26 b) and c)), reducing the material while obtaining a more aesthetic model.

Figure 27. Final design for the cover (Source: Author's own).

However, it was decided that the best option to optimise this part was by taking advantage of topology optimisation. So, the final design for the cover is shown in Figure 27, which has been optimised. To see its optimization, read section 5.3.

In addition, the drawings of each component with the most relevant detailed measurements can be found in Appendix 2. It is worth mentioning that these drawings have only been made considering the design, without optimizations, since the purpose of these drawings is to detail the most relevant measures of the rolling furler.

5.3 Topology optimization process

Topology optimization has become necessary to create pieces with complex geometric configurations that have an organic appearance in order to demonstrate the capabilities of implementing MAM for printing complex geometries (Sulaymon et al., 2022).

For TO the chosen program is Altair Inspire, a software for creating structures that are optimized considering criteria for design including expected loads, available design space, materials, and cost into consideration (Altair, 2023).

The typical topology optimization workflow (shown in Figure 28) begins with a simple 3D model, followed by the specification of a set of loading and boundary conditions for the model. Subsequently, the topology optimization software optimizes the model according to with the stated constraints.

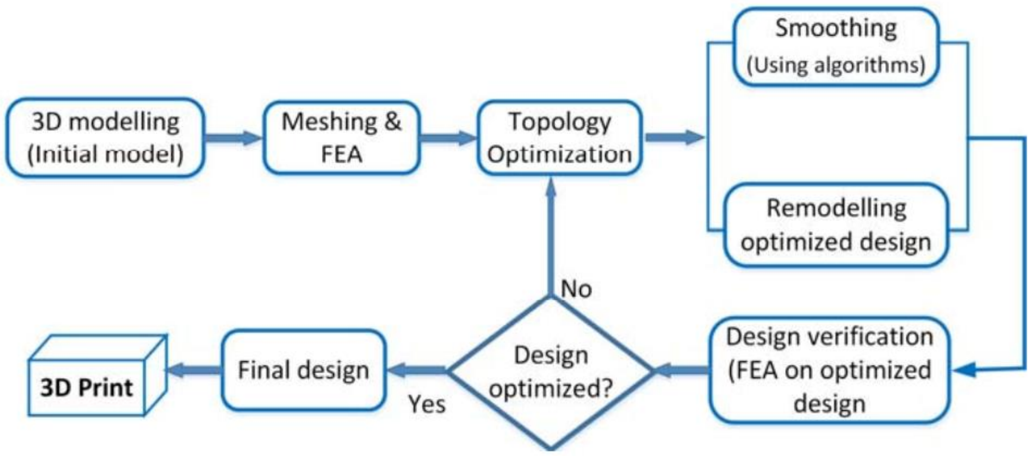


Figure 28. Typical workflow for topology optimization (Aliyi and Lemu, 2019).

The part of the rolling furler that is optimized is the cover, the smallest piece of the whole design. It has been chosen to use TO for it, as it was difficult to make a good design and topology optimizations usually result in a good-looking organic design.

Optimization consists of maximum material reduction, eliminating areas not needed for load or stress-bearing, but retaining the previously established mechanical properties. To achieve this, the following steps must be followed for running any optimization in Altair Inspire.

The first step consists of importing the 3D part in a STEP file extension and opening it in the Altair software (Figure 29). Then, the material of which the part will be manufactured is assigned, Stainless Steel 316L in this case, and also the design space. The design space should be set since it defines the part of the geometry that will be affected during the optimization.

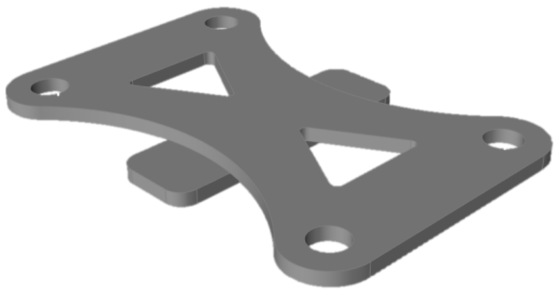


Figure 29. Imported file to Altair (Source: Author's own).

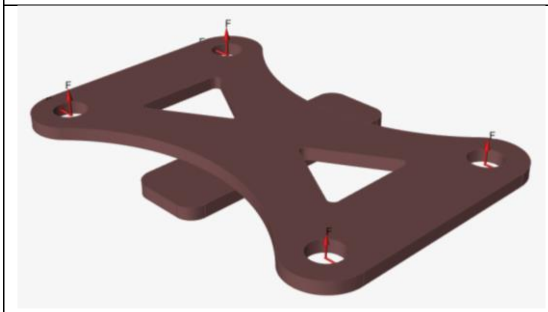
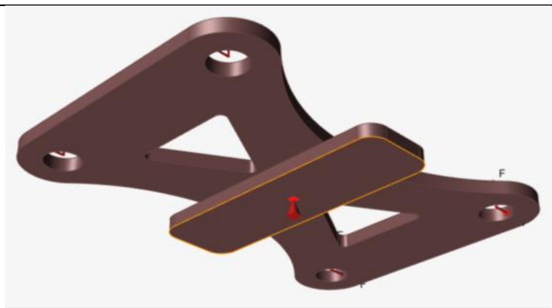
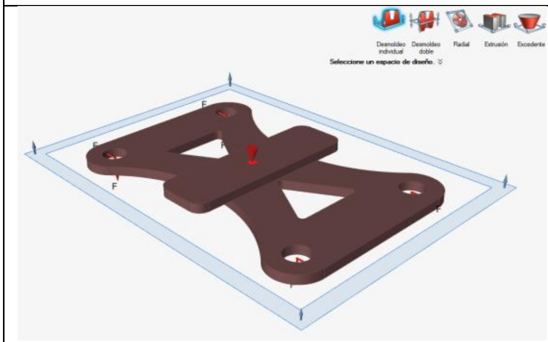
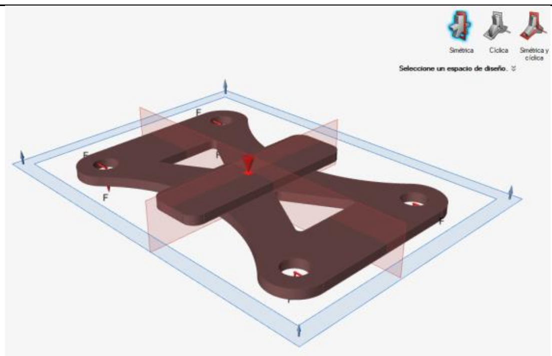
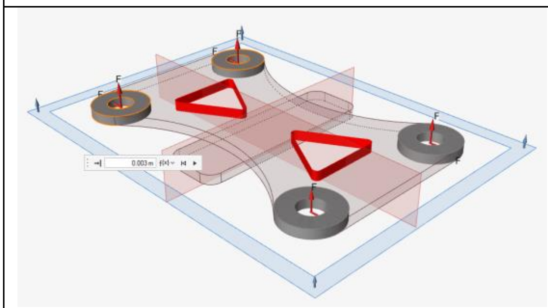
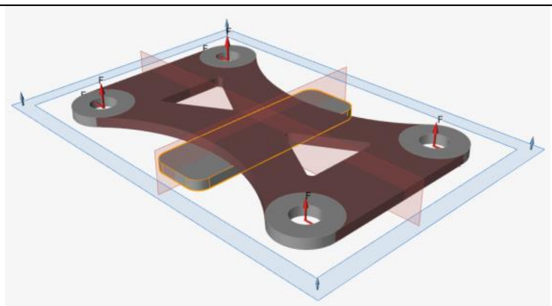
Next, the constraints are defined by applying the different settings that can be found in the upper toolbar. These are specific for each optimization and can vary depending on the desired constraints, the following steps for defining them for the cover of the furler are listed in Table 4.

First, the different loads that will have to resist are set (a) and the defining support surface (b), in this case, the bottom one which will be in contact with the other parts of the furler. Then, it is defined how the demolding will be carried out after printing, specifying the plane and the direction in which the part will be placed in the printer (c).

The option of determining symmetry planes is also available in Altair (d) to obtain a symmetrical optimization according to the planes of interest. For this, the profile planes have been chosen as symmetrical.

Finally, on the geometry ribbon, there is a partition tool, which consists in dividing the part into design and non-design regions that you want to keep out of the optimization for designing reasons. For this model, two types of partitions are set (e). First, as the cover will be assembled with four screws, one in each hole, it is necessary that these holes remain untouched so that the diameter previously set according to the established screw is not modified. This partition is for 3mm around each hole. Then, it is also wanted to keep the bottom plate unaffected by the optimization, since this is fitting and is in contact with other parts of the furler. So, a 1,5mm partition (the total thickness of the bottom plate), is defined.

Table 4. Defining constraints in Altair.

a. Definition of the loads	b. Definition of the support
	
c. Definition of the demolding	d. Symmetrical parts
	
e. Set the partions for the screws and the fitting part	
	

(Source: Author's own).

After the set-up is complete, the optimization is executed on the play button on the optimization icon. A setting window for the optimization is displayed where the mass objective can be selected and, some other specifications can be set (Figure 30.a). Pressing the execution box, Altair starts to execute the topological optimization (Figure 30.b).

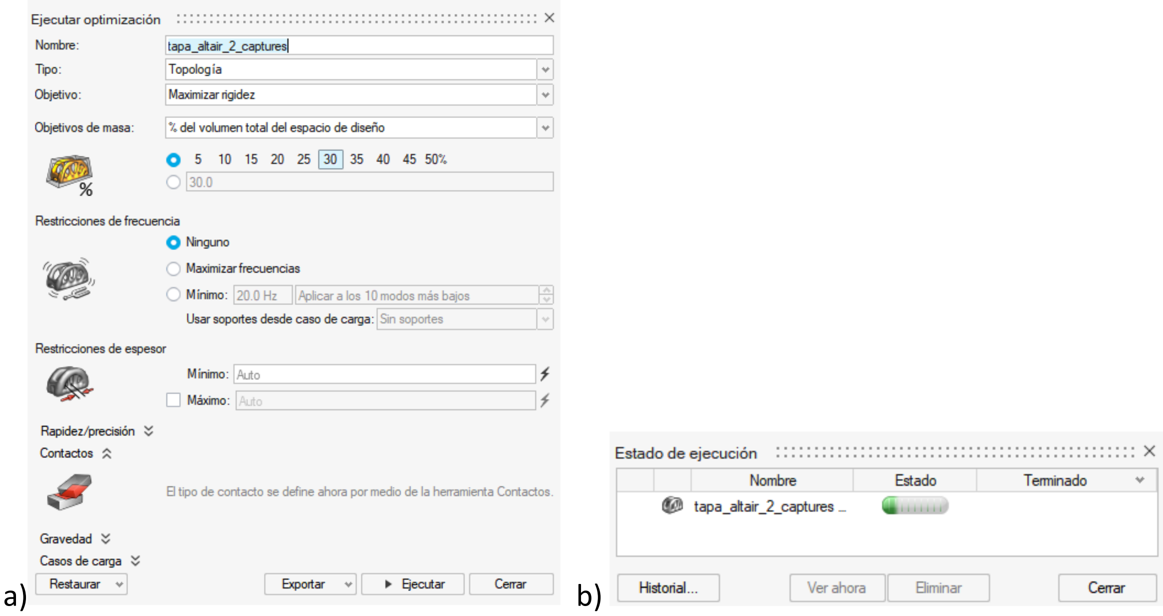


Figure 30. a) Optimization settings. b) Optimization progress. (Source: Author's own)

The result of the optimization is shown in Figure 31. Altair also gives the option to reduce more material or to add some if the result is not the desired one. For this part, the given solution was suitable.

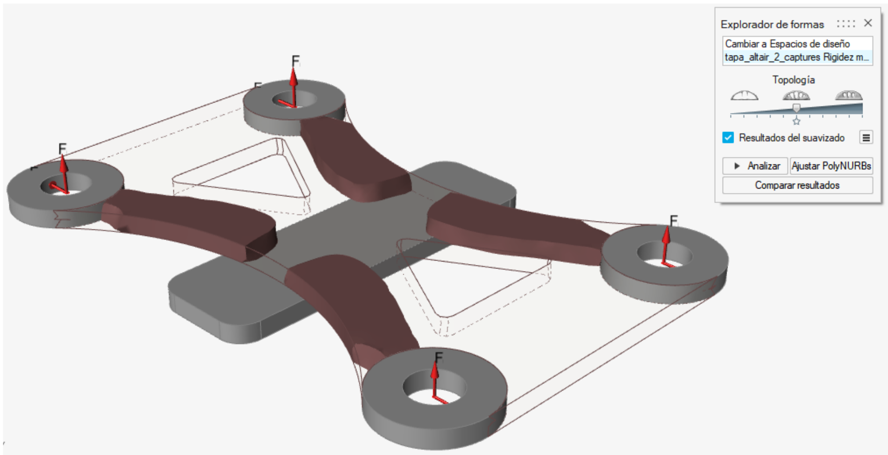


Figure 31. Optimized solution (Source: Author's own).

Afterwards, following the optimization lines, these are shaped using the 'fit' tool to give to the component a smoother finish. This process is carried out for the four 'legs' (Figure 32).

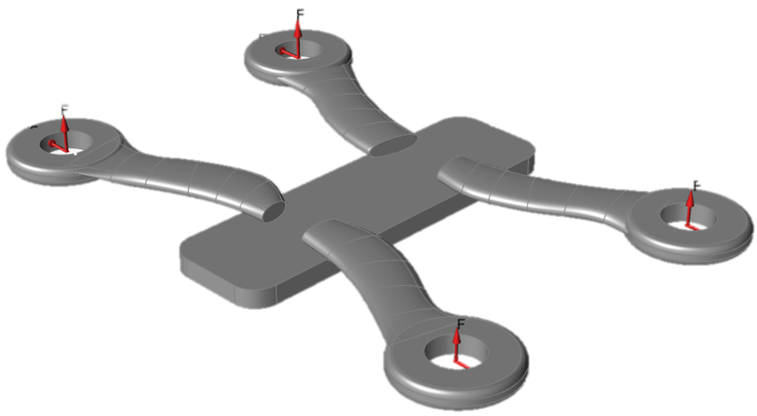


Figure 32.Fit of the optimized part (Source: Author's own).

After having made the relevant modifications, it is desired to achieve a final smoothed surface finish between the different parts of the piece, in which they can be seen to be correctly integrated. This function is called 'straightening' and it is shown in Figure 33.

Figure 33. Straightening of the optimized part (Source: Author's own).

The rectiling has generated material between the base and the upper "legs". Although aesthetically the finish looks better, this is not of interest for our design as the bottom plate part must fit with the other parts.

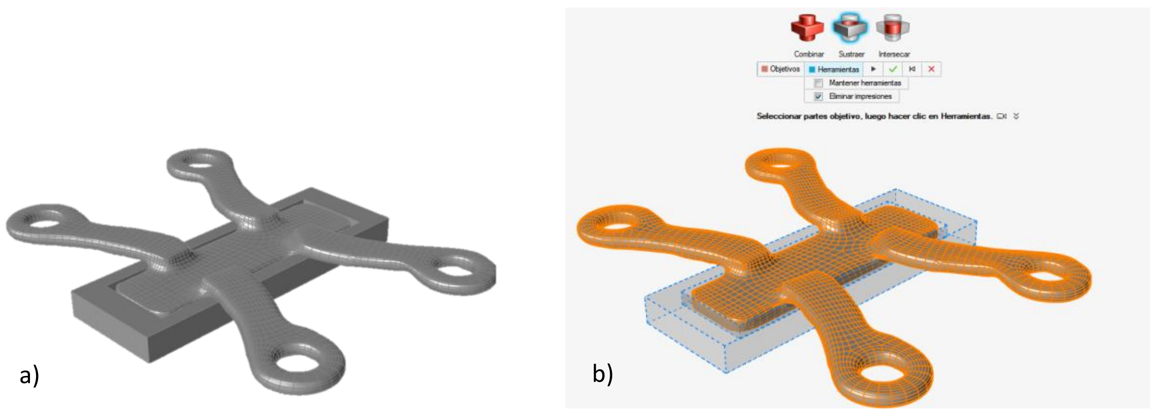


Figure 34. a) Block of removing material. b) Substaction of the desired material part. (Source: Author's own)

This process consists of a subtraction of the excess material around the bottom plate is made. This process is represented in Figure 34, where first a cube with the dimensions of the different parts that envelope the base part is created defining the part of the material to be removed (Figure 34 a).) and using the boolean function to reduce material, the part that is desired to keep it and the removal one are selected (Figure 34 b).)

Figure 35. Topology optimization for the cover (Source: Author's own).

Figure 34 shows the final result of the topological optimisation. Then, this file is directly exported as an 'STL' file to print it later.

5.4 Lightweighting with lattice structures

As industries continue to strive for greater efficiency and sustainability, achieving lightweight designs has become increasingly important. The use of lattice structures in CAD has appeared as a promising technique for reducing the weight of parts while maintaining structural integrity (Jain, 2022).

nTopology is a CAD that offers designers and engineers powerful tools for advanced design and testing. Despite the wide range of possibilities it gives for engineering design, this thesis will focus on creating complex lattice structures with ease.

In this chapter, the exciting potential of using nTopology is going to be explored to generate lightweight lattice structures for a variety of CAD pieces. Also, it will be analyzed how lattice structures can offer significant weight reductions without sacrificing performance, and how nTopology's advanced algorithms make it easier to create geometrically complex lattice structures.

There are several types of lattice structures used in engineering designs, which have been introduced previously in subsection 2.2.5. However, the created lattices for the different mazed parts of the furler that are generated are classified into volume lattices (5.4.1), merge shell and infill (5.4.3) and surface lattices (5.4.2).

It is important to note that to apply the lattices on the desired parts, these must be separated from the rest of the piece and imported into nTopology software. After that, these will later have to be joined with the rest of the piece using the software Materialise Magics (see section 5.5).

When working with nTopology, the imported files should be in STEP format, the same as for the topology optimization with Altair Inspire.

