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OTIMIZAÇÃO NA MANUFATURA ADITIVA

WESLEY FERNANDES CAMELO
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OPTIMIZATION IN ADDITIVE MANUFACTURING

Wesley Fernandes Camelo

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ISEP – School of Engineering, Polytechnic of Porto

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Dissertation presented to the ISEP – School of Engineering, Polytechnic of Porto to fulfill the requirements necessary to obtain a Master's Degree in Mechanical Engineering, under the guidance of Dr. Francisco José Gomes da Silva and Dr. Raul Duarte Salgueiral Gomes Campilho, Adjunct Professors at ISEP.

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Keywords

Optimization; Rapid prototyping; Additive Manufacturing

ABSTRACT

Additive Manufacturing is a mechanical productive process whose utilization is increasing rapidly. This dissertation was focused in the topological optimization of mechanical parts with a view to reduce their weight, keeping or increasing their mechanical strength. Two different parts usually obtained by conventional techniques were used as case studies, being applied successive iterations leading to their optimization, regarding the use of Additive Manufacturing to produce them in the future. The optimization allowed for parts weight reduction, which will contribute to the always wanted global weight reduction of the set where they belong, improving the sustainability and reduction of emissions. The Altair Hypermesh software was used exclusively as an instrument for performing optimizations.

Palavras Chaves

Otimização; Impressão 3D; Manufatura Aditiva.

RESUMO

A Fabricação Aditiva é um processo produtivo mecânico cuja utilização está a aumentar rapidamente. Esta dissertação foi focada na otimização topológica de peças mecânicas com vista a reduzir o seu peso, mantendo ou aumentando a sua resistência mecânica. Duas peças diferentes, geralmente obtidas por técnicas convencionais foram usadas como casos de estudos, sendo aplicadas sucessivas iterações, levando à sua otimização com vista ao uso de Fabricação Aditiva para as produzir no futuro. A otimização permitiu uma redução do peso de peças, que contribuirá para a redução do peso global sempre procurado no conjunto onde elas pertencem, melhorando a sustentabilidade e a redução das emissões. A aplicação informática Hypermesh Altair foi usada exclusivamente como instrumento para realizar otimizações.

ABBREVIATIONS AND SYMBOLS LIST

Abbreviations List

2D	Two-Dimensional
3D	Three-Dimensional
3DP Technology	Three-Dimensional Printing Technology
ABS	Acrylanitrile Butadiene Styrene
Al	Aluminium
ALM	Additive Layer Manufacturing
AM	Additive Manufacturing
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CNC	Computer Numerical Control
DED	Direct Energy Deposition
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
DOD	Drop on Demand
DSPC	Direct Shell Production Casting
EBM	Electron Beam Melting
EDP	Polymer Technologies
EOS	Electro Optical System
FDM	Fused Deposition Model
FEM	Finite Element Method
HDPE	High Density Polyethylene
HIPS	High Density Polystyrene
IP	Performance Index
LOM	Laminated Object Manufacturing
PA	Polyamide
PBF	Poiser Bed Fusion
PC	Polycarbonate
PMMA	Polymethylmethacrylate
PP	Polypropylene
PS	Polystyrene
SCS	Solid Creating System
SGC	Solid Ground Curing
SHS	Selective Heat Sintering
SL	Stereolithography
SLA	Stereolithography Apparatus
SLM	Selective Laser Melting

SLS	Selective Laser Sintering
SOUP	Solid Object Ultraviolet Plotter
SS	Stainless Steel
TO	Topological Optimization
UAM	Ultrasonic Additive Manufacturing
USA	United States of America
UV	Ultraviolet

Unit List

kg	Kilogram
MPa	Mega Pascal
mm	Millimeter
µm	Micrometer
mbar	Millibar
N	Newton

Lista de Símbolos

%	Percentage

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1 INTRODUCTION

1.1 Contextualization

Nowadays, Additive Manufacturing (AM) has a predominant role in several market areas, namely aeronautic, automotive and aerospace. Rapid Prototyping (RP) utilizes the additive process, layer by layer, for manufacturing parts or objects, differing from the subtractive process. Additive Layer Manufacturing (ALM) creates parts or objects that were previously impossible. Within this technology there are several techniques which are as follows: Ink-jet printing; photo-polymerization Stereolithography (SLA); Selective Laser Sintering (SLS); Fused Deposition Modeling (FDM); Selective Laser Melting (SLM); Direct Metal Deposition (DMD); Electron Beam Melting (EBM); Sheet Lamination and, recently, the Hybrid manufacturing, which joins the subtractive and additive methods.

Each technique has its purpose and peculiarity. It all depends on the material requirements and application. The Ink-Jet, SLA and FDM techniques can use plastic, composite powder, plastic spools or curable photo resins as raw materials, while for metals, the SLM, DMD and EBM techniques must be used. ALM and Optimization are being used together because ALM can reproduce just about everything and thus does not limit Optimization, which, depending on the goal, can have a complex Design in which traditional manufacturing would have difficulty reproducing.

1.2 Main Goals

This dissertation presents a two-part study through Optimization. Such approach makes it necessary to obtain the best results in terms of structural reinforcement via Topography and in terms of material minimization via Topology, for subsequent printing in 3D Technology.

To overcome this problem, it is necessary to outline some objectives that make possible finding a solution. These are:

- The study of types of optimization and their qualities and limitations;
- The Study of types of Additive manufacturing methods;
- Optimization of case studies in OptiStruct utilizing the Hypermesh as mesh software;
- Printing of Optimized Parts in ALM machine;
- Execution of real tests for comparison between optimized and original parts.

1.3 Methodology used

The main objective of this project was to do a two-part optimization for printing in AM technology taking into account the continuation of the aforementioned objectives. This has led to the need to define a methodology, divided into the following tasks:

- Define the part goal;
- Mesh the part in Hypermesh and put it in initial analysis in OptiStruct;
- Define the type of optimization to be done and define the parameters;
- Run Optimization in OptiStruct;
- Analysis of the optimized part in OptiStruct and compare with the original.

1.4 Thesis structure

This thesis is divided into five main chapters.

In the first chapter, which deals with Introduction, a brief framework is carried out, its objectives are presented, the methodology described, and its structure outlined.

In the second chapter, titled State of Art, all the information necessary to the foundation of the work developed is presented, involving theoretical, technical and scientific references to the study being carried out.

In the third chapter, addressed as Development, the analysis of the data from the provided parts is performed, such as programming the parts optimization in the software and implementing the objectives of the work.

In the fourth chapter, the Conclusion, a reflection of the project developed is carried out and proposals for future studies are presented.

Finally, in the fifth chapter, named Bibliography and Other Sources of Information, it is possible to find bibliographical references, articles, publications and other sources of information, used in the accomplishment of this work.

STATE OF ART

2 State-of-the-art

2.1 Why using Additive Manufacturing

The Process of AM is different from traditional manufacturing processes as for instance cutting, forming and casting processes. The difference lies in the fact that, in old-style manufacturing processes, shaping of materials takes place across the total physical domain of the desired part, while in ALM processes the shaping of material primarily takes place in the formation of the elements like voxels, layers and filaments, which make up the requested part. The stages in the shaping of elements are applied in computer automated environments in which production of physical 3-dimensional objects from computer-aided design models are realized using biological, polymeric, metallic, ceramic and composite materials (Yang *et al.*, 2017).

The principal point to how AM works is that parts are made by depositing materials in layers, and each layer is a thin cross-section of the part developed from the original CAD data (Figure 1). Apparently, in the physical world, each layer must have a finite thickness and so the resulting part will approximate the original data (Gibson *et al.*, 2015). To get closer to the final part in terms of shape accuracy, a thinner layer is recommended. The most commercialized AM machines to date use a layer-based approach, and the major ways that they differ are in the materials that can be used, how the layers are fused to each other, and how the creation of layers is accomplished. These differences will determine elements like the accuracy of the final part plus its material and mechanical properties. There are factors that also determine the process ability, e.g. how rapidly the part can be made, how much post-processing is required, the size of the additive manufacturing machine used, and the overall cost of the machine and process (Gibson *et al.*, 2015).

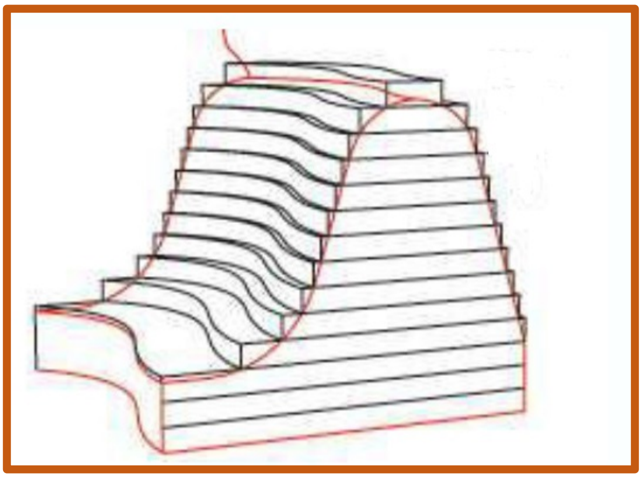


Figure 1 - Schematization of a product made layer by layer (Henry, 2014).

2.2 Brief history about the process

The idea of producing a 3-dimensional object layer by layer came about long before the development of ideas around additive manufacturing. The first concept patented can perhaps be traced back to Peacock for his patented laminated horse shoes in 1902. Half century later in 1952, the benefits of layer manufacturing processes were demonstrated (Yang et al., 2017). A number of additional patents and demonstrations took placed in the period of 60-80s, which further solidified the concept of producing a three-dimensional object by applying a layer wide approach based on this principle to manufacture physical concepts (Yang *et al*., 2017). In 1987 the rapid prototyping system emerged, called the SLA-1 (SLA Stands for Stereolithography Apparatus), from the 3D system company, that was the first system commercialized in the world (Figure 2). This process is based on a laser-induced photo-polymerization resin. 3D prototypes are formed by curing the monomer resin layer by layer while in between each layer the build platform submerges deeper into the resin vat (Yang *et al*., 2017).

The rapid prototyping machine by 3D System kept evolving, while other players in system and materials development in the field gradually surfaced. Ciba-Geigy introduced in 1988, in cooperation with 3D system, the first generation of acrylate resins, which marks the genesis of a large part of currently available photopolymer resins in the market. In the same period DuPont and Loctite also entered the market of resin and system development. According to Yang Li et al. (Yang *et al*., 2017) in Japan NTT Data CMET and Sony/D-MEC launched the Solid Object Ultraviolet Plotter (SOUP), and Solid Creating System (SCS), respectively. These systems were also based on the same photopolymerization principle. Asahi Denka Kogyo introduced the first epoxy-based photo-curable resins in the same period. Epoxy-based resins keep, to this date, another large part of available materials for photopolymerization-based 3D printing methods. At the same time, the first Stereolithography-based system was introduced by Electro Optical System (EOS) and Quadrax in Europe, while Chemical Industries inserted the first photopolymer in the visible wavelength range.

Figure 2 – In the left Chuck Hull and in the right Carl Deckard with the Stereolithography prototype machine. (UT-Austin, 1984)

An important milestone took place in the years 1991 and 1993 on how the present land-scape of additive manufacturing toke shape. In the respective years five technologies were commercialized: Fused Deposition Model from Stratasys, Solid Ground Curing (SGC) from Cubital and Laminated Object Manufacturing from Helisys in 1991. Soon after that, the Direct Shell Production Casting from Soligen and the Selective Laser Sintering from DTM were initiated. In the present landscape of AM, the FDM technology represents a wide part, while the LOM process has a small market share. Though, the SGC process did not have a big commercial appeal, but its operating principle became the forefather of the projection technology from Carbon 3D. A big portion of the addictive manufacturing market is currently occupied by the SLS and DSPC processes. While the SLS technology continues largely similar to its original invention, the DSPC technology has evolved into the systems on which industries such as Voxel Jet and EX-one base their production machines (Yang *et al*., 2017).

Over the past two decades the AM development had a notable accelerated period. While the primary existing technologies continued to evolve, new technologies such as the Polyjet materials printing, Aerosol Jetting, Selective Laser Melting of metals, Laser Engineered Net Shaping, Ultrasonic Consolidation, and very recently the continuous liquid Interface Production technology were developed, commercialized and demonstrated. Also through the same time frame, existing materials were enhanced, new material were commercialized and demonstrated, covering polymers, composites, ceramics, metals, foods and biological materials for a varied range of applications. The 3D printed parts ceased to be prototypes and became functional, fully useful end-user parts, assemblies, and even complete systems on scales as small as a diameter of human hair, to habitable modular homes constructed by a large gantry printing system, and the idea of creating a space colony supported by 3D printing became possible (Yang *et al*., 2017).

Formerly the idea of building 3D objects layer by layer was impossible, today is clear that is not only feasible, but has demonstrated to potentially change every usual manufacturing style. According Yang et. al. (2017) from the early 2016, every week some form of innovation is being introduced, either a modern technology, a new product, a new material, or a new application. In the next decade probably, we will see a real breakthrough in additive technology in the manufacturing industry, where the sole responsibility of mass production will cease to exist, giving place to hundreds or thousands of machines of “micro factories” that coproduce in parallel.

2.3 Main Principles

The term “3D printing” is increasingly used as a synonym for Additive Layer Manufacturing. However, the latter is more precise in the sense that it describes a professional construction technique that is clearly distinguished from conventional methods of material removal. ALM technologies manufacture models by sintering, fusing or polymerization of materials in predetermined layers without using tools. The manufacture of complex geometries in AM makes possible including internal part details that are not possible to manufacture using molding and machining process, because this technology does not require predetermined tool paths, draft angle and under cuts (Essays, 2015).

In AM the layers of a model are formed by slicing CAD data with professional software. All AM systems work based on the same principle. However, the layer thickness depends upon parameters of machine being used and thickness of layer, which ranges from 10 to 200 µm (Essays, 2015). In AM manufacturing, layers are clearly visible on the part surface, which controls the quality of the final product. The relationship between the thickness of the layer and the orientation of the surface is known as the ladder effect. However, the thinner the layer is, the longer the processing time will be and the higher the partial resolution (Essays, 2015).

The AM layers are built from base to top previously on the Z axis. In the resin-based system, the resin, in powder, is spread using a roller or wiper. On the other hand, in some systems the material is deposited through a nozzle because the recoating time is longer than the layer processing time. For this reason, multiple parts can be constructed together in the time of single material recoating build (Essays, 2015).

There are parts, during the construction process, that need a support structure to hold them in the work platform. Each ALM machine uses a different support structure, according to manufacturer and the software employed. These structures are typically thin. Thus, they can have easily removed with hand tools (Essays, 2015).

2.4 Techniques

AM techniques can essentially be classified by the nature and the aggregate state of the feedstock, as well as by the binding mechanism between the joined layers of materials (Herzog *et al.*, 2016). Over the years, many AM techniques have been developed, initially focused on polymers and including: Ink-jet printing, photo-polymerization Stereolithography (SLA), Selective Laser Sintering (SLS) and fused deposition modeling (FDM). The Technology in which manufactured metal parts were recently included includes techniques such as Selective Laser Melting (SLM), Direct Metal Deposition (DMD) and Electron Beam Melting (EBM). More recently, hybrid manufacturing concepts came into place, joining the best concepts of additive and subtractive manufacturing knowledge.

2.4.1 Vat Photopolymerization

This technology uses a vat of liquid photopolymer resin as the main raw material. An Ultraviolet (UV) light is initially used to cure or harden the resin where required and, after this, the platform moves down the length of a new layer thickness and the previous one is cured (Group, 2015).

As the process uses liquid to form objects, there is no structural support from the material during the manufacturing phase, unlike powder based methods, where the support is supplied from the material itself (properly cured) but, in some cases, the support structure often needs to be added – Platform (Figure 3). Resins are cured using a process of photo polymerization or UV light, where the lights are directed across the surface of the resin with the use of motor controlled mirrors. Where the resin encounters the light, it cures or hardens (Group, 2015).

A step-by-step description of the Photopolymerization technique is presented (supported by Figure 3):

1. The building platform lowers as new layers are constructed;
2. UV light cures the resin on the surface. After, the platform continues to move downwards layer by layer from the top to the base;
3. Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on;
4. After completion, the resin is drained, and the object removed.

