Design Optimization for Additive Manufacturing of a 1U CubeSat’s Mechanical System

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Dedicated to my beloved family and friends
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Resumo

A fabricação aditiva (FA) é um processo de manufatura emergente que está a transformar a indústria aeroespacial, criando componentes mais leves, mais fortes e mais complexos, que são difíceis ou impossíveis de fabricar através de métodos tradicionais. O desenvolvimento contínuo de ferramentas de otimização de design que estimam a distribuição ideal de material para um determinado problema, como a otimização topológica, promoveu a produção de peças por FA. A combinação da FA com a otimização topológica é benéfica para a indústria aeroespacial, pois apresenta uma oportunidade para redução de peso e custo, além de aproveitar ao máximo as duas tecnologias.

O objetivo desta dissertação de mestrado é desenvolver e otimizar um subsistema mecânico do 1U CubeSat para posterior produção por FA. Neste trabalho, foi desenvolvido um subsistema mecânico que garante a integridade estrutural do CubeSat durante o lançamento.

O procedimento adotado para o design do CubeSat começou com a determinação dos requisitos do projeto, com base nas especificações de design do CubeSat, no contentor P-POD e no lançador Vega.

A estrutura foi otimizada e uma análise de elementos finitos foi realizada para verificar se o CubeSat é capaz de sustentar as cargas estáticas lineares durante o lançamento. Após a produção do componente otimizado, foram realizados ensaios experimentais para validar o projeto e a análise computacional.

A estrutura otimizada apresenta uma considerável redução de peso, bem como uma diminuição no número de componentes necessários. Os ensaios mecânicos revelaram uma pequena alteração nas propriedades mecânicas, mas uma análise de tensão estática comprovou que esta discrepância não trazia consequências para a integridade do CubeSat.

Abstract

Additive manufacturing (AM) is an emerging manufacturing process that is transforming the aerospace industry by creating lighter, stronger and more complex components which were difficult or impossible to fabricate by traditional methods. Continuous development of design optimization tools which estimate the optimal material distribution for a given problem, such as topology optimization (TO), has fostered the production of parts by AM. The combination of AM with TO is beneficial for the aerospace industry as it presents an opportunity for weight and cost saving, while taking full advantage of both technologies.

The purpose of this master’s dissertation is to develop and optimize a 1U CubeSat Mechanical Subsystem for further production by AM. In this work, a Mechanical Subsystem that guarantees the structural integrity of the CubeSat during launch was developed.

The procedure adopted for the design of CubeSat began with the determination of project requirements, based on the CubeSat Design Specifications, the P-POD container and the Vega launcher. The structure was optimized and a finite element analysis was carried out to verify if the CubeSat is able to sustain the linear static loads during launch. Following the production of the optimized component, experimental tests were performed to validate the design and computer analysis.

The optimized structure presents considerable weight reduction as well as a decrease in the number of components required. The mechanical tests revealed a small change in mechanical properties but a static stress analysis proved this discrepancy posed no consequences for the integrity of the CubeSat.

Keywords: CubeSat, Additive Manufacturing, Topology Optimization, Finite Element Method, Aerospace Industry.
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Nomenclature

**Greek symbols**

δ  Elongation

ε  Strain

ρ  Density

ρ(𝑥)  Material distribution

σ  Stress

σᵥ  Von Mises Stress

θᵸ  Rotation about the 𝑥 axis

θᵳ  Rotation about the 𝑦 axis

θᵣ  Rotation about the 𝑧 axis

ν  Poisson Ratio

Ω  Design Domain

**Roman symbols**

A  Area

C  Elasticity Matrix

CGH  Center of Gravity Height

E  Elastic Modulus

E₀  Elastic Modulus of solid material

Eₑ  Elastic Modulus of the element

F  External Forces Vector

f  Local Function

F₀  Objective Function
General Constraints

Volume Constraint

Stiffness Matrix

Stiffness of solid material

Stiffness of the element

Outbox Volume

Penalization Parameter

Part Height

Supported Area

Safety Factor

Support Volume

Displacement

Displacement in the $x$ direction

Displacement in the $y$ direction

Displacement in the $z$ direction

Cartesian components
Acronyms

**ACDS** Attitude Determination and Control Subsystem.

**AM** Additive Manufacturing.

**ASTM** American Society for Testing and Materials.

**CAD** Computer Aided Design.

**CDH** Command and Data Handling Subsystem.

**CDS** CubeSat Design Specifications.

**DED** Directed Energy Deposition.

**DFAM** Design for Additive Manufacturing.

**DOF** Degrees of Freedom.

**EPS** Electrical Power Subsystem.

**ESA** European Space Agency.

**FEM** Finite Element Method.

**ISS** International Space Station.

**MAM** Metal Additive Manufacturing.

**MSS** Mechanical Subsystem and Structures.

**NASA** National Aeronautics and Space Administration.

**NSF** National Science Foundation.

**P-POD** Poly Picosatellite Orbital Deployer.

**PBF** Powder Bed Fusion.

**RP** Rapid Prototyping.
**SIMP**  Solid Isotropic Material with Penalization.

**SLM**  Selective Laser Melting.

**TCS**  Thermal Control Subsystem.

**TO**  Topology Optimization.

**TTC**  Telemetry, Tracking and Control Subsystem.
Chapter 1

Introduction

1.1 Motivation

The aerospace industry is constantly seeking for innovation and technological progress to efficiently address not only the main challenges of producing high performance products but also the society’s yearning for innovation. Consequently, the industry’s strict requirements and the demand for complex and optimized structures led to the introduction of additive manufacturing (AM) in the sector, allowing the aerospace industry to be one of its early adopters [1].

In recent years, AM has gained increased attention due to the several advantages it offers, such as: production of components with complex geometries, design freedom, customization, reduction of waste and tooling, among others [2]. One of the primary benefits for the aerospace industry is the production of lightweight parts, since the reduction of the overall weight of an aircraft translates in fuel savings and, consequently, in less costs and emissions. This is usually attained using lightweight materials, like titanium and aluminium, or by creating honeycomb structures.

The fast-growing field of topology optimization (TO) is of special interest to the aerospace industry since it enables the creation of components with reduced structure volume, weight and cost, allowing the generation of more sustainable products. As as matter of fact, TO methods can simultaneously improve structural performance and allow mass reduction by computing the best general shape and arrangement of the structural components when solving a design problem with predefined constraints. Nevertheless, traditional manufacturing processes frequently fail to achieve the designs that result from topology optimization application and therefore AM, for its design freedom and lack of manufacture constraints, emerges as a particularly suited manufacturing process to take full advantage of topology optimization design [3]. Consequently, the combination of TO as a design method and AM is beneficial for the aerospace industry as it presents an opportunity for weight saving and eventually less manufacture costs.

In the past decades, there has been a growing development of missions based on small satellites which led to the development of the CubeSat concept. The CubeSat program was developed in 1999, as a collaboration between Prof. Jordi Puig-Suari, from California Polytechnic State University, and Prof.
Bob Twiggs, from Stanford University. The program’s main goal was the standardization of design of picosatellites [4]. Since the launch of the first CubeSat, several government agencies, like ESA, NASA and others, adopted the CubeSat standard and so encouraged the growth of CubeSat-based missions [5]. Despite the intrinsic challenges to CubeSat missions that still need to be addressed, new research and technological advances will continue to drive the space industry to invest in the utilization of CubeSat platforms both for commercial and scientific purposes [6].

This work aims to develop and optimize the $1U\text{ CubeSat}$ mechanical subsystem and to manufacture the first prototype of the structure with AM.

## 1.2 Objectives

CEiiA introduced the challenge of developing and optimizing a modular structure for a $1U\text{ CubeSat}$, to be used in future space missions. Simultaneously, this work aims to manufacture the prototype of the $1U\text{ CubeSat}$ structure through AM production and further explore the advantages this technology presents, such as mass or component reduction.

The objectives established for this dissertation are:

- Investigate the different Standards and Requirements for the design of a $1U\text{ CubeSat}$;
- Design the $1U\text{ CubeSat}$ mechanical subsystem;
- Perform a topology optimization of the $1U\text{ CubeSat}$;
- Conduct a structural analysis on the $1U\text{ CubeSat}$;
- Simulate the manufacturing process and produce the $1U\text{ CubeSat}$ mechanical subsystem by AM.

## 1.3 Thesis Outline

This thesis is composed by five chapters.

This first chapter consists of an initial introduction to the problem studied throughout this thesis, the motivation behind the development of the $1U\text{ CubeSat}$ mechanical subsystem and the definition of the thesis’ objectives. The second chapter focus on a literature review of all the concepts necessary to support the decisions made throughout this dissertation: a short description of AM processes, structural analysis, topology optimization and small satellites. Chapter 3 presents the main problem addressed in this dissertation and covers the project requirements that shall be considered in the design of the $1U\text{ CubeSat}$ mechanical subsystem, together with a description of the hardware and respective functionalities. Chapter 4 presents the adopted procedure in the TO and finite element analysis of the $1U\text{ CubeSat}$ structure. This chapter also presents the results of the manufacturing process simulation and the experimental tests. Chapter 5 outlines the major achievements of this dissertation and leaves some suggestions for future work.
1.4 CEiiA

CEiiA – Centro de Excelência e Inovação para a Indústria Automóvel - is a centre of engineering and product development created in 1999 with the aim of enhancing the competitiveness of the Portuguese automotive industry. Ever since, CEiiA expanded its activity, and is now developing and implementing original products and systems to promote innovation in several industries such as Aeronautics, Ocean and Space, Mobility and Automotive.

Currently, CEiiA is one of the main R&D investors in Portugal and its main mission is to develop a more competitive industry and simultaneously become an international reference in the sustainable mobility industry. In order to accomplish this, CEiiA works together with a network of universities, scientific institutions and other organizations. Moreover, this non-profit organization is greatly concerned with the community and the development of future generations, supporting the growth of a sustainable environment [7].
Chapter 2

Background

This chapter contains a review of theoretical concepts important for the development of this dissertation. It starts with an introduction of AM, followed by a detailed description of Metal Additive Manufacturing (MAM) and the Selective Laser Melting (SLM) process, explaining its advantages and disadvantages. After, a brief Design for Additive Manufacturing (DFAM) guide was created. Finally, the structural analysis, topology optimization and small satellites topics are introduced and discussed in order to create a foundation for the research work carried out in this dissertation.

2.1 Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing, is an emerging method of manufacturing that is transforming the industrial production by creating lighter, stronger parts and systems and bringing digital flexibility and efficiency to manufacturing operations [2]. The American Society for Testing and Materials (ASTM) has defined AM as a “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [8].

Originally, AM was used as a method of Rapid Prototyping (RP) to rapidly fabricate a scale model of a product under development but nowadays, as the technology evolved, it can produce fully functional parts in an extensive variety of materials such as plastics, resins, metals, wax or ceramics [9, 10].

Despite the fast growth of AM technologies there is still a scarcity of fundamental design principles and standardization of best practices [11]. As as matter of fact, qualification and certification have been recurrently identified as a challenge to widespread adoption of AM components [9, 12]. Hence, in an effort to standardize terminology and processes on a global level several committee forums have been created such as: ASTM F42 Committee, ISO Technical Committee, SASAM Project, BSI Committee and so forth [13].

The use of AM in the space industry, among others, has created the possibility to manufacture entirely new components with complex shapes that were difficult or even impossible to fabricate by traditional methods [12]. Moreover, the continuous development of design optimization tools and process preparation software has allowed the increase of production of AM parts capable of meeting the aerospace
industry’s need for complex, lightweight and optimized structures. Actually, different small satellite structures are being produced with AM materials, not only facilitating the fabrication but also decreasing mass [14]. As an example, the Tomsk-TPU-120, Russia’s first 3D-printed CubeSat, was launched from the International Space Station (ISS) on August 2017 [15].

AM presents great potential for many industries as medicine, architecture, or aerospace since it provides numerous advantages like waste and weight reduction, customization, and others. Accordingly, the 2019 Wohlers Report [16] states that the 3D printing industry grew by 33.5% in 2018, as depicted in Figure 2.1.