5.4.1 Volume lattices

Volume lattices are complex structures that consist of interconnected cells or struts arranged in a specific pattern (Park et al., 2021). The properties of a volume lattice depend on the cell structure used. These patterns are designed not only to reduce the weight of the part but also to optimize the strength, making it more efficient and cost-effective. Here is presented how they are created using various techniques for the base disc and for the support part, which are the pieces that have some mazed parts.

Initially, conformal pattering lattices were applied to obtain an irregular triangular geometry that adapts to the shape of the figure. The result obtained can be seen in Figure 36.

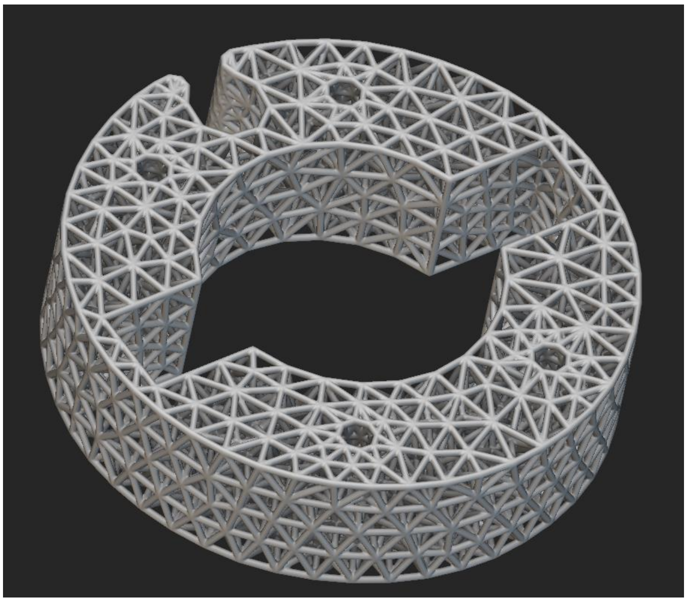


Figure 36. Non-periodic volume lattice for the bottom disc (Source: Author's own).

As can be seen in Figure 36, the created lattices are following a non-periodic geometry, making irregular triangles, and thus, the corner degrees differ for each triangle, depending on their shape of them. These lattices are aesthetic, but for printing, not knowing these degrees can lead to the creation of supports, and one of the main challenges is to reduce the overhanging as much as possible.

Then, it was decided to choose periodical lattices with a face-centred cubic cell structure (FCC). A face-centred cubic structure is a crystal structure where there are eight lattice points at each corner, it is similar to a simple cubic, but with one additional lattice point at the centre of each face of the cube (University of Cambridge, 2016).

There is a specific function in nTopology to create an infill volume lattice, where you set the type of unit cell, the cell size, rotation and lattice thickness. This setting is specified in

Appendix 3.2. where the workflow code for the periodic volume lattice for the base disc is presented. Figure 37, displays how the lattices look in the maze part of the base disc.

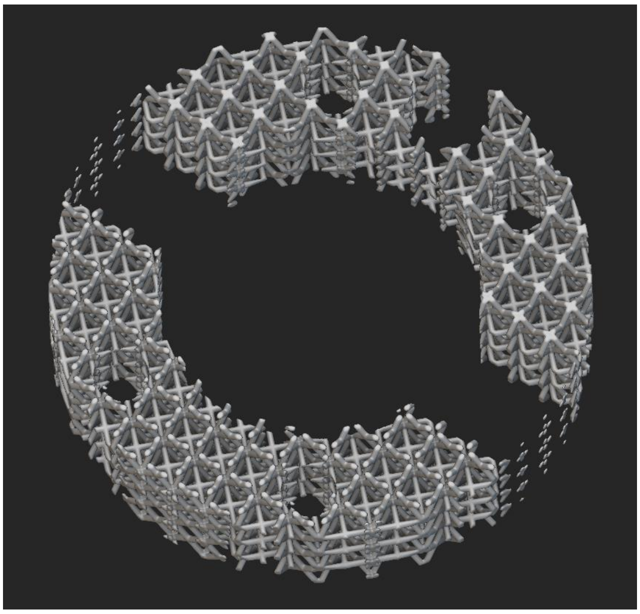


Figure 37. Periodic volume lattice (FCC cell) for the bottom disc (Source: Author's own).

However, this type of lattice was not self-supported at all, because there was a horizontal part that was less than 5mm, so it was following the overhang rules. However, it was decided to choose them to be diamond cubic (DC) lattices. The diamond cubic crystal structure is based on the face-centred cubic Bravais lattice. Each of the 8 atoms in a unit cell has four nearest neighbours according to tetrahedral coordination (Brandon, 2021).

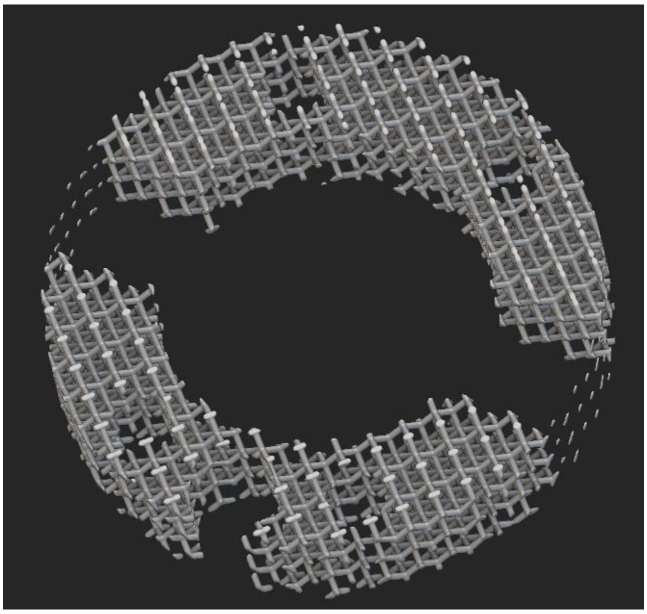


Figure 38. Periodic volume lattices (diamond cell) for the base disc (Source: Author's own).

As this program was suitable for the bottom disc component, it has been also used for the maze support part, since both are very similar in terms of the size and type of geometry of the parts. This result is shown in Figure 39. And its code can be found in Appendix 3.3.

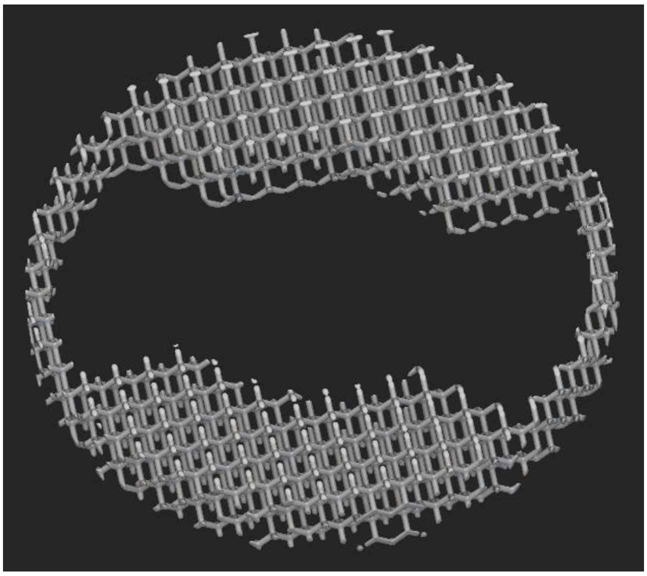


Figure 39. Periodic volume lattice (diamond cell) for the support (Source: Author's own).

As expected, this previous lattice code fitted perfectly for the support. However, the specific workflow for this part is in Appendix 3.4.

For these two parts, it was preferable to use simple volume lattices instead of merging shell and infill, to be able to have some visible lattices faces in the furler.

5.4.2 Merge shell and infill

This type of lattice consists of doing two functions at the same time, merging and infilling.

Infill lattices, as introduced before, refer to the patterns used to fill the empty space inside of a 3D-printed object. And, on the other hand, merge shells refer to the process of merging individual shells or surfaces together to create a single solid object.

nTopology offers a function where both actions are done at the same time to the same part. The workflow for applying the merge shell and infill can be found in Appendix 3.5, where it has been developed particularly for the auxiliar part of the furler to reduce its weight.

The structure used for these lattices is exactly the same as with the periodic volume lattices (subsection 5.4.1), a diamond cell structure.

Figure 40. Merge shell and infill for the auxiliar part (Source: Author's own).

As it is possible to see in Figure 40, from the outside the part looks exactly the same, however, with a section view as shown in Figure 41, it is possible to see the infill lattices.

Figure 41. Section for the merge and infill for the auxiliar part (Source: Author's own).

For this part, this type of latices has been chosen because of the interest in reducing material without affecting the outer side of the piece. It is important since the purpose of this part is to fit perfectly in the lower support to limit the movement of the swivel carbine.

5.4.3 Surface lattices

Surface lattices are two-dimensional patterns that can be also used to reduce material, but it is also very popular to use them as decoration to make some parts more aesthetic. This thesis has taken advantage of both. For lightweight for the wall of the inferior support, reduce the support material in the printing since this part is not touching the printing bed. And on the other hand, these types of lattices have been also used as decoration for the top disc thanks to the freedom of the design that allows additive manufacturing, while slightly reducing its weight.

Due to the method of printing two parts that can rotate independently of each other, the need arises to reduce the material in the parts that are "floating" and that will be printed with the use of supports. Thus, it was decided to use a surface lattice for the wall of this part.

The chosen lattice for this part is a periodic lattice with a diamond unit cell structure and the obtained result for this can be seen in Figure 42.

This part had to be split in two, as the wall was interrupted by the perforations through which the rope goes through. And thus, in Figure 42, only one part of the wall is shown since the other is exactly the same, but symmetrical.

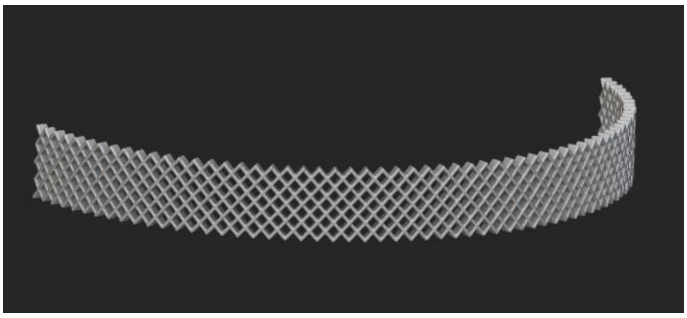


Figure 42. Surface diamond lattice for the walls of the support (Source: Author's own).

The top disc was the only part that was not taking advantage of the additive manufacturing process. So, to have a completely additively manufactured furler, it was decided to use some surface lattice to decorate this disc and at the same time make it lighter. So, another type of lattice was used for its decoration, the Voronoi lattice. All the settings established can be found in Appendix 3.7.

A Voronoi diagram is a kind of tessellation pattern which separates a set of points spread throughout a plane into exactly n cells that each enclose the area of the plane nearest to each point (Bellelli, 2023).

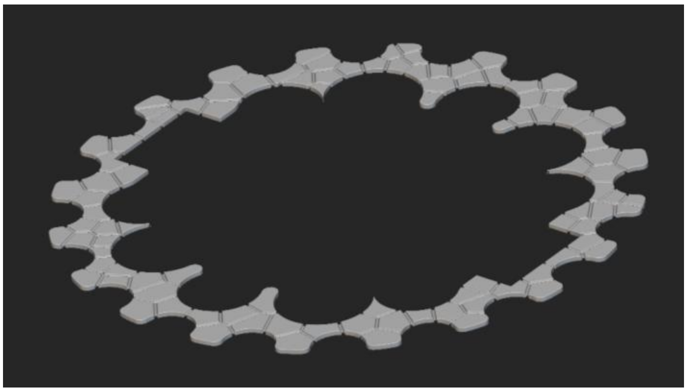


Figure 43. Voronoi surface lattice for the disc (Source: Author's own).

Figure 43 shows the final result of the part of the top disc and where the Voronoi structure can be noticed.

Finally, it is worth noting that the parts in nTopology can be exported by using various functions. For this project, it has been determined first to mesh the lattices and finally to export that mesh. This process has been followed for exporting all the parts, so it can be seen in the various workflows in Appendix 3. The parts are exported as an STL file, the appropriate extension for later printing.

5.5 Data preparation for printing – Materialise Magics

Materialise Magics is a software platform for designing, editing, and repairing 3D models allowing users to prepare 3D parts for printing. The software provides tools for fixing errors, optimizing designs for specific materials, and creating support structures for 3D printing.

For this thesis, this tool has been used to merge the different parts with its lattices, to fix generated errors made by the previous optimizations and to create the printing supports.

Below the steps taken for preparing the different parts for printing are described. Since it is the same for all, only the process for one part will be detailed.

The first step is to define a "new scene" to simulate the original printing bed of the printing. For this, the machine used for printing should be chosen, Printsharp 250 (see Figure 44).

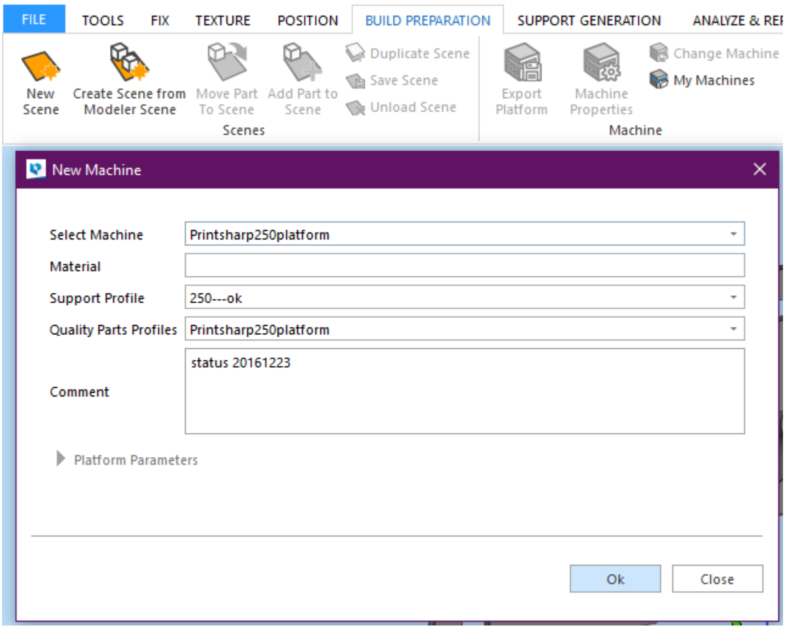


Figure 44. Build preparation (Source: Author's own).

Next, the desired part is imported into Magics. Subsequently, an importing message appears to define its placement (Figure 45 a).). Then, as shown in Figure 45 b) the orientation of the part in the printing bed has to be defined. For all the furler components these settings are defined as 'As Is' for the placement and 'Original' for the select orientation. Further changes are done in some previous steps.

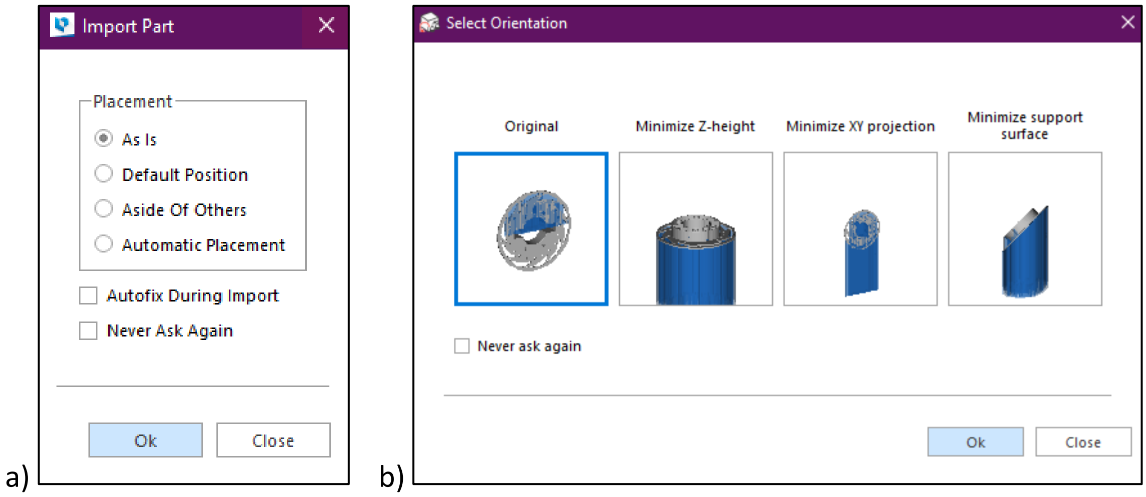


Figure 45. a) Import component to Magics. b) Select the orientation of the component (Source: Author's own).

Afterwards, it is desired to place the components in the optimum position for printing, minimising the supports that are created later (if needed) for the component. It is desired to position the larger surface parallel to the bottom plate. To do this, the component must be rotated slightly with the larger surface facing the bottom plate (Figure 46 a).). Next, the face parallel to the surface is defined according to Figure 46 b) with the function 'Button/ Top Plane', followed by 'Indicate Plane', the user indicates the plane and finally clicks 'Ok'.

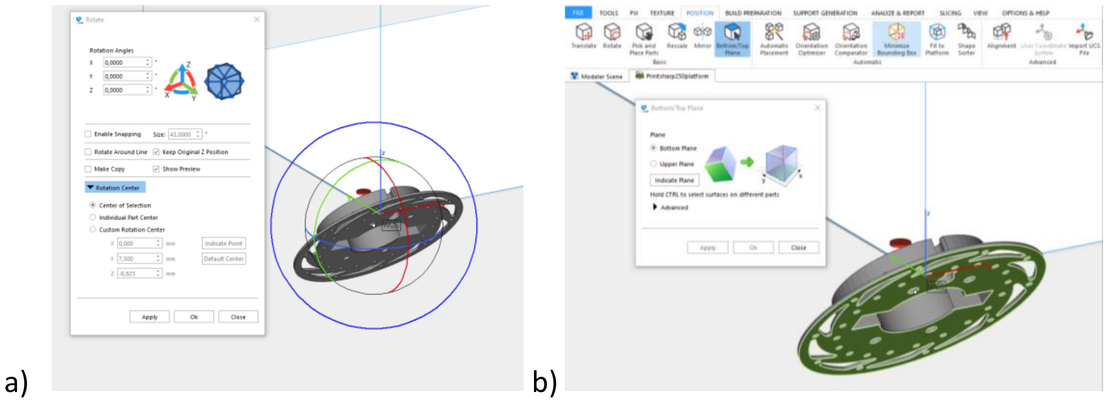


Figure 46. a) Rotation of the component. b) Definition of the component parallel to the bottom plane. (Source: Author's own)

Subsequently, the component is translated in the 'x', 'y' and 'z' axis, as can be seen in Figure 47. It must be considered that the component is inside the defined printing bed. Particularly, for the machine located in the Metal for Additive Manufacturing laboratory, it is preferable to place the parts on the left side of the printing bed.