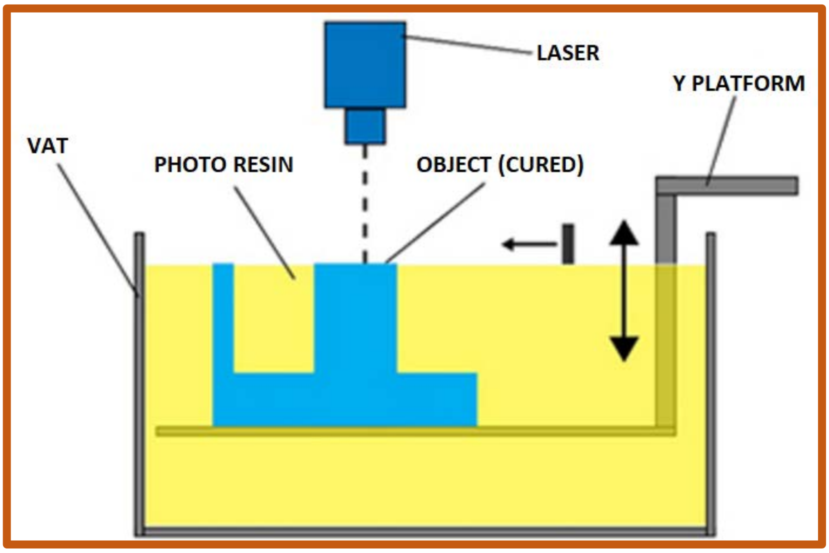


Figure 3 – Description of the Photopolymerization technique (Group, 2015).

The SLA has an elevated level of accuracy and good finishing, but often requires support structures and post curing for the part to be strong enough for structural use. The process of photo polymerization can be achieved using a single laser to ensure that there are no defects in the resin for the construction of the next layer. The photo polymerization process and support material may likely cause defects such as air gaps, which need to be filled with resin in order to achieve a high-quality model. The typical layer thickness for the process is 0.025 – 0.500 mm (Group, 2015). The materials available for the use in the vat process are Plastic and Polymers:

- Polymers: UV-curable Photopolymer resin;
- Resin: Visijet SL Clear.(Transparent/ Polycarbonate-like/Bio-compatible)

An example of a vat process machine is presented in Table 1.

Table 1 - Machine example from Vat technique (Group, 2015).

Machine	Max part weight	Build area
3D System ProX950	450 kg	1500 mm x 750 mm x 550 mm

The main advantages of the Vat Photopolymerization process are as follows:

- Hight level of accuracy and good finishing;
- Relatively quick process;
- Typically, large build volumes up to 1000 x 800 x 500 mm and max model weight of 450 kg.

However, some disadvantages can also be pointed out:

- Relatively expensive;
- Lengthy post processing time and removal from resin;
- Limited material used for photo-resins;
- Often requires support structures and post curing for the parts to be strong enough for structural use.

2.4.2 Material Jetting

This technique is very similar to a two-dimensional ink jet printer. The material is jetted on top of the build platform using either the continuous or Drop on Demand (DOD) methods (Figure 4). Layer by layer the material is jetted on top of the building platform at the surface, where it solidifies. The material is deposited with a nozzle that moves horizontally across the build platform. In terms of complexity and methods for controlling the deposition of material, each machine has its specific setting. UV light is then used to cure or harden the layers of the material (Group, 2015).

The material must be deposited in drops. The amount of material available for use is limited since, due to its viscous nature, tends to form drops. Waxes and polymers are the most suitable and commonly used materials (Group, 2015). The Material Jetting technique is described next step-by-step:

1. The building platform is prepared, and the print head is positioned above it;
2. Using the thermal or piezoelectric methods, the droplets of material are deposited from the print head on the top surface;
3. Because of the UV light the droplets of material solidify and make up the first layer;
4. Layers are built from top to bottom;
5. Post processing includes the removal of support material.

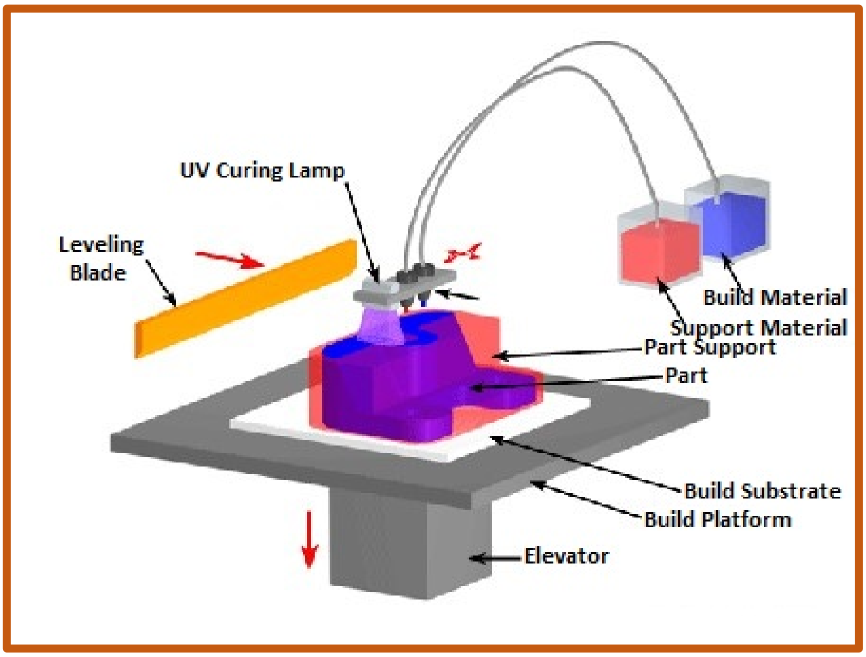


Figure 4 – Description of the Material Jetting technique (Group, 2015).

In the post processing stage, the support material can be removed using a sodium hydroxide solution or water jet. Due to the high accuracy of the process technology, the level of post processing required to enhance the properties is limited and the functional and aesthetic qualities of a part are largely determined during the printing stage. Stratasys polyjet technology cures the material using UV light and, therefore, no post curing process is needed (Group, 2015).

The raw material used in this process are polymers: Polypropylene (PP), High Density Polyethylene (HDPE), Polystyrene (PS), Polymethylmethacrylate (PMMA), Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), High Density Polystyrene (HIPS), Polymer Technologies (EDP).

Table 2 shows an example of a material jetting machine and its specifications.

Table 2 - Machine Example of Material Jetting (Group, 2015).

Machine	Build Area	Layer Thickness	No of Colors
Objet 500 Connex 3	490 x 390 x 200 mm	Layer thickness 16 microns	46

The main advantages of Material Jetting are:

- The process benefits from a high precision of deposition of droplets, which results in low waste;
- The process allows multiple material parts and colors under one process.

However, disadvantages for this process can also be pointed out:

- Support material is often required;
- A high accuracy can be achieved but materials are limited and only polymers and waxes can be used.

2.4.3 Binder Jetting

As the name suggests, this technique uses a binder as principal material to process the powder. The binder acts as an adhesive between powder layers. The build material is usually in powder form and the binder in liquid. A print head moves horizontally along the *x* and *y* axes of the machine and deposits the binding material layer by layer. After each layer, the object being printed is lowered on its building platform (Figure 5) (Group, 2015). This kind of biding methods is not always suitable for structural uses and, despite the relative speed of printing, additional post processing can add considerable time to the process (Group, 2015).

The object being printed is self-supported with the powder bed and is removed from the unbound powder once completed, as with other powder based manufacturing methods. The technology is often referred to as 3DP technology and is copyrighted under this name (Group, 2015). Step by step, next the Binder Jetting technique description is presented:

1. With the use of a roll, the powder material is spread over the construction platform;
2. Where it is needed, according to the processed commands, the print head deposits the binder adhesive on top of the powder;
3. Another layer of powder is spread over the previous layer. The object is formed where the powder is bonded to the liquid;
4. The unbounded powder remains in position around the object;
5. The process is repeated over and over until the object is made.

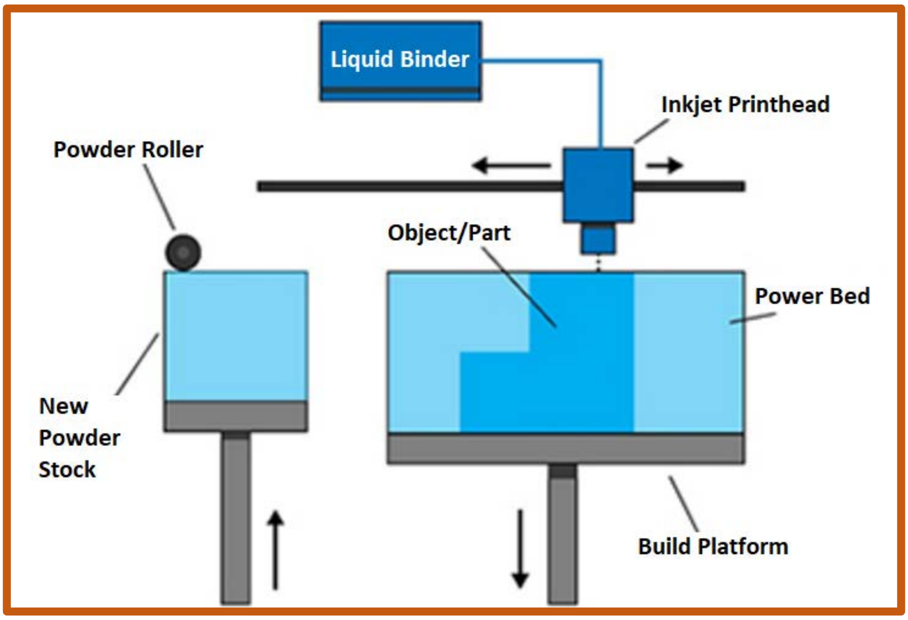


Figure 5 – Description of the Binder Jetting technique (Group, 2015).

There are three types of material that can be used with the binder jetting process:

- Metals: Stainless Steel;
- Polymers: Acrylonitrile Butadiene Styrene (ABS), Polyamide (PA), Polycarbonate (PC).
- Ceramic: Glass.

In Table 3, an example of binder jetting machine specifications is presented.

Table 3 - Example of binder jetting machine (Group, 2015).

Machine	Layer Thickness	Print Speed
Spectrum Z 500	0.089 mm – 0.203 mm	2 layers/minute

The advantages of this technique are:

- The parts can be made with a range of different colors;
- It uses a wide range of materials: metal, polymers and ceramics;
- The process is generally faster than others;
- The two-material method allows for a large number of different binder-powder combinations and various mechanical properties.

However, few disadvantages also exist:

- Not always suitable for structural parts, due to the use of a binder material;
- Additional post processing can add considerable time to the overall process.

2.4.4 Material Extrusion

FDM, which is a copyrighted trademark by Stratasy, is a common material extrusion process. This is the most widely used and cheap technique on the market. It is often found in home appliances due to the easy usability and compactness compared to other techniques. Basically, the material is drawn through a nozzle, where it is heated and is then deposited (Group, 2015).

The concept is similar to other 3D techniques, built layer by layer, the difference is in the fact that the material is added through a nozzle (Figure 6) under constant pressure and in a continuous stream. This pressure must be kept steady and at a constant speed to enable accurate results. The material layer can be bonded by temperature control or through the use or chemical agents. The raw material is fed to the machine in spool form (Group, 2015). Step by step, below is presented the Material Extrusion technique description.

1. The first layer is constructed as a nozzle deposits material where required onto the cross-sectional area of the object;
2. Layer by layer the material is added on top of the previous one.

Because the material is in a melted state, the layers join after the material deposition.

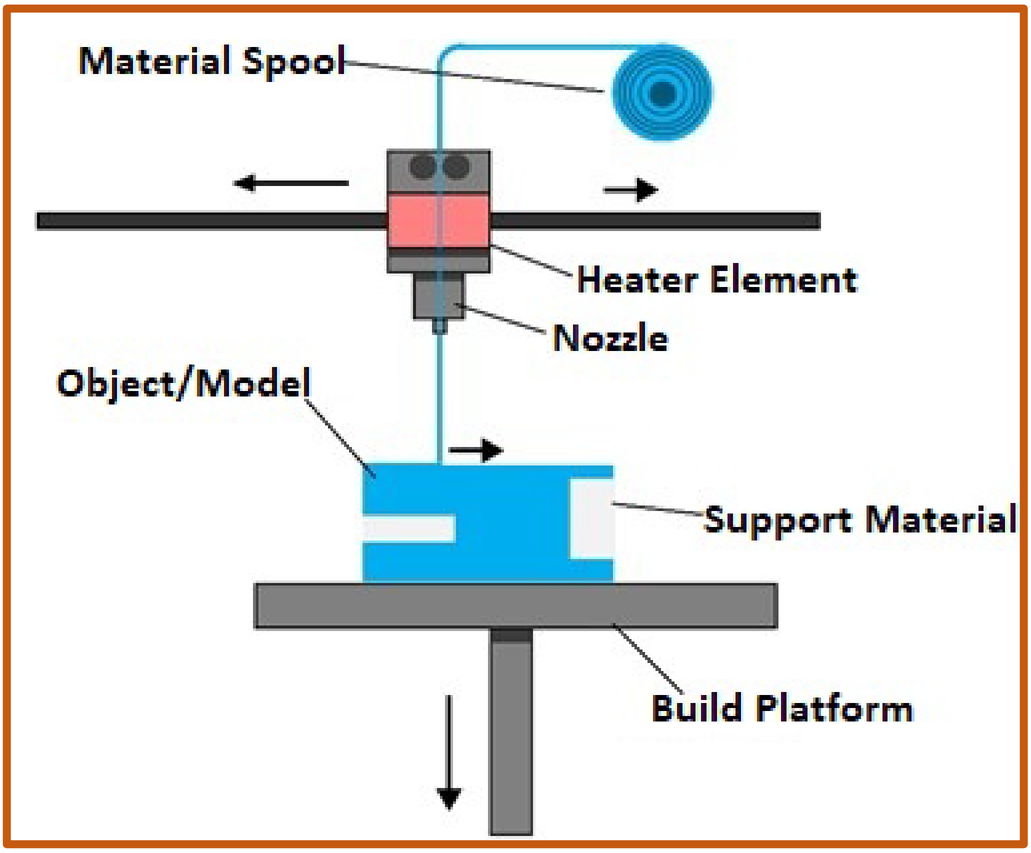


Figure 6 – Description of the Material Extrusion technique (Group, 2015).

When using the process for components where a high tolerance must be achieved, gravity and surface tension must be accounted for. The typical layer thickness varies from 0.178 mm – 0.356 mm (Group, 2015).

The materials that can be used in the Material Extrusion process are:

- Polymers: ABS, Nylon, PC.

In the Table 4, we can see example specifications of a material extrusion machine:

Table 4 - Machine example from material extrusion (Group, 2015).

Machine	Area	Layer Thickness	Built Volume
Insstek MX3	1000 mm x 800 mm x 650 mm	0.178 mm – 0.356 mm	520 l

The main advantages of this process are:

- Widespread and inexpensive process;
- ABS plastic can be used, which has good structural properties and is accessible.

However, some disadvantages can be pointed out:

- The nozzle radius limits and reduces the final quality;
- The accuracy and speed are low when compared to other processes and the accuracy of the final model is limited to the material nozzle thickness;
- Constant pressure of material is required in order to increase quality of finish.

2.4.5 Power Bed Fusion

The Power Bed Fusion (PBF) process includes other techniques like Direct Metal Laser Sintering (DMLS), Selective Heat Sintering (SHS), Selective Laser Sintering (SLS), Electron Beam Melting (EBM) and Selective Laser Melting (SLM) (Group, 2015).

To melt and fuse material powder together, the PBF methods use a laser or electron beam. EBM requires vacuum but it can be used with metals and alloys in the creation of function parts. The entire PBF process involves spreading the powder material over the previous layers. There is a different mechanism to enable this, including a roller or a blade. A hopper or a reservoir below the side provides the bed with a supply of fresh material. The SLS and the DMLS are identical, but with the use of metals and not plastics. The process (Figure 7) sinters the powder, layer by layer. SHS differs from the other processes by using a heated thermal print head to melt the powdered material together. As before, layers are added with a roll between layers merging. A platform reduces the model accordingly (Group, 2015).