![Figure 2.1: AM industry growth [16]](image)

### 2.1.1 Processes

In an effort to develop a comprehensive set of standards on AM and improve communication between AM users, a partnership between ISO and ASTM International led to the creation of ISO/ASTM 52900 [8], in which the current AM processes are grouped in seven categories as follows:

- **Binder jetting**: the particles of powder material are selectively joined using a liquid bonding agent. Once a layer is formed, a new layer is created, and the process is repeated until the part is produced;

- **Directed Energy Deposition (DED)**: focused thermal energy distributed via laser, electron beam or plasma arc is used to melt and fuse material as it is being deposited;

- **Material extrusion**: material is selectively distributed on a platform through a nozzle or orifice that moves in a predetermined path;

- **Material jetting**: droplets of build material are selectively deposited, and UV light is used to cure the droplets before the next layer is created;

- **Powder Bed Fusion (PBF)**: the particles of powder material are selectively fused using a thermal energy source and, once a layer is scanned, the next layer of powder is spread via a rolling mechanism. Subsequently the layer is scanned and fused to the previous layer;
- **Sheet lamination**: sheets of material are joined, through cutting, stacking, and gluing, to form a part;

- **Vat photopolymerization**: liquid photopolymer is selectively cured in a vat through light-activated polymerization.

Binder jetting, Sheet Lamination, **PBF** and **DED** are (MAM) processes, the last two being the most relevant. The SLM technique, which is a PBF process, will be further described in the following sections since it is the technique used in this study.

### 2.2 Metal Additive Manufacturing

AM processes can be categorized with respect to the material feedstock, heat source, the deposition technique, and so forth [10]. Currently, metals and polymers are the two main groups of materials used in AM processes. Although polymers drew the most attention in the early days of AM, the use of metal AM for production applications continues to grow [17]. In fact, revenue from metals grew an estimated 41.9% in 2018, thus keeping revenue above 40% growth per year in the last five years [18].

Bearing in mind the rising use and interest in MAM, a more exhaustive understanding of the relationship between microstructure, processing, and properties for MAM fabricated parts is necessary to produce defect-free and reliable AM parts. As a matter of fact, during manufacture, MAM parts undergo a complex thermal cycle including rapid heat transfer and solidification together with repeated melting. Consequently, greater complexity is introduced to the study of microstructural evolution, with properties usually not found in conventional processes [19].

#### 2.2.1 Powder Bed Fusion

As previously mentioned, PBF is an AM process in which a heat source selectively fuses or melts a region of a powder bed. PBF systems utilise either laser or electron beams as the heat source. These different heat sources require diverse operating atmospheres to minimize degradation of the powder material: an inert atmosphere, for the laser systems, and near vacuum, for the electron beam processes [20]. Additionally, it is commonplace for PBF systems to have infrared heaters located above the build platform and the feed cartridges to sustain a high temperature and simultaneously preheat the powder, reducing the laser power requirements of the procedure and avoiding warping of the part [21].

The PBF process is common to a variety of popular additive printing techniques: electron beam melting (EBM), direct metal laser melting (DMLM), directed metal laser sintering (DMLS), selective laser melting (SLM), selective laser sintering (SLS) [10].

**Selective Laser Melting**

SLM, Figure 2.2, is a PBF technology in which a high powered laser is used to melt metallic powders to build up the part, in agreement with the information provided by a CAD file. The process begins with
the application of a powder layer on the building platform using a recoater. Once the layer is formed and preheated, a laser beam selectively melts the layer of powder to form the 2D cross section. Then, the build platform is lowered by one layer thickness and a new layer of powder is applied with a recoater. This process is repeated and after several cycles, depending on the manufacturing requirements, the part is built. Lastly, the parts are removed from the platform and, if required, undergo extra finishing operations [21–23].

2.2.2 Advantages and Limitations of MAM

MAM is an attractive alternative to traditional processes as it presents numerous benefits for a wide range of applications and can be used in several markets to solve different problems in a rapid and sustainable way. Some of the main advantages of MAM are discussed in more detail below:

- **Production of components with complex geometries and shapes**: MAM allows the creation of parts with geometries that would be difficult or even impossible to obtain using conventional methods. Furthermore, the performance of these new parts is improved [24];

- **Reduction of the number of parts in a product**: the fabrication of more complex parts enables the same product to have a smaller number of parts. Thus, the time and labor required to assemble the final product are lower, also with a reduction in production costs [22];

- **Manufacturing lightweight parts**: with the AM’s geometric freedom to create complex geometries it is often possible to design parts with the same functional specifications but with less material [3];

- **Prototyping**: subtractive methods take longer to produce a prototype, whereas MAM provides the reduction of production steps, speeding up the product design process and facilitating its development [2];

- **Customization**: MAM allows the production of customized parts since it does not require the use of moulds, and the design of parts can simply be changed without any influence on the required tools or machines [25];
• **Reduction of material waste**: only the amount of material required for the final product is used in MAM technologies as opposed to subtractive techniques, therefore minimizing material waste and leaving a small footprint [10];

• **Reduction of tooling**: unlike conventional manufacturing methods, MAM demands the use of tooling only in post-processing treatments, making the process faster and more efficient [24].

In order to take full advantage of MAM technologies and to ensure its rapid growth it is very important to be aware of the obstacles to the implementation of these technologies. The prime challenges to the application of MAM technologies are summarized below:

• **Affordability**: the cost of materials and machinery required to manufacture a part is a strong barrier to the implementation of MAM. On one hand, the price of the printing equipment is high but it is predictable to decrease with new technical developments and more producers accessing the industry. On the other hand, the materials required for MAM are also expensive, showing a huge difference between the cost of materials for traditional methods and for MAM. As in the case of printers, the price of materials is likely to decrease as more options are accessible in the market and companies find ground-breaking ways to manufacture and sell materials for a reduced cost [2];

• **Production time**: in contrast with traditional manufacturing methods, MAM is considerably slow and so these technologies are ideal for mass customization manufacturing and low-volume production. Conventional manufacturing is preferred over MAM for larger series but if progresses are made to increase machine productivity MAM processes may become relevant for mass production [26];

• **Quality and Reliability**: MAM technologies are not able to compete with traditional techniques on reliability or reproducibility, because the parts produced by MAM present small variations in terms of physical properties when compared to the original material. Thus, the variability of MAM processes must be mitigated and a potential solution is the hybrid processing which consists in combining AM and conventional techniques [26];

• **Standards**: Although industry standards for AM qualification are being developed there is still a great lack of regulation that will support the advancement of AM. Moreover, as AM continues to evolve, the creation of standards should keep pace with the innovative developments on this field to enhance its growth. For example, it is mandatory to train and teach engineers about the benefits and restrictions of the different AM processes, the required rules and software to design CAD models for MAM in order to take full advantage of the technology. [10].

### 2.3 Design for Additive Manufacturing

When using AM it is possible to create parts with geometries that would be difficult or even impossible to obtain using conventional methods, as previously stated in 2.2.2. Nevertheless, AM also introduces
limitations to the design of these parts. Consequently, it is of utmost importance to define a set of rules when designing AM parts not only to change the way of thinking of designers but also to optimize the production of AM parts [27].

Design for Additive Manufacturing (DFAM) can be characterised as the engineering practice of designing products to optimize performance through the combination of shapes, structures and materials while considering the capabilities of AM processes. Hence, DFAM demands comprehensive knowledge of AM processes and machines, material behaviour, amongst others, to take full advantage of AM’s potential [28].

In order to attain the purposes of DFAM, several best practices have been established by researchers and companies. These guidelines will be addressed in the following subsections.

**Surface Quality**

The orientation of a part can highly influence the surface quality obtained by AM processes. Defining the angle between the build platform and the tangent line of the part surface as \( \alpha \), surfaces can be characterized according to their orientation: Up-facing \((\alpha > 90^\circ)\), Down-facing \((\alpha < 90^\circ)\) and Middle surfaces \((\alpha = 90^\circ)\) [29].

![Figure 2.3: Build angle \( \alpha \) [29]](image)

Furthermore, the surface quality is also greatly affected by the stair stepping effect. The stair stepping effect is intrinsic to AM technologies due to the layered nature of the method and it is caused by the

![Figure 2.4: Stair stepping effect [29]](image)
offset between two layers of the part. The effect is likely to decrease with increasing inclination angle and to increase with greater layer thickness [30]. On up-facing surfaces the stair stepping effect is more important than on down-facing areas where the formation of dross is predominant. Dross is a mass of molten material with dispersed particles that results from melting on loose powder [29, 31].

The following factors should be reviewed during the design process to further improve surface quality [29, 30, 32]:

• Overhang sections or down-facing surfaces must be avoided since these surfaces usually require support structures, thus presenting high roughness. In fact, for down-facing areas, the larger the angle $\alpha$ the smaller the formation of dross, contributing to better surface quality.

• The stair stepping effect can be effectively reduced by building vertical or horizontal surfaces. Actually, the optimum orientation is at $\alpha = 90^\circ$, presenting best surface quality.

• Features like holes, screw threads or pockets, must be printed in the Z-direction to obtain the best quality possible.

Thermal Stresses

AM parts undergo a complex thermal cycle which involves high melting temperatures when the layers are heated and fast cooling rates when they are cooled down. During the thermal cycle the expansion and shrinking of layers are blocked by other solidified layers, leading to additional residual stress throughout the layers [29]. With the aim of avoiding warp formation caused by the accumulation of residual stresses, support structures are essential to keep the designed model.

The following guidelines are critical to ensure efficient heat transfer and avoid warping [29, 33]:

• Before support removal, heat treatment is necessary to release the stresses that remained in the part after building and thus prevent part deformation.

• Considering that thermal tension is proportional to the melted surface area, one must reduce the melted area per layer, thus opting for small cross-sections. In fact, printing several small sections is more advantageous than printing a large section.

• Taking into account that thermal tension is dependent on the cooling rates during solidification, an efficient heat transfer to the baseplate and machine is crucial to avoid warping of the part.

Supports

Support structures are extremely important for AM as they are used to keep models fixed to the baseplate during an SLM build process and to counter any geometry displacement. Supports can be formed in specialist software for preparing components for various AM technologies and some examples of types of AM support structures are: tree-like support, linear support and lattice supports, etc [29, 34].

Support structures present a major impact on the building process as they reduce dross formation on downfacing regions, allow a more efficient heat transfer, diminish shrink lines and avoid warping, and so
on. Nonetheless, the usage of supports can have implications for the processing and post-processing time, the quality of supported surfaces, and so forth. Therefore, it is always best to minimize the use of supports. The number of supports is related with the orientation of a part and if designers can determine the optimal orientation of a part the support structure may be further improved or even reduced [32]. The self-supporting angle $\alpha_s$ is the minimum build orientation of a self-supporting geometry and it changes according to material and printing process. Down-facing surfaces with $\alpha > \alpha_s$ don’t require support structures, increasing the overall quality of that part. In the case of SLM, $\alpha_s \approx 45^\circ$ [29].

**Small features**

Regarding small features, several design constraints must be considered [29, 32]:

- A minimum gap distance between features is required to avoid the merging of surfaces, and it varies depending on the AM process used.
  - Horizontal holes can be built in a self-supporting position parallel to the build platform but a minimum gap distance must be maintained so that the hole does not close.
  - Vertical holes can be built without supports but their accuracy is very poor. In order to improve accuracy, holes may be designed as near net shape drilling holes for post processing.

- The minimum wall thickness depends on the capabilities of the hardware, like the printer model, the geometries and the AM process.

- Whenever two distinct objects are converging in a layer, shrink lines are formed in the joining surface, pulling the two objects together. As the following layer is printed on original dimensions, the shrink lines are distinguishable in the part. A diverging orientation allows the creation of new entities, eradicating shrink lines.

### 2.4 Structural Analysis

In the interest of solving any engineering problem, several methods such as analytical, numerical or experimental can be applied. In spite of the fact that the analytical method is the one that provides the most accurate solutions, the Mechanical Subsystem of the 1U CubeSat has a too complex geometry for this method. Apart from this, the experimental methods are obligatory for validating the structure but they are not yet applicable because the Mechanical Subsystem is still being developed [35]. As a result, the Finite Element Method (FEM) is the numerical method chosen for this analysis.

#### 2.4.1 Finite Element Method

The Finite Element Method (FEM) is a numerical approach used to determine the approximate solution of the differential equations that describe a physical phenomenon on a defined domain. In other words,
the FEM is utilized for predicting how a real world object reacts to forces, vibrations, among others, and whether the object will break or work the way it was intended.