Another important issue is that the component in the ‘z’ axis should be placed at a distance of 2 - 2.5 mm, as after printing and post-processing it will be sliced.

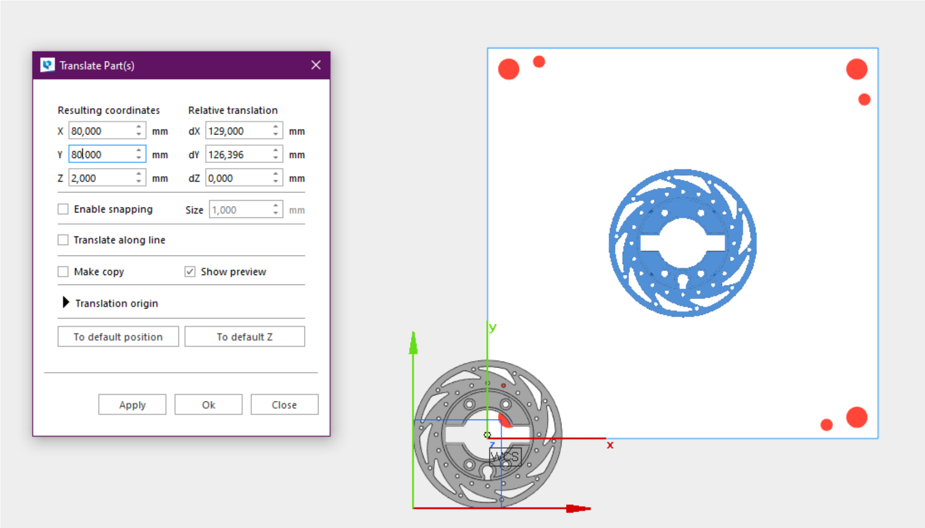


Figure 47. Positioning of the component (Source: Author’s own).

In order not to have the part 'floating' due to the gap left in the z-axis, an extrusion must be made at the bottom of the component. To add material to the bottom part, the ‘Extrude’ has to be selected, then define the parameters as in Figure 48 a) and the result obtained is shown in Figure 48 b).

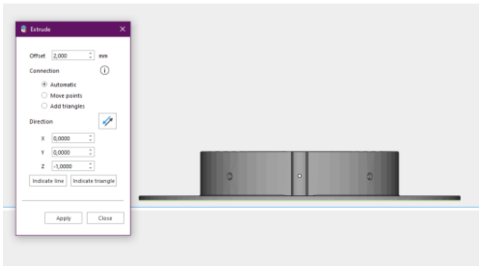
a)  b) 

Figure 48. Extrusion of the 2 mm in 'z' axis. a) Setting for extrusion. b) Result of the extrusion. (Source: Author’s own)

Magics is also useful for merging parts. It is fundamental for the different parts of the furler since with the creation of lattices structures for some solid parts require them to be separate from the main part to first apply the lattices and then merge these parts together. First this both parts are imported to Magics, then selected and merged using the ‘Merge parts’ function. An example of the result of this is shown in Figure 49.

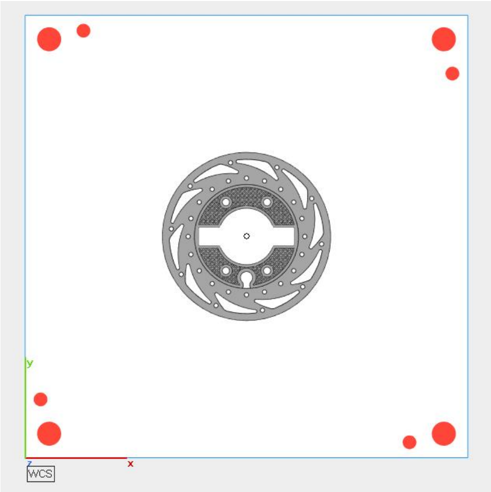


Figure 49. Merge parts (Source: Author’s own).

The other interesting tool offered by the software consists of fixing the components from the errors generated by the previous steps in the design, especially with the topology optimization and lattice structures. To fix them, initially, the ‘Autofix’ function is used to reduce some failures. Then, the ‘Fix Wizard’ is used to make a diagnostic of the different mistakes. For the component analysed, as shown in Figure 50, some overlapping and intersecting triangles are detected.

Overlapping triangles are triangles that partially occupy the same space (Kimbrough, 2022).

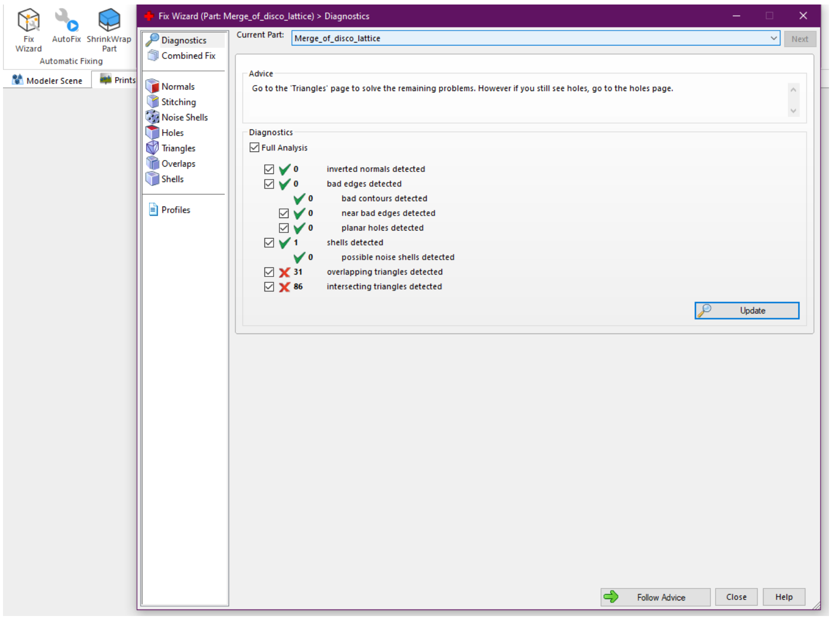


Figure 50. Diagnosis to detect error to fix in the components (Source: Author’s own).

To fix these, the button ‘Follow Advice’ should be clicked. It leads to the tab displayed in Figure 51, where the ‘Automatic Fixining’ option should be pressed until the mistakes are reduced to the maximum. These are not always reduced to 0, since there are some mistakes that need to be corrected manually.

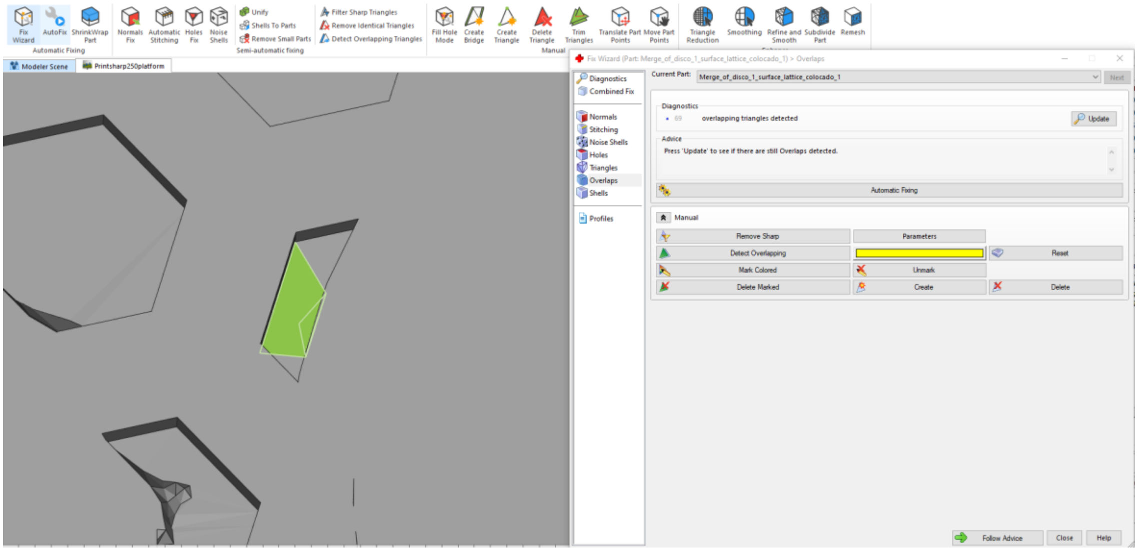


Figure 51. Detection of overlapping triangles (Source: Author's own).

In Figure 51 it is shown an example of a part where overlapping is detected. To correct it, first, the triangles should be deleted with the 'Delete Triangle' tool, obtaining a result as in Figure 52 a), where all these parts are highlighted in red. Then, as these triangles have been deleted, new fixed ones should be created in the same position with the 'Create Triangle' tool (result in Figure 52 b).).

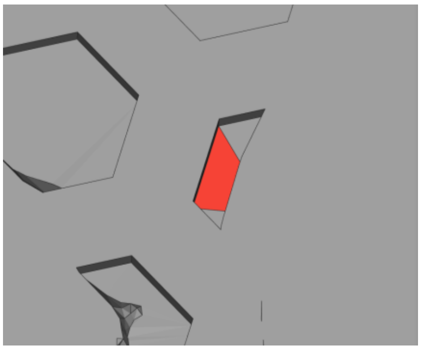
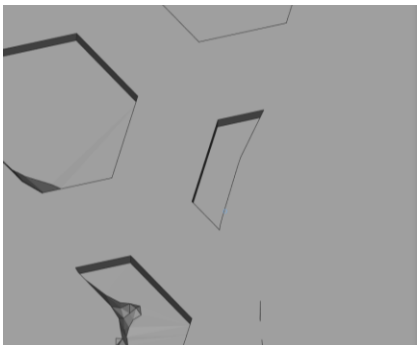
a)  b) 

Figure 52. Deleting overlapping. a) Delete Triangle. b) Create a Triangle. (Source: Author's own)

After completing this fixing process, the 'Fix Wizard' is used again to repeat the diagnostic of the component. This should have been improved from the first one after trying to fix the mistakes. As expected, in Figure 53 this reduction can be seen. It is important to note that sometimes it is not possible or very difficult to fix everything and some errors can be accepted. However, this could affect later in the support generation.

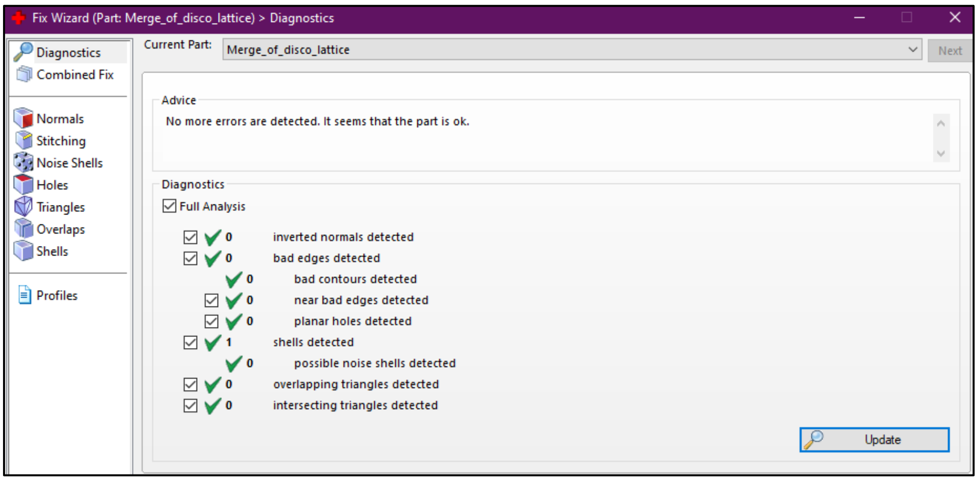


Figure 53. Diagnosis after fixing the component (Source: Author's own).

As more than one component can be printed on the same printing bed, if it is permitted by the size of them, the next step is to perform the same process for each component and place them on the plate. The optimal placement would be to have them separated, on different horizontal lines, since the blade of the printer works from right to left, and in this way, it would be avoided that if one piece fails it could affect the others.

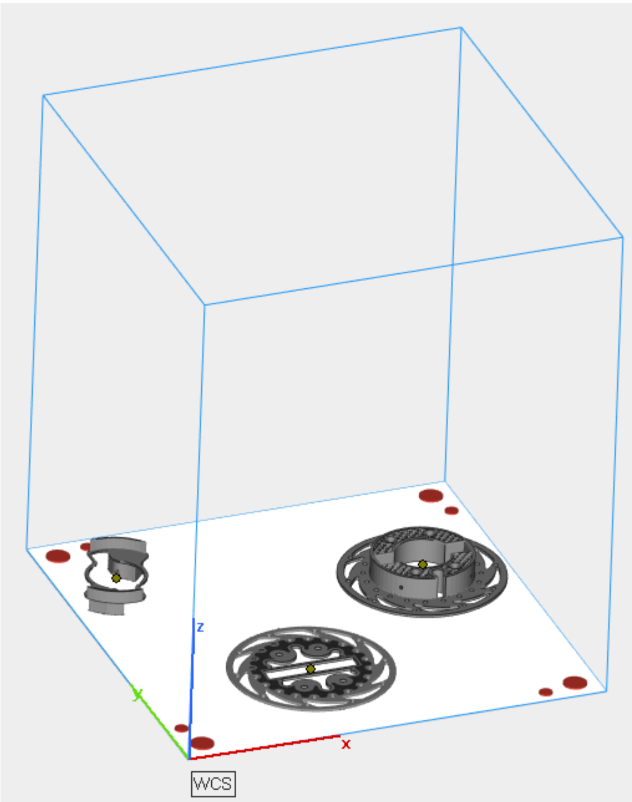


Figure 54. Position of the different parts desired to print at the same printing bed (Source: Author's own).

The last step in the preparation of the print is the slicing of the components. For this, the slicer properties are defined in Figure 54. The important parameters are the slicing format, since it has to be exported in 'CLI', to later use this file in the Hatch software (section 6.2). And, the layer thickness, that for Printsharp 250 is 0,03 mm.

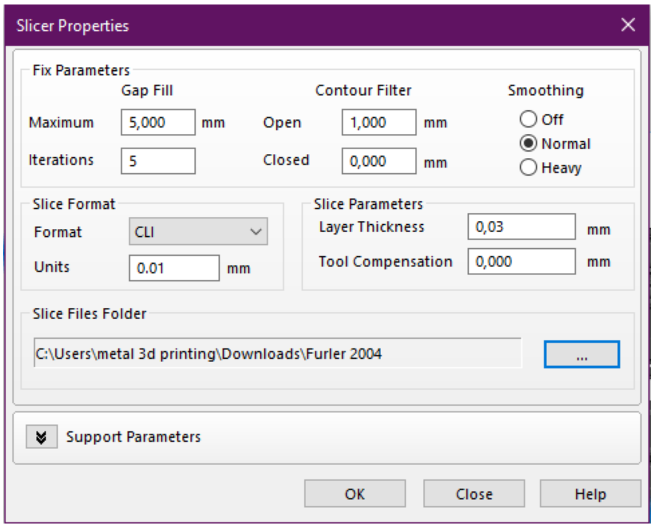


Figure 55. Definition of slicing properties (Source: Author's own).

After completing the whole process, a file is obtained for each component that was placed in the printing bed.

6 Operation and assembly

In this section the operation of the furler and how it works is specified, as it is a mechanism used only in a very specific sector, the maritime sector, and it can be an unknown device for many people. In addition, to understand its operation, it is essential to understand how it is assembled.

The assembly of the furler is such a key part of the thesis, as one of the proposed requirements was to avoid mechanical joints and try to find a way to join the parts together taking advantage only of additive manufacturing.

6.1 Assembly

Assembly is process of joining different components to make a complete product (Genung, 2021). The furler is composed of 4 main parts and in this section we will detail the different steps to finish assembling the furler.

The first step is to join the base part with the swivel carbine. For this purpose, the ring of the swivel carbine is inserted at the part where the rotating sphere protrudes slightly. In this position, the swivel carbine can move freely vertically and rotate. To limit its movement, a joining system has been engineered which consists of rotating the lower part of the swivel carbine counterclockwise to limit the vertical movement. And to limit the rotational movement, an auxiliary part has been designed that perfectly fits in the gap left between the base part and the swivel carbine after rotating it. These two steps of the assembly are represented graphically in Figure 56.

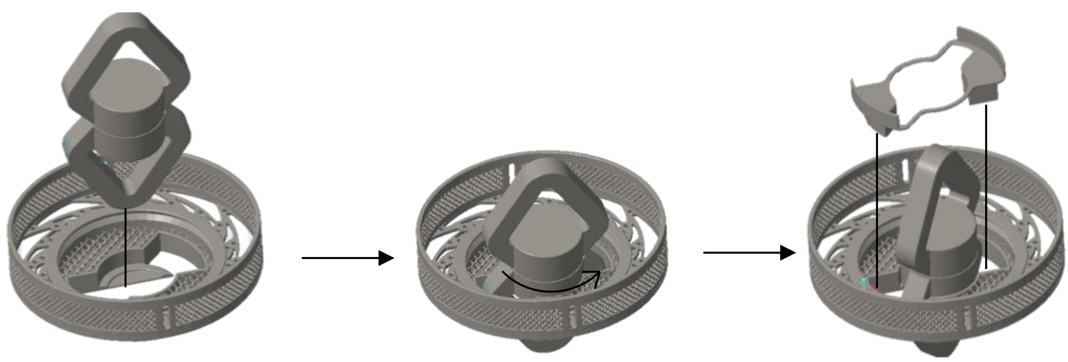


Figure 56. Assembly of the base part (Source: Author's own).