The AM technique is described next step-by-step:

1- A layer thickness of material is usually 0.1 mm and is spread over the construction platform;

2- A laser fuses the first layer cross section of the model;

3- A new layer of powder is spread across the previous layer using a roller;

4- Other layers or cross-sections are fused and added;

5- Until all models are created the process repeats, the powder that is not used stays in the same place but is removed in the post processing.

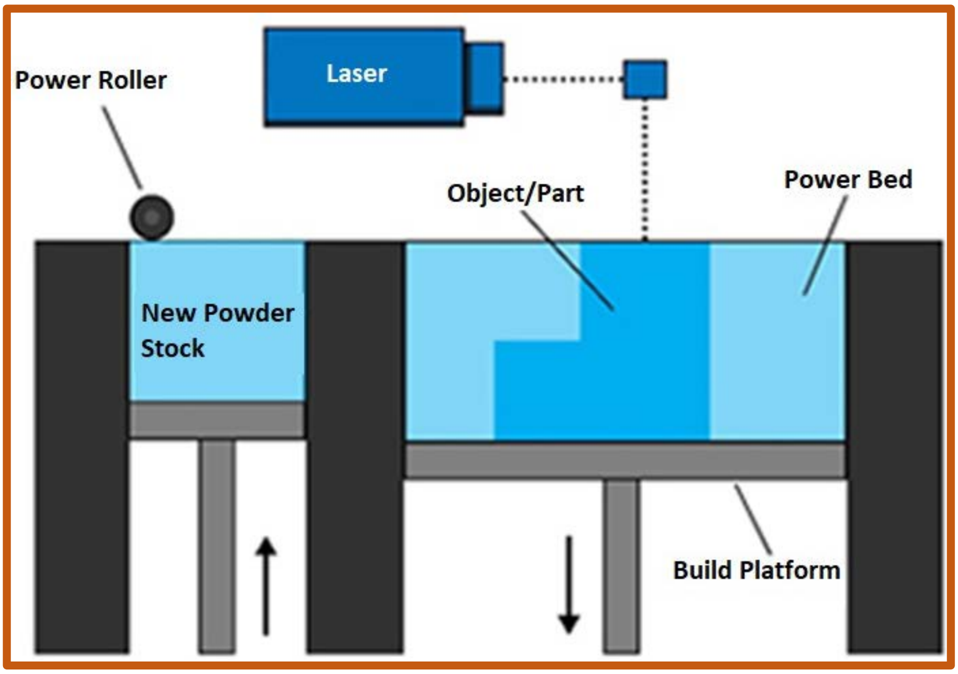


Figure 7 – Description of the Bed Fusion technique (Group, 2015).

2.4.5.1 Selective Laser Sintering (SLS)

SLS uses a PBF to build up the 3D object. However, instead of using a spray solution, SLS uses a laser to bind the powder particles together. During the printing process, the laser is directed to draw a specific pattern onto the surface of the power bed. Once the first layer is completed, a roller distributes a new layer of powder on top of the previous one (Fina *et al.*, 2017).

The build platform is within a temperature controlled chamber, where the temperature is usually a few degrees below that of the material melting point, reducing the dependency of the laser to fuse layers together. The chamber is often filled with nitrogen to minimize oxidation and end quality of the model. Models require a cool down period to ensure a high tolerance and quality of fusion. Some machines monitor the temperature layer by layer and adapt the power and voltage of the laser respective to improve quality (Group, 2015).

2.4.5.2 Selective Laser Melting (SLM)

The SLM technique is gaining popularity for manufacturing complex net shaped parts of many materials. The SLM technique uses a laser as the energy source and powder as the starting raw material (Enneti *et al.*, 2018). By comparing SLM with SLS, SLM is often faster, but requires the use of an inert gas, has higher energy cost and typically has a poor energy efficiency of 10 to 20 % (Gibson *et al.,* 2010). The process uses either a roller or a blade to spread/encourage a more even distribution of powder. A hopper or a reservoir below or aside the bed provides the raw material (Group, 2015).

2.4.5.3 Selective Heat Sintering (SHS)

SHS uses a heated thermal print head to fuse powder material together. As before, layers are added with a roller in-between fusion of layers. The process is used in creating concept prototypes and less for structural components. The use of a thermal print head and not a laser benefits the process by reducing significantly the heat and power levels required (Group, 2015).

2.4.5.4 Direct Metal Laser Sintering (DMLS)

The DMLS is one of the widely used additive manufacturing processes, which can produce solid metal parts directly from metal powder with faster production rate and better accuracy (Hussain *et al.*, 2017). This method uses the same process as SLS, but with the use of metals and not plastic powders. The process sinters the powder layer by layer, and a range of engineering metals are available (Group, 2015).

2.4.5.5 Electron Beam Melting (EBM)

Using this method, layers are fused using an electron beam to melt metal powders. Machine manufacturer Arcam used electromagnetic coils to control the beam and a vacuum pressure of $1x10^{-5}$ mbar (Group, 2015). The EBM is used to create a selective densification of metal powder by melting it in a layer in a wise manner following a CAD design (Biamino *et al.*, 2011). The EBM provides models with very good strength properties due to an even temperature distribution during fusion. The high quality and finish that the process allows for makes it suited for the manufacture of high standard parts used in airplanes and medical applications. The process offers several benefits over traditional methods of implant creation, including hip stem prosthesis. Compared to CNC machining, using EBM with titanium and layer thickness of 0.1 mm enables achieving better results, in a faster time and can reduce the cost by up to 35% (Group, 2015).

Post processing requirements include removing excess powder, further cleaning and CNC work. One advantage and common aim of post processing is to increase the density or powder combination in order to achieve homogenization and a more continuous microstructure throughout the material. However, shrinking during the process must be accounted for. Hot isotactic pressing is another method to increase density, in which a vacuum sealed chamber is used to exert high pressure and temperatures of material. Although this is an effective technique to improve strength, the trade-off is a longer and more expensive build time (Group, 2015). The materials used in EBM processes can be any powder based materials, but the most common metals and polymers used are:

- SHS: Nylon;
- DMLS, SLS, SLM: Stainless Steel (SS), Titanium, Aluminum (AL), Cobalt Chrome, Steel;
- EBM: Titanium, Cobalt Chrome, SS, AL and copper.

The principal advantages of the EBM technique are listed as:

- Relatively inexpensive;
- Suitable for visual models and prototypes;
- (SHS) Ability to integrate technology into small scale, office sized machine;
- Powder acts as an integrated support structure;
- Large range of materials options.

The main disadvantages of EBM are:

- Relatively slow speed (SHS);
- Lack of structural properties in materials;
- Size limitations;
- High power usage;
- Finish is dependent on powder grain size.

2.4.6 Sheet Lamination

The process includes Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM). The UAM process (Figure 9) use ribbons or sheets of metal, which are joined together using ultrasonic welding. Often during the welding process, the process of sheet lamination requires additional CNC machining and removal of the unbound metal. LOM uses a similar layer by layer approach but uses paper as material and adhesive instead of welding. The LOM process uses a cross hatching method during the print process to allow for easy removal post build. Laminated objects are often used for aesthetic and visual models and are not suitable for structural use. UAM uses metals such as aluminum, stainless steel, copper and titanium. The process is of low temperatures, allows the creation of internal geometries besides linking dissimilar materials using a small amount of energy because the metal is not melted (Group, 2015).

A step by step description of the Sheet Laminating technique is presented:

1. The material is positioned in the cutting bed platform;
2. Using an adhesive, another piece of material is positioned above the one;

3. The shape is obtained either by cutting the layer in situ or by a pre-cut later;
4. The next layer is added;
5. Steps two and three can be reversed and, alternatively, the material can be cut before being positioned and bonded.

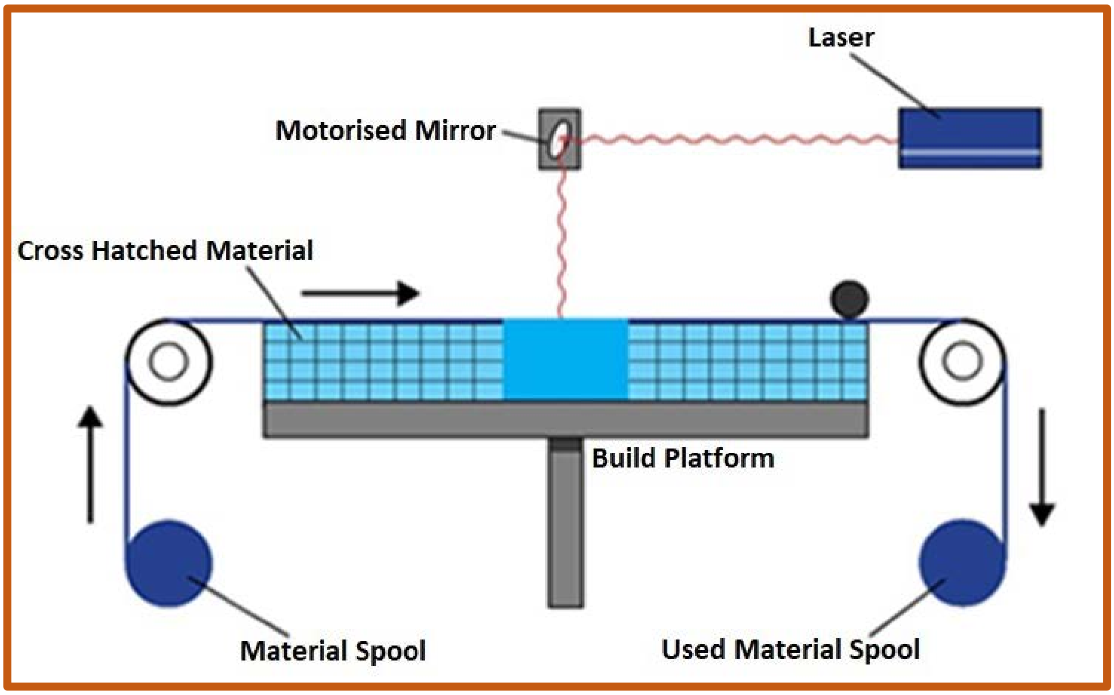


Figure 8 – Description of the Sheet Lamination technique (Group, 2015)

2.4.6.1 Lamination (LOM)

This method is one of the first additive manufacturing techniques created and uses a variety of sheet material, namely paper. Benefits include the use of A4 paper, which is readily available and inexpensive, as well as a relatively simple and inexpensive setup, when compared to others (Group, 2015).

The principle of this method is to use a laser to cut the 2D contour from slicing a 3D CAD file on the working table. After that, by means of a conveyance mechanism, the sheet-based material being cut is sent to another working table to carry out the pressing and bonding process. All unnecessary waste material is removed during the process (Chiu *et al.,* 2003).

2.4.6.2 Ultrasonic Additive Manufacturing (UAM)

UAM or ultrasonic consolidation is a continuous solid state additive manufacturing process where thin foils of similar or dissimilar metals are ultrasonically welded together in a layer by layer process to form gapless 3D metal parts (Hehr & Dapino, 2017). The process requires additional CNC machining of the unbound metal. Unlike LOM, the metal cannot be easily removed by hand and unwanted material must be removed by machining. Milling can be necessary after each layer is added or at the end of the entire process (Group, 2015).

Metals used include aluminum, cooper, stainless steel and titanium. The process is done at a low temperature and allows for internal geometries to be created. One key advantage is that the process can bond dissimilar materials and requires relatively low energy as the metal is not melted, instead using a combination of ultrasonic frequency and pressure. Materials are bonded by plastic deformation of the metals. Plastic deformation allows for more contact between surfaces and backs up existing bonds (Group, 2015).

Post processing requires the extraction of the part from the surrounding sheet material. With LOM, cross hatching is used to make this process easier, but as paper is used, the process doesn't require any special tools and is time efficient. Whilst the structural quality of the parts is limited, adding adhesive, paint and sanding can improve the appearance, as well as further machining (Group, 2015).

In this technique any sheet material is capable of being rolled. The most commonly used material is A4 paper.

In the Table 5, example of a sheet lamination machine is presented.

Table 5 - Machine Example of sheet lamination (Group, 2015).

Machine	Area	Layer Thickness
MCor Matrix 300 plus	A4 paper: 256 x 169 x 150 mm	0.1 mm – 0.19 mm

The advantages of this technique are:

- Benefits include speed, low cost, ease of material handling, but the strength and integrity of the models is reliant on the adhesive used;
- Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross-sectional area.

The main disadvantages are listed as:

- The surface finish can vary depending on paper or plastic material and may require post processing to achieve desired effect;
- Limited material use;
- Fusion processes require more research to further advance the process into a more mainstream positioning.

2.4.7 Direct Energy Deposition

With this technique there is a lot of terminology like Laser engineered net shaping, direct light fabrication, direct metal deposition, 3D laser cladding. This is the most complex printing process used to repair or add additional material to existing components (Group, 2015).

A machine of DED consists of a nozzle mounted on a multi-axis arm, which deposits the molten material on a specified surface, where it solidifies (Figure 9). The process closely resembles material extrusion, but the nozzle can move in several directions and is not fixed to a specific axis. A diversity of metals can be used, but polymers and ceramics can also be used in the form of powder or wire (Group, 2015).

A step by step description of this DED technique is presented:

1. Having a fixed object, a 4 or 5 axis arms with a nozzle moves around it;
2. Through the nozzle the material is deposited onto the existing surface of the object;
3. The material is provided in wire or powder form;
4. Materials are melted using a laser, electron beam or plasma arc upon deposition;
5. Layer by layer the material is added and solidifies, creating or repairing new material features on the existing object.

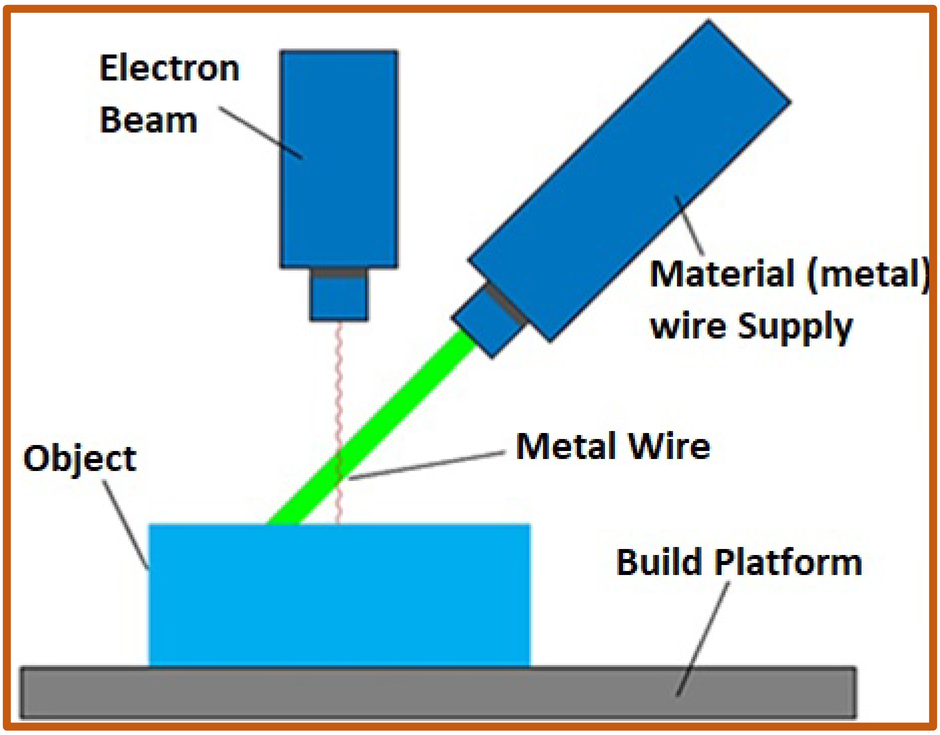


Figure 9 – Description of the DED technique (Group, 2015)

The DED process uses metals as raw material such as:

- Metals: Cobalt Chrome and Titanium.

In Table 5, an example of DED machine specifications is presented.

Table 6 - Example of DED machine (Group, 2015).

Machine	Area	Layer Thickness	Print Speed
Insstek MX3	1000 mm x 800 mm x 650 mm	0.089 – 0.203 mm	2 layers per minute

The following advantages can be presented for this process:

- Ability to control the grain structure to a high degree, which allows for great performance of functional parts;

- A balance is needed between surface quality and speed, although with repair applications, the speed can often be sacrificed for a high accuracy and a pre-determined microstructure.