Bearing in mind that real life objects are continuous and present unlimited degrees of freedom (DOF), the goal of FEM is to divide the body into finite elements, connected by nodes, and obtain an approximate solution. In fact, the process of generating the mesh consists of the discretization of a continuous system with infinite DOF to one with finite DOF. The calculation is performed at the nodes, which are coordinate locations in space where the DOF are defined. With respect to structural analyses, the DOF represent the possible movement of a point due to the loading of the structure. According to Figure 2.5, six degrees of freedom are required to define the position of a point A or B in space: three translations $U_x, U_y$ and $U_z$ and three rotations $\theta_x, \theta_y$ and $\theta_z$. Nevertheless, elements do not always have six DOF per node since the number of DOF depends on the type of element and the type of analysis. The total number of DOF for a mesh model is equal to the number of nodes multiplied by the number of DOF per node [36].

![Figure 2.5: Degree of freedom [35]](image)

In general, the accuracy of the solution is greater when the number of elements increases but, simultaneously, the computer time and the cost also increase. So, there must be a compromise between the desired accuracy of the solution and the computation time required. The FEM predicts the behavior of parts or assemblies with regard to different applications, as for example linear, nonlinear, buckling, thermal, dynamic and fatigue analysis [35, 37].

### 2.4.2 Linear Static Analysis

Generally, three types of analysis methods are considered: static, transient and random vibration analysis. The main focus will be on the static analysis methods, which are used to predict the distribution of loads and displacements throughout a structure when slowly varying forces are applied to it.

On one hand, in linear analyses, the finite element solver will follow a straight line from origin to the deformed state. For instance, with respect to the stress–strain curve portrayed in Figure 2.6, the first stage is the linear elastic region where the stress, $\sigma$, is proportional to the strain, $\epsilon$, obeying the general Hooke’s law:

$$\sigma = E \times \epsilon$$  \hspace{1cm} (2.1)

This equation represents a straight line passing through the origin, with its slope being constant and equal to the Elastic Modulus $E$. It is worth mentioning that stress can also be defined as the force acting
per unit area:

$$\sigma = \frac{F}{A}$$  \hspace{1cm} (2.2)  

Regarding the actual stress–strain curve, the material follows a nonlinear curve after crossing the yield point but software based on linear analysis follows the same straight line and so it is up to the analyst to infer if the structure being examined has failed or not by comparing the maximum stress value with the ultimate stress [35, 37].

![Figure 2.6: Stress–strain curve [35]](image)

On the other hand, for the case of static analysis, the force must be static, meaning that there is no variation with respect to time, and equilibrium conditions must be achieved, with the summation of all external forces and moments being equal to the internal reaction forces and moments.

The basic finite element equation to be solved for structures experiencing static loads can be defined as:

$$[K] \cdot \{u\} = \{F\}$$  \hspace{1cm} (2.3)  

where $K$ is the global stiffness matrix of the structure, $u$ is the displacement vector and $F$ is the external forces vector applied to the structure. This equation expresses the equilibrium between internal and external forces [35].

Following the calculation of displacements at the nodal points of the elements, the strain and stress can be estimated. The strain, $\epsilon$, is characterised as the quotient between elongation, $\delta$, and the original length $l_0$:

$$\epsilon = \frac{\delta}{l}$$  \hspace{1cm} (2.4)

where $\delta = l - l_0$ is the difference between the length of the element once the load is applied and the original length of the element. Once the strain, $\epsilon$, is computed, the stress, $\sigma$, which is assumed to be a linear function of the strain in the linear elastic region, can be calculated by using the constitutive
relation of the material, or Hooke’s law, described as:

$$\sigma = C \cdot \epsilon$$  \hspace{1cm} (2.5)

where $C$ is the elasticity matrix of the material.

Considering equation 2.3, the force is usually known, the displacement is unknown, and the stiffness is a very important property that depends on the geometry and the material employed. Once the stiffness matrix for a given shape is formulated, then the analysis can be performed by meshing it and then solving Equation 2.3 [35, 36].

### 2.5 Topology Optimization

Topology optimization is a process that consists in finding the optimal approach to place material within a specified design domain with the purpose of obtaining the greatest structural performance. The general topology optimization problem can be written in mathematical form as:

$$\begin{align*}
\text{Minimize } \rho : F &= F(u(\rho), \rho) = \int_{\Omega} f(u(\rho), \rho) dV \\
\text{Subject to } G_0(\rho) &= \int_{\Omega} \rho(x) dV - V_0 \leq 0 \\
&: G_j(u(\rho), \rho) \leq 0, j = 1, \ldots, m \\
&: \rho(x) = 0 \text{ or } 1, \forall x \in \Omega
\end{align*}$$  \hspace{1cm} (2.6)

where $F_0$ is the objective function to be minimized, $\Omega$ is the design domain, $G_0$ is a volume constraint and $G_j$ are other possible constraints to which the objective function is subjected, $\rho(x)$ is the material distribution, $f$ is a local function and $u$ is the state field which satisfies the state equation. The optimization problem consists in finding the material distribution, $\rho(x)$, that minimizes the objective function $F_0$, subject to different constraints $G_0$ and $G_j$ [38, 39].

There are four distinct types of topology optimization: density-based methods, hard-kill methods, boundary variation methods and biologically inspired methods [40]. The method addressed in this dissertation is a density-based method called Solid Isotropic Material with Penalization (SIMP).

The main purpose of SIMP is to minimize the objective function $F_0$ on a predetermined design domain, by determining whether each element consists of a void or solid material. The SIMP method keeps a fixed finite element discretization where each finite element is associated with a density distribution $\rho(x)$ whose value lies between zero and one. When $\rho(x) = 0$ it denotes a void and when $\rho(x) = 1$ it denotes a solid, whereas the values between zero and one are termed as intermediate densities. These intermediate densities are considered as artificial material that cannot be achieved in practice and therefore it is necessary to penalize these densities, forcing the solution to be 0 or 1. In the SIMP method the
The relation between the density design variable and the material property is as follows:

\[ E_e(\rho(x)) = \rho(x)^p \cdot E_0 \]  

(2.7)

where \( p \) is the penalization parameter, \( E_0 \) is the elastic modulus of solid material and the \( E_e(\rho(x)) \) is the elastic modulus of the element [38]. The penalization parameter \( p \) is imposed to every element's stiffness as shown in the following Equation 2.8:

\[ K_e = \rho(x)^p \cdot K_0 \]  

(2.8)

where \( K_e \) is the stiffness of the element, \( p \) the penalization parameter and \( K_0 \) is the stiffness of the material [39, 40]. According to [40], the lowest allowable penalization parameter \( p \) for a three-dimensional analysis is three and can be defined as:

\[ p \geq \max\{15 \left(1 - \frac{1}{7 - 5\nu^0}\right), \frac{3}{2} \left(1 - \frac{1}{2\nu^0}\right)\} \]  

(2.9)

where \( \nu^0 \) is the Poisson ratio of the material.

The fast-growing field of topology optimization is of special interest to industries such as the Automotive and Aerospace because it enables the creation of components with reduced structure volume, weight and cost, allowing the generation of more sustainable products. Nevertheless, traditional manufacturing processes frequently fail to achieve the designs with complex geometries and shapes that result from the application of topology optimization and thus additive manufacturing, for its design freedom and lack of manufacture constraints, emerges as a particularly suited manufacturing process to take full advantage of topology optimization design [3]. As a matter of fact, the combination of AM with topology optimization is being developed with the objective of making the most of both technologies. As an example, Figure 2.7 exhibits an optimized Airbus A320 nacelle hinge bracket to be manufactured it by AM. While the original part weighted 918 g, the optimized bracket weights 326 g, showing a 64% weight reduction. This example certainly highlights the benefits of combining topology optimization with AM [41].

![Figure 2.7: A320 nacelle hinge bracket before and after topology optimization [41]](image)
2.6 Small Satellites

An artificial satellite is by definition an artificial body intentionally launched into space and that orbits around a planet or another body to gather information or to facilitate communications [42]. Satellites can be classified by different ways: their mission, mass, type of orbit, and so forth. The mass based classification in Table 2.1 has become widely adopted [43].

<table>
<thead>
<tr>
<th>Class</th>
<th>Mass Range [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Satellite</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>Medium Satellite</td>
<td>500 – 1000</td>
</tr>
<tr>
<td>Minisatellite</td>
<td>100 – 500</td>
</tr>
<tr>
<td>Microsatellite</td>
<td>10 – 100</td>
</tr>
<tr>
<td>Nanosatellite</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Picosatellite</td>
<td>0.1 – 1</td>
</tr>
<tr>
<td>Femtosatellite</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Table 2.1: Classification of satellites by the mass [43]

As can be seen in Table 2.1, mini, micro, nano, pico and femto-satellites weigh less than 500 kg and can be defined as small satellites. In the past decades, there has been a growing development of missions based on the this class of satellites spurred by an increased interest in smaller missions and also by the microminiaturization of electronics [44]. Subsequently, this trend led to the rise of small satellites and ultimately to the development of the CubeSat concept, a subclass of small satellites.

2.6.1 CubeSat

The CubeSat program was developed in 1999, as a collaboration between Prof. Jordi PuigSuari, from California Polytechnic State University, and Prof. Bob Twiggs, from Stanford University. The program’s aim was the standardization of design of picosatellites, thereby reducing expenses and accelerating the development cycle. Simultaneously, the program would provide universities with access to space through small payloads, allowing students to develop, launch and operate small spacecrafts [4].

As stated in the CubeSat Design Specification (CDS) [4], "a CubeSat is a 10 cm cube with a mass of up to 1.33 kg". They are measured in units \( U = 10 \times 10 \times 10 \, \text{cm}^3 \) and this form factor ranges from \( 1U \) up to \( 12U \), although new configurations are under development. As depicted in Figure 2.8, CubeSats can either be used as a standalone satellite or as a combination of several cubes [45].

Since the launch of the first CubeSat in 2003 several government agencies, like ESA, NASA, NSF and others, adopted the CubeSat standard and so encouraged other entities to use the standard, leading to the growth of CubeSat-based missions [46]. Indeed, as reported by SpaceWorks, 294 nano/microsatellites will be launched in 2019, showing a 17% growth compared to 2018. Additionally, SpaceWorks predicts 2,000 to 2,800 nano/microsatellites will be launched in the next 5 years, as evidenced in Figure 2.9 [5].

CubeSats are progressively shifting from educational tools or technology demonstrating platforms to
real science or commercial missions, creating the opportunity for missions with high scientific return or revenue and with less costs than traditional missions [5, 47]. Despite the intrinsic challenges to CubeSat missions that still need to be addressed, new research and technological advances will continue to drive the space industry to invest in the utilization of CubeSat platforms both for commercial and scientific purposes [6].

Furthermore, the CubeSat Design Specification (CDS), published by the California Polytechnic State University, defines the requirements that a CubeSat shall meet to ensure a safe deployment in the launch vehicle. For the purpose of designing the CubeSat’s structure, the general requirements expressed in the CDS shall be taken into consideration. Also, the CDS document defines the testing requirements the CubeSat shall satisfy to be launched [4].
2.6.2 P-POD

The Poly Picosatellite Orbital Deployer (P-POD), developed by the California Polytechnic State University, was selected as the CubeSat’s container. The P-POD is a standard deployment system whose primary goal is to guarantee the safety of the CubeSat, the launch vehicle and other payloads while providing a common interface between CubeSat and launch vehicle. The P-POD presents a tubular design and can carry deployable hardware up to 340.5mm x 100mm x 100mm, corresponding to three 1U CubeSats. This deployer weighs 3kg and is made of Aluminum 7075-T73. CubeSats are launched into space by the P-POD once a control signal from the launch vehicle is sent to the P-POD door’s mechanism thereby opening the door and activating the spring mechanism. Ultimately, CubeSats are deployed by the deployment spring, sliding through the P-POD’s rails [48].

![Poly Picosatellite Orbital Deployer](image)

Figure 2.10: Poly Picosatellite Orbital Deployer [48]

2.6.3 Vega Launcher

![VEGA’s stages](image)

Figure 2.11: VEGA’s stages [49]
The Vega launch system was adopted as the CubeSat's launcher. Vega was developed by ESA and the Italian Space Agency and was first launched in February 2012 at the Guiana Space Centre. This launch vehicle was designed with the goal of launching small satellites for scientific and Earth observation missions [50]. Vega offers a payload capacity of 1500 kg in low Earth orbit and comprises three stages with solid rocket motors and the fourth stage, AVUM, is a liquid rocket, as evidenced in Figure 2.11 [49].