After having the base part together with the swivel carbine, it is time to assembly the rest of the parts that are fitted in the upper part of the swivel carbine as shown in Figure 57 and Figure 58.

The bottom disc, the one that has the volume lattice structure, is introduced into the upper ring of the swivel carbine. And the pulling rope is wound around this part and then pulled out through one of the two holes of the 'wall' of the base. These two steps are represented in Figure 57. Once assembled, this disc can rotate independently of the base releasing more rope outwards or retracting it, depending on the direction of rotation of the disc.

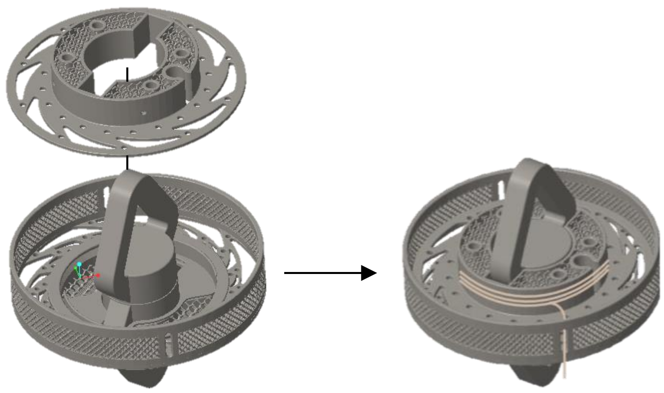


Figure 57. Assembly of the bottom disc in the upper part and wounding the pulling rope (Source: Author's own).

Next, as shown in Figure 58, the top disc is also introduced in the same way as the bottom one, being these two able to rotate together. Since these two are allowed to move vertically a small screwed cover with 4 screws of type M4 X 20 is placed on the top.

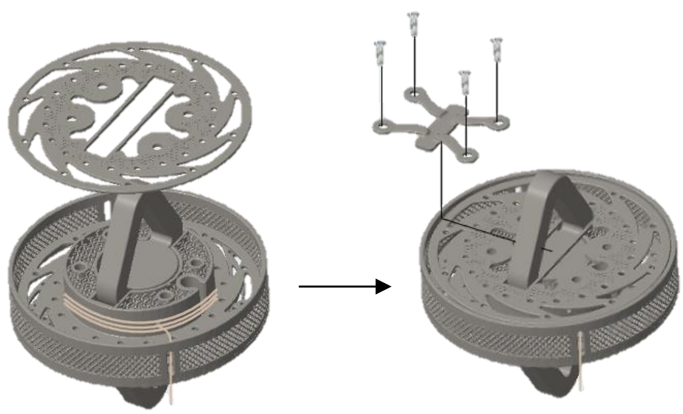


Figure 58. Assemble of the top disc and the cover in the upper part (Source: Author's own).

The result of the furler assembled can be seen in Figure 59. Where all the parts are correctly positioned and ready for its operation.

Figure 59. Furler assembled (Source: Author's own).

Also, in Appendix 4, an assembly manual can be found, where the different steps are represented graphically as well as all the needed components for it. Understanding its assembly is essential in order to better comprehend its operation, which is specified in the following subsection (section 6.2).

6.2 Operation

A rolling furler is a device used to assist the user in exerting a force to transmit a rotating momentum to the sailboat mast for the purpose of furling and unfurling the sail around the mast.

The furling line attaches the sail mast to the boat, as the lower ring of the swivel carbine is anchored to the boat while the upper ring is anchored to the mast. The bottom rotates together with the lower ring of the swivel carbine, while the two discs (the bottom and the top) rotate with the upper part that goes to the mast.

In the rolling furler, 3 independent rotary movements are allowed. It is possible to rotate the covering wall with respect to both the bottom and the discs. However, the most important movement is the rotational movement between the upper and lower part, which is provided by the swivel carbine.

The operation of the furler consists of, after having mounted and anchored the furler to both the boat and the mast, getting the rope furled or un-furled as shown in Figure 59.

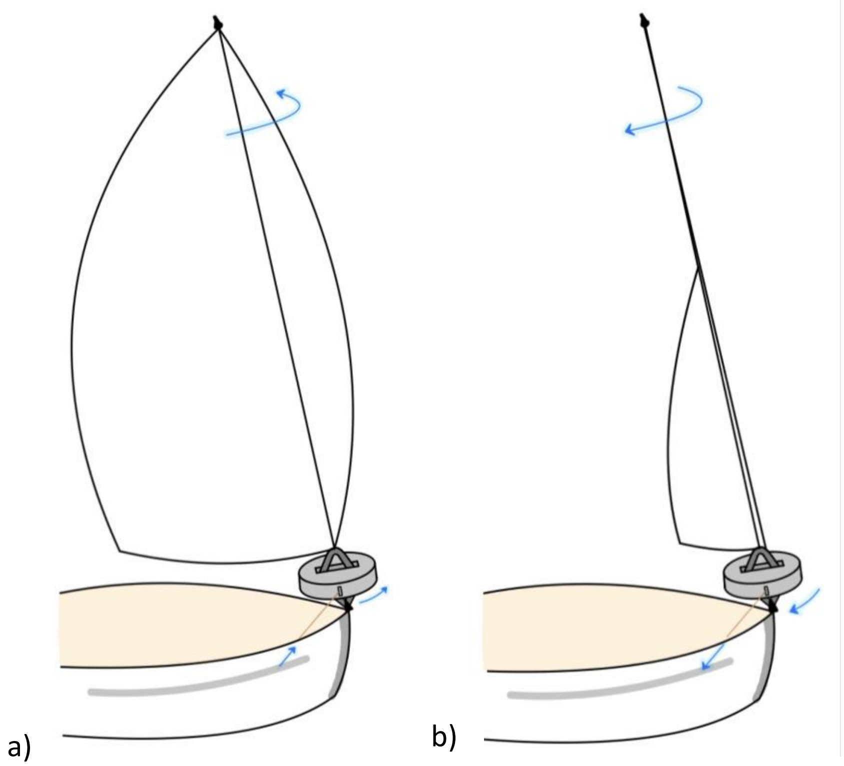


Figure 60. Operation of the furler. a) Furling. b) Unfurling. (Source: Author's own).

As detailed in Figure 60, to unfurl the sail, the rope must be released so that the top of the furler, and in turn the mast, rotates in an anti-clockwise direction (a). In contrast, to furl the sail, force must be applied through the rope in the direction shown in the illustration so that the mast rotates clockwise, and the sail is furled (b).

7 Printing

The printing process is very important in the development of the thesis, as it will allow the digital design to be converted into a physical product. Fulfilling one of the objectives of the project.

The final product is desired in Stainless Steel 316L (metal) taking advantage of Metal for Additive Manufacturing. However, due to its high cost, some drafts will previously be printed in PLA (polymer). There are some differences between the prints with different materials, but the result is similar enough to determine whether the metal model will be successful after seeing it previously printed on plastic.

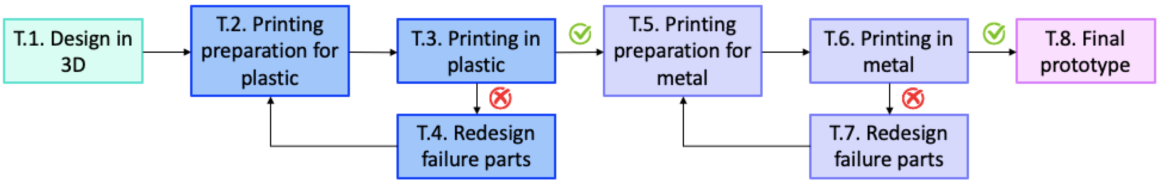


Figure 61. 3D Printing process (Source: Author's own).

Thus, the process followed for the printing of the final prototype is shown graphically in Figure 61. Firstly, each part is designed in 3D, then it is prepared and printed in plastic and if everything works correctly, the same process is carried out for the metal printing. If it this is successful, the final prototype is obtained.

7.1 Plastic

Once each component is designed and exported as an 'STL' file, the different parts are imported into a slicing program. In this thesis, the chosen programme is Ultimaker Cura, the software designed by UltiMaker, the same company behind the printers found in the Techno Bothnia.

The first step consists of defining the printer that is going to be used (Ultimaker S3) and importing the maximum number of components that can fit in the printing bed as shown in Figure 62. The components are strategically positioned to generate the minimum possible support and that the different components are not touching each other.

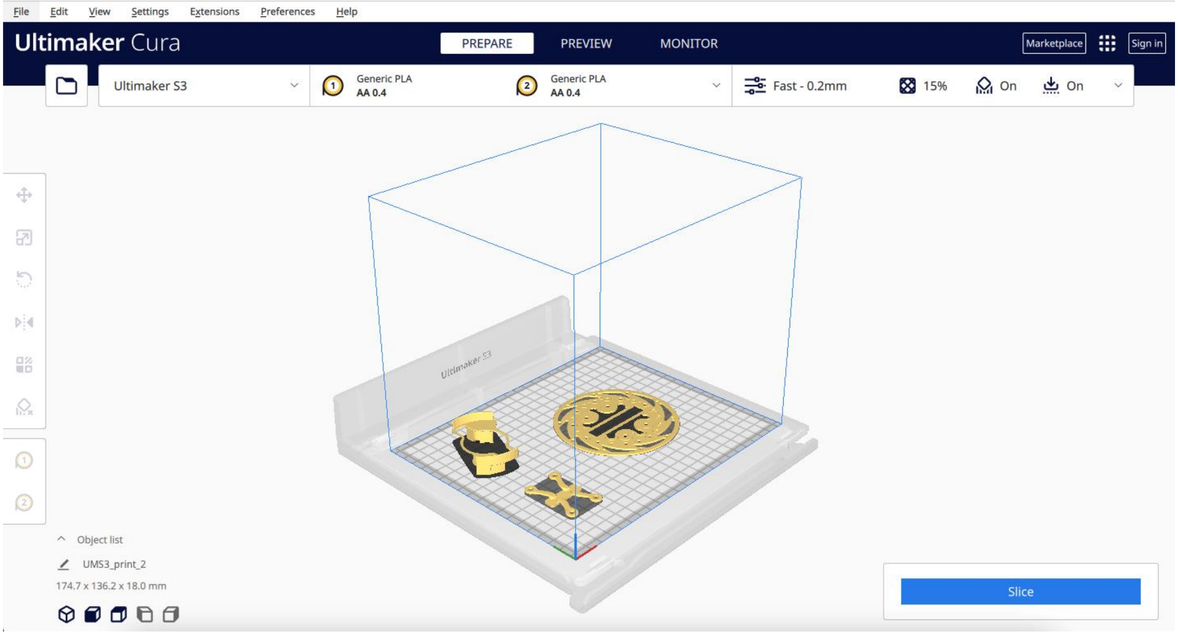


Figure 62. UltiMaker Cura software general view (Source: Author's own).

Subsequently, the printing settings are defined. Defining the quality of the printing by determining the layer Height (0.15 mm - normal), the infill density and the printing speed. The supports are also set in this part of the process, where it is possible to decide if the components need support and the overhang angle (defined at 45º).

After this, the slicing of the printing is executed. As shown in Figure 63, slicing is the process of converting a 3D model into a set of instructions for 3D printers (Ekaran, 2022). It is an important step in the printing process since it converts a 3D CAD model from an STL format file into a g-code that gives commands to the printer.

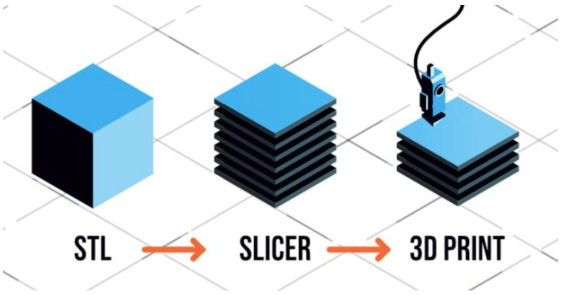


Figure 63. Files evolution in printing process (Source: https://fabheads.com/).

After slicing, the printing time and the needed material for the printing are detailed as shown in Figure 64.

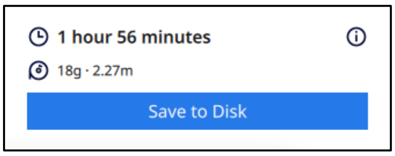


Figure 64. Printing time and material needed for the printing given by Ultimaker Cura (Source: Author's own).

Also, a preview of the components and its supports is given by the software (Figure 65). Afterwards, the printing file is ready to be uploaded to the printing with a removable disk.

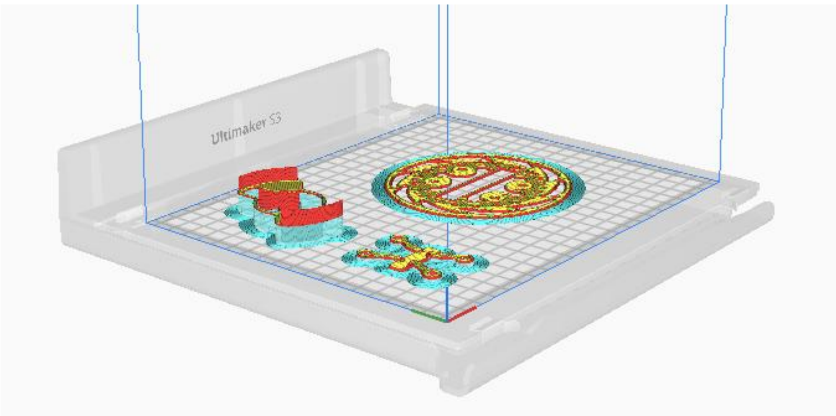


Figure 65. Preview of the printing in Ultimaker Cura (Source: Author's own).

The used printings in this thesis have been Ultimaker S3 and Ultimaker 3. Both are similar printings and the difference between them is that S3 provides a substantial update on a hardware level and a better optimization of the workable built space (Jackson, 2019). However, the printings taken by the two printers are appropriate for this thesis. The printing volume in Ultimaker S3 is 230 x 190 x 200 mm (source: www.impresoras3d.com) and in Ultimaker 3 it is 215 x 215 x 200 mm (source: tienda3d.abadiatecnologica.es).

The material chosen is a generic PLA, that was previously available in the printing laboratory. PLA is a more sustainable thermoplastic because it does not come from finite resources, as is the case with petroleum, but is made from natural and renewable resources (Lucía, 2023). Also, PLA is an excellent material to use while learning about 3D printing due to its easy printing, very economical and that it creates parts that can be used for a wide variety of applications.

To start printing, first, it is recommended to clean the printing bed since it has to be clear before printing to avoid possible failures. When uploading the file to the printer, it makes a calibration and then, the printing is ready to start. Figure 66 shows how a print is being carried out.

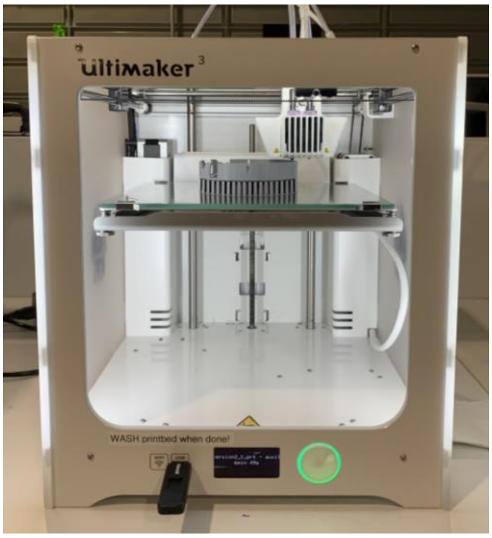
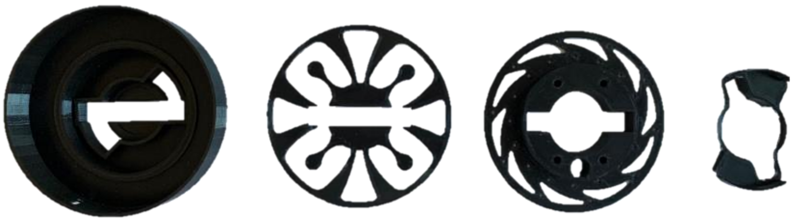


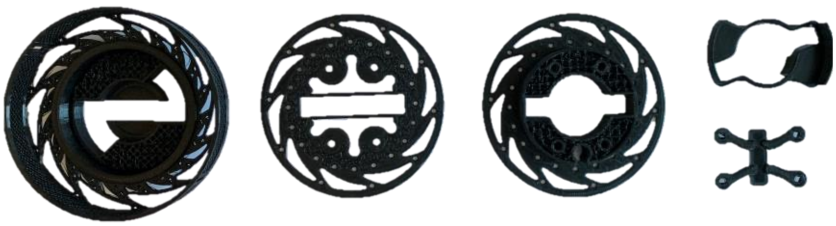
Figure 66. Printing in Ultimaker 3 printer (Source: Author's own).

After printing is complete, all parts can be removed from the printer. If supports are required, they should be removed and the parts are ready.

During the design and development of the furler two complete printings were made of all the components that make up the furler. Both can be seen in Figure 67.



a)



b)

Figure 67. a) First printed prototype. b) Final prototype. (Source: Author's own)

The first printing was done to analyse whether the parts fitted correctly both with each other and with the swivel carbine and to determine whether the tolerances between the different parts were appropriate. Also, various models for the disc were printed to see the one suited better physically.

In the second printing, the weight of the different components was reduced by means of lattices and topological optimisation. And some measurement parameters were also slightly modified.

7.2 Metal

The print preparation process is similar to the plastic process, however for printing on metal the software used is different and there is some additional steps, due to its complexity.

For this type of printing the EPHatch software (source: www.eplus3d.com) is used. First of all, to create a print, the material to be printed on is determined. In this case, as can be seen in Figure 68, 316L-30micron.ini (Stainless Steel) is chosen. And the files for each component, previously exported in Magics in 'CLI' format, are imported one by one to the software.