Some disadvantages are listed as:

- Finishes can vary depending on paper or plastic material but may require post processing to achieve the desired quality;
- Limited material use;
- Fusion processes require more research to further advance the process into a more mainstream positioning.

2.4.8 Hybrid Technology

Often, to produce a part with precision and with the required specifications, it is necessary to use several manufacturing processes in a row. This is often referred to as a “hybrid process”. Having this approach each process helps with its best advantages (Monagharan *et al.,* 2015).

LMD integrates additive and CNC machining in one system, which optimizes the entire manufacturing process (Monagharan *et al.,* 2015).

Hybrid Machining is also referred to other purpose depending on the application. For example, this process could be applied to cases that relate to material usage, composite process, cases that relate to a combination of more than on active principle, laser assisted milling, or even cases that relate to the combination of different energy forms (Monagharan *et al.,* 2015).

Referring specifically to the manufacture of hybrid additives, this is a term that can be used for several different purposes, like the use of various techniques, such as the melting of deposited material under different heat conditions, the mixing of varied materials during deposition, or the deposition of discrete materials, among others. For the purpose of the ideal design, the hybrid manufacturing process refers to a combination of an additive and subtractive manufacture, including planning for fixation and orientation in the search for the usable end part (Monagharan *et al.,* 2015).

The major collective characteristics, according to Monagharan *et al.,* (2015), of the existing hybrid systems (within the realm of additive hybrid process) include:

- Advantage of constant/fixed part coordinates system to seamlessly switch between additive and subtractive operations; and uses various CNC machine cutting;
- Multiple machining operations such as milling, drilling, grinding etc. can be pursued along with the additive approach;
- The requirement of significant process planning to identify the sequence of AM deposition and subtractive machining since inference/gauge check is indispensable to ensure that the deposition element (weld or laser heads, power feed) and the machine tool do not collide with each other or with the part;
- Down-time associated with constant tool changes caused by switching between deposition and milling is a non-value-added for the part;
- Concerns about the microstructure associated with the irregular heat distribution cycles (e.g., machining every 2 layers vs. machining after 10 layers of deposition);
- The post-processing heat treatment requirement;
- Use of coolant during machining is not feasible because of the use of laser and welding heads;
- Weldability of super alloys is inferior to that of other commonly used alloys;
- Complex part designs with non-uniformly varying cross-sections are a challenge to produce using such process due to the infeasibility of incorporating support structures for overhanging edges;
- In addition to these characteristics, it should be noted that the current hybrid processes are applicable only to direct energy deposition processes.

The major challenge of integrating AM and subtractive machining in the current hybrid methods is the need for a hybrid process-planning protocol for post-processing of AM that accounts for the varying processing nature of AM (material shrinkage, layer thickness, orientation, etc.), machining (tool design, machining allowance, etc.) and part-specific attributes (critical features and tolerance requirements).

2.5 Optimization techniques

The concept of Optimization according the dictionary is “a mathematical technique for finding a maximum or minimum value of a function of several variables subjected to a set of constraints, as linear programming or systems analysis.”.

The market and industries always search to make their product more efficient alongside with the best cost benefit possible, making the concept of optimization a perfect fit. If it is possible to construct mathematical models representative of a respective dynamic system under study, it is possible to apply to optimization mathematical techniques to maximize or minimize a function previously defined as performance index (IP), in order to find an optimal solution for the problem. The result is the best possible performance of the system, according to this performance criterion previously defined (Silva, 2015).

To better understand this concept one can consider an example of a vehicle chassis designed to obtain the maximum stiffness with the smallest volume of material. Suppose you are free to change some variables in the chassis design to achieve the goal, such as width and moment of inertia of the reinforcements, distance between reinforcements and their position, plate thickness at different points and chassis. Therefore, we have a total of 10 parameters that can be changed. Suppose that each parameter can assume 10 defined values (Silva, 2015).

There are two approaches to solving this problem. The first is the so-called analysis approach. It consists essentially of analyzing the chassis designs that result from different combinations of the previous parameters (Silva, 2015).

However, there is a consequence of this approach. If you consider only three parameters for the chassis project and how each can assume only 10 values, there are a total of 10^3 combinations to be analyzed. Each combination corresponds to a different chassis design. If CAE software performs each analysis, and assuming that this software takes 0.1 seconds to perform each analysis, the total time to analyze the 10^3 combinations will be 100 seconds (Silva, 2015).

Consider now that you have 10 parameters in the project. If each one can take 10 values, there are now 10^{10} combinations to analyze. Assuming now in a more realistic estimate that each analysis, using a CAE software, takes 10 seconds. The total time will be 10^{11} seconds or, in other words, 3200 years. Therefore, this approach is unfeasible for a large number of parameters (Silva, 2015).

The second approach to solving the problem is called the synthesis or optimization approach. In this approach, computational methods of optimization are used, which perform a rational search of the optimal solution, that is, the algorithm will search within the space of solution defined by 10^{11} combinations, the one that provides the best performance of the chassis. The use of an optimization algorithm makes it systematic and automatic to search for the optimal point, that is, independent of the designers' experience. Thus, the solution time of the previous problem would be reduced to a few hours, for example. In this way, the term optimization is correctly used when using a mathematical method of systematically searching the optimal solution, based in steepest descent, and the least squares that go back to Gauss, and not based in trial and error (Silva, 2015).

2.5.1 Mathematical theory optimization

The basic principle of optimization is to find the best possible solution under given circumstances (Rao, 1996). The objective of the optimization is always to minimize or maximize some response. To be able to find the optimum solution, depending on a particular set of design variables, the solution needs to be expressed with a numerical value. This is usually done with a function of the design variables known as the cost function.

The general problem of optimization, mathematically speaking, is most often formulated as minimization of the cost function subjected to constraints, and this can be expressed in function (1) below (Rao, 1996):

$$\text{Find } \boldsymbol{x} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \text{which minimizes } f(x) \qquad (1)$$

$$\text{subject to } \begin{cases} g_i(x) \leq 0, i = 1,2,\ldots,m \\ h_j(x) = 0, j = 1,2,\ldots,n \end{cases}$$

Where X is the vector of design parameters and $f(x)$ is the cost function. The functions $g_i(x)$ and $h_j(x)$ are called the inequality constraint function and the equality constraint function, respectively, and they define the constraints of the problem. This is called a constrained optimization problem (Rao, 1996).

2.5.1.1 Multicriteria optimization

The functions below and variables are always present in a structural optimization problem:

Objective Function (f): this function is used to categorize designs. For every possible design, f returns a number which indicates the goodness of the design. Usually we choose f such that a small value is better than a large one. Regularly f measures weight, displacement in each direction, effective stress or even cost of production (Christensen & Klarbring, 2009).

Design variable (x): A function or vector that describes the design, and which can be altered during optimization. It may represent geometry or choice of material. When it defines geometry, it may relate to a sophisticated interpolation of form or it may simply be the area of a bar, or the thickness of a sheet (Christensen & Klarbring, 2009).

State variable (y): For a given structure, i.e., for a given design x, y is a function or vector that represents the response of the structure. For a mechanical structure, response means displacement, stress, strain or force (Christensen & Klarbring, 2009).

And now the structural optimization problem takes the form:

$$\text{(SO)} \quad \begin{cases} \text{minimize f (x, y) with respect to x and y} \\ \text{subject to} \begin{cases} \text{behavioral constraints on y} \\ \text{design constraint on x} \\ \text{equilibrium constraint} \end{cases} \end{cases} \qquad (2)$$

A problem with several objective functions can be imagined, called multiple criteria, or vector optimization:

$$\text{minimize } \big(f_1(x,y), f_2(x,y)\big), \dots, f_l(x,y)), \qquad (3)$$

where l is the number of objective functions, and the constraints are the same as for (SO). This is not a standard optimization problem since all f_l in general are not minimized for the same x and y. Instead, one therefore typically tries to achieve the so-called Pareto optimality: a design is Pareto optimal if there does not exist any other design that satisfies all of the objectives better. Thus, (x*, y*) satisfying the constraints is Pareto optimal if there is no other (x, y) satisfying the constraint such that

$$\begin{aligned} f_i\,(x,y) &\leq f_i(x^*,y^*), \qquad \text{for all } i = 1,\dots,l, \qquad (4) \\ f_i\,(x,y) &< f_i(x^*,y^*), \qquad for \text{ at least one } i\epsilon\{1\dots.\ ,l\} \end{aligned}$$

The most common way to obtain a Pareto optimal point of (4) is to form a scalar objective function:

$$\sum_{i=1}^{l} w_i f_i(x,y), \qquad (5)$$

Where $w_i \geq 0, i = 1, \ldots., l$, are the weight factors satisfying $\sum_{i=1}^{1} w_i = 1$ (Christensen & Klarbring, 2009).

2.5.2 Types of Optimization

Inside the optimization there are techniques that help, depending on the project goal. They are: Topology, topography and free size for the principals. There are also Shape, Size, Gauge and free shape to the fine tuning-level Optimization.

2.5.2.1 Topology optimization

Topology optimization combines the Finite Element Method with mathematical optimization formulas to provide the best distribution of fixed space design material. The material approach to the layout optimization method was initially proposed by Bensoe and Kikuchi (1988), considering a homogenized constitutive equation that depends only on the density of material (VirtualCAE, 2016).

An optimization algorithm is used to iteratively find the optimal material distribution, which makes the process fast. Otherwise, millions of analyzes would be required to find the optimal distribution (Bendsoe, 1995). In the acceleration of the search process of the optimum material distribution, the optimization methods use the information of the gradients in relation to the quantity of material in each element. The material distribution is represented, for example, by associating a density value to each element obtained from the discretization of the initial domain. In this way, Topological Optimization (TO) essentially combines optimization methods with the FEM (Bensoe & Kikuchi, 1988).

Topological Optimization emerged in the 80´s in the academic area in the United States and Europe with the article publication “Generating Optimal Topologies in Structural Design Using a Homogenization Method” by Bensoe and Kikuchi in 1988. In the 1990s it became widely used in the automotive and aeronautical industries of the USA, Japan and Europe for the design of optimized mechanical parts, and has recently expanded to other areas of engineering in the academic field such as the design of flexible mechanism, piezoelectric actuators, antennas and electromagnetic motors (Nishiwaki *et al.,* 2001). It makes the design process more generic, systematic, optimized, and independent of the specific experience of some engineers, providing the initial topology, optimized for a certain application, of the device being constructed (Silva, 2015).

In order to use the topological process, the first step is obtaining the shape of the part, mesh it, do an initial analysis, know what are the constraints and design parameters and, with this information, optimize in a Solver. After this, a Post analysis is used to transform the result part in a manufactured component (Silva, 2015). Figure 10 shows better how this process is done.

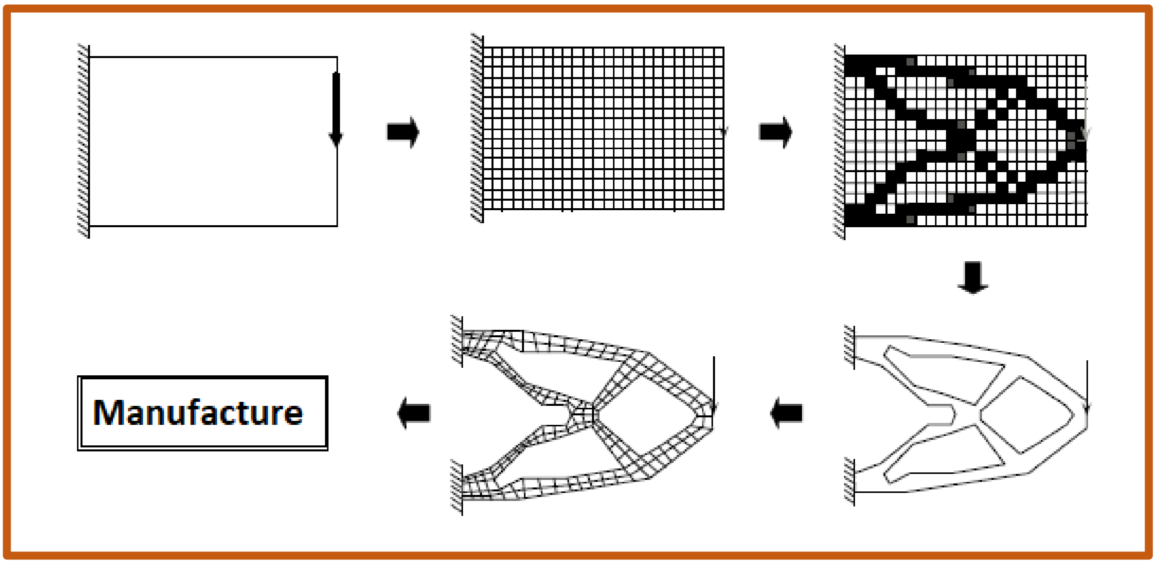


Figure 10 - Procedures for employing topological optimization (Silva, 2015)

Regarding this shape, it is important to define the domain as large as possible to not limit the TO domain work. As in any optimization method, the more constraints are imposed, the lower the performance improvement of the obtained solution. Thus, space occupancy constraint of the structure reduces the optimality of the solution in the case of topological optimization (Silva, 2015).

In the third step, the domain is discretized in finite elements and the boundary conditions are applied. In the third Step, the domain data is supplied to the topological optimization software that, by an iterative process, distributes the material in the domain, in order to minimize or maximize the specified objective function (Bendsoe, 1995). The Figure 10 in the third step one can perceive the trace of material that the software provided where the dark color indicates the presence of material and the white color indicates the absence of material at the point of domain. Note that dots with intermediate color, called the gray scale. These points indicate the presence of intermediate material that cannot be implemented in practice and always occur, therefore, the presence of the gray scale is inherent in obtaining the optimal solution (Bensoe & Kikuchi, 1988).

In this way, the image of the structure obtained by TO represents an excellent starting point that needs to be interpreted to obtain the final design of the structure (Silva, 2015).

This interpretation can be done using image processing methods, or simply by designing a structure based on the image obtained by TO. The penultimate stage consists of verifying the final result of the structure. In general, the results generated by TO are not intuitive and it is advisable to do a verification of the final structure using FEM, to create confidence in the solution by providing the optimality of the result. Finally, the last step is the manufacture of the optimized structure (Silva, 2015).

TO can also be applied to design discrete structures, such as trusses (Bendsoe, 1995). The idea is to start from a highly discretized extended fixed domain in trusses and to use as design variables the areas of trellis element that can vary from zero to a maximum value. At the end of optimization, the topology of the discrete structure is given by trellis element (Figure 12) with an area greater than a minimum value. Figure 11 shows some examples of initial design domains for two-dimensional and three-dimensional problems (Silva, 2015).

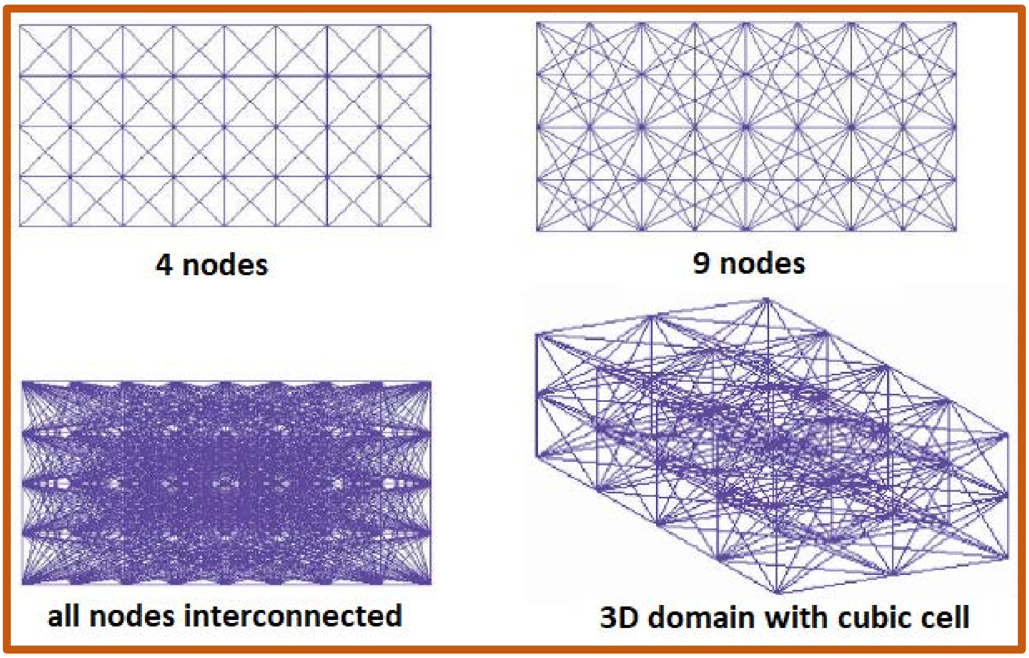


Figure 11 - Initial design domains for two-dimensional and three-dimensional problems (Silva, 2015).