2.6.4 General System Architecture

A CubeSat can be divided into three segments: the ground segment, the launch segment and the space segment, according to Figure 2.12. First, the ground segment comprises the communication between the vehicle and the ground station. Secondly, the launch segment includes the launch vehicle responsible for the transportation of the spacecraft to orbit. Lastly, the space segment can be split into two modules: the payload and service module. The payload module covers all the equipment specific for the mission and the service module combines the subsystems necessary for its operation. The service module consists of 6 subsystems: the Mechanical Subsystem and Structures (MSS), the Thermal Control subsystem (TCS), the Electrical Power subsystem (EPS), the Attitude Determination and Control subsystem (ADCS), the Command and Data Handling subsystem (CDH) and the Telemetry, Tracking and Control subsystem (TTC) [51].

![Architecture diagram of the CubeSat system](image)

**Figure 2.12: Architecture diagram of the CubeSat system [51]**

**Electrical Power Subsystem (EPS)**

The EPS subsystem generates, stores and supplies electricity to all subsystems. In other words, it is the power source of the entire system. Besides, it is important to highlight that this subsystem includes solar arrays and batteries which are extremely important since the spacecraft needs on board energy storage.
capacity to deliver power in periods of eclipses or to satisfy peak power requirements of the avionics.

**Attitude Determination and Control Subsystem (ADCS)**

The ADCS subsystem controls and monitors the rotation of the spacecraft about its center of mass, by measuring and stabilizing the satellite’s orientation through the use of attitude and orbit sensors, attitude control actuators and controllers.

**Command and Data Handling Subsystem (CDH)**

The CDH subsystem, consisting of the on board computer, is a vital subsystem of the spacecraft as it receives, decodes, and distributes commands to the remaining subsystems. Additionally, it is responsible for management, storage and control of all ground commands, payload data and telemetry.

**Telemetry, Tracking and Control Subsystem (TTC)**

The TTC subsystem, composed of an antenna and a transceiver, allows the communication between the ground station and the satellite by, for instance, receiving satellite position and sending commands from Earth.

**Mechanical Subsystem and Structures Subsystem (MSS)**

The MSS subsystem comprises the primary structure of the spacecraft that mechanically supports all its subsystems while taking into account the payload requirements and the launch vehicle selected. Generally, CubeSat structures are made of aluminum and, as a result of the development of AM, these structures are being manufactured with this method and applied on multiple missions.

**Thermal Control Subsystem (TCS)**

Taking into consideration that the spacecraft may suffer severe temperature changes for short periods of time, the TCS subsystem is crucial for the CubSat’s service and payload modules since it can regulate and maintain the temperature range of payload and BUS modules.
Chapter 3

Implementation

This chapter presents the main problem addressed in this dissertation and provides a list of the project requirements that shall be considered in the design of the mechanical subsystem, together with a description of the hardware and respective functionalities. When designing a new satellite structure various factors must be considered in order to guarantee that the final design will meet all of its objectives. Regarding the design of the 1U CubeSat, the project requirements were divided into Mission requirements, previously established by CEiiA [51], and Design requirements, set in accordance with the CubeSat Design Specifications (CDS) [4].

3.1 Problem Description

CEiiA introduced the challenge of developing and optimizing a modular structure for a 1U CubeSat to be used in future space missions. In parallel with this, the objective was also to produce the structure by AM to exploit the advantages this technology presents, such as mass or component reduction.

In the interest of achieving the objectives of this dissertation, CEiiA provided a set of CAD files representing the structure of a 1U CubeSat already developed in accordance with the specifications outlined in Appendix A and B. In addition, documentation related to the launch opportunity on a Vega flight, which specifies the loads the satellite must endure during launch, was also given [52]. With the information supplied by CEiiA and the requirements set in this Chapter it was possible to proceed to the design and simulation of the 1U CubeSat Mechanical Subsystem and Structures (MSS).

3.2 Mission Requirements

Starting with mission requirements, Table 3.1 presents the requirements defined in conformity with payload and subsystems specifications in order to fulfill all mission objectives [51].

According to the Table 3.1, requirements No. 4,5,6,7 and 8 express the necessity to select the Service Module subsystems. In this way, the choice of hardware for the CubeSat 1U was proposed by CEiiA and based on the architecture previously defined in the Subsection 2.6.4. Starting with the TTC
<table>
<thead>
<tr>
<th>No.</th>
<th>Mission Requirements</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The spacecraft design shall follow the CubeSat Design Specifications (CDS)</td>
<td>Technological</td>
</tr>
<tr>
<td>2</td>
<td>Commercial off-the-shelf (COTS) components will be preferred</td>
<td>Educational</td>
</tr>
<tr>
<td>3</td>
<td>The payload's volume shall be less than 1U</td>
<td>Payload</td>
</tr>
<tr>
<td>4</td>
<td>The spacecraft shall contain an EPS</td>
<td>Subsystem</td>
</tr>
<tr>
<td>5</td>
<td>The spacecraft shall contain an AOCS</td>
<td>Subsystem</td>
</tr>
<tr>
<td>6</td>
<td>The CubeSat shall contain a TTC</td>
<td>Subsystem</td>
</tr>
<tr>
<td>7</td>
<td>The CubeSat shall contain a CDH</td>
<td>Subsystem</td>
</tr>
<tr>
<td>8</td>
<td>The CubeSat shall contain a MSS</td>
<td>Subsystem</td>
</tr>
</tbody>
</table>

Table 3.1: Mission requirements

subsystem, it consists of a NanoCom ANT430 Antenna and a NanoCom AX100 Transceiver [53, 54].

Figure 3.1: NanoCom ANT430 Antenna and NanoCom AX100 Transceiver [53, 54]

Secondly, the CDH subsystem is composed of a NanoMind A3200 On-Board Computer [55].

Figure 3.2: NanoMind A3200 On-Board Computer [55]

Additionally, the ADCS subsystem requires a NanoTorque GST-600 Magnetorquer [56].

Figure 3.3: NanoTorque GST-600 Magnetorquer [56]

Finally, the EPS subsystem comprises a NanoPower P31u Electric Power System and six Solar Panels, two NanoPower P110C and four NanoPower P110B [57, 58].
Figure 3.4: NanoPower P31u EPS and NanoPower P110C Solar Panel [57, 58]

All the selected components are manufactured by GOMspace and a summary of their physical characteristics is presented in the next Table 3.2.

<table>
<thead>
<tr>
<th>Components</th>
<th>Mass [g]</th>
<th>Dimensions [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NanoCom ANT430</td>
<td>30</td>
<td>98 x 98 x 110</td>
</tr>
<tr>
<td>NanoCom AX100</td>
<td>24.5</td>
<td>65 x 40 x 6.5</td>
</tr>
<tr>
<td>NanoMind A3200</td>
<td>24</td>
<td>65 x 40 x 7.1</td>
</tr>
<tr>
<td>NanoTorque GST-600</td>
<td>156</td>
<td>90.5 x 96.9 x 17.2</td>
</tr>
<tr>
<td>NanoPower P31u</td>
<td>200</td>
<td>89.3 x 92.9 x 25.6</td>
</tr>
<tr>
<td>NanoPower P110B</td>
<td>26</td>
<td>82.6 x 98 x 1.1</td>
</tr>
<tr>
<td>NanoPower P110C</td>
<td>29</td>
<td>98 x 98 x 1.1</td>
</tr>
</tbody>
</table>

Table 3.2: Components physical characteristics [53–58]

### 3.3 Design Requirements

Once the mission requirements were identified, it was necessary to establish the design requirements. Consequently, a launcher and a container for the CubeSat 1U had to be adopted. The Vega Launcher, described in the Subsection 2.6.3, was selected as the launcher and the P-POD, described in the Subsection 2.6.2, was selected as the CubeSat container [48]. Subsequently, the general requirements specified in the CubeSat Design Specification (CDS) shall be taken into consideration to ensure a safe deployment [4]. In addition, it was imperative to define the hardware stacking method with the purpose of later designing the structure of the CubeSat 1U. Thus, the PC/104 staking method, standardized in 1992 by the PC/104 Embedded Consortium, was the chosen one [59]. Taking everything into account, from the CubeSat Design Specification (CDS), the standard PC/104 requirements, to the VEGA Launcher and P-POD requirements, the Design Requirements are outlined on the Table 3.3.
<table>
<thead>
<tr>
<th>No.</th>
<th>Design Requirements</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Structural Subsystem shall integrate all the spacecraft equipment</td>
<td>Subsystem</td>
</tr>
<tr>
<td>2</td>
<td>The Structural Subsystem shall ensure the integration within the P-POD</td>
<td>Subsystem</td>
</tr>
<tr>
<td>3</td>
<td>The origin of the coordinate system is located at the geometric centre of the CubeSat</td>
<td>CDS</td>
</tr>
<tr>
<td>4</td>
<td>The maximum mass of a 1U CubeSat shall be 1.33 kg</td>
<td>CDS</td>
</tr>
<tr>
<td>5</td>
<td>No components shall exceed 6.5 mm normal to the surface</td>
<td>CDS</td>
</tr>
<tr>
<td>6</td>
<td>Rails shall have a minimum width of 8.5mm</td>
<td>CDS</td>
</tr>
<tr>
<td>7</td>
<td>Rails shall have a surface roughness less than 1.6 $\mu$m</td>
<td>CDS</td>
</tr>
<tr>
<td>8</td>
<td>The edges of the rails will be rounded to a radius of at least 1 mm</td>
<td>CDS</td>
</tr>
<tr>
<td>9</td>
<td>Only the rails shall touch the inside of the P-POD</td>
<td>CDS</td>
</tr>
<tr>
<td>10</td>
<td>The ends of the rails on the $\pm$ Z face shall have a minimum surface area of 6.5 mm x 6.5 mm contact area for neighboring CubeSat rails</td>
<td>CDS</td>
</tr>
<tr>
<td>11</td>
<td>The CubeSat center of gravity shall be located within 2 cm from its geometric center in the X, Y and Z direction.</td>
<td>CDS</td>
</tr>
<tr>
<td>12</td>
<td>Aluminum 7075, 6061, 5005, and/or 5052 will be used for both the main CubeSat structure and the rails.</td>
<td>CDS</td>
</tr>
<tr>
<td>13</td>
<td>The CubeSat rails shall be hard anodized aluminum to prevent any cold welding within the P-POD</td>
<td>CDS</td>
</tr>
<tr>
<td>14</td>
<td>The CubeSat shall use separation springs to ensure adequate separation</td>
<td>CDS</td>
</tr>
<tr>
<td>15</td>
<td>The Subsystems shall be distant from each other 15.24mm</td>
<td>PC/104Plus</td>
</tr>
<tr>
<td>16</td>
<td>The Structural Subsystem must withstand the longitudinal and lateral loads imposed by the launcher during all the phases of ascension</td>
<td>VEGA</td>
</tr>
</tbody>
</table>

Table 3.3: Design requirements
Chapter 4

Results

This chapter presents the adopted procedure in the TO of the 1U CubeSat structure, along with the definition of simulation conditions such as the material, loads, constraints and meshing. Furthermore, the finite element analysis of the 1U CubeSat structure and its results are presented. This chapter also presents the results of the manufacturing process simulation and the experimental tests.

4.1 Structural Design

Initially, an analysis of the solution developed by CEiiA was performed. The developed structure consists of six components: four ribs and two side frames, as depicted in Figure 4.1. Moreover, the solution is composed of an Al7075 aluminum alloy and weighs approximately 85 g, not counting with the mounting components. This solution requires a mounting system for the electronic components previously defined in the Chapter 3 which weighs around 20 g. Therefore the overall solution weighs approximately 105 g. The structure developed by CEiiA was designed to be manufactured by conventional methods. However, the goal of the new solution is to create a structure that can be manufactured by AM, with the purpose of reducing the number of components or the mass. It is important to emphasize that since the solution of CEiiA is already developed and optimized, mass reduction is highly unlikely to occur and therefore the focus is on component reduction.

Subsequently, it was necessary to define a solution for the assemblage and disassemblage of the systems inside the 1U CubeSat, bearing in mind that the part will be manufactured by AM and the goal is to reduce the number of components and consequently the complexity of assembly. Although the satellite could be built in one piece, it would be impossible to install the Service Module subsystems inside the structure since most of them are larger than the distance between the rails. Thus, as the structure has a cubic shape and access to the interior of the cube is required for the assembly of the Service Module Subsystems, the structure must be separated into at least two components.

In the case of the new solution, the structure was divided into two L-shaped components and has incorporated drawers to hold the electronic components inside the CubeSat, as shown in the Figure 4.2. This new solution has the advantage of using the systems supports both as supports for the systems...
and as fixing points for the two L-shaped components, allowing a reduction of mounting components and consequently of mass. Therefore, it was possible to reduce not only the number of components from six to two but also the assembly components. The dimensions of the 1U CubeSat and the height between the drawers were defined in accordance with design requirements from Table 3.3, Section 3.3 and the specifications from Appendix A. The software used to design the structure was CATiA®, from Dassault Systemes [60].