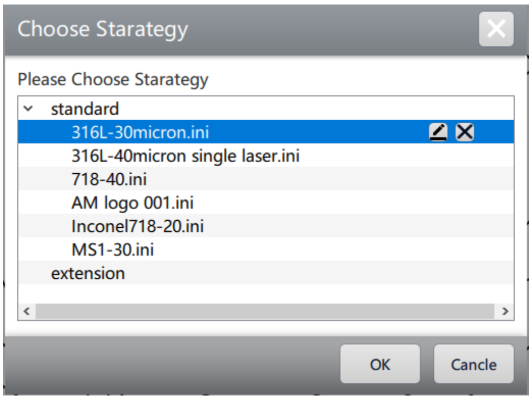


Figure 68. Define the printing material in EPHatch (Source: Author's own).

Figure 69 shows the software overview, where the basic settings have just been defined. This view also shows the total number of layers of the part.

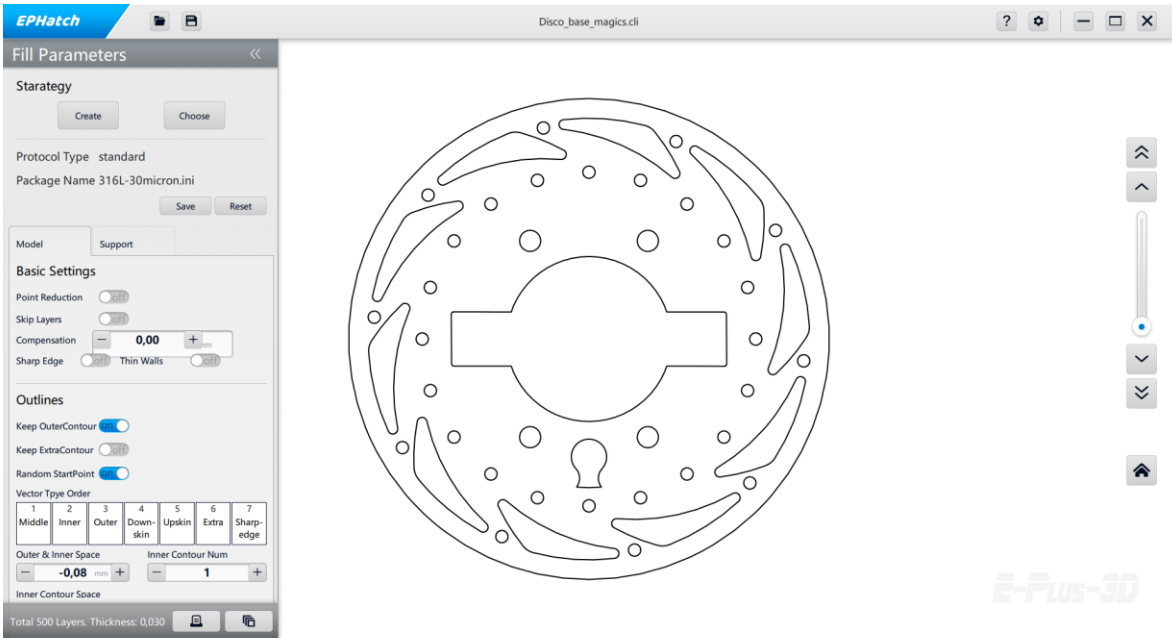


Figure 69. EPHatch software general view (Source: Author's own).

Subsequently, it is necessary to check that the slicing has been done correctly, with a preview of each layer. Figure 70 shows a zoomed-in type view of one of the layers of a disc. Parallel lines can be seen, showing the printing direction of this layer. To confirm that the slicing is correct, it is checked that all the layers have parallel lines between them and that they change direction with respect to the previous layer.

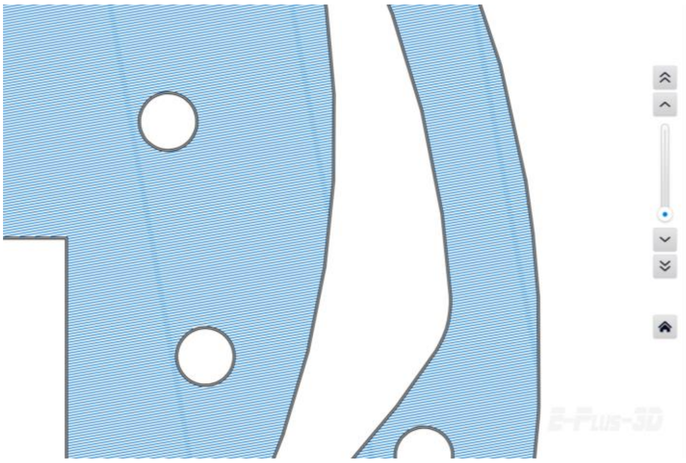


Figure 70. Printing direction of one of the printing layers (Source: Author's own).

After checking that the different layers will print correctly, the file is exported in 'EPI' format, suitable for printing. Then, the file is uploaded to the machine. Figure 71 shows the printing machine, where the file has been uploaded. If the parts to be printed require supports, the 'SLC' file previously exported in Magic must also be uploaded to the machine.

Figure 71. Upload of the printing file to the machine (Source: Author's own).

The view of the file in the printer can be seen in Figure 72, where a preview of the parts to be printed can be observed, as well as the different machine parameters defined for printing.

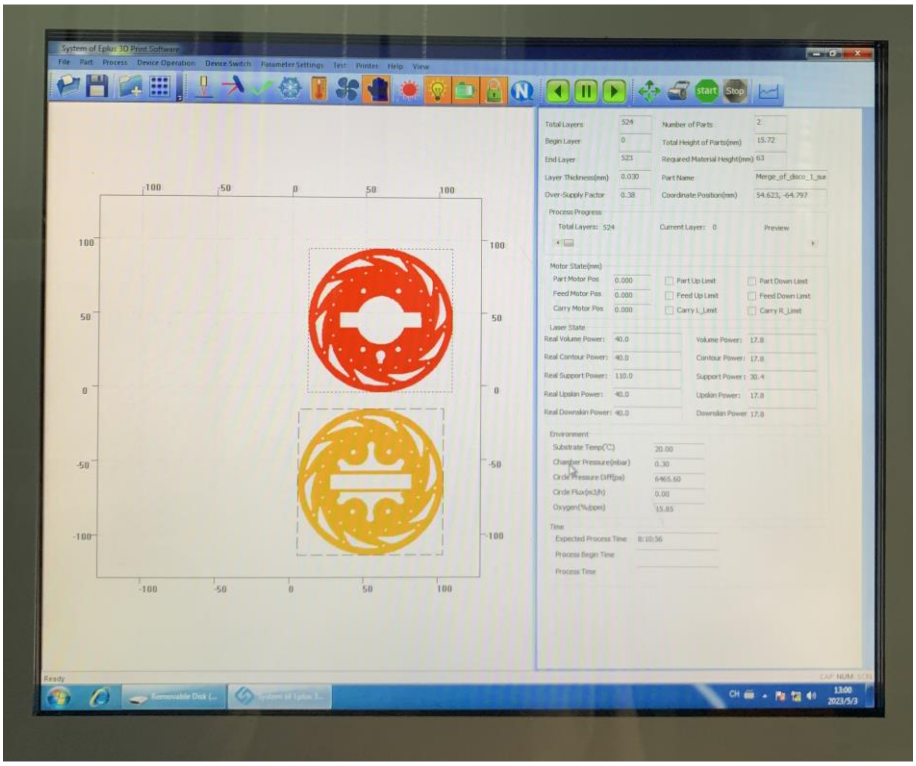


Figure 72. Printing screen with the printing parameters (Source: Author's own).

Also, the environmental settings for the machine are defined as shown in Figure 73, where the substrate temperature, the chamber pressure, the circle pressure, the circle flux and the percentage of oxygen are set.

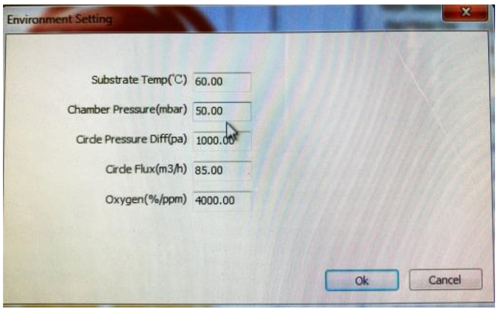


Figure 73. Environmental settings for the printing (Source: Author's own).

Next, the printing baseplate must be prepared. This is done by milling the baseplate, as shown in Figure 74, to obtain a flat and smooth surface, and minimise printing errors.

Figure 74. Milling the baseplate (Source: Author's own).

Afterward, some previous steps to prepare the printing machine are done. However, these are not specified in this thesis. Because these could not have been carried out due to there was not safety equipment ad only the professor, Miguel Zamora, could develop his step. Safety equipment is very important to be able to handle any part of the machine, as the metal powder used for printing is very toxic and harmful to health.

In Figure 75, it is possible to see how the printing is being carried out. It is possible to see the baseplate with the powder and the laser.

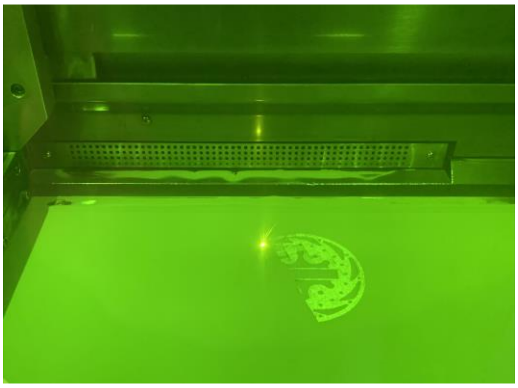


Figure 75. Printing in Prima Additive Printsharp250 machine (Source: Author's own).

The powder required for each layer may vary depending on the geometry. And the amount of powder can be adjusted at the moment for each layer, as it is very important that after spreading the powder, the impression of the previous layer cannot be seen. By keeping an eye on this parameter, especially in the first layers, many mistakes can be avoided.

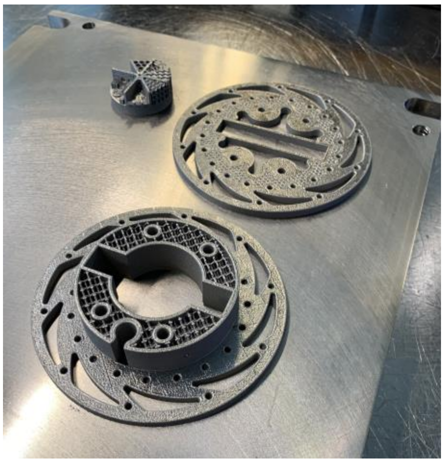


Figure 76. Result after printing in Stainless Steel 316L (Source: Author's own).

And finally, in Figure 76 can be seen the result of two components of the furler after the printing and after removing the remaining powder.

These two components will be separated from the baseplate and post-processed with a CNC machine for cutting the suprplus material of the bottom.

8 Economic feasibility

The economic feasibility has been studied to determine whether the production of the rolling furler is cost-effective compared to those currently available on the market. For this purpose, the furler's production cost has been calculated with the Select AM software (Source: selectam.io).

Select AM is a program that estimates the cost of parts manufactured in additive manufacturing. In order to calculate the price, each part must be imported independently and the material to be used for printing must be defined. Table 5 shows all the results obtained for each component.

Table 5. Cost of the different components of the furler.

	1 unit			20 units		
Component	Conv. man.	AM	Difference	Conv. man.	AM	Difference
Bottom support	235,10€	446,01€	+89,66%	91,52€	314,61€	+243,77%
Auxiliar support	167,87€	88,69€	-47,17%	24,23€	54,87€	+126,44%
Bottom disc	194,25€	257,82€	+32,73%	50,61€	182,88€	+261,38%
Top disc	173,26€	115,93€	-33,09%	29,61€	82,89€	+179,9%
Cover	158,54€	69,15€	-56,58%	14,90€	45,40€	+204,81%
Total	929,02€	**977,60€**	+5,22%	210,87€	680,65€	+322,78%

(Source: Author's own).

Two studies have been carried out, since in a production line the printing price per part will vary depending on the number of parts to be printed.

First of all, the cost of producing a single print of each component has been calculated, which is the most relevant result for this project, as only one print is to be produced. Secondly, the price per component has been analysed by manufacturing about 20 units.

The software displays a graph, as shown in Figure 77, which shows the evolution of the cost according to the number of parts to be printed. In this graph, it can be seen that from 5 pieces onwards the price of each piece is stabilised.

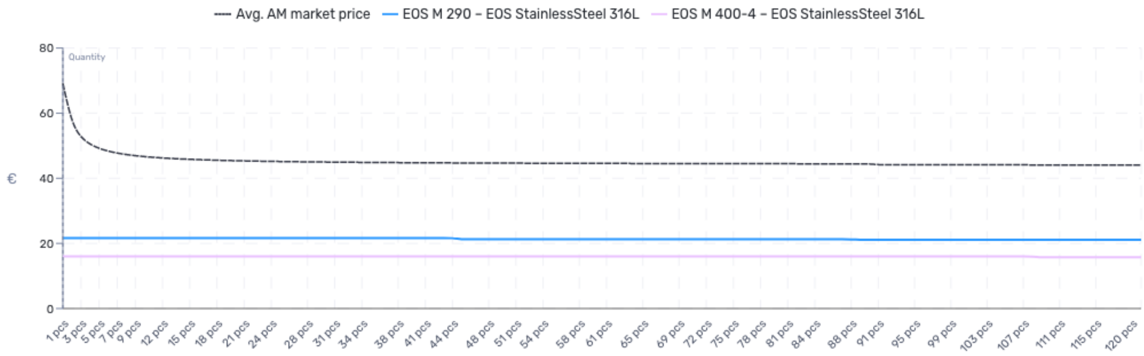


Figure 77. Evolution of the price depending on the printed parts (Source: Author's own).

In addition, the software also provides you with the cost price of manufacturing a similar part to the one imported but in another conventional manufacturing method. Although this will not be exactly the same since each component of the furler is designed to be manufactured only with AM, the proposed prices for each component with a conventional manufacturing method have also been included in Table 5.

Analysing the results from Table 5, it can be seen that in Additive Manufacturing it is more cost-effective to print a few units compared to other manufacturing methods, as 3 of the 5 components studied are cheaper in AM. On the other hand, when a large-scale production is carried out (20 pieces for example), it is more profitable to make a design suitable for manufacturing with some other conventional method.

The final price for the designed rolling furler print is €977.60 and if this is produced on a larger scale, making around 20 components, the price is reduced to €680.65.

Comparing both prices obtained with some furlers currently available on the market (see section 2.3.3), it can be concluded that the prices are similar. However, it should be noted that the final price calculated for the furler only takes into account the costs of printing, i.e. machine and material. This does not include the cost of the hours of engineering work, both design and documentation.

Also, to see how the data in Table 5 has been obtained, see Appendix 5. It shows screenshots of the Select AM software with the data obtained for the 'cover' component.

9 Results

This section will present the results obtained for the thesis regarding to the aim and objectives set at the beginning. And also, the innovative advances that have been developed in this thesis are highlighted here. Firstly, in section 9.1 the evolution in the design of the different furler components is presented, as well as a comparison of its weight is carried out in section 9.2. Then, in section 9.3, the assembly operation of the support component is discussed. Section 9.4 proves the application of part consolidation. And finally, in section 9.5 the result of the furler printed in Stainless Steel is exposed.

9.1 Furler design evolution

This section summarizes the design part by presenting three models of each component of the furler in order to observe its evolution. These three designs correspond to those that have been printed in the various plastic tests.

The changes made for each component can be due to different reasons. Initially, part consolidation, i.e. reducing the number of parts as much as possible, was considered. In some cases, however, modifications have been made simply for aesthetic reasons. But the main purpose of all these modifications has been to reduce as much as possible both the weight and the material required of each component.

For the bottom support component, as shown in Figure 78, an assembly of the two parts that initially composed it, has been carried out firstly, maintaining the rotational movement between these two parts. And finally, the maximum possible material has been reduced with volume lattice structures and surface lattices for the wall.

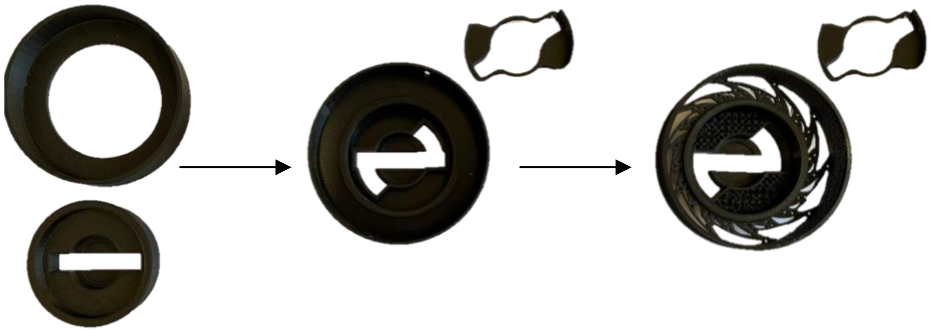


Figure 78. The design evolution of the support component (Source: Author's own).

Subsequently, for the bottom disc, a similar sequence is followed as with the support component. First, the three initial parts are merged into one, maintaining the same dimensions and functions as the initial parts together. A more visually appealing design has also been created. And in the final design, volume lattices were used for the solid body (Figure 79).

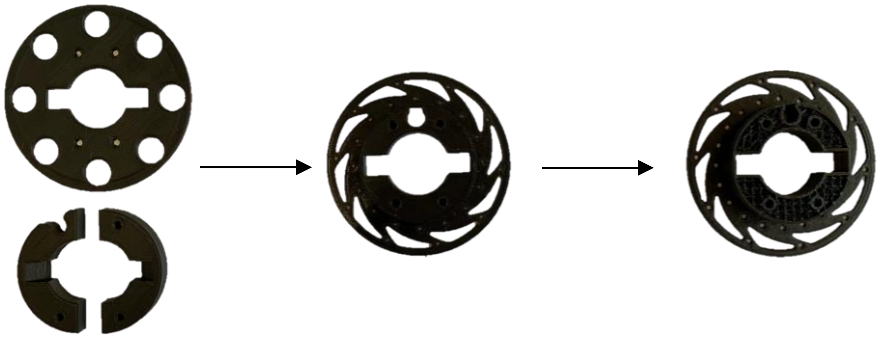


Figure 79. The design evolution of the bottom disc (Source: Author's own).