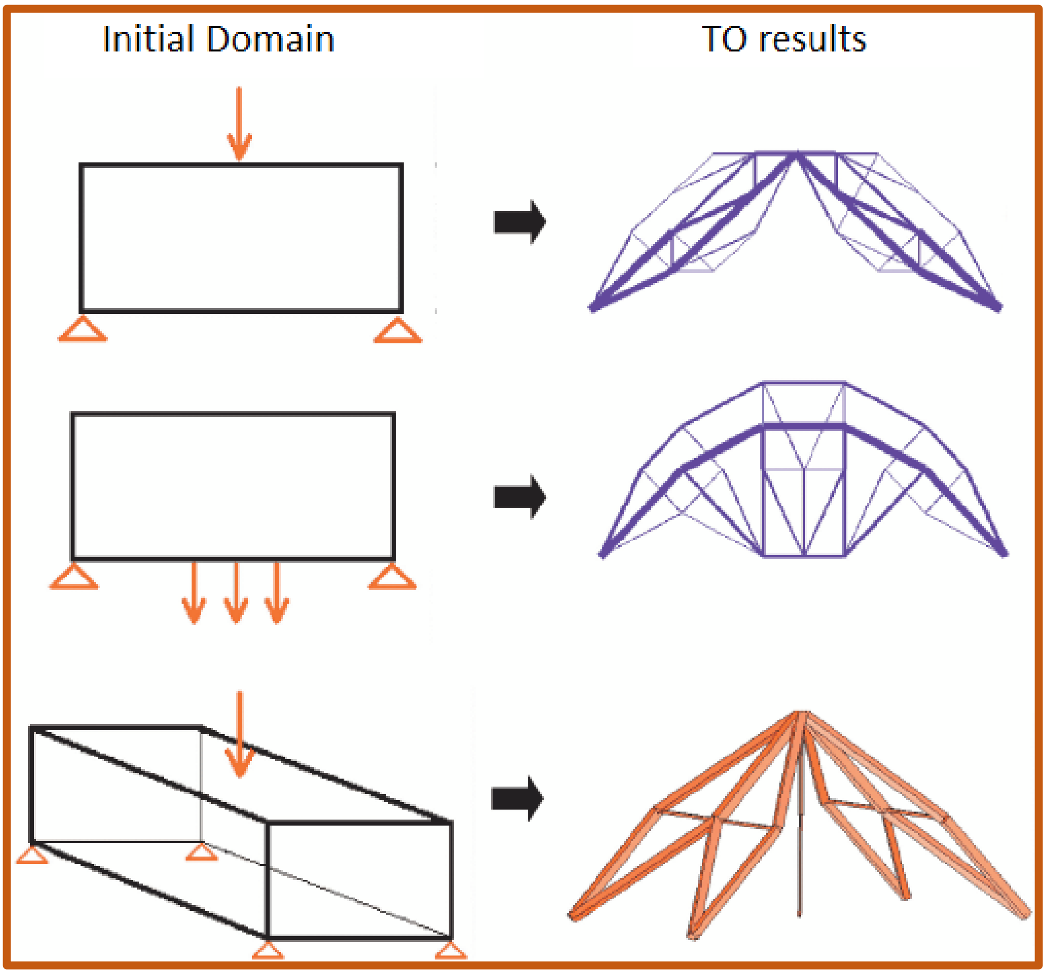


Figure 12 - Trellis Optimization (Silva, 2015).

2.5.2.2 Topography Optimization

This technique is used specifically for the design of plate and shell reinforcements. It combines the idea of TO with the size optimization. It consists of finding the distribution of a reinforcing pattern, called beads, in the structures of plate and shells. Figure 13 represents this bead (Altair, 2015).

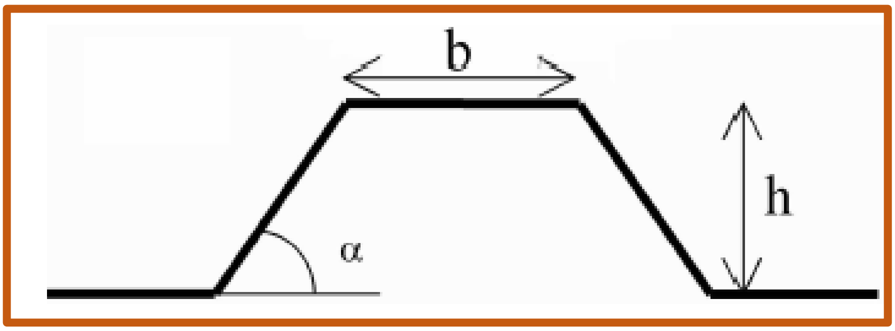


Figure 13 - Bead (Silva, 2015).

Figure 14 shows a contrast between the concept of analysis and the concept of synthesis. In this figure, several typical solutions are illustrated for the reinforcement of a torsion plate. These solutions were proposed based on the physical intuition of the problem or process of trial and error (Silva, 2015).

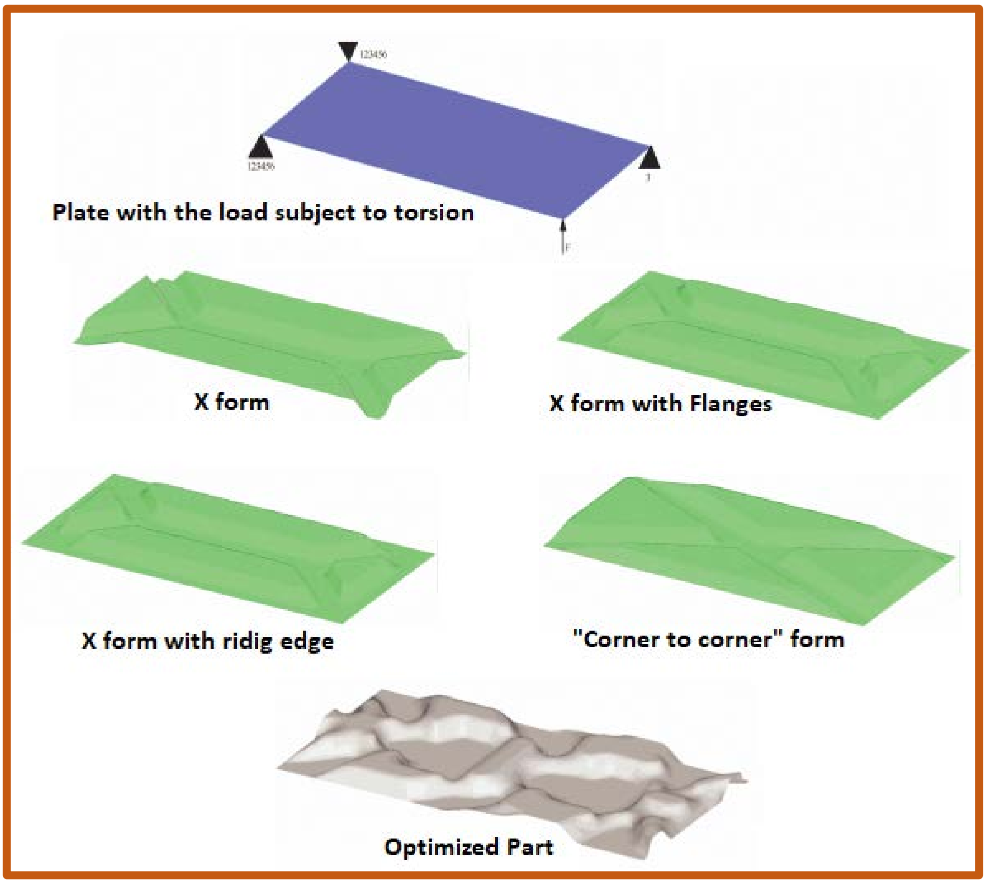


Figure 14 - Comparing the trial and error with the optimized part from software (Silva, 2015).

2.5.2.3 Free size Optimization

Free size optimization was developed in order to take advantage of the flexibility of the thickness parameter when performing topological optimization on shell elements or composite structures. The element density method used for topology optimization is best managed when optimizing solid elements but does not work as precisely when modifying the density of shells. However, shell property cards offer an easy and straightforward fixture by altering the thickness. Free size optimization can alter the thickness of elements in the design space per element to obtain a topology like optimization results (Figure 15) (Silva, 2015).

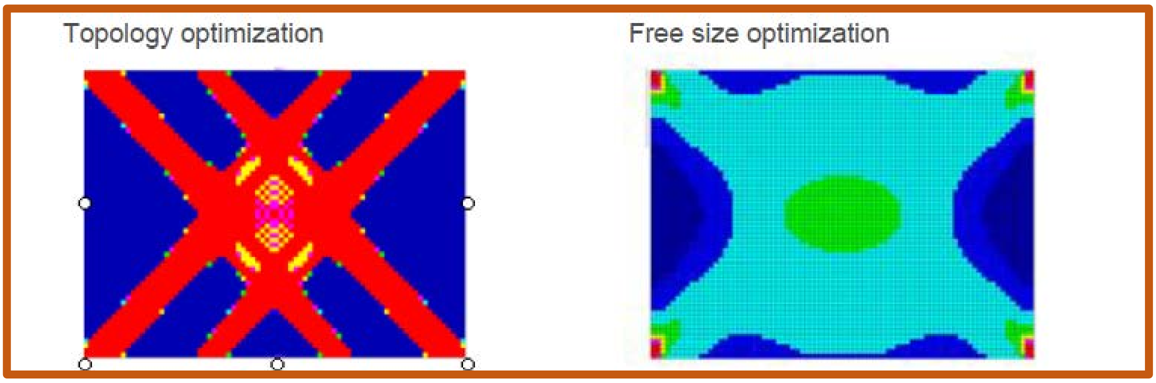


Figure 15 - Comparing topology with free size (Altair, 2015).

For a shell cross-section, free size optimization allows thickness to vary freely between T and T0 (Figure 16) for each element. This is in contrast to topology optimization, which targets a discrete thickness of T or T0 (Silva, 2015).

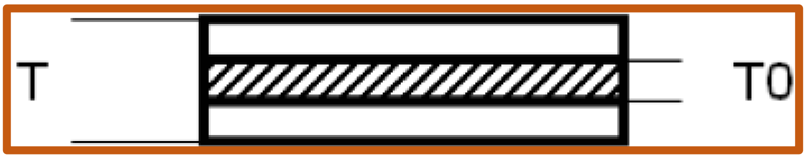
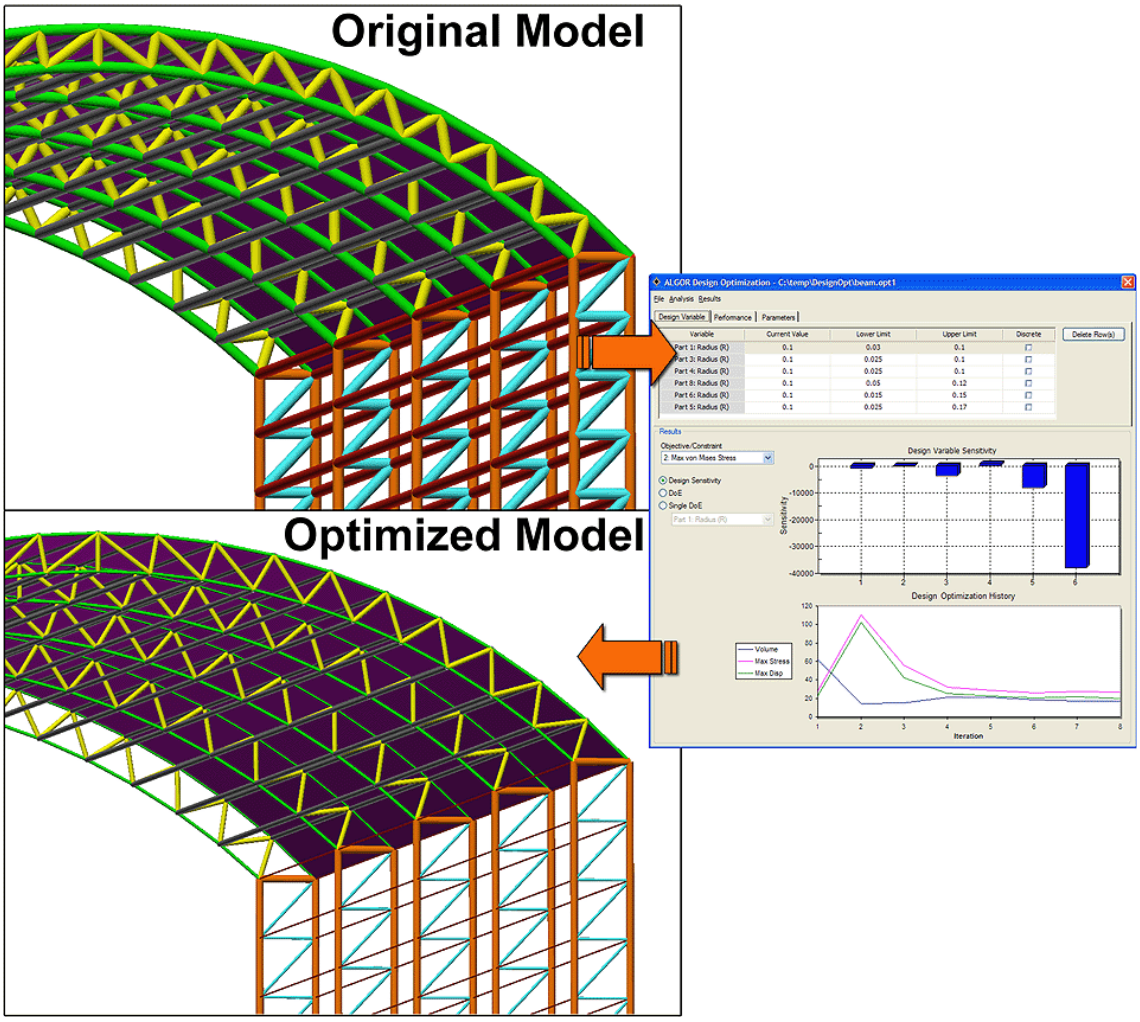


Figure 16 - T and T0 cross section (Altair, 2015).

2.5.2.4 Size Optimization

Size optimization changes the design properties, being the dimensions of the part modified without compromising the global mechanical strength. As the optimization occurs on the property, it is not possible to change the individual element thickness, all elements assigned to a property must have uniform thickness. You can define discrete values that represent manufacturing dimensions.

Figure 17 shows an example of an airplane hangar, in which the objective of size optimization was to minimize the volume parameter.