After the integration of all the Service Module Subsystems and the design of the Mechanical subsystem, the preliminary design of the 1U CubeSat was concluded, as represented in Figure 4.2.

4.2 Topology Optimization

As previously mentioned in Section 2.5, topology optimization is a method that involves finding the optimal approach to place material within a specific domain with the aim of obtaining the best structural performance possible. The Fusion 360 software from Autodesk was used to perform the topology optimization process of the new 1U CubeSat structure. This software has a density-based optimization tool that improves the design process and enables the creation of geometries ideal for additive manufacturing [40, 61].
Considering that the Fusion 360’s tool does not allow the simulation and topology optimization of assemblies, the two L-shaped components, Figure 4.2, were united in CATiA so as to form a single solid capable of being subjected to simulation. The geometry, previously defined in Section 4.1, underwent through some changes like the creation of holes in the drawers and also in the satellite walls to accommodate the solar panels. In fact, small perforations were designed in the drawers, to house the endless screws that secure the electronic components inside the CubeSat, and in the walls, to create mounting points for the six solar panels and the antenna. Apart from this, the drawers were simplified by reducing their volume, as portrayed in Figure 4.3. The proposed new model weighs 0.202 kg and the next step is to reduce its weight while optimizing its shape. In this manner, the geometry was imported into Fusion 360 and, in simulation mode, topology optimization was chosen.

![Figure 4.3: 1U CubeSat model before topology optimization](image)

### 4.2.1 Material

The first step of the topology optimization process was to define the material under study. Thereby taking into account requirement number twelve from Table 3.3, Section 3.3, aluminum alloys must be used in the construction of the Mechanical Subsystem and Structures (MSS) Subsystem. Besides, NASA suggests the use of materials with low melting points for the CubeSat design because if the satellite survives reentry it can pose a risk to the population [62].

<table>
<thead>
<tr>
<th>Material: AlSi10Mg − A</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>2669.99</td>
</tr>
<tr>
<td>Young Modulus [MPa]</td>
<td>75000</td>
</tr>
<tr>
<td>Yield Strength [MPa]</td>
<td>190</td>
</tr>
<tr>
<td>Ultimate Tensile Strength [MPa]</td>
<td>330</td>
</tr>
</tbody>
</table>

Table 4.1: AlSi10Mg − A Mechanical properties [63]

In this case, Aluminum AlSi10Mg − A powder was the material chosen to produce the parts on
the Trumpf machine. The mechanical properties of the $\text{AlSi}_{10}\text{Mg} - A$ powder\(^1\), printed at $0^\circ$, were introduced into the material library of *Fusion* 360, as summarized in Table 4.1 [63].

Furthermore, the chemical composition of this powder, expressed as a percentage, is:

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Ni</th>
<th>Zn</th>
<th>Pb</th>
<th>Ti</th>
<th>Sn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.0-11.0</td>
<td>$\leq$ 0.55</td>
<td>$\leq$ 0.05</td>
<td>0.2-0.45</td>
<td>$\leq$ 0.05</td>
<td>$\leq$ 0.1</td>
<td>$\leq$ 0.05</td>
<td>$\leq$ 0.05</td>
<td>$\leq$ 0.05</td>
<td>$\leq$ 0.1</td>
<td>Rest</td>
</tr>
</tbody>
</table>

Table 4.2: Chemical composition of $\text{AlSi}_{10}\text{Mg} - A$ powder [weight %]

### 4.2.2 Loads and Point Masses

As mentioned earlier in Section 3.3, the structural subsystem must resist the longitudinal and lateral loads imposed by the VEGA launcher during all the phases of ascension. Hence, as stated in VEGA’s User Manual [49] and in Announcement of Opportunity on a Vega Flight [52], the CubeSat will lay down horizontally on the lower module of the VEGA launcher and it will experience the highest loads during the launch sequence. Considering the coordinate system set in Appendix A, the peak quasi-static accelerations in the lateral Y axis of the CubeSat are $14.5 \, g$ in compression and $10.5 \, g$ in tension. On the other hand, the maximum lateral loads are $3 \, g$ in the X and Z axis, both in compression and tension, as shown in Figure 4.4. Taking this into consideration, the loads were set as gravity loads in *Fusion* 360, which are basically gravity acceleration vectors, and a gravity acceleration of $9.807 \, m/s^2$ was assumed to calculate the accelerations experienced by the satellite. Ultimately, all these critical loads that the satellite must endure during launch are summarized in Table 4.3. These scenarios are in accordance with the information presented in Appendix B and will result in six different TO simulations.

![Figure 4.4: Loads acting on the CubeSat inside the VEGA launcher](image)

In the interest of simplifying the simulation, it was essential to calculate the positions of the center of gravity of each electronic component and its attachments to the structure. Thus, the physical characteristics of each electronic component summarized in Table 3.2, Section 3.3, were taken into account to assign the respective point masses. In fact, the Auto Point Mass functionality was used to represent the electronic components within the model through equivalent point masses. Firstly, the points masses are

---

\(^1\)Based on the datasheet released by CEiiA’s supplier Trumpf
Table 4.3: Gravity loads requirements for the VEGA launcher

<table>
<thead>
<tr>
<th>Gravity load</th>
<th>g</th>
<th>a [m/s²]</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.5</td>
<td>142.202</td>
<td>0</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>102.974</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>29.421</td>
<td>+1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>29.421</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

placed at the centroids of the bodies they represent. After, the faces within the model to where the point masses are attached are selected. Lastly, the point masses are automatically determined based on the volume, shape, and material density of each electronic component. Figure 4.5 shows all the mass points applied inside the model.

![Figure 4.5: Point masses inside the CubeSat](image)

### 4.2.3 Constraints

After the critical loads were identified, the constraints must be applied to the structure. Consequently, and based on the design requirements described on Section 3.3, the CubeSat is not fixed inside the P-POD and solely its rails touch the deployer. As a result the satellite will only be simply supported. Accordingly, for each gravity load, constraints were applied on surfaces opposite to the movement, blocking it in that direction. Besides that, the rails vertices were constrained in the other two directions to avoid infinite displacement of the part. Taking the fifth gravity load from Table 4.3 as an example, acceleration is acting in the X direction and so the surfaces opposite to the movement are constrained in the X direction and the rails vertices in the Y and Z directions, as reflected in Figure 4.6. The same happens in the other cases except for loads 3 and 4 where the acceleration is applied to rails vertices in the Z direction and so the rails vertices are constrained in the Z direction and the edges of the rails are constrained in the X and Y direction. Furthermore, as the simulation will remove material from the model displayed in Figure 4.3, Section 4.2, it is required to ensure that material will remain present around critical areas of the model. In this way, the “Preserve Region” functionality was used to define the
areas of material to be preserved in the structure. In the case of the 1U CubeSat, the critical zones that must be preserved are the Cubesat rails and edges, the holes in the drawers to secure the electronic components and the holes in the Cubesat walls to accommodate the solar panels. As an example, Figure 4.7 exhibits the preservation of the rails.

![Figure 4.6: Boundary conditions for the fifth gravity load](image)

![Figure 4.7: Preserved rails region](image)

### 4.2.4 Meshing

As discussed in the Subsection 2.4.1, the main goal of FEM is to divide a body into finite elements, which in turn are connected by nodes, and therefore obtain an approximate solution for the differential equations that describe and predict how the body will react to a physical phenomenon on a defined domain. Accordingly, the mesh consists of a group of elements, which in turn are formed by the nodes where the calculations are performed [35, 37].

The creation of the mesh is essential to the finite element analysis because the quality of the mesh directly influences the quality of the results generated [35, 64]. As a result, the next step is to define the mesh element type and size. Currently, the solid elements available in Fusion 360 are tetrahedral. In Fusion 360 there are two types of parabolic tetrahedral elements, with or without curved edges. In
other words, for elements with curved edges, the middle nodes do not have to lie on a straight line that connects the corner nodes but on the actual surface of the curved face. For this reason, curved mesh elements conform more accurately along curved geometry and therefore increase the simulation accuracy. For this model, parabolic tetrahedral elements with curved edges were chosen, composed of four triangular faces and six edges each. These elements connect four nodes at the corners plus a mid-side node along each edge, resulting in a total of ten nodes per element, as depicted in Figure 4.8. However, the size of the elements depends on the number of elements required for the model. In this case, the smallest possible size was assigned to the mesh. The finest mesh possible was used because the simulation was performed in the cloud, which allowed to greatly reduce the computation time and simultaneously the mesh quality to be superior.

![Parabolic tetrahedron element in Fusion 360](image)

**Figure 4.8: Parabolic tetrahedron element in Fusion 360**

### 4.2.5 Optimization Results

Prior to the simulation, the shape optimization target mass was set to 50%, which is not a fixed value and may vary after the simulation. Eventually, the analysis was solved on cloud and the Load Path Criticality result was reviewed so as to identify the regions in the model that were critical in resisting the applied loads. The Load Path Criticality is a discrete variable that ranges from 0 to 1, with 1 representing red regions in the model that are critical in resisting the applied load and 0 representing blue regions that are not critical in resisting the applied load.

In view of this, several iterations were performed for all the gravity loads presented in Table 4.3 and, by way of example, both the first and final results for the first gravity load are illustrated in Figures 4.9 and 4.10, respectively. It is worth noting that in the first simulation performed, if the target mass were minimal, the Load Path Criticality would be close to 1 and almost all of the structure material would be removed, with only the rails remaining. This means that the rails of the 1U CubeSat structure would be enough to withstand the gravity loads to which the structure is submitted. In spite of this, the result obtained would not form a viable structure and further studies were conducted. Moreover, it should be pointed out that this was an iterative process that proved to be slightly time consuming and the result presented in Figure 4.10 is its last iteration. As evidenced in the Figures 4.9 and 4.10, the first result presents the original model with 0.202 kg whereas the last result shows the new developed model with 0.099 kg, thereby achieving the goal of weight reduction through topology optimization.
Once the result depicted in Figure 4.10 is accepted, the mesh generated will be used as a template for making modifications to the original geometry. In fact, the mesh is exported to the design workspace and is automatically superimposed on the original model design, as illustrated in Figure 4.11. Subsequently, closed sketch objects are created around the material to be removed and after cut out to leave only the required geometry. On one hand, for example, the side walls are symmetrical and the same sketch was made on the walls, with holes being created between the drawers. On the contrary, the top and bottom walls show no symmetry and different sketches were drawn on the two walls. Finally, the model developed from the last result of the topology optimization simulation is presented in Figure 4.12 and, as demonstrated in Figure 4.10, the mass is now 49% of the original, resulting in a structure with 99g.

The geometry created from the topology optimization simulation performed in Fusion 360 was then reproduced in CATiA and applied to the two L-shaped components separately, as seen in Figure 4.13.

Comparing this solution with the structure initially proposed by CEiiA, which weighs 85g, a mass increase of 16% is noticed. However, considering that the drawers incorporated in the new solution
replace the rods used for mounting the nanodocks, according to the PC/104 staking method, and these in turn weigh 20g in total, this means that actually there is a mass reduction achieved with the new solution. Bearing in mind that the structure proposed by CEiiA together with the rods would weigh approximately 105g and that the new developed solution, which integrates drawers that replace these rods, weighs 99g, there is actually a 6% mass reduction. The solution currently proposed by CEiiA and the new result obtained through topology optimization are represented in Figure 4.14.

With reference to the geometries shown in the Figure 4.14, the number of components required for the 1U CubeSat mechanical subsystem and their approximate weight, for both the current and new solutions, are presented in Table 4.4. In addition, a comparison is made between the current and new solutions in terms of number of components and respective weight, and it can be concluded that the new solution accomplishes both weight reduction of 6.0% and component reduction from 6 to 2. In conclusion, with this topology optimization tool it was possible to achieve a lighter structure and with fewer assembly components, which is of the utmost importance in the space industry, where there is a growing interest in optimizing structures in terms of weight [14]. Then, the new solution must be tested and validated for all the gravity loads previously defined in Table 4.2.2.