In Figure 80, the different designs made for the top disc are shown. The third is considered the most visually appropriate for a furler. Furthermore, it was desired that the design of the bottom disc and the top disc were in consonance, and the latter design was fitting better for both.

Figure 80. The design evolution of the top disc (Source: Author's own).

Finally, for the cover that is screwed on to limit the discs from slipping out, it was first redesigned to obtain a more aesthetic and reduced design. And finally, it was decided to carry out a topological optimization, that eliminated the surplus material according to the established forces (see Figure 81).

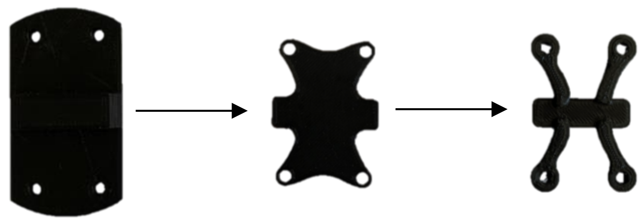


Figure 81. The design evolution of the cover (Source: Author's own).

These are the results in terms of the overall design of the furler. Where it can be seen that it has been taking advantage of the Design for Additive Manufacturing (DfAM), with each component being unique to produce for this type of manufacturing.

9.2 Lightweight

One of the main advantages of additive manufacturing is the freedom that additive manufacturing allows in terms of component design. This allows more complex parts to be designed by freely reducing material, optimising the designs. The optimisations that have been carried out in this thesis as mentioned in the previous section (section 9.1) are both lattice structures and topology optimisation.

To determine the reduction of material achieved for each component, the mass of each component was obtained in the Altair software. Altair provides the properties of all the 3D parts desired to analyse. But first, to do this, it is necessary to determine the material, Stainless Steel 316L, to later calculate its weight.

All the data obtained have been collected in Table 5, where the weight (in grams) of each component is detailed in each designing step (first design, redesign and final design). The three designs mentioned above correspond to those set out in section 9.1. Also, the following table includes the percentage of weight reduced compared to the first design.

Table 6. Mass comparison between the different designs.

Component	First design	First redesign	Reduced %	Final design	Reduced %
Bottom support	308 g +126 g	368 g.	15,21 %	235 g.	45,85 %
Auxiliar support	-	41 g.	-	30 g.	26,83 %
Bottom disc	68 g + 176 g.	238 g.	2,46 %	140 g.	42,62 %
Top disc	74 g.	67 g.	9,46 %	58 g.	21,62 %
Cover	23 g.	15 g.	34,78 %	8 g.	65,22 %
Total	**775 g.**	**729 g.**	5,94 %	**471 g.**	39,22 %

(Source: Author's own).

As can be observed in Table 6, the weight of all the components has been reduced considerably.

After the first redesign, the overall weight reduction percentage was only 5.94%. This is so low because a new part was added to the furler to be able to join the support component to the swivel carbine, something that was not considered in the first design. Furthermore, this first redesign was basically to merge some parts (part consolidation), and improve the functionality and the aesthetic.

However, in the final design, material optimization methods were used and for this reason, the percentage of weight reduction regarding the initial design was very high, 39.22%.

9.3 Assembly of the support component

One of the main challenges in the design of the furler was that an assembly system had to be invented to join the support component to the swivel carbine without using any mechanical joint. In the first design, this joint was not taken into account.

In order to be able to carry out the assembly, holes have been drilled in the lower part following a rotating path of the swivel carbine, as sown in the assembly process shown in Figure 82. In this way, the swivel carbine can enter perfectly vertically, then is rotated to limit the vertical movement. And finally, the auxiliary part designed is fitted on it, limiting the rotary movement and fixing the swivel carbine.

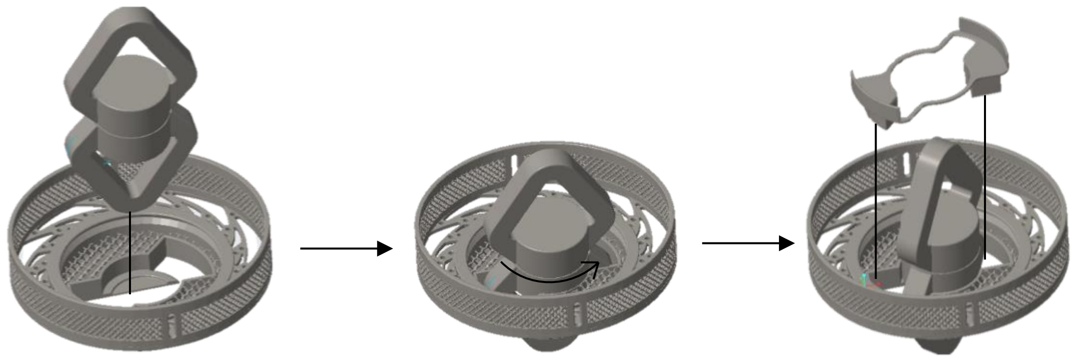


Figure 82. Assembly of the support component with the swivel carbine (Source: Author's own).

The auxiliar part is not mechanically attached to any component, but it cannot be moved because when the bottom disc is mounted on top, this part is fixed and its movement is limited.

This design is one of the main challenges and, thanks to its success, one of the greatest achievements of this work, as it facilitates its assembly.

9.4 Part consolidation of the support component

The most outstanding component of the furler due to its innovative manufacturing design is the bottom support. This is composed of two parts that were previously manufactured independently of each other.

These two parts have been joined together but have free rotational movement relative to each other, even though they are printed together. This has been achieved by taking into account one of the rules of overhanging, which is that with an inclination of 45º, no support is generated.

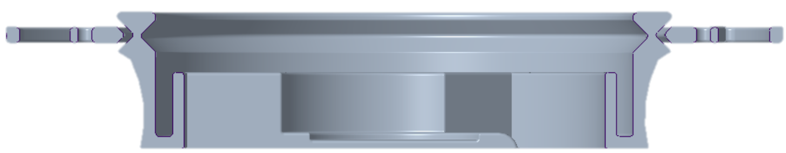


Figure 83. Profile view section (Source: Author's own).

Figure 83 shows the profile section view, where the 45º joint between the two parts can be seen with a separation of 1.25mm between them.

9.5 Stainless Steel printing

One of the objectives of the thesis was the complete printing of a final prototype in Stainless Steel 316L, as the entire design has been carried out for this purpose.

However, despite the low availability of the machine and various technical problems with the printing machine, it was not possible to print the entire furler within the set schedule. But in order to be fully familiar with this process, two of the components have been printed. These two were printed in the same baseplate and the printing was successful. The remaining components will be printed in the near future, after publishing this thesis.

In addition, regarding metallic printing, the Select AM software has provided an approximation of the cost of printing the entire furler in Stainless Steel 316L. And this, with Additive Manufacturing, has an estimated cost of €977.6 for a single print.

Comparing this result with the other furlers currently on the market, we can state that the cost of this furler is similar to those of the furlers analysed. However, it should also be noted that when calculating the total costs of the furler, the hours of engineering work for both design and documentation have not been considered.

10 Discussion

Section 10.1 is concerned with the discussion of the initial objectives proposed of the thesis, and the analysis of the results obtained. Next, section 10.2 examines the thesis limitations, and section 10.3 outlines the different consistencies and inconsistencies with the results obtained. Finally, in section 10.4 presents some suggestions for improvements for further studies.

10.1 Aims and objectives result

The main purpose of this thesis has been achieved by designing a rolling furler taking advantage of the additive manufacturing process and using a swivel carbine. To accomplish this, a number of objectives were set.

The first objective was to design and optimize a rolling furler taking advantage of AM, specifically, of lattice structures and topological optimization. For this purpose, an exclusive design for additive manufacturing has been developed for each component of the furler, which makes it possible to produce only with this manufacturing process. In addition, it has been possible to considerably reduce the weight of the various components and at the same time reduce the material required. Thus, contributing to a more sustainable model.

The second objective was to reduce the number of parts, by merging them together (part consolidation). Two pairs of components have been joined together, reducing the material and the number of parts to be printed from 7 to 5. Special mention should also be made of the bottom support, as it is a consolidation between two parts that can rotate independently, even being printed together. This printing has been carried out without the use of supports between these two, as a space of 1.25 mm has been left between at an angle of 45º, thus preventing them from overhanging.

Also, regarding the third objective of assembly the swivel carbine without using mechanical joints, a locking system has been designed with satisfactory results. In which an auxiliary piece fits with the bottom support, thus limiting the movement of the swivel carbine with respect to the support component.

Finally, the last objective was to print a final prototype in Stainless Steel 316L. Due to machine availability and various technical problems with the machine, it has not been possible to print all the components. However, two of them have been printed in Stainless Steel in order to get to know the process and validate the design for this type of printing.

10.2 Limitations

During the thesis's development, some limitations have arisen that have hindered the development of the thesis. One of the main limitations that affected the thesis the most was the fact that the final printing of the entire furler was not possible, as mentioned in the previous section.

Then, another barrier has been that the Creo software files when exported as 'STL' or 'STEP' files are of very low quality. For this reason, an intermediary CAD, OnShape, has been used to perform the export with better quality.

Regarding the Magics software, a high-cost licence with various configurations specific to the printer used is required for its use. And this software could only be utilised on the computer of my supervisor, Miguel Zamora, as it was only installed there.

Also, because of the high cost of printing and the low availability of the machine, there was no chance of error. As a result, the design had to be checked several times, involving several re-designs with meticulous changes.

10.3 Consistencies and inconsistencies

The project is based on theoretical studies and designs of the furler, as it has not been possible to test it on a ship and carry out a verification test in a real situation. Moreover, it is a sector of which I had not had much knowledge and the whole study has been based on information found in articles and different websites, not on my experience.

However, with the work performed in this thesis, it has been possible to validate the process of creating a furler with Additive Manufacturing.

10.4 Improvement suggestions

Despite the fact that almost all the objectives have been achieved, in the course of the work, some possibilities for the extension of this project have arisen, which could not be covered due to the large scale of it.

As this is a product development, it would be desirable for future studies to extend the economic study of the prototype and to make a commercialisation plan for a larger-scale production.

Also, some mechanical tests should be carried out in order to determine the mechanical properties of the furler and its behaviour under different stresses. The proposed mechanical tests are tensile and compression tests, hardness tests, and a final chemical corrosion test.

11 Conclusion

The maritime sector in the city of Vaasa is of great importance, since it is a coastal city. For this reason, a motivation has arisen from the university to investigate the design and development of an element of a light sailboats that help to furl the sails, a rolling furler.

This thesis proposes a design carried out with additive manufacturing (AM), an innovative manufacturing process, which is still in the process of research and expanding in the business sector due to its high costs. By taking advantage of Design for Additive Manufacturing (DfAM) and the CAD software Creo Parametric 5.0.6.0, it has been possible to develop and optimise a rolling furler. The two optimization methods for reducing redundant material that have been employed in this thesis are lattice structures, using nTopology software, and topological optimization, through Altair Inspire software. Thus, the weight of the final prototype has been reduced by 39,22% with respect to its initial model, with a final weight of 471 g.

Additionally, the redesign of the different components has also taken into account the need to merge together some parts in order to reduce the printing process and minimise the material used. This has been achieved by reducing the initial number of components from 7 to 5. The most successful and innovative merge of the furler is that two parts have been printed together and these can rotate independently, without the need for supports between them due to avoiding overhanging by designing joining angles of 45°.

Subsequently, the cost of the printing of the rolling furler has been calculated with the Select AM software. And, the final cost estimation of the Stainless Steel printing for the rolling furler is 977,60€. However, in further studies, the economical feasibility of the prototype could be extended by determining a commercialization plan for large-scale production.

Finally, the printing process was carried out. To do so, some drafts had been made on plastic first. And to conclude, the printing in metal has been carried out, specifically in Stainless Steel 316L, in the printing machine PrintSharp 250 by Prima Additive. For this process, the individual components were previously prepared and repaired with the softwares Magics and EPHacth. Despite the fact that not all the components could be printed in Stainless Steel, two of them have been carried out to be able to analyze the performance of the whole process.

It can be concluded, that complete work has been done in terms of design and taking advantage of Additive Manufacturing, contributing to the research of this type of manufacturing. Furthermore, the designed rolling furler is ready to be finished printed and tested on a conventional boat. However, before testing it in a sailboat, some mechanical tests should be carried out to determine its mechanical properties and its behaviour under different stresses.

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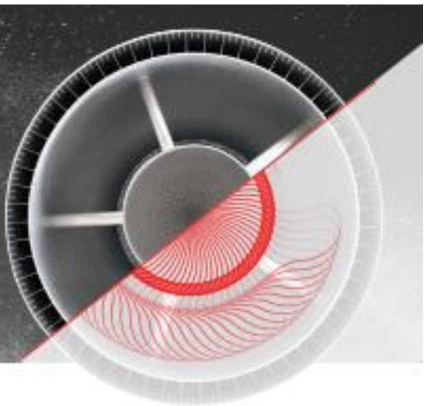
Appendix 1. Stainless Steel 316L specifications

Oerlikon – 316L Stainless Steel

Source: www.addimen.com

oerlikon
am

Additive Manufacturing
316L Stainless Steel



Designed for Processing in Laser Powder Bed Fusion (PBF-LB), Electron Beam Powder Bed Fusion (PBF-EB) or Directed Energy Deposition (DED) Systems

MetcoAdd™ 316L is a family of austenitic steel powders with chemistry similar to EN 1.4404 and UNS S316603

Room temperature static properties of PBF-LB processed, as-built, material coupons have been shown to be comparable to those of AMS 5424.

For reference purposes Oerlikon has processed MetcoAdd 316L-A using fixed parameters and 40 µm layer thickness to provide data below. Additional testing has been performed by an extensive network of consortia and customer partners on a broader range of machine types. Properties may be optimized based on application specific requirements.

Applications

- Aerospace: Clamping elements and heat exchangers
- Medical: Surgical tools and orthopedic implants
- Transport: Maritime components
- Tooling: Pressure injection dies and molds
- Consumer: Jewelry and watch components

Typical As-built Properties (316L-A) [1] [2] [3]

	Concept Laser M2 Cusing	EOS M290	Test Method
Ultimate Tensile Strength (MPa), XY/Z	670±2 / 635±9	677±7 / 609±2	ASTM E8
Yield Strength (MPa), XY/Z	548±15 / 491±4	562±12 / 500±3	
Elongation at break %, XY/Z	45±2 / 44±8	45±3 / 59±1	
Hardness (VHN_{300g})	216±23	228±6	ASTM E384-17
Relative Density %	>99.6%	>99.8%	Internal Spec.

[1] Disclaimer: All data published in this datasheet has been shared for reference purposes only and is not sufficient to design or certify parts. No warranty or guarantee is made against these results.
[2] Bounds are based on one standard deviation of each population with ten samples per orientation and machine. Test specimens were 6.35 mm diameter round bars machined from coupons (75x75x13mm). Direction XY data is an average of both X and Y horizontal build orientations.
[3] The process parameters and heat treatments of AM builds produced with other powder cuts (316L-D) and or AM processes (DED and PBF-EB) may be optimized based on application specific requirements.

As-built Microstructure (x 20 magnification, Vertical Build Direction)

	Concept Laser M2 Cusing	EOS M290
MetcoAdd 316L-A		

Chemical Composition

	Weight Percent (nominal)					
	Fe	Cr	Ni	Mo	C	Other
MetcoAdd 316L-A / 316L-D	Balance	18	12	2	< 0.03	< 1.0

Particle Size Distribution and Hall Flow

	Nominal Range [µm]	D90 [µm]	D50 [µm]	D10 [µm]	Hall Flow [s/50 g]
MetcoAdd 316L-A	-45 +15	46	30	19	< 20
MetcoAdd 316L-D	-106 + 45	-	-	-	-

For the nominal range, particle size analysis 45 µm or above measured by sieve (ASTM B214), analysis below 45 µm by laser diffraction (ASTM C 1070, Microtrac). | Fractional analysis (D90, D50, D10) are nominal values by laser diffraction. Hall flow (ASTM B213).