Variable	Current Value	Lower Limit	Upper Limit	Discrete
Part 1: Radius (R)	0.1	0.03	0.1	☐
Part 3: Radius (R)	0.1	0.025	0.1	☐
Part 4: Radius (R)	0.1	0.025	0.1	☐
Part 8: Radius (R)	0.1	0.05	0.12	☐
Part 6: Radius (R)	0.1	0.015	0.15	☐
Part 5: Radius (R)	0.1	0.025	0.17	☐

Objective/Constraint: 2: Max von Mises Stress

● Design Sensitivity

○ DoE

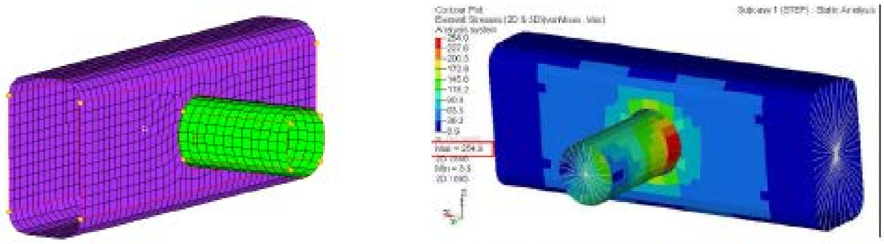
○ Single DoE

Figure 17 - Airplane Hanger process of size optimization (Williams, 2007)

2.5.2.5 Shape Optimization

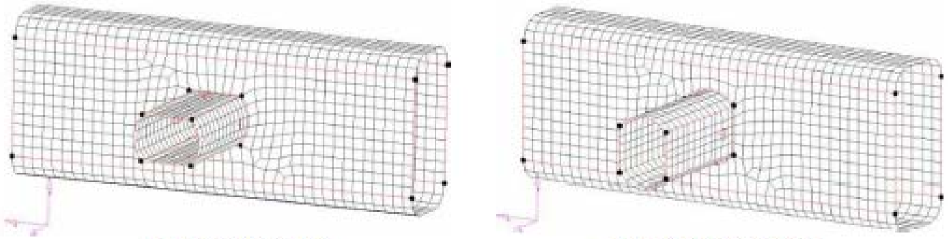
As the name itself suggests, shape optimization allows changing the shape of the structure so as to find the optimal solution. The design parameters can be coefficients of a curve that represent the shape of the part or the coordinates of some points belonging to the work piece contour (Altair, 2015).

Figure 18 shows an initial project that was subjected to shape optimization.



Rail Joint

Von Mises Stress For The Initial Design (255 MPa)



First Shape Variable sh1

Second Shape Variable, sh2.

Figure 18 – Description of the Shape Optimization technique (Altair, 2015).

Due to the complex shapes that can be obtained, the FEM is used to analyze the structures during optimization. The main disadvantage of form optimization in this case is that with the change in the shape of the structure the FEM mesh is distorted requiring a re-domain during optimization (Haftka & Gürdal, 1992). There are remeshing techniques for two-dimensional domains, however for three-dimensional domains it is not advisable.

DEVELOPMENT

3 DEVELOPMENT

3.1 Case Study 1 - Part 1

A part of 7075 T651 aluminum (aeronautical aluminum) was chosen as a case study (Figure 19). The goal for this particular part was to create a structural reinforcement, using beads, through a topological optimization process.

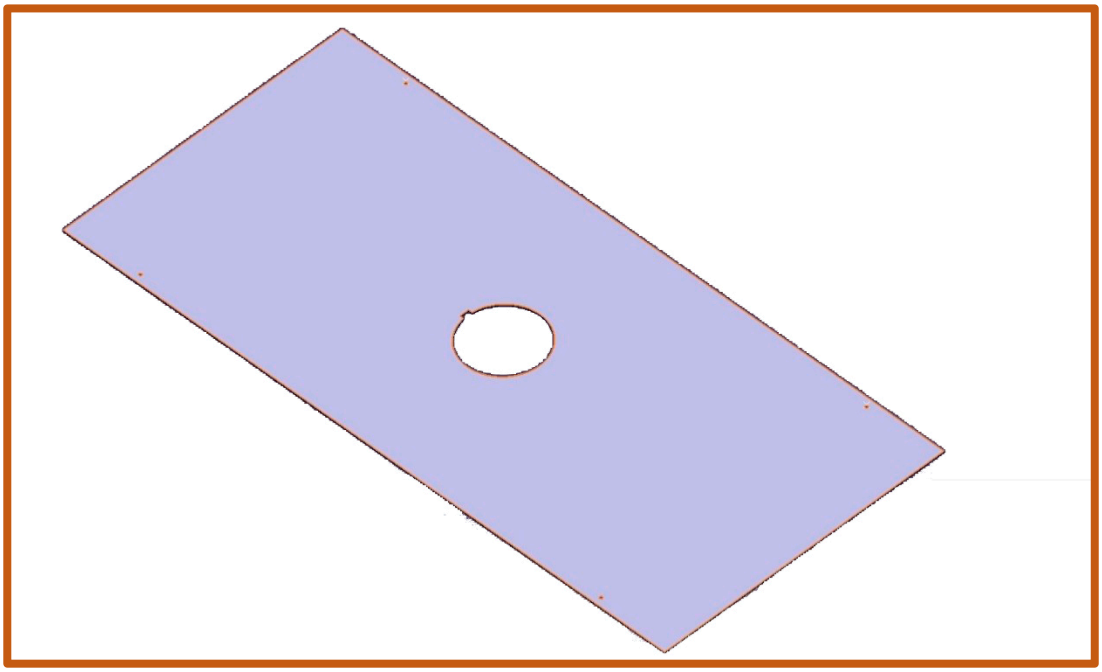


Figure 19 - Part 1 designed in Hypermesh.

The part has the global dimensions of 1090 x 500 x 2 mm^3. During service, the part is subjected to a load of 20 kg, applied around the central hole, while the part is fixed at both sides (marked by four small holes), as it can been seen in Figure 20.

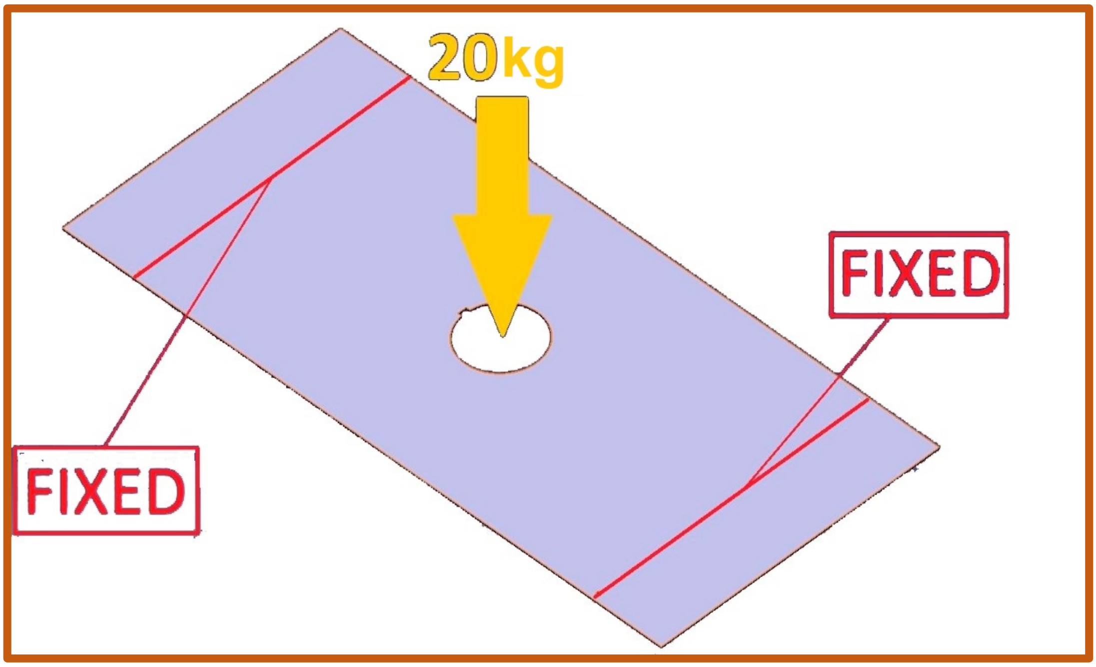


Figure 20 - Part 1 with load and constraint.

This Study Case was made using empirical research, which is a way of acquiring knowledge by means of direct and indirect observation or experience. Same values of the optimization were taken from trial and error procedures, that is, several attempts were made until finding the ideal value, also with the help and knowledge of the people working in this area.

3.2 Critical analysis of empirical research

To operate the software, you have to know the basic and essential concepts like procedural shortcuts, information menus and screens for each one need among some more. For the optimizations, pre-determined values were used according to the knowledge of the most experienced workers in the Optimization area and the level of success they obtained.

For the topographic optimization, in the creation of the beads the values of minimum width, draw angle and drawn height were determined by the satisfaction and requirements of the project with only 1 plane of symmetry. For this type of optimization these are the values of greater importance.

In the topological optimization there was a greater search and attempts to obtain the values that would fit better in the project. For the mass minimization we have some responses such as volume fraction, mass fraction, mass and volume. Through the tests, the parameter that obtained the most satisfactory result was the MASS where it obtained a satisfactory design and a great reduction of mass.

Through the analysis observations in Software and optimization attempts, concrete values and a realistic final model were stipulated.

3.3 Structured Methodology

As previously mentioned, the use of AM technology was proposed to optimize parts to take advantage of this technology. The software used to do the optimization was the OptiStuct in conjunction with Hypermesh and Hyperview, all belonging to Altair.

The main objective of using this part was to create a structural reinforcement with Topographic Optimization and the first step is to process the part. In Figure 21 the mesh results can be seen. This determines where you will interact and where you will not. In Figure 21 it is also observed the separation of these interactions where the yellow color is where it will interact and the green color where it will not have.

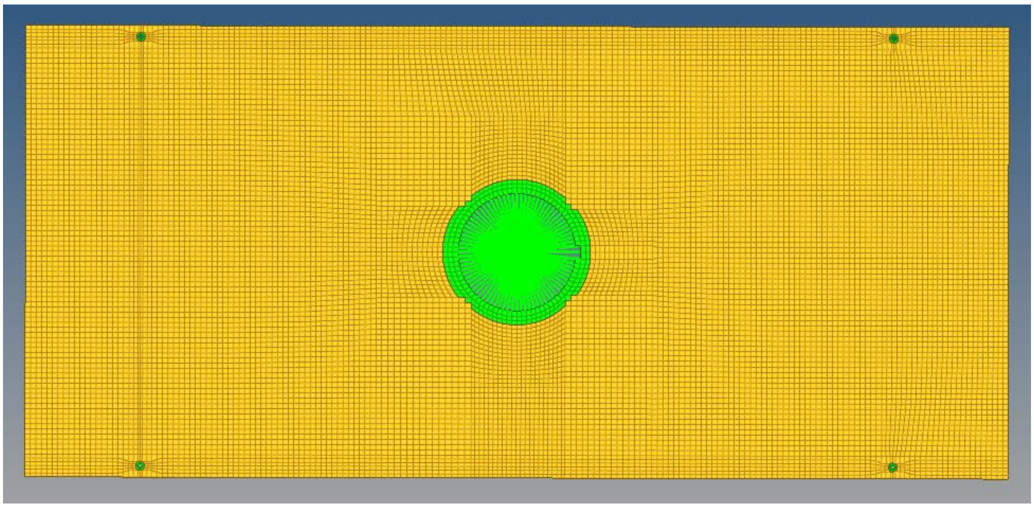


Figure 21 – Part 1 with mesh and the separation

After this, the loads and the material are determined, which in this case is an Aluminum 7075 T651 (annex 1). The loads and constraints can be observed in Figure 22. The load units used by the software for the analysis was Newton, therefore considering that 1 kg is 10 N and the part has a load in the Z direction of 20 kg, a 200 N response will be present.

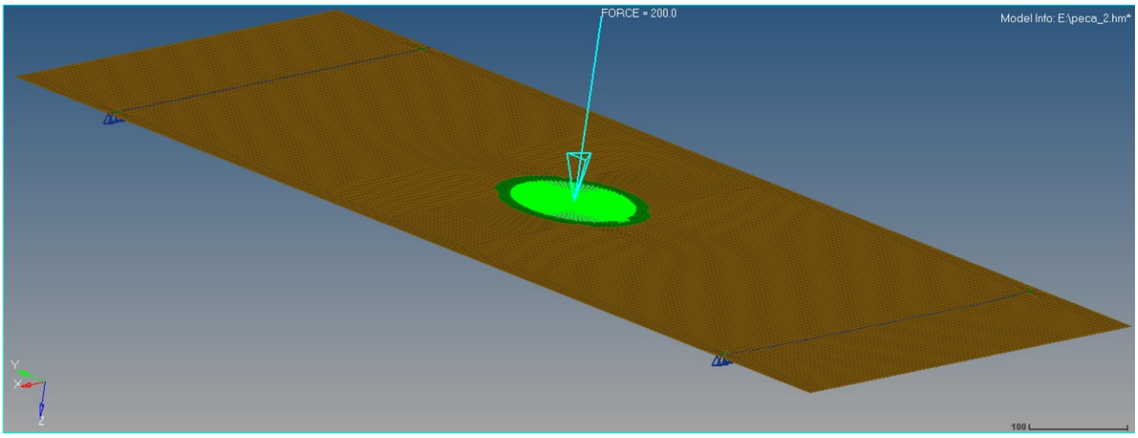


Figure 22 – Applied loads and constraints

With the load applied and the part meshed, the software analyzes the original part to observe the values of Displacement and Stress and for a comparison of values at the end. In Figure 23, Figure 24 and Figure 25 we observe these values and the schematization of displacements and stresses.

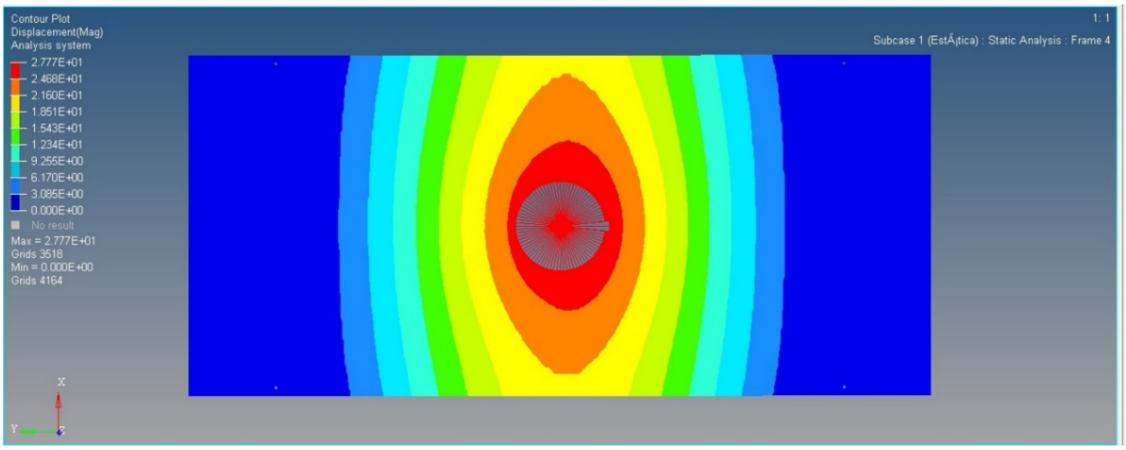


Figure 23 – Dislplacement in the original part

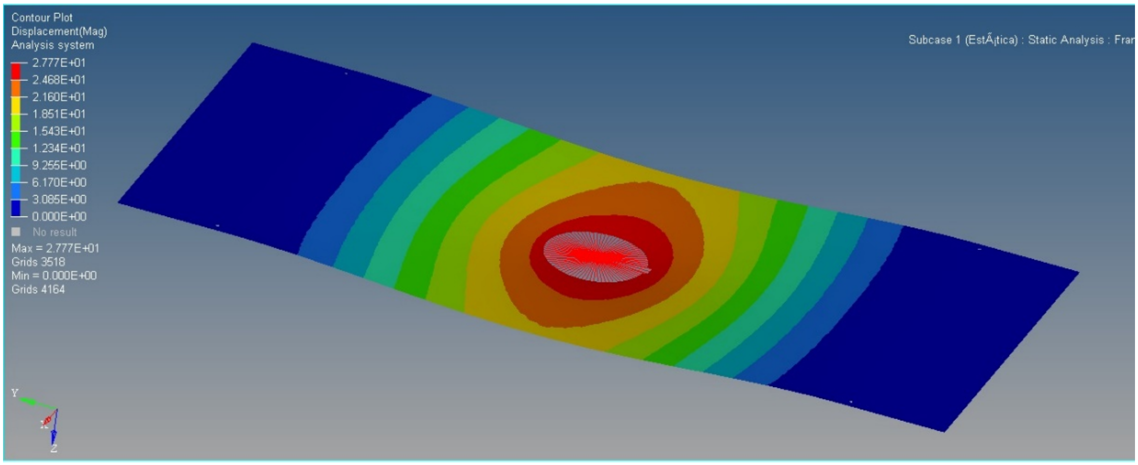


Figure 24 – Displacement in a different view

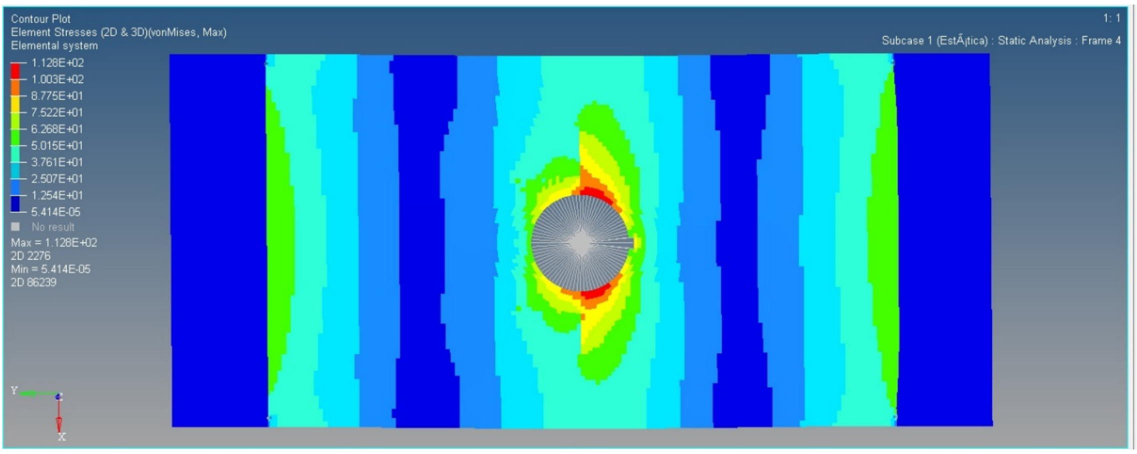


Figure 25 - Points of high Stress in original part 1.