<table>
<thead>
<tr>
<th></th>
<th>Current Solution</th>
<th>New Solution</th>
<th>Δ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of components</td>
<td>6</td>
<td>2</td>
<td>66.7</td>
</tr>
<tr>
<td>Total weight [kg]</td>
<td>0.105</td>
<td>0.099</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 4.4: Comparative analysis between the current and the new solutions
4.3 Structural Analysis

As mentioned in the previous Subsection 4.2.5, the objective of the topology optimization study was to reduce the weight of the model to approximately 50% of the original weight and to maximize its stiffness. Nevertheless, a static stress analysis is required to verify if the stress and displacement of the final model, Figure 4.13, meet the design requirements. For this reason, to validate the model obtained it is indispensable to simulate its behavior when the critical loads, defined in Subsection 4.2.2, are applied, in order to verify that no failures occur during its use, such as fracture or even permanent plastic deformation. Accordingly, *Autodesk Fusion 360* software was used again, this time to perform a static stress study capable of validating the previously obtained model.
### 4.3.1 Definition of Simulation Conditions

The first step of the static stress analysis was to define Aluminum $AlSi10Mg - A$ as the material under study, assuming the properties previously defined in Table 4.1. After the material was defined, the forces and respective constraints, formerly defined in Subsections 4.2.2 and 4.2.3, were applied to the 1U CubeSat structure. As a consequence, six different simulations were performed for each of the gravity loads enumerated in the Table 4.3, Subsection 4.2.2. In addition, for the static stress study, a seventh simulation was performed in which the gravity load vector was defined as the sum of $14.5g$ on the $y$ axis, $3g$ on the $x$ axis and $3g$ on the $z$ axis. This last simulation represents the case that will probably be more critical for the 1U CubeSat structure since the satellite is subjected to the greatest gravity load vector possible [52]. As depicted in Figure 4.15, the structure of the 1U CubeSat with the applied loads and respective constraints, for the seventh simulation, is displayed. Likewise, the electronic components within the model were represented through equivalent point masses for each simulation, as explained in the Subsection 4.2.2.

Prior to the simulation it was still necessary to determine the mesh parameters which are responsible
for ensuring a higher quality in the simulation results. As discussed in Subsection 4.2.4, the elements used in Fusion 360 are parabolic tetrahedral elements with curved edges and it is essential to estimate their most suitable size for the 1U CubeSat model. From this perspective, one must compute the most appropriate density of elements for the CubeSat model through a mesh convergence study, to ensure the accuracy of simulation results.

In this way, the entire CubeSat structure was used for the convergence study and the gravity load number one from Table 4.3, Subsection 4.2.2, was chosen. In order to find the dimensions of the mesh for which the displacement and stress values converge, various element sizes were considered from 0.5$t$ to 1.5$t$, where $t$ is the minimum model thickness. When performing the mesh convergence study, the displacement and stress comparison were based on a consistent vertex of the original geometry since the mesh may be different for each iteration, with nodal coordinates varying between iterations.

![Mesh Convergence Study - Displacement](image1)

Figure 4.16: Mesh convergence study - Displacement

![Mesh Convergence Study - Von Mises stress](image2)

Figure 4.17: Mesh convergence study - Von Mises stress

The results of the mesh convergence study for both displacement and stress are shown in Figures 4.16 and 4.17. The displacement and strain changes begin to be lower from the point where the mesh element number is 1200000, corresponding to 0.6$t$, and, eventually, the displacement and stress results level off when the mesh element number is 1500000, corresponding to 0.5$t$. Ultimately, further mesh
density increase would have a diminishing effect on the results and a higher computational time, so a mesh with parabolic tetrahedral elements with 0.5 mm side was created.

4.3.2 Structural Analysis Results

After all the conditions were defined, the simulation was solved and results in terms of stress, displacement and safety factor were obtained and will be analyzed below.

Stress Distribution

As previously described in Subsection 2.4.2, stress is defined as the force acting per unit area, Equation 2.2, and it can be computed from strain $\epsilon$ and the material stiffness $K$. In Fusion 360, the solver outputs six individual components, known as stress tensors, and three combined stress results, known as Von Mises Stress, 1st and 3rd Principal Stresses. Usually, the previously described multi-directional tensor stress components are combined into an equivalent stress magnitude, also known as the Von Mises stress, $\sigma_v$. The Von Mises stress can be described by the following equation:

$$
\sigma_v = \sqrt{\frac{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2}{2} + 3 \cdot (\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)} \tag{4.1}
$$

This equation is applicable to isotropic materials, which have the same modulus of elasticity $E$ and Poisson’s ratio $\nu$ for loads applied in any direction [65]. In order to predict failure in the 1U CubeSat structure the Von Mises stress will be compared to the yield strength of the Aluminum AlSi10Mg - A below.

As mentioned in the previous Subsection 4.3.1, seven simulations were performed, including the six simulations for each of the gravity loads enumerated in the Table 4.3, Subsection 4.2.2, and a seventh simulation in which the 1U CubeSat structure is subject to the greatest gravity load vector possible. Hence, the maximum Von Mises Stress results are summarized in the Table 4.5 for each simulation.

<table>
<thead>
<tr>
<th>Gravity load</th>
<th>g [m/s²]</th>
<th>a [m/s²]</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Maximum Von Mises Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.5</td>
<td>142.202</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>39.840</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>102.974</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>28.850</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>2.003</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>2.003</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>29.421</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>2.201</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>29.421</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>2.201</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>9.807</td>
<td>+3</td>
<td>+14.5</td>
<td>+3</td>
<td>63.540</td>
</tr>
</tbody>
</table>

Table 4.5: Stress distribution results with seven gravity loads

According to the Table 4.5 it can be confirmed that the seventh simulation is the worst case for the 1U CubeSat structure since it presents the higher Maximum Von Mises Stress, which is consistent with
being the case with the highest applied acceleration. Thus, the results for the most critical scenario, the seventh simulation from Table 4.5, are portrayed below in Figure 4.18 and the plots for the rest of the other simulations can be found in Appendix C.1.

As previously mentioned in Subsection 4.2.1, the material used is Aluminum AlSi10Mg – A, which has an average yield strength of 190 MPa and a ultimate tensile strength of 330 MPa\(^2\). Moreover, as evidenced in Figure 4.18, the model will reach a maximum Von Mises stress of approximately 63.540 MPa, which is very localized and well above the average stress. As a consequence, both the average stress and the maximum stress, for all seven simulations, are well below the yield strength indicated by Trumpf and so it can be concluded through this analysis that the stresses to which the component may be subjected will not cause material plastic deformation or even fracture.

**Displacement**

Next, it is important to investigate the results in terms of the displacement of the 1U CubeSat structure from its original position. Although the previous results do not predict the existence of plastic deformation, it is possible that there may be a small elastic deformation of the material, recoverable after the removal of the gravity loads. In that way, the maximum displacement results for each simulation are set out in the Table 4.6.

Additionally, the results of the seventh simulation regarding the model displacement are shown in Figure 4.19 and the plots for the remaining simulations can be consulted in Appendix C.2.

Analyzing the Figure 4.19, it is clear that if the component is subjected to the greatest gravity load vector possible, it may suffer a maximum displacement of approximately $2.580 \times 10^{-1}$ mm, relative to its initial position. As would be expected, this displacement will occur in the side wall where the loads are applied and the farthest from its fixed area. On the contrary, moving towards the wall where the constraints are applied, the displacement decreases until it reaches zero. This gradual reduction in displacement, from the surface where the forces are applied to the surface where the constraints are

\(^2\)Information given by CEiiA’s supplier Trumpf
<table>
<thead>
<tr>
<th>Gravity load</th>
<th>g</th>
<th>a [m/s²]</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Maximum Displacement [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.5</td>
<td>142.202</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>2.370 × 10⁻¹</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>102.974</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>1.720 × 10⁻¹</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>7.376 × 10⁻⁴</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>7.376 × 10⁻⁴</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>29.421</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>5.874 × 10⁻³</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>29.421</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>5.874 × 10⁻³</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>9.807</td>
<td>+3</td>
<td>+14.5</td>
<td>+3</td>
<td>2.580 × 10⁻¹</td>
</tr>
</tbody>
</table>

Table 4.6: Maximum displacement

Figure 4.19: Displacement

applied, is verified for all the other simulations in Appendix C.2. Beyond this, it may be concluded that the maximum displacements presented in Table 4.6 may be considered negligible since there is no occurrence of plastic deformation and the structure shows no permanent deformation even when the expected maximum forces are applied. It should be noted that these results are significant for the electronic components, which may be very sensitive to deformation and are unlikely to be affected.

**Safety Factor**

The safety factor describes how much stronger a system is than it is required for a pre-defined load and thus assesses how suitable a design is for its intended application. In Autodesk Fusion 360, the safety factor is calculated as the ratio of the material yield strength and the Von Mises equivalent stress, specifying whether the design is likely to bend or break when submitted to the applied loads:

\[
SF = \frac{\text{Material Yield Strength}}{\text{Von Mises Stress}}
\]

(4.2)
The safety factor results are extremely relevant because, in the real world, all aspects of the design present some degree of uncertainty and therefore a factor of safety is imperative.

Lastly, the safety factor results are presented, that is, how much stronger the 1U CubeSat mechanical subsystem is than necessary to sustain the predefined critical loads. In this manner, the minimum safety factor results for each simulation are set out in the Table 4.7.

<table>
<thead>
<tr>
<th>Gravity load</th>
<th>g</th>
<th>a ( [m/s^2] )</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Minimum Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.5</td>
<td>142.202</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>4.769</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>102.974</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>6.585</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>15.0</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>29.421</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>15.0</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>29.421</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>15.0</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>29.421</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>15.0</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>9.807</td>
<td>+3</td>
<td>+14.5</td>
<td>+3</td>
<td>2.99</td>
</tr>
</tbody>
</table>

Table 4.7: Minimum safety factor

Generally, the greater the risk of component failure the greater the safety factor should be. In the present case, the highest risk that can result from the 1U CubeSat structure failure is to jeopardize the mission objectives. In addition, a safety factor of 1 is considered a high risk factor since the designed system can not handle more loads than those applied to it. As a result, a safety factor of more than 1 is required for the 1U CubeSat structure to ensure that the satellite can withstand unforeseen conditions without exceeding the elastic stresses or even without achieving fracture failure.

Taking into account that NASA and the aerospace industry have strict guidelines for design factors, the choice of safety factor for this project was based on their standards [66]. However, considering that several assumptions were made throughout the simulations, the selection of the safety factor was even more conservative. In this way, the minimum safety factor for the 1U CubeSat structure was defined as 2.0. The results for the seventh simulation from Table 4.7, are illustrated below in Figure 4.20 and the plots for the other simulations can be accessed in Appendix C.3.

Examining the Figure 4.20, it is clear that the 1U CubeSat structure has an average safety factor higher than 6, which is more than necessary to ensure that this component resists the predefined critical loads. Nonetheless, it should be noted that the lowest safety factor found was 2.99. As expected, the lowest safety factor was obtained in a small area, identified in the Figure 4.20, coincident with the region in which the highest accumulated stresses were observed in the Figure 4.18. As a consequence, it could be assumed that, in extreme and unlikely conditions, the area with the lowest safety factor is most likely to fail if the system is subjected to much higher loads. Overall, the results obtained for the safety factor are considered acceptable, since practically the whole volume of the 1U CubeSat mechanical subsystem has a safety factor greater than 6, and even the areas which are more critical have a safety factor that allows them to handle loads 2.99 times higher than the predefined critical loads. Finally, after
verifying all the results provided in the finite element analysis performed, it can be concluded that the 1U CubeSat Mechanical Subsystem and Structures (MSS) is validated in terms of stress, displacement and safety factor, and thus ready to proceed to the product development process.

4.4 Manufacturing Process

After the structural analysis has been successfully completed and the structure has been validated, a simulation of the manufacturing process was performed to predict the outcomes of printing the 1U CubeSat structure using SLM. It is important to note that for the manufacturing process simulation only one of the two L-shaped components developed in Section 4.1 was simulated since these components are nearly identical.

Software

Amphyon was the software selected to simulate the manufacturing process. Amphyon is a pre-processing and simulation software for AM processes whose main goal is to integrate advanced process analysis approaches into the process preparation. First, the assessment tool of Amphyon was used to determine the automatic orientation of the part, allowing the calculation of the optimal part orientation based on predefined process specifications. Secondly, the simulation module offers an analysis of process stresses and identifies critical stages of the process like failure of the supports, amongst others. So, the integration of this simulation tool into the design phase enables the geometric accuracy and process stability to increase [67].