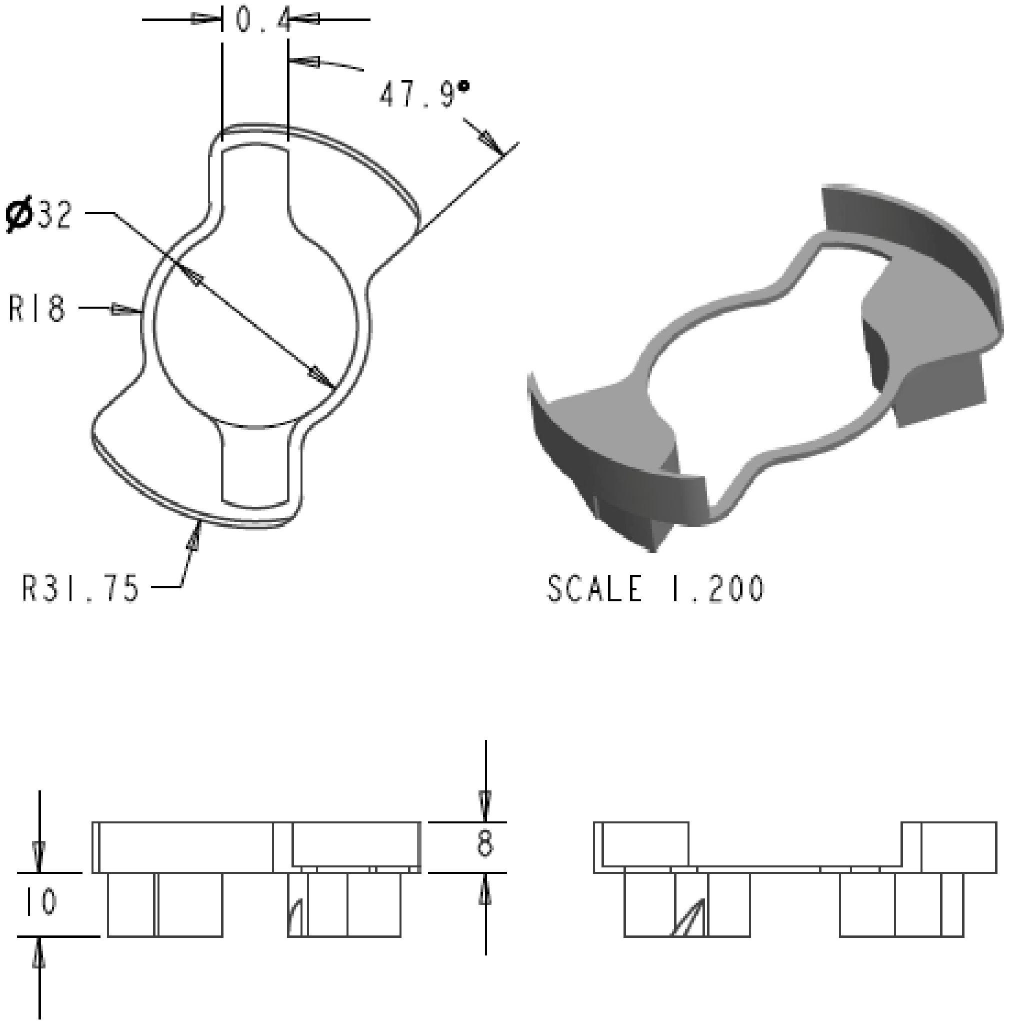
Product Information

Classification	Alloy, Iron Base
Chemistry	FeCrNiMoC
Manufacture	Gas atomized (Nitrogen)
Morphology	Spheroidal
Apparent Density	>4 g/cm³ (typical)
Solidus	1390 ± 10 °C / 2534 ± 18 °F
Liquidus	1448 ± 10 °C / 2638.4 ± 18 °F
Process	Laser Powder Bed Fusion (PBF-LB) Electron Beam Powder Bed Fusion (PBF-EB) Directed Energy Deposition (DED)
Safety Data Sheet	50-1990 www.oerlikon.com/metco
Package size	316L-A: 4.5 kg / 10 lb approx. (stock) 316L-D: 4.5 kg / 10 lb approx. (stock)
Distribution	Global
Order No.	316L-A: 1093739 316L-D: 1305325

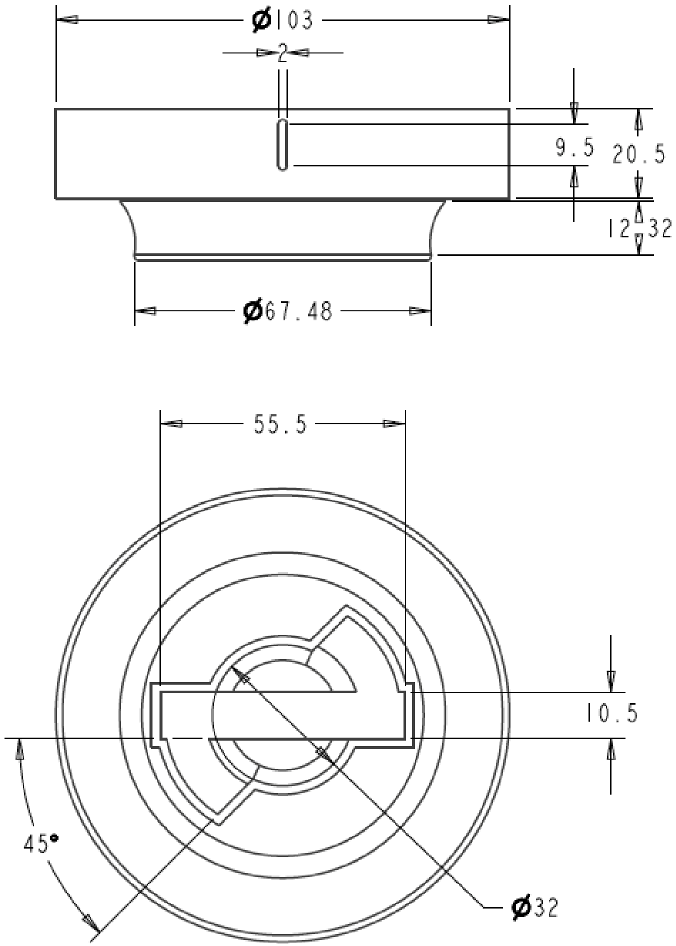
Usage Recommendations

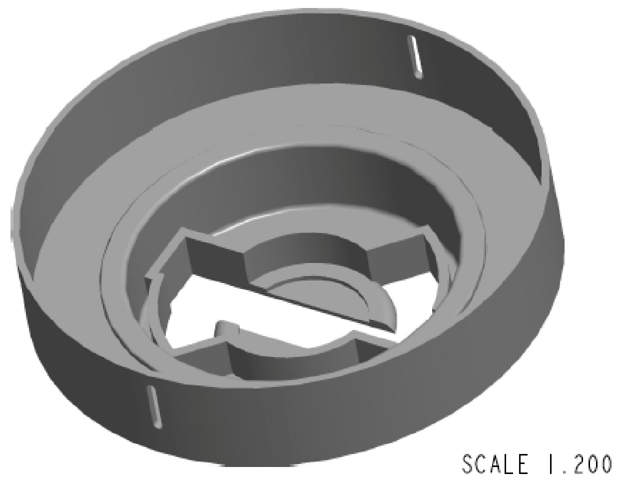
- Blend contents prior to use to prevent segregation
- Keep in the original container, or an approved alternative, tightly closed when not in use
- Powder from previously opened containers should be stored in a humidity-controlled environment

Appendix 2. Component drawings

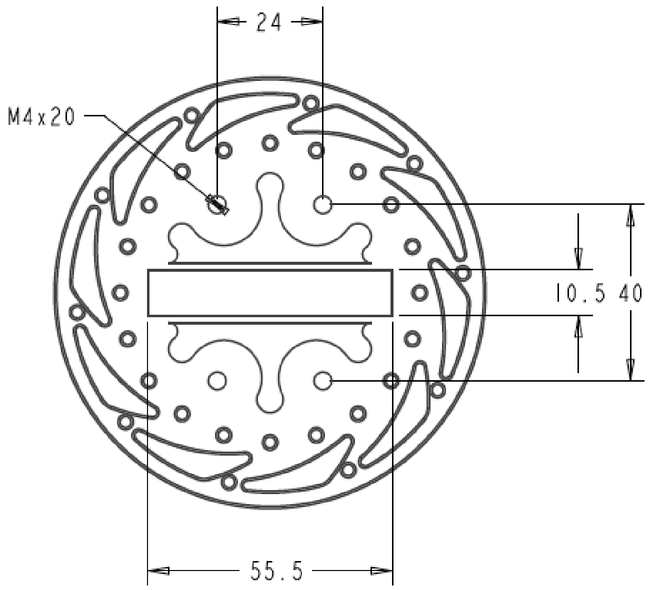


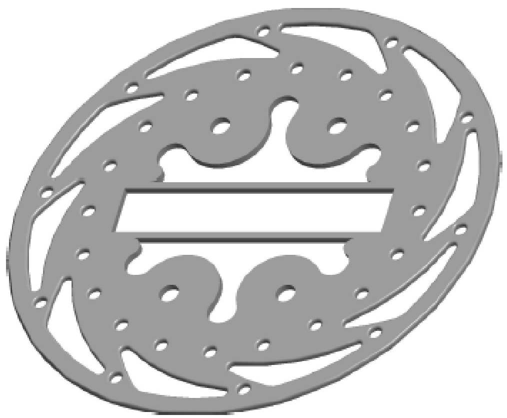
Material: **Stainless Steel**	General tolerancies (mm)		General Information	Novia UAS / Universitat de Lleida
Weight (g): **30**				
Manufacture: **Additive Manufacturing**	Dimension	Tolerancies	R 0,2	
	0 - 10	± 0,1		
	10 - 50	± 0,2		
Surface Treatment: -	50 - 200	± 0,8	0,5 x 45°	Description: **Measurements of the auxiliar component of the rolling furler.**
	> 200	± 1		
Author: **Mariona Royes Molto**	Roughness not specified:			Reference
Supervisor: **Miguel Zamora**			Scale: **1.000**	**Auxiliar**
			Format: **A4**	Revision: **1** Page: **1/1**



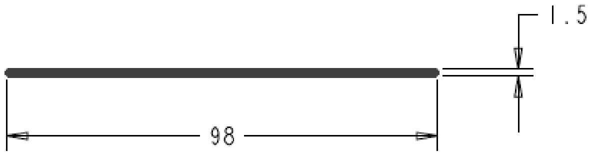


Material: Stainless Steel	General toleranciess (mm)		General Information	Novia UAS	Universitat de Lleida	
Weight (g): 235	Dimension	Tolerancie	R 0,4	Description		
Manufacture: Additive Manufacturing	0 - 10	± 0,1	0,5 x 45°	Planes of the bottom support of the rolling furler		
Surface treatment: -	10 - 50	± 0,2				
	50 - 200	± 0,8				
	> 200	± 1				
Author: Mariona Royes Molto	Roughness not specified:			Reference		
Supervisor: Miguel Zamora			Scale: 1.000	Bottom support		
			Format: A3	Revision: 1	Page: 1/1	





ESCALA 1.200



Material:	Stainless Steel
Weight (g):	58
Manufacture:	Additive Manufacturing
Surface Treatment:	-
Author:	Mariona Royes Molto
Supervisor:	Miguel Zamora

General Tolerancies (mm)

Dimension	Tolerancies
0 - 10	± 0,1
10 - 50	± 0,2
50 - 200	± 0,8
> 200	± 1

General information: R 0,4; 0,5 x 45º

Roughness not specified:

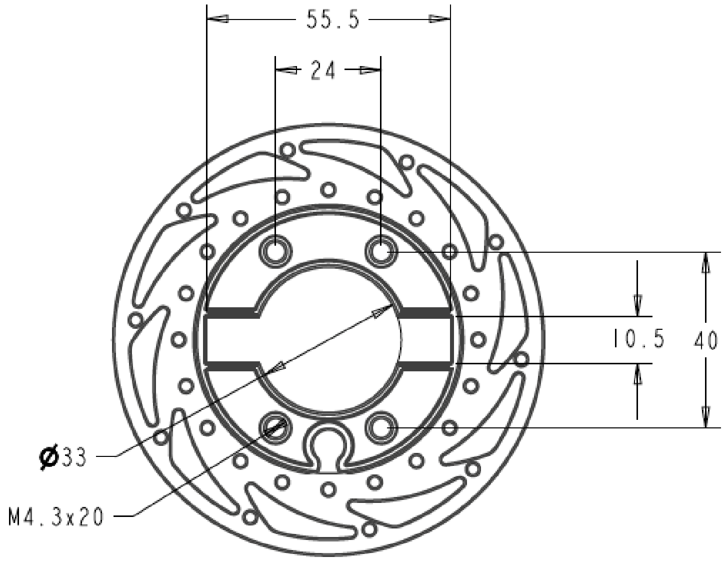
Scale: 1.000
Format: A3

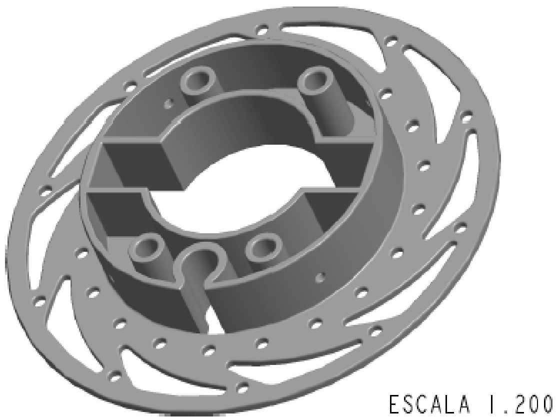
Novia UAS
Universitat de Lleida

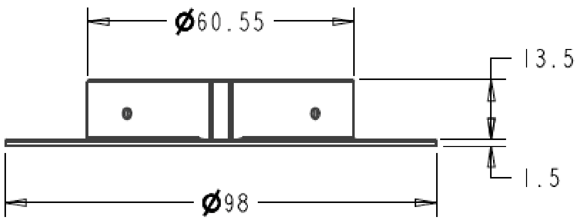
Description: Measurements of the top disc of the rolling furler.

Referència: Top disc

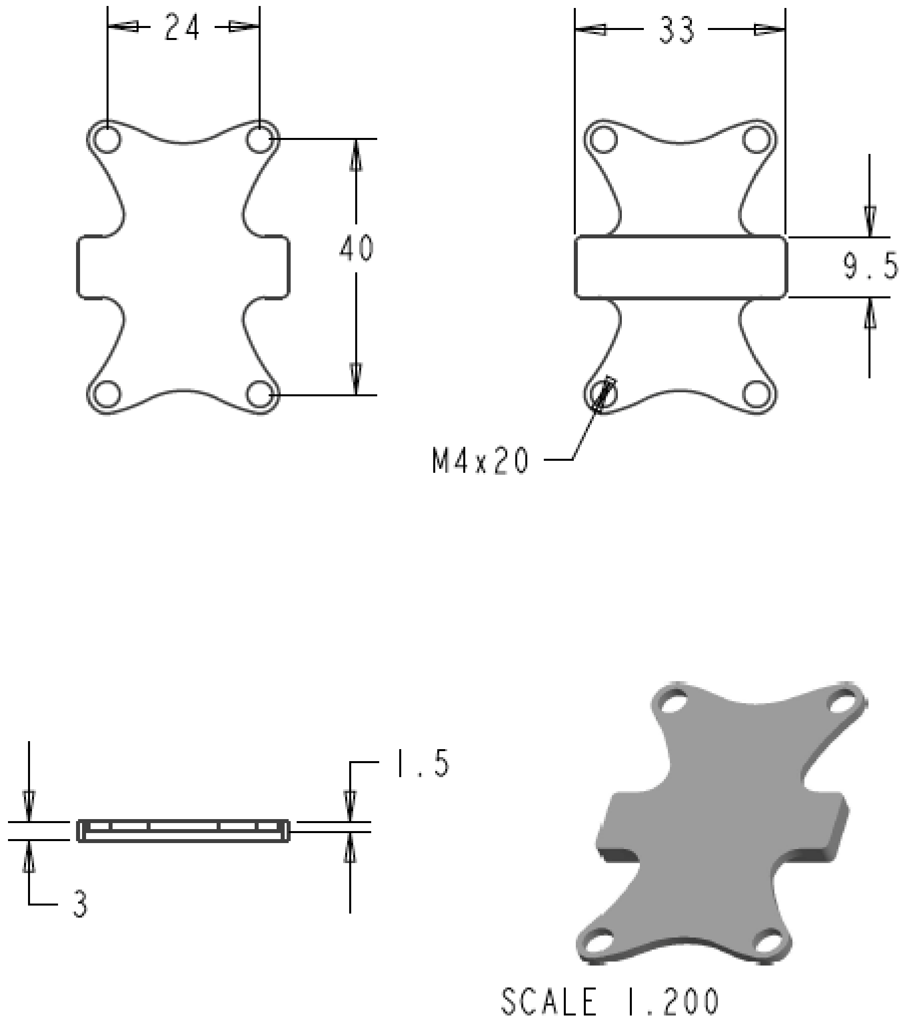
Revision: 1 | Page: 1/1







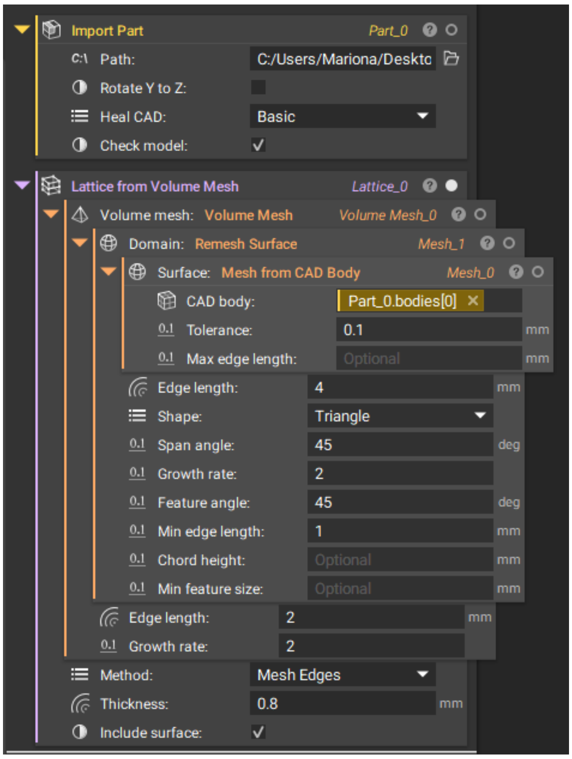
Material: Stainless Steel Weight (g): 140	Generals Tolerancies (mm)		Acords no indicats	Novia UAS / Universitat de Lleida
Manufacture: Additive Manufacturing	Dimension	Tolerancies	R 0,2 0,5 x 45º	
Surface Treatment: -	0 - 10 10 - 50 50 - 200 > 200	± 0,1 ± 0,2 ± 0,8 ± 1		Description: Measurements of the base disc of the rolling furler.
Author: Mariona Royes Molto	Roughness not specified:			Reference: Base disc
Supervisor: Miguel Zamora			Escala: 1.000 Format: A3	Revision: 1 — Page: 1/1