With the mesh made and the part analyzed, the optimization process is started. In the software, the type of optimization (for this case is the topography) and the beads parameters, which are minimum width, draw angle and draw height, are specified. The chosen parameters were 15, 85 and 5 respectively, with the grouping pattern with 1 plane of symmetry.

Once the configuration of the topography panel is chosen, a response, a goal and a constraint are defined for this purpose. For this optimization a Static displacement response was chosen with the objective to minimize it. In Figure 26 we can see how the creation of the beads was made for the structural reinforcement of this part.

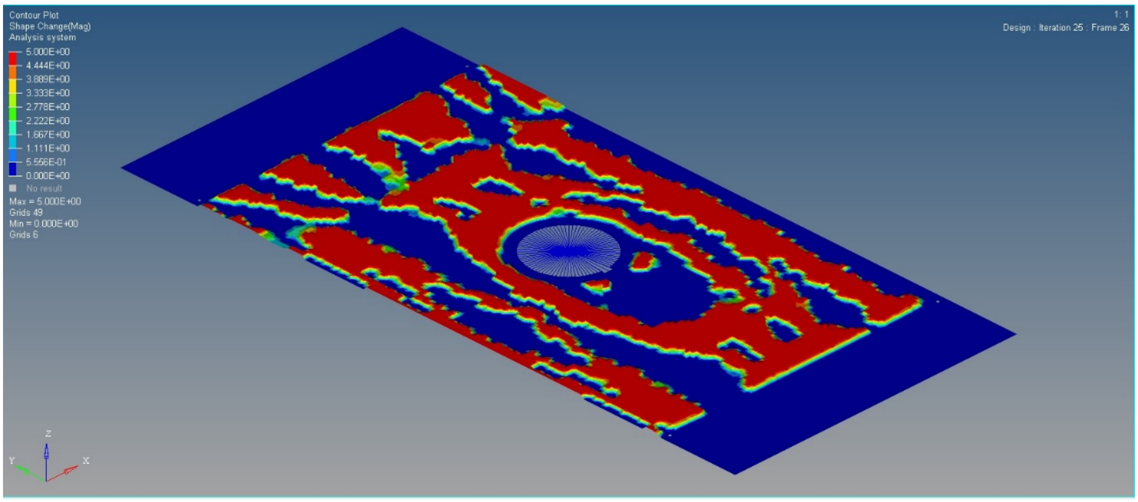


Figure 26 – Creation of the beads

After the creation of the Beads, one uses the Hyperworks own post-processing software called Ossmooth that will create the part with the reinforcements. In Figure 27 we have the part with the beads re-meshed for a new analysis and to verify if the behavior improved.

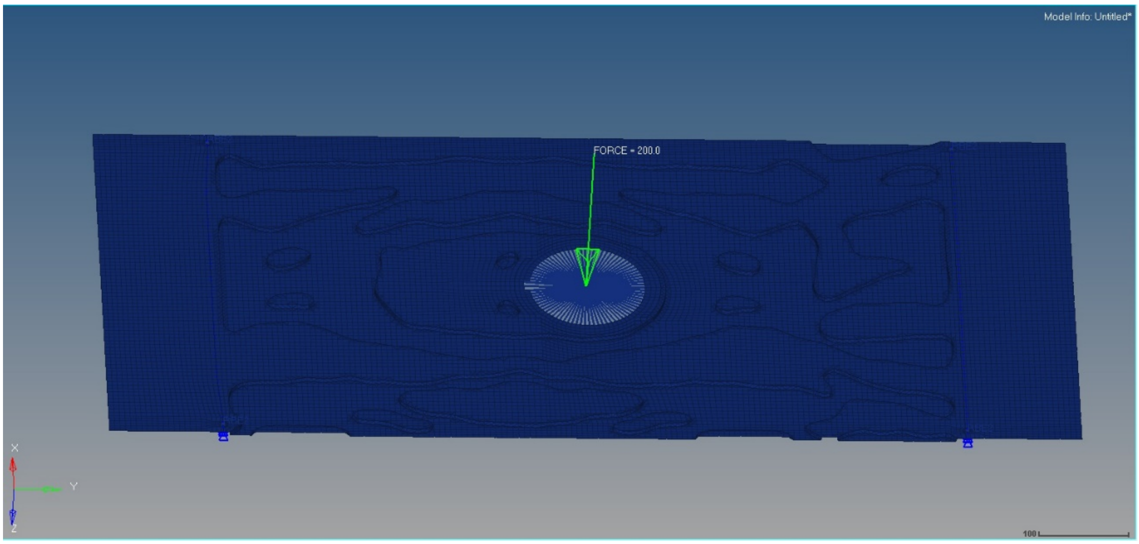


Figure 27 – Optimized part 1 prepared to analysis.

By the analysis, one can verify the values and compare with the original. Figure 23 shows the displacement from the original part and Figure 28 shows the displacement from the optimized part. The original part shows a displacement of 27.7 mm while the optimized part shows only 3.5 mm, clearly showing an improvement.

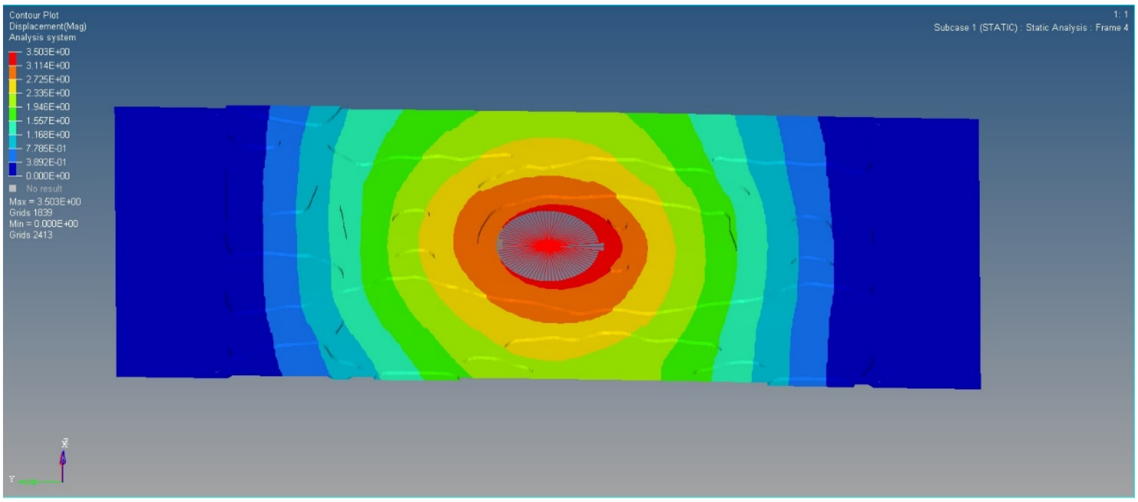


Figure 28 – Optimized analysis part

In a stress analysis, the stress level installed in the original part was 112 MPa while in the optimized part it just 53.04 MPa (as observed in Figure 29), under the same conditions.

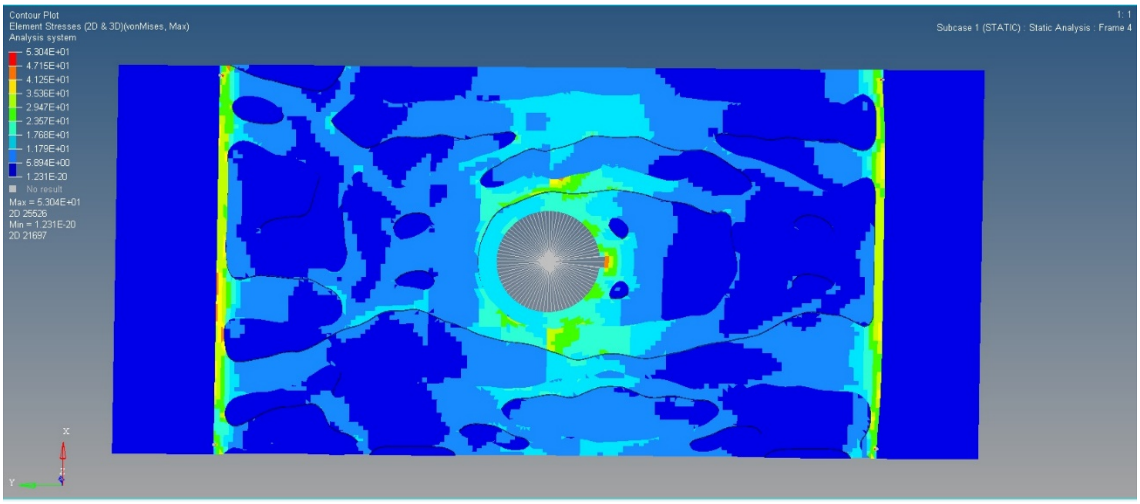


Figure 29 – Stress Analysis from optimized part.

Through a basic equation (4) one can verify the improvement of optimization in a percentage wise.

$$\text{Improvement in percentage} = \frac{(\text{Displacement}_{\text{initial}} - \text{Displacement}_{\text{final}})}{\text{Displacement}_{\text{initial}}} \text{x}100$$

$$x = \frac{(27.7 - 3.5)}{27.7} x100 \tag{6}$$

$$x = 87.36\%$$

Figure 30 depicts a preview part in CAD modelling.

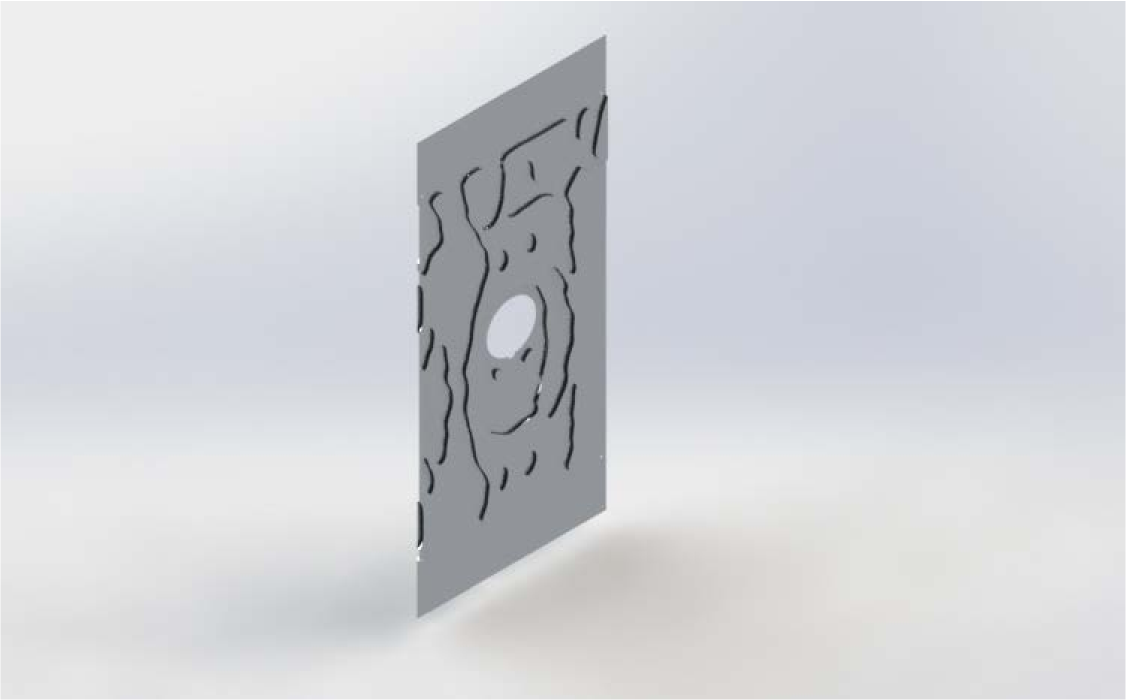


Figure 30 – Preview part in a CAD software.

3.4 Flowchart

Through the case study 1 we can see that for the realization of the optimization, a pattern can be created to fit the entire process. By creating the flowchart of Figure 31, Figure 32 and Figure 33, visualization of the process becomes easier.

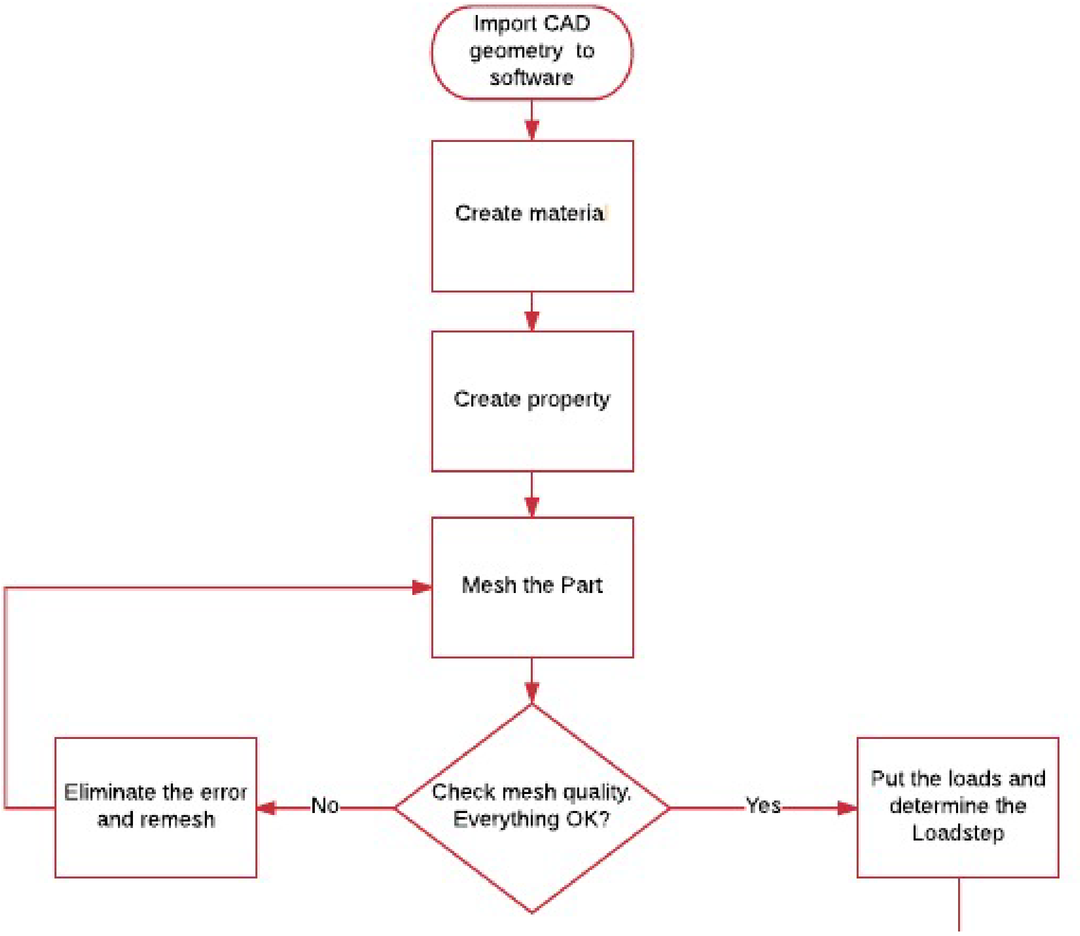


Figure 31 – Flowchart part 1.