4.4.1 Definition of Simulation Conditions

In order to simulate the manufacturing process it is necessary to consider several factors such as the machine specifications, the orientation of the structure, the type and volume of supports to be used and others, discussed below.
Material and Machine

With regard to material, $AlSi10Mg - A$ was once again selected and the properties specified in Amphyon’s workspace are equal to those defined above in Table 4.1, Subsection 4.2.1.

Moreover, several machines were investigated with base on the different advantages they present until the TruPrint 3000 machine was selected to produce the structure of the 1U CubeSat. The TruPrint 3000 is a medium format machine designed for the production of complex metal components using AM and the main advantages it presents are summarized below:

- Large build volume of $300 \times H 400$ mm where components can be easily arranged;
- Quickly exchangeable build cylinders, allowing for a reduction of setup times and an increase of machine productivity;
- External management of part or powder, promoting the reduction of time and cost;
- Industrial software and monitoring solutions that foster the optimization of production;

The machine parameters are described in Table 4.8 and must be taken into account before producing the model through SLM. It is noteworthy that the parameters can be adjusted for the manufacture of any other component by powder bed fusion (PBF) technology.

<table>
<thead>
<tr>
<th>TruPrint 3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build volume $[mm \times mm]$</td>
</tr>
<tr>
<td>Build rate $[cm^3/h]$</td>
</tr>
<tr>
<td>Laser power $[W]$</td>
</tr>
<tr>
<td>Beam diameter $[\mu m]$</td>
</tr>
<tr>
<td>Scan speed $[m/s]$</td>
</tr>
<tr>
<td>Layer thickness $[\mu m]$</td>
</tr>
</tbody>
</table>

Table 4.8: Machine specifications

After the part was imported to Amphyon’s workspace, the TruPrint 3000 printer was chosen from the machine library provided by the software, as can be seen in Figure 4.21.
Part Orientation

When producing a part by additive manufacturing (AM), the choice of orientation is one of the main factors to consider before its production as it has a major influence on the final quality of the component, as formerly mentioned in Section 2.3. Consequently, it is necessary to analyze the various factors that, in turn, influence the orientation of a component, such as: the volume of the part, the volume of supports, the supported area, the center of gravity of the part, area of powder to melt per layer, among others.

Amphyon software was used to determine the ideal orientation of the 1U CubeSat structure within the Trueprint 3000 build-chamber. This software has an orientation assessment tool which allows the calculation of the optimal part orientation based on predefined process specifications. In such manner, the 1U CubeSat model is assessed with respect to several aspects relevant for AM, such as:

• Build time - the assessment tool estimates the time it would take to build the component and the required support volume for the orientation chosen;

• Support volume - both the orientation with minimal needed support volume and the support volume needed for every orientation are computed;

• Post-processing - the tool generates approximations of the expected post-processing effort necessary for each orientation;

• Deformation - the distortion and stress tendencies are evaluated for all orientations;

For the best possible orientation prediction, the assessment module allows the customization of various parameter sets, taking into account relevant information specific to the process. For this specific case, some values were adapted within the settings. Firstly, the self-supporting angle $\alpha_s$ was set to 45°, according to the information previously defined in Section 2.3. Next, the critical distance to boundary, which describes the minimum distance to the base plate, was set to 5 mm. Lastly, the support density percentage for overhanging and down-facing surfaces was defined as 40% and 10%, respectively. As stated in Section 2.3, the surface quality of up-facing surfaces of the part is generally better than for down-facing surfaces since these require a bigger volume of supports, specially overhanging surfaces. In view of this, the support density percentage for overhanging surfaces is higher than for down-facing surfaces with $\alpha_s > 45^\circ$. The rest of the evaluation parameters and its weighing factors were implemented as default.

Taking into consideration that the time, energy and material necessary for generating support structures are a major cost driver in AM of complex structures, the orientation was further restricted in terms of support volume. On top of this, the orientation was also restricted in terms of deformation since the distortion and stress formation tendencies are dependent on the chosen orientation. After the calculations are finished, the assessment results are presented in 2D assessment maps which can be further restricted according to requirements set in terms of build time, support volume, post-processing and deformation, as demonstrated in Figure 4.22. Based on the orientation plots presented in Figure 4.22, two optimal orientations were chosen for the case of the 1U CubeSat model.
On one hand, the first orientation corresponds to a horizontal position at $0^\circ$, represented as the green geometry in Figure 4.23. On the other hand, the part was reoriented a second time with the inner faces facing upwards, illustrated as the grey geometry in Figure 4.23. From now on, the first orientation will be called the *Horizontal* orientation while the second orientation will be called the *V* orientation.

Alternatively, the *Autodesk Netfabb* software was also used to determine the ideal orientation of the CubeSat’s structure. *Netfabb* also has an orientation tool that automatically provides the various options available and ranks them based on previously defined constraints. Hence, after the part was imported to *Netfabb’s* workspace, the search for the best component orientation began by defining the self-supporting angle $\alpha_s$ as $45^\circ$ and the distance to platform, on the Z axis, as 5 mm.
Afterwards, the ranking parameters were customized according to their relevance. The criteria available were the supported area (SA), supported volume (SV), outbox volume (OV), part height (PH) and center of gravity height (CGH). Considering the 1U CubeSat configuration and requirements, the SA and SV parameters were classified with high importance, PH and CGH with medium importance and the OV of low importance.

<table>
<thead>
<tr>
<th></th>
<th>Horizontal orientation</th>
<th>V orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supported area [cm²]</td>
<td>38.199</td>
<td>1.635</td>
</tr>
<tr>
<td>Support volume [cm³]</td>
<td>49.868</td>
<td>3.891</td>
</tr>
<tr>
<td>Outbox volume [cm³]</td>
<td>1123.650</td>
<td>1754.073</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>118.5</td>
<td>109.7</td>
</tr>
<tr>
<td>Center of gravity [mm]</td>
<td>51</td>
<td>56.9</td>
</tr>
</tbody>
</table>

Table 4.9: Orientation results

Then, after the calculations were completed, the Netfabb software proposed eleven solutions which can be found in Appendix D. From these solutions the best ranked correspond to the second and ninth orientation, whose results are represented in Table 4.9 and Figure 4.24. As can be seen from Figure 4.24, the ideal orientations suggested by the Netfabb software are similar to those calculated by the Amphyon software. Despite this, as the Netfabb software does not allow the manufacturing simulation to be performed, the rest of the analysis will continue to be done with Amphyon software.

**Supports**

After the component orientation is established, the next step is to create the supports. The utmost attention has been paid to the generation of the supports since they are a fundamental aspect for the correct production of the 1U CubeSat structure by AM, as mentioned earlier in Subsection 2.3. So, the Amphyon support generation tool was used to create the support structures that are adapted to the specific needs of 1U CubeSat model. It is important to mention that Amphyon’s tool only produces thin walled support structures.

The first step in generating support structures within Amphyon is to define in which areas supports
are actually necessary. Considering that the parts will be produced by SLM and according to what was mentioned earlier, the self-supporting angle $\alpha_s$ was manually set to $45^\circ$. Besides, bearing in mind that with an $z$ offset of $0$ mm the parts lowest point would be placed directly on the base plate, a safety distance of $5$ mm was assigned. In this software there is a predefined script for the creation of supports for a powder bed fusion (PBF) process. Nonetheless, as it is possible to manually specify the support structures’ features including, for example, the wall spacing, the support wall thickness, and more, minor changes have been made to the script to achieve the desired functions for the supports. Subsequently, the supports for the $\text{Horizontal}$ and $V$ orientation were generated as shown in Figure 4.25.

![Generated supports in Amphyon](image)

(a) $\text{Horizontal}$ orientation  
(b) $V$ orientation

Figure 4.25: Generated supports in Amphyon

When the part orientation and respective supports were defined, the simulation is ready to be computed, as will be analyzed below.

### 4.4.2 Process Simulation Results

Additive manufacturing process simulation is an innovative and necessary tool to fully exploit the potential of AM since errors associated with this manufacturing technology can be predicted and further reduced. In fact, the prediction of defects, failures, warps, and even interference with the recoater system can be predicted before printing. In this way, it is possible to obtain final components with only one manufacturing attempt, thus minimizing production times, raw material consumption, associated costs, and so forth. Consequently, the manufacturing process was simulated using Amphyon software to predict process results and possible errors. It should be noted that the correct execution of this simulation was challenging because, being a tool under development, it was necessary to solve some problems that appeared during the process with the Amphyon team. Upon completion of the manufacturing process simulation, several results were obtained for analysis. These results were used to predict possible component production failures and identify possible design problems. In this manner, the results considered most relevant are presented below, namely component displacement or stress and recoater interference.
Recoater interference

Amphyon provides an easy tool for the analysis of simulations with respect to likely recoater interferences. In this way, the recoater crash risk during the simulation was evaluated, for both the Horizontal and V orientations, and it was concluded that none of the orientations present any risk. This is in accordance with what was expected given the high volume of the build chamber and the small volume of the components.

Displacement

The displacement results represent the distance, in millimeters, that the component moves in relation to the original geometry at a given point in the manufacturing process. Moreover, the displacement generated during manufacture is due to internal stresses accumulated in the components. In turn, these internal stresses are created by the expansion and contraction of the material due to the large thermal gradients inherent to the process. Afterwards, when the component manufacture is complete and supports are removed, the displacement results for both the Horizontal and V orientation, defined in the Subsection 4.4.1, are represented in Figures 4.26 and 4.27. Analyzing the Figures 4.26 and 4.27, one can easily observe a significant displacement in the components compared to their original geometry. While the largest displacement computed for the Horizontal orientation was 2.72 mm, the greatest displacement obtained for the V orientation was 2.83 mm. It is important to note that the maximum displacements are located in the yellow and white regions marked with red circles in Figures 4.26 and 4.27. By way of illustration, a simulation was run for the V orientation before removing the supports and the maximum displacement is equal to 1.55 mm, as shown in Figure 4.27. Comparing the maximum displacement of the part before and after the removal of supports it appears that there is an increase in displacement for the second case. By analyzing the results, one can conclude it is still possible to decrease the displacement of the component by, for example, pre-heating the chamber, the manufacturing platform and the metal powder. Likewise, one can further predict the need for a stress relief heat treatment, prior to any removal of either platform or supports, in order to reduce the internal material stresses within the component.

Figure 4.26: Displacement results for Horizontal orientation
Stress

The stress results provided by Amphyon describe the stress experienced by the component after manufacture and which can eventually lead to structure failure. Usually, component failure is associated with the displacement generated by accumulated residual stresses in the component and, as shown in the results presented above, a failure in the structures can be foreseen.

Analyzing the results, it is possible to verify if the structure presents stresses higher than the yield strength of the material, previously defined as \(190\) MPa in Subsection 4.2.1. In this case, if any region of the structure presents stresses greater than the yield strength, there may be the possibility of deformation or even fracture of the component. Figures 4.28 and 4.29 show the stress results obtained in the
simulation after the end of the manufacturing process in the \( x \), \( y \) and \( z \) directions for both \( \text{Horizontal} \) and \( \text{V} \) orientations.

![Stress result images](image)

(a) Stress X in MPa  
(b) Stress Y in MPa  
(c) Stress Z in MPa

Figure 4.29: Stress results for the \( \text{V} \) orientation

Additionally, the maximum stress results for each orientation and respective directions are summarized next in the Table 4.10. In general the structure presents stresses below the yield strength but in some small regions the maximum stress is above yield strength and thus the structure failure, predicted during the analysis of displacement results, is confirmed, as evidenced in Figures 4.28 and 4.29. It is important to note that the maximum stresses are located in the yellow and white regions marked with red circles for the \( x \) and \( y \) directions and the maximum stresses in the \( z \) direction are located at the base of the part and therefore are not marked in Figures 4.28 and 4.29.

In order to address this problem and improve the manufacturing process, one solution would be to create more robust and resilient support structures since they would allow an improvement in heat transfer to the manufacturing platform, significantly reducing the stresses caused by thermal gradients. Another suggestion would be to preheat the chamber, work platform and metal powder to reduce the thermal gradients caused by the process, and consequently, the internal stresses.

<table>
<thead>
<tr>
<th>( \text{Horizontal orientation} )</th>
<th>( \text{V orientation} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress X [MPa]</td>
<td>687</td>
</tr>
<tr>
<td>Stress Y [MPa]</td>
<td>621</td>
</tr>
<tr>
<td>Stress Z [MPa]</td>
<td>721</td>
</tr>
<tr>
<td>Stress Y [MPa]</td>
<td>805</td>
</tr>
<tr>
<td>Stress Z [MPa]</td>
<td>639</td>
</tr>
</tbody>
</table>

Table 4.10: Maximum stress results
4.5 Production of Parts

As stated above in Section 4.4, the components were manufactured by Trumpf and several work steps were necessary before the final parts were produced, as briefly described below.