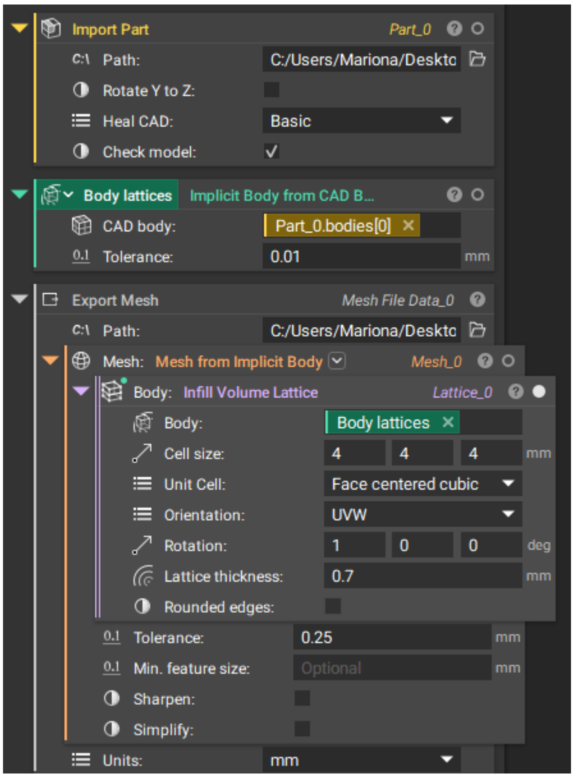
Material: Stainless Steel	General Tolerancies (mm)	General Information	Novia UAS / Universitat de Lleida
Weight (g): 8			
Manufacture: Additive Manufacturing	Dimension / Tolerancies: 0 - 10 ± 0,1; 10 - 50 ± 0,2; 50 - 200 ± 0,8; > 200 ± 1	R 0,4; 0,5 x 45º	
Surface Treatment: -			Description: **Measurements of the cover of the rolling furler.**
Author: **Mariona Royes Molto**	Roughness not specified:		Reference: Cover
Supervisor: **Miguel Zamora**		Scale: 1.000	
		Format: A4	Revision: 1 — Page: 1/1

Appendix 3. Workflow codes from nTopology

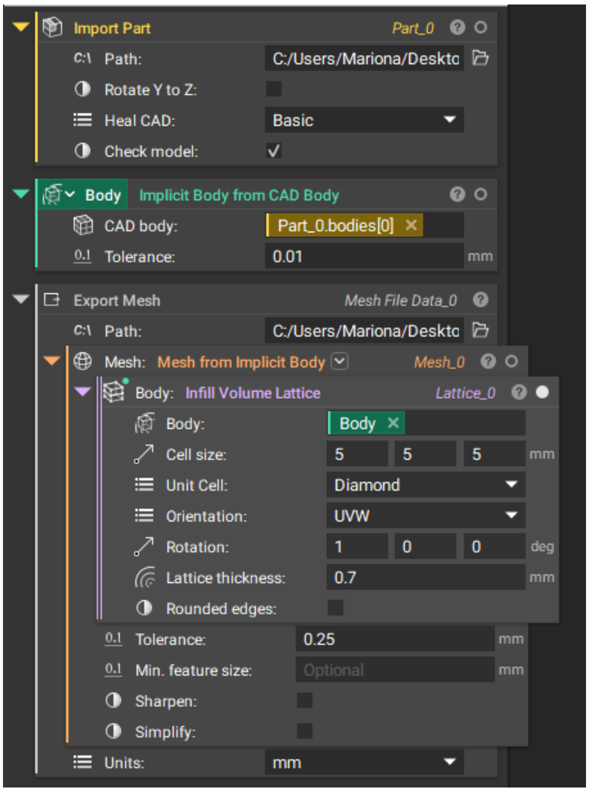
Appendix 3.1. Workflow code of the non-periodic volume lattice for the bottom disc



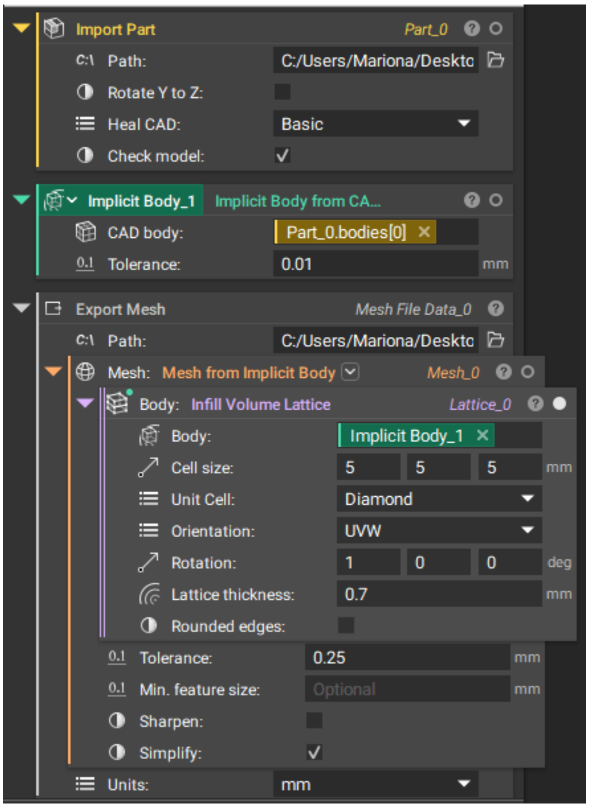
Appendix 3.2. Workflow code for the periodic volume lattice for the bottom disc



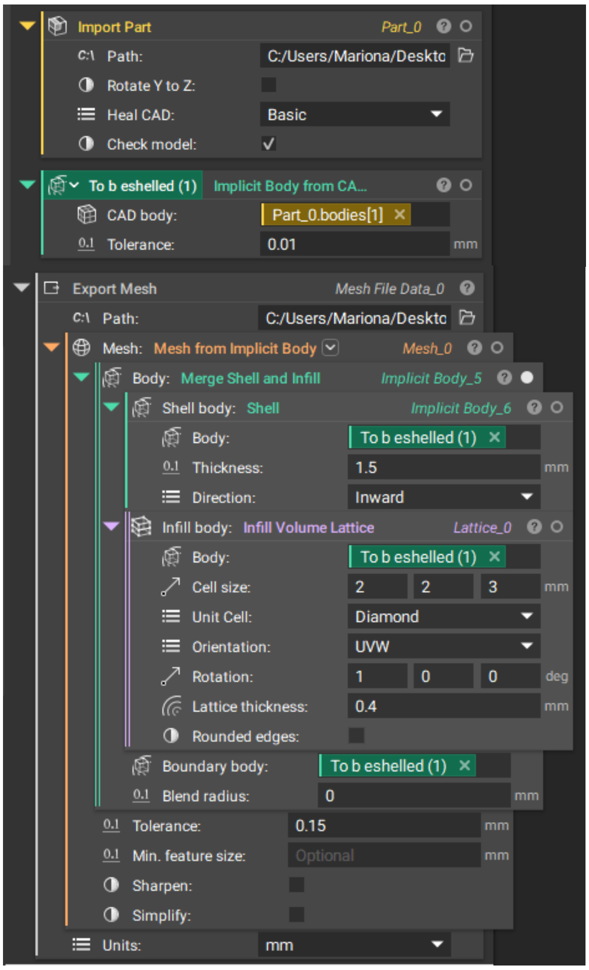
Appendix 3.3. Workflow code for the periodic volume lattice for the bottom disc

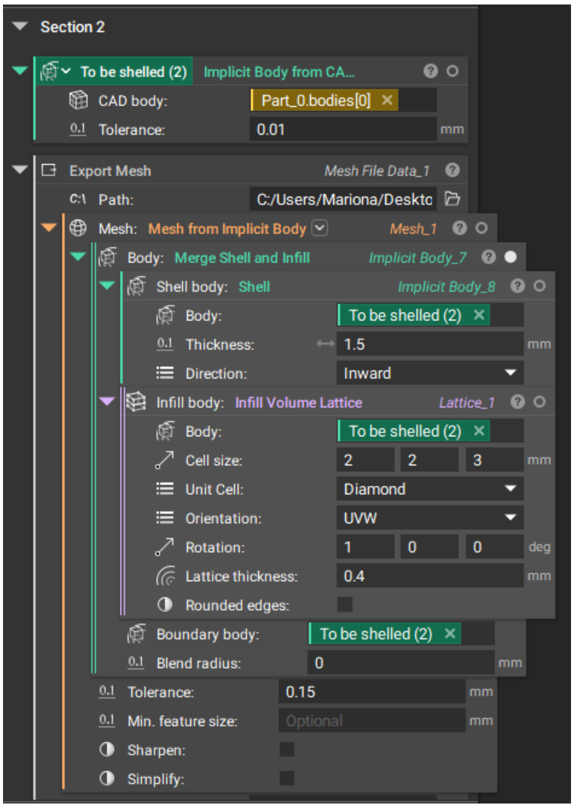


Appendix 3.4. Workflow code for the periodic volume lattice for the support.

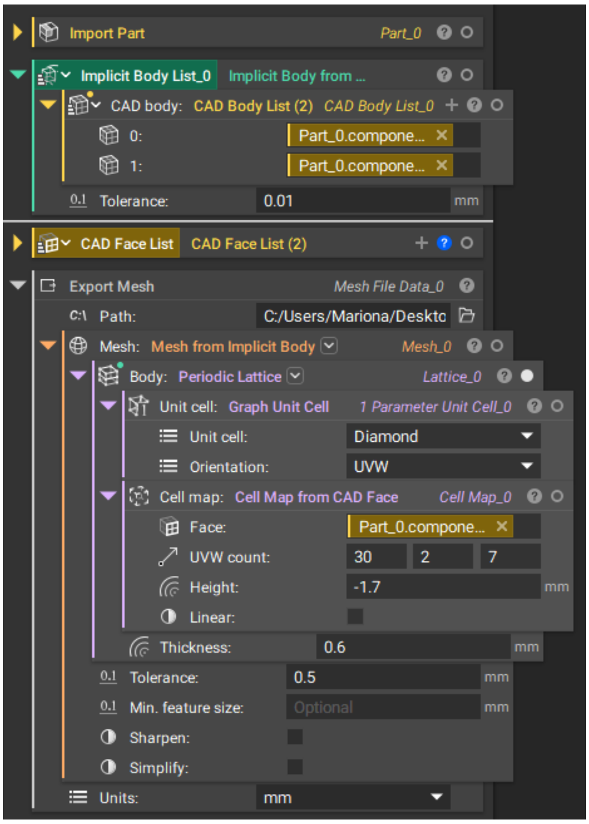


Appendix 3.5. Workflow code for merge shell and infill for the auxiliar part.

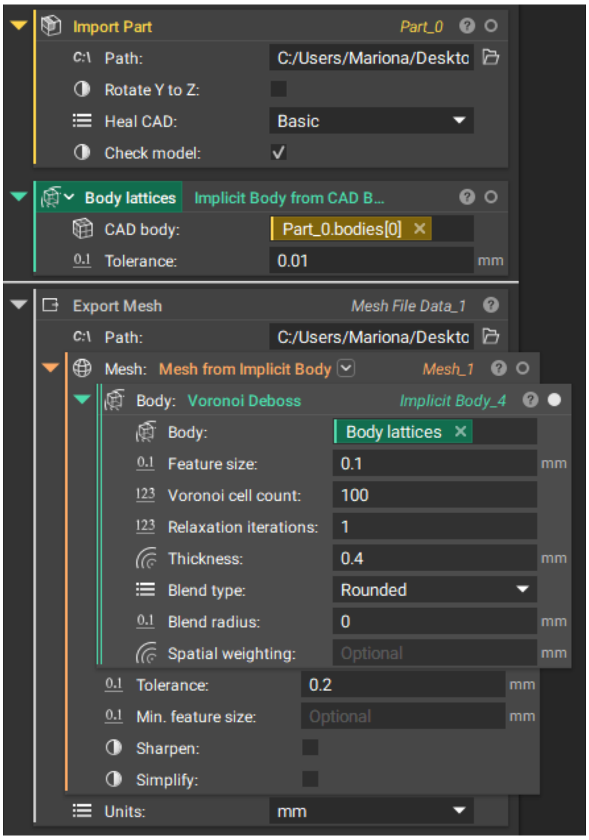




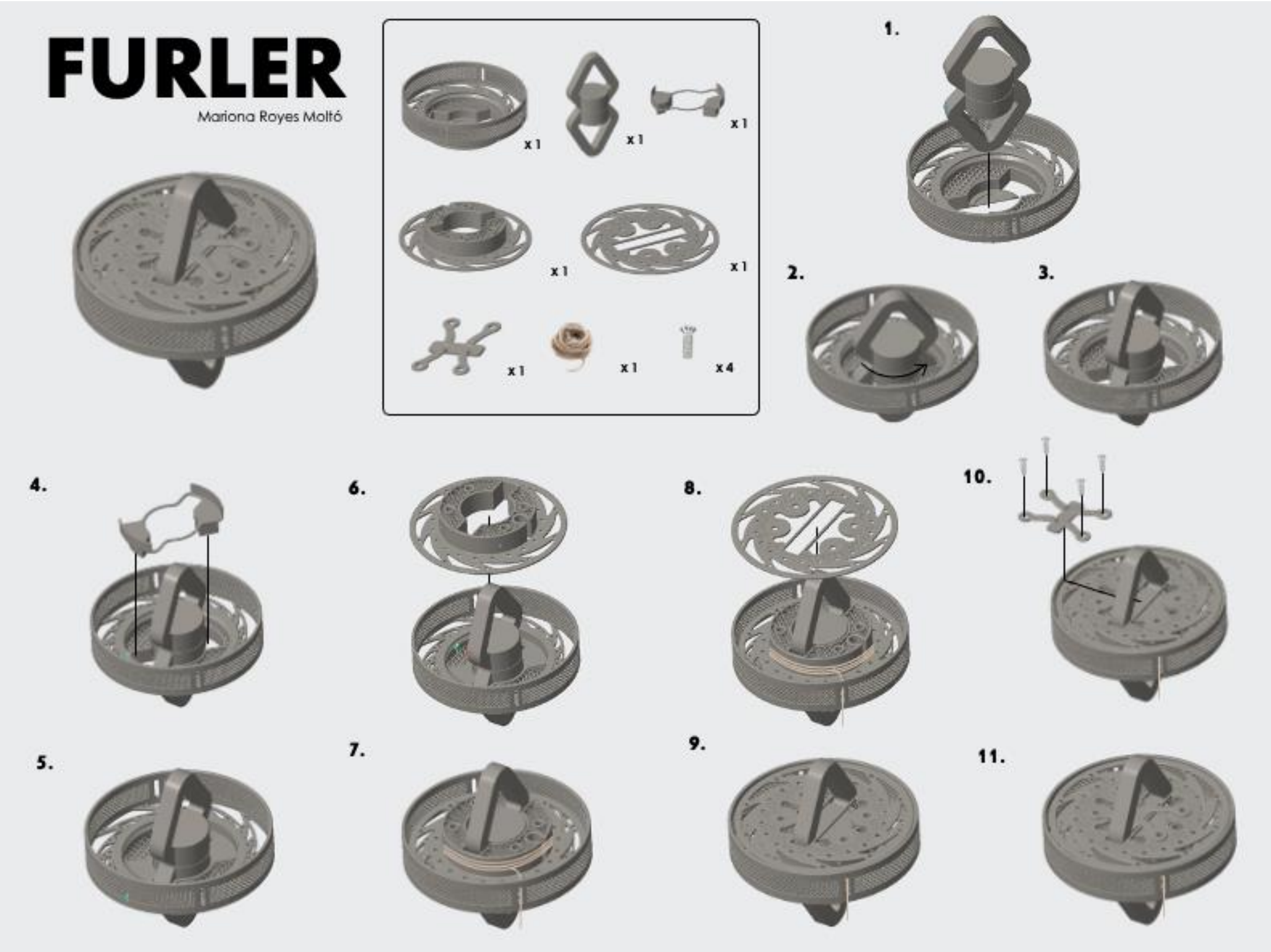
Appendix 3.6. Workflow code for the surface diamond lattice for the walls of the support



Appendix 3.7. Workflow code for the Voronoi surface lattice for the top disc.

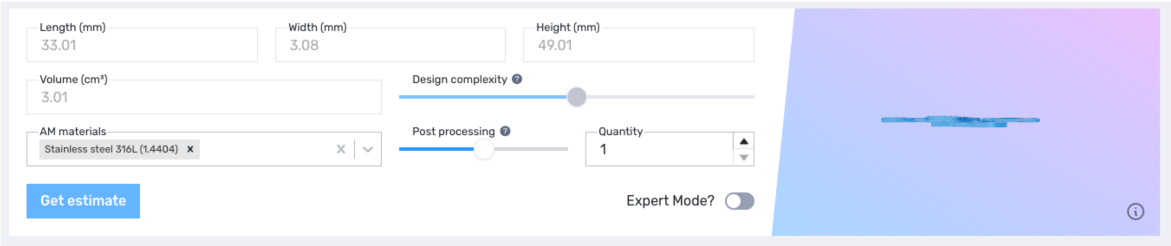


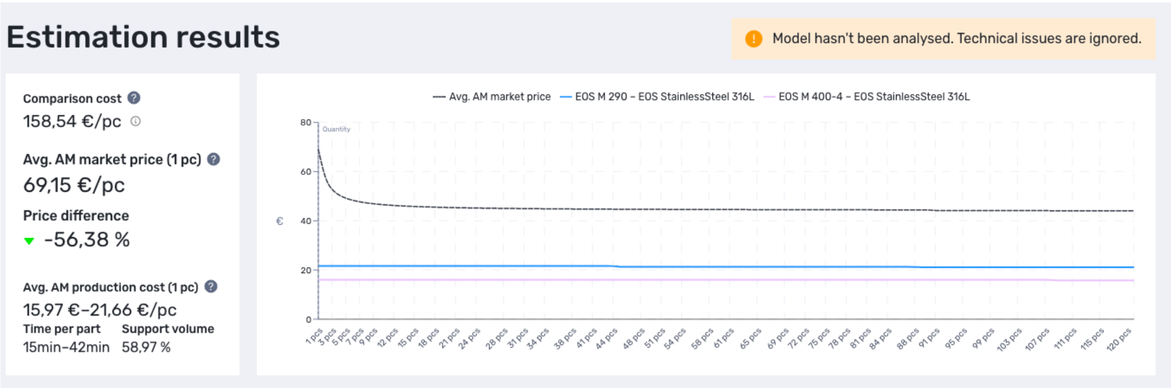
Appendix 4. Assembly manual



Appendix 5. Price calculation Select AM

Appendix 5.1. Results obtained for the printing of 1 piece of the cover component.





Appendix 5.2. Results obtained for the printing of 20 pieces of the cover component.