4.5.1 Production Process

The production of the parts is divided into three phases: pre-process, process and post-process. The time distribution is as follows: the process phase lasted 14.5 hours, representing 52% of the overall time, the post-process phase lasted 11 hours, representing 39% of the overall time, and the pre-process phase lasted 2.5 hours, representing 9% of the overall time.

Pre-process

The pre-process phase consists of data preparation, which lasted for about one hour, and the machine preparation, which lasted one hour and an half. The used support and the position of the tensile specimens can be found below in Figure 4.30. Besides, the two L-shaped parts were built with an offset for the connection to the baseplate as previously done in the manufacturing process simulations, in Section 4.4.

The orientation of the two L-shaped parts chosen by the producer is aligned with the orientation suggested in the process simulation, in the previous Subsection 4.4.1. Therefore, the choice of orientation and support of the producer corroborates the solution developed in the Amphyon software.

Process

The machine parameters have been set within a range of values in the Subsection 4.4.1 but, for the production of the two L-shaped parts, the exact final values of these parameters have been defined.
along with the inert gas used in the manufacturing process, as illustrated in the following Table 4.11.

<table>
<thead>
<tr>
<th>Process</th>
<th>Inert gas</th>
<th>Layer thickness [(\mu m)]</th>
<th>Focus diameter [(\mu m)]</th>
<th>Preheating temperature [(^\circ C)]</th>
<th>Layer amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>60</td>
<td>100</td>
<td></td>
<td>200</td>
<td>1721</td>
</tr>
</tbody>
</table>

Table 4.11: Parameters of the process

**Post-process**

Finally, a heat treatment process was carried out in order to reduce the distortion of the two L-shaped parts caused by the stresses which result from very high cooling speeds that occur during production. Afterwards, the parts were cut from the substrate plate with a band saw, the supports were removed manually with the aid of multi functional tools like electric chisels and milling heads and, at last, the two L-shaped parts were sandblasted. The finished parts are depicted in Figure 4.31.

![Figure 4.31: Finished parts](image)

**4.5.2 Tensile Testing**

Taking into account that tensile tests are a fundamental tool to characterize the behaviour of materials, these tests were performed to verify if the mechanical properties of \(AlSi10Mg - A\) previously defined in the Subsection 4.2.1 are similar to the real values obtained in the experimental test. In this way, nine specimens were manufactured by Trumpf according to the ASTM Standard E8/E8M-13a and their dimensions and shape are shown in Figure 4.32 [68].

The first batch consisted of four samples without heat treatment whereas the second batch was composed of five samples that subsequently underwent heat treatment, both with orientations at 0°, 45° and 90°.
It is noteworthy that the manufactured specimens had small dimensional variations in relation to the expected standard.

The tensile tests were performed according to the ASTM E8M standard on the Instron 3669 machine and an extensometer was used to measure the elongation $\delta$ of the specimens, as reflected in Figure 4.33.

Afterwards, the Elastic modulus, $E$, the yield strength at 0.2 per cent of elongation, $\sigma_{0.2}$, and the tensile strength, $\sigma_m$, were estimated based on the stress-strain curves obtained in Figures 4.34 and 4.35. These mechanical properties of the nine specimens with and without heat treatment are shown in Tables 4.12 and 4.13, respectively. The mechanical properties of the $AlSi10Mg−A$ powder, summarized in Table 4.1, Subsection 4.2.1, were after used in the TO and the structural analysis to validate the structure of the $1U\ CubeSat$. It is important to highlight that the mechanical properties were defined for powder printed at $0^\circ$ and without heat treatment. For this reason, it is relevant to analyze the results obtained for the specimens $G$ and $H$ since they were printed with a $0^\circ$ orientation and did not undergo heat treatment.
Figure 4.34: Stress-strain curves for heat treated specimens

<table>
<thead>
<tr>
<th>Heat treated specimens</th>
<th>Orientation</th>
<th>$E$ [MPa]</th>
<th>$\sigma_{0.2}$ [MPa]</th>
<th>$\sigma_{\text{m}}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$0^\circ$</td>
<td>60577</td>
<td>149.28</td>
<td>321.83</td>
</tr>
<tr>
<td>B</td>
<td>$90^\circ$</td>
<td>64881</td>
<td>170.21</td>
<td>291.12</td>
</tr>
<tr>
<td>C</td>
<td>$90^\circ$</td>
<td>61190</td>
<td>149.07</td>
<td>270.71</td>
</tr>
<tr>
<td>D</td>
<td>$45^\circ$</td>
<td>71134</td>
<td>153.80</td>
<td>273.07</td>
</tr>
<tr>
<td>E</td>
<td>$45^\circ$</td>
<td>56933</td>
<td>148.10</td>
<td>283.01</td>
</tr>
</tbody>
</table>

Table 4.12: Tension tests results for heat treated specimens

<table>
<thead>
<tr>
<th>As-fabricated specimens</th>
<th>Orientation</th>
<th>$E$ [MPa]</th>
<th>$\sigma_{0.2}$ [MPa]</th>
<th>$\sigma_{\text{m}}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>$45^\circ$</td>
<td>68378</td>
<td>167.76</td>
<td>309.68</td>
</tr>
<tr>
<td>G</td>
<td>$0^\circ$</td>
<td>68206</td>
<td>185.14</td>
<td>339.42</td>
</tr>
<tr>
<td>H</td>
<td>$0^\circ$</td>
<td>71945</td>
<td>187.62</td>
<td>334.26</td>
</tr>
<tr>
<td>I</td>
<td>$90^\circ$</td>
<td>69203</td>
<td>176.25</td>
<td>295.83</td>
</tr>
</tbody>
</table>

Table 4.13: Tension tests results for as-fabricated specimens
Observing the average tension tests results for specimens with and without heat treatment in Table 4.14 it can be concluded that the heat treatment led to a decrease in both yield and tensile strength, which is in agreement with literature data [69, 70]. Indeed, the average yield strength obtained in the experiment was reduced from 179.19 to 154.09 MPa, whereas the tensile strength of the heat-treated samples showed a reduction of 319.80 to 287.95 MPa. These results confirm that post-processing is capable of influencing the mechanical properties of SLM-processed parts [69, 70].

Table 4.15 shows the mechanical properties of the AlSi10Mg-A powder defined in conformity with the datasheet released by Trumpf, the average of the experimental values obtained for the $G$ and $H$ specimens from the tensile tests and the difference between these values.

Furthermore, observing the Table 4.15 it is possible to conclude that the values of the yield and
Mechanical Properties | $E$ [Mpa] | $\sigma_{0.2}$ [Mpa] | $\sigma_{m}$ [Mpa]  
--- | --- | --- | ---  
Trumpf | 75000 | 190 | 330  
Tensile testing | 70075.50 | 186.38 | 336.84  
$\Delta$ [%] | 6.57 | 1.91 | 2.07  

Table 4.15: Mechanical properties of Trumpf versus Tensile Testing

tensile strengths, $\sigma_{0.2}$ and $\sigma_{m}$, obtained in the tests are acceptable considering that they present a small difference of approximately 2% when compared to the values proposed by Trumpf.

On the contrary, the value of the modulus of elasticity $E$ obtained in the tests shows a slightly considerable difference of about 7%. One of the reasons for these results may be the presence of defects in the specimens as, for example, the lack of fusion between layers which can cause a fracture of the material [71, 72].

![Figure 4.36: Static stress analysis with new mechanical properties](image)

Figure 4.36: Static stress analysis with new mechanical properties

In light of this, a static stress analysis was run to verify whether the difference in the mechanical properties would have significant consequences for the stability of the structure of the 1U CubeSat. For this purpose, the simulation was again run for the scenario considered most critical, where all loads are applied to the structure and, as can be seen in Figure 4.36, the change in the mechanical properties of the material creates slight differences in the results in terms of displacement and safety factor. While the maximum stress remains at 63.54 MPa, displacement increased to 0.2787 mm and the safety factor decreased to 2.82. Despite the results presented, it is concluded that the difference in mechanical properties is not sufficient to affect the validity of the simulations previously performed in Subsection 4.3.2.
Chapter 5

Conclusions

This dissertation aimed to develop an original structure for the 1U CubeSat, with the ultimate goal of minimizing the weight and the number of parts required through an innovative assembly configuration. This chapter summarizes the major achievements of this work and leaves some suggestions for future work.

5.1 Achievements

During the development of this dissertation different accomplishments were achieved.

Firstly a literature review was conducted on the most important concepts behind the processes that supported this work. Topics such as AM, structural analysis, TO and CubeSats were introduced and discussed in order to create a foundation for the research work carried out in this dissertation.

Secondly, an investigation of the mission and design requirements was carried out and a preliminary design of the 1U CubeSat was accomplished on CATIA.

Additionally, a TO was performed and the optimized structure obtained presents both weight reduction of 6.0% and component reduction from 6 to 2, respectively. Then, a FEM structural analysis was executed to verify if the CubeSat is able to sustain the launch loads, validating the 1U CubeSat. Prior to the production of the structure, a simulation of the manufacturing process was performed to predict the outcomes of printing the 1U CubeSat structure using SLM.

Finally, a new optimized structure of the 1U CubeSat was successfully produced by AM and experimental tests validated the mechanical properties used in the computer analysis, which confirmed the success of the design and the successive steps that led to its production.

5.2 Future Work

Actually, it does exist further work that can be done in the future to improve the process of developing, optimizing and producing a 1U CubeSat structure, managing to take full advantage of all the applied technologies.
The first step in the future work must be the analysis of the 1U CubeSat structure with the real subsystems inside the CubeSat as their presence will affect the stiffness of the structure and the design may have to be reevaluated.

The building process must be carefully studied in order to understand its full capacity as well as its limitations.

Concerning the FEM analysis, only the linear static analysis were assessed and so, it is indispensable that transient and random vibrations analysis are performed. Furthermore, a thermal analysis is also mandatory to validate the satellite.

Lastly, a cost model must be created to evaluate the costs involved in the AM production of the 1U CubeSat structure.
Bibliography


[54] *NanoCom AX100 Datasheet*. GOMspace, 2019.


Appendix A

CubeSat Design Requirements

Figure A.1: 1U Cubesat Design Specification Drawing [4]
# Appendix B

## Design requirements for Cubesat deployers

<table>
<thead>
<tr>
<th>S/C Design Requirements</th>
<th>Requirement</th>
<th>Reference Values</th>
<th>Negotiable?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masses, CoG and Inertia</td>
<td>CoG Position: distance from separation plane</td>
<td>$\leq 300$ mm</td>
<td>yes</td>
<td>Subject to Stack configuration</td>
</tr>
<tr>
<td></td>
<td>Static unbalance: distance &quot;d&quot; between CoG and the longitudinal axis</td>
<td>$d \leq 10$ mm</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Main Frequencies</td>
<td>Lateral frequencies</td>
<td>$&gt; 115$ Hz</td>
<td>yes</td>
<td>Down to 90 Hz</td>
</tr>
<tr>
<td></td>
<td>Longitudinal frequencies</td>
<td>$&gt; 115$ Hz</td>
<td>yes</td>
<td>Down to 90 Hz</td>
</tr>
<tr>
<td>QSL at S/C CoG</td>
<td>Longitudinal$^*$</td>
<td>$-14.5$ g $+10.5$ g</td>
<td>yes</td>
<td>Depending on Stack configuration and relevant CLA</td>
</tr>
<tr>
<td></td>
<td>Lateral$^{**}$</td>
<td>$\pm 3$ g</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Longitudinal and Lateral axes of the Launcher are referred: For S/C installed on the lower module, this implies that the longitudinal loads are applied in lateral direction for the spacecraft.

$^*$: The minus signs indicate compression along the longitudinal axis and the plus signs tension. The gravity load is included.

$^{**}$: The lateral load on payloads may act in any direction in the range [0-360°]. Moreover they must be considered simultaneous and uncorrelated.

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Figure B.1: Design requirements for Cubesat deployers
Appendix C

Final Model FEM

C.1 Stress

Figure C.1: Stress Distribution
C.2 Displacement

Figure C.2: Displacement

C.3 Safety Factor
Figure C.3: Safety Factor
Appendix D

1U Cubesat orientations calculated in Netfabb

Figure D.1: Orientations obtained for the 1U Cubesat model
Figure D.2: Orientations obtained for the 1U Cubesat model