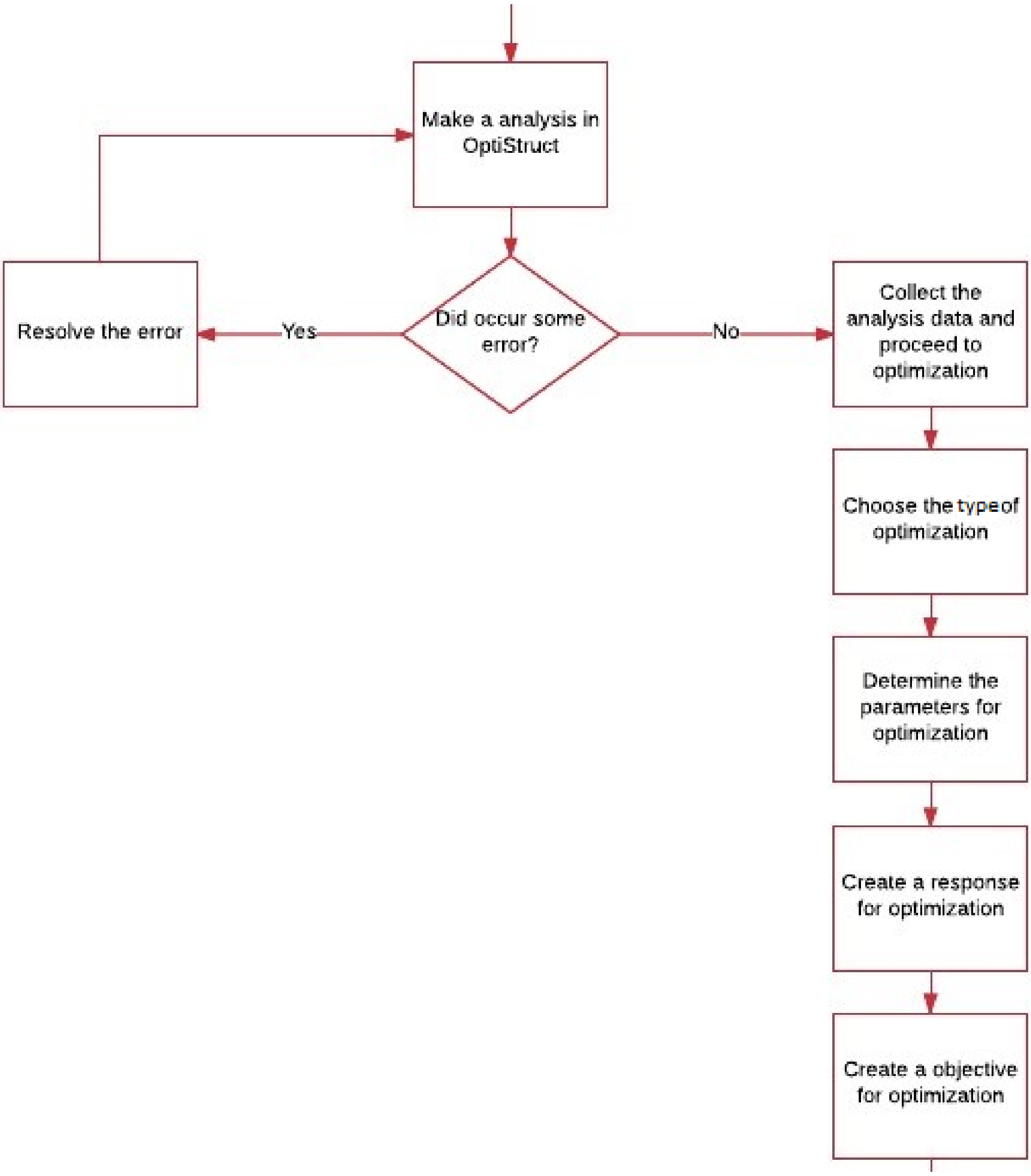


Figure 32 – Flowchart part 2.

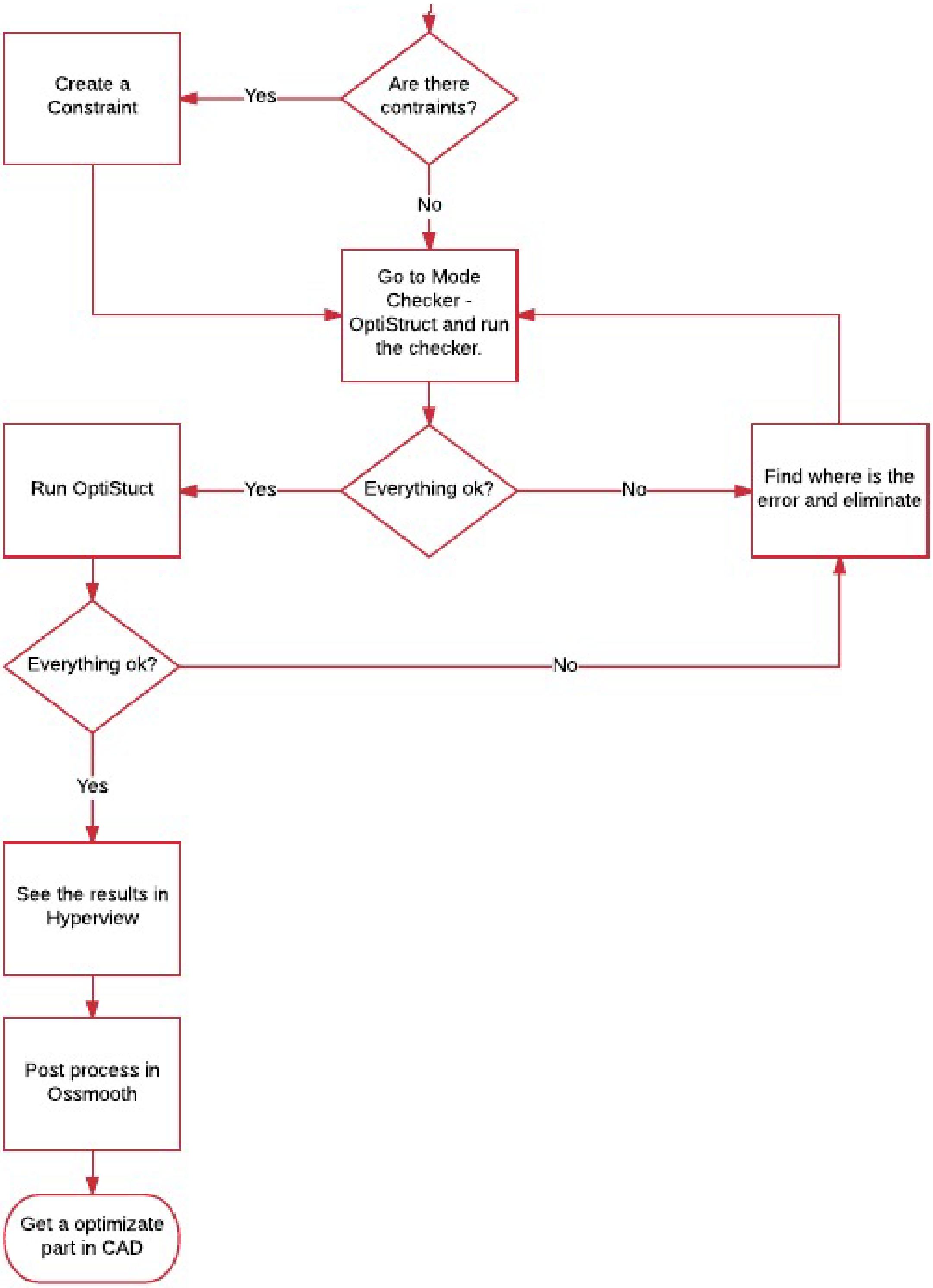


Figure 33 – Flowchart part 3.

3.4.1 Detailed explanation

- Requirements for the Part Geometry

The geometry interface is specified in some terms, as explained below:

Predefined Parts	Determine the shape and position of the parts that must not be changed by the optimization. E.g. connections to other structure, contact surfaces and others.
Symmetry	Are there pattern repetitions or symmetries that are desired?
Parts that be necessary to be present	Determine what part is necessary to be present in the final structure but can be positioned according to the optimization. E.g. Connections to other structure, screw holes, etc.
Largest allowed design volume	Determine the largest allowed volume or area in which the final structure must be formed.
Accessibility for mounting	In the structure which points must be accessible for mounting or other requirements? They must be defined.

- Property

The property is determined after the creation of the material, where you choose the property type according to the element you have, that are: 0D_RIGIDS, 1D, 2D, 3D, ACOUTIC CONTACT, SPRINGS_GAPS. After this choose the card image and determine the material for the property. The property assigns elements that define design domain and non-design domain.

- Material

For the creation of the material the program provides several cards where numerical information of the material is placed according to its purpose. But for optimization you need to have the basic material information, which consists of the Young’s Modulus, Poisson’s Ratio and Mass Density.

- Load cases and constraints

Mesh the model with an element size of a third of the desired minimum member size. Determine the loads (FORCES), constraints (SPC) and the load cases that the structure is subjected to. Connect the model to possible adjacent structures completing it.

Static Loads	Determine the position, direction and magnitude for forces as well as the corresponding constraints. The absolute magnitude is not as important as the right relation between the loads.
Acceleration Loads	Gravitational loads can simulate acceleration or shake tests.

- Mechanical requirements

Displacement	Determine the largest or smallest allowed displacement in distinct parts.
Mass	Determine the largest or smallest allowed mass of the final structure.
Stress	Define the largest allowed stress of final structure. Is there any safety limit?

As the parts will be constructed using the ALM method. The optimized design does not have any manufacturing constraints, while when using conventional manufacturing methods these could have existed. For instance, when using other methods, design influences the direction of extrusion or, in case of using casting, one must determine if the part will be done by a single or split mold. However, the material thickness depends of the design part.

- Types of Optimization

Six types for part optimization can be chosen as shown below:

Topology	It can be used in either 2D or 3D elements and basic design chooses the best load path between elements according to their configuration.
Topography	It is a technique used specifically for the design of plate and shell reinforcements. Consists of finding the distribution of a reinforcing pattern, called beads.
Free Size	It is a technique that allows for a flexibility of the thickness parameter when performing topological optimization on shell elements or composite structures.
Shape	Allows to change the shape of the structure to find the optimal solution.
Size	Changes the design properties, such that the dimension or dimension ratios of the part do not change, but rather its appearance.
Free shape	Allows change of the contour

- Parameters

First of all, it can be choose an optimization parameter for certain part, because this parameter needs to be defined and it will be specific to each type of optimization. Some examples of optimization parameters are presented following.

DESMAX	This determines the maximum number of iterations. Default is 30 and when MINDIM is used it reaches 80.
MINDIM	Controls the minimum member size and should be to 3 times the average element size. Proves be very effective enforcing a discrete solution and suppressing checkerboard patterns.
SCREEN	This is a control card that is used to output information about the commands that were used and values in iterations.
DISCRETE	This parameter controls the penalization of densities. The default is 1.0 for shell (2-d) elements and 2 for solids (3-d) elements.
DRAW ANGLE	Determine the angle of the sides of the beads to use in topography.
MINIMUM WIDTH	Controls the width of the beads in the model

- Response

The responses determine the focus of optimization and can determine more than one. Next are some examples.

MASS
VOLUME
COMPLIANCE
STATIC DISPLACEMENT
FREQUENCY
STATIC FORCE
COMPOSITE STRESS
WEIGHTED COMPLIENCE
TEMPERATURE
THERMAL COMPLIENCE
BUCKLING
SPC FORCE

- Objective

Its permitted only one objective per optimization that chooses a response to either maximize or minimize.

- Constraints

The constraint limit is a response preventing from exceeding a certain value. For example, in a volume response, if the optimization must not exceed 40% of this volume, one should choose a constraint limit of 40%, depending the designs goals.

- OSSmooth

After optimization, software is needed to make it real, in this case OSSmooth. The OSSmooth is a semi-automated design interpretation software. This software simplifies the recovery of a modified geometry resulting from a structural optimization. It can be used for topography optimization results, to give a new geometry from the optimized shape, reduce the amount of surface data, etc. The main output formats are IGES, STL and H3D.

3.5 Case Study 2 - Support

The other part chosen for analysis was a support bracket that is part of a marine project (Figure 34). It is made out of 7075 T651 Aluminum and one of the objectives of the study was to combine the various components that compose the bracket into a single part to produce via AM. This method allows to create the component in a single process, alongside with the ability to reduce volume and mass using topological optimization.

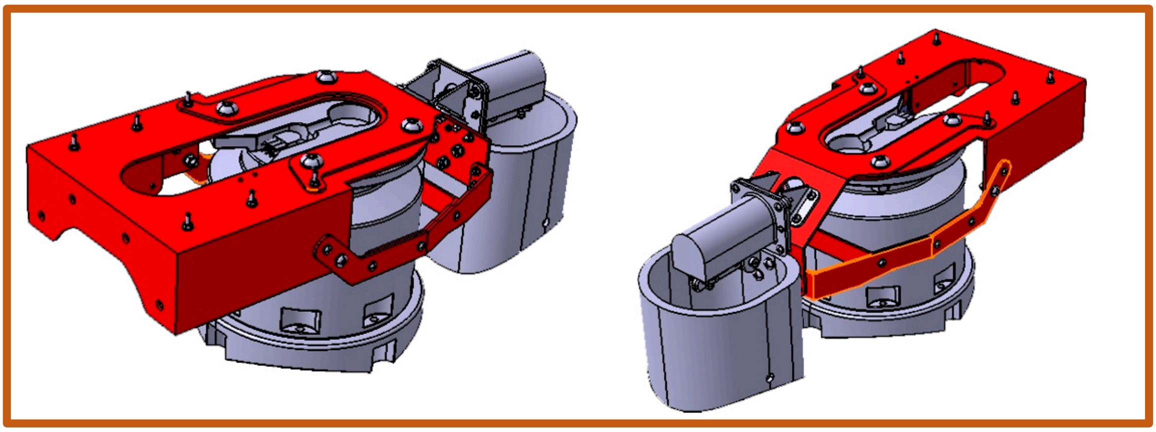


Figure 34 - Original support highlighted in red

The support was redesigned in CAD as a single body part, following the standards and measurements of the original bracket. Figure 35 and Figure 36 illustrate the new design.

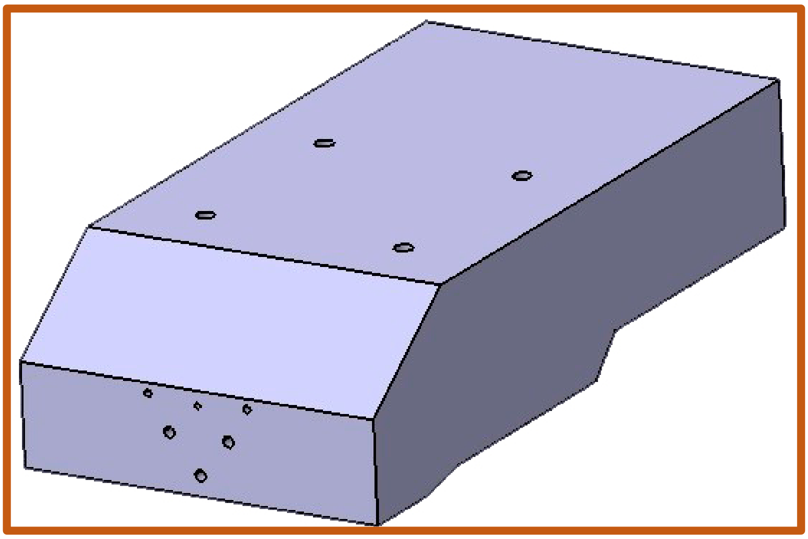


Figure 35 – Support made in single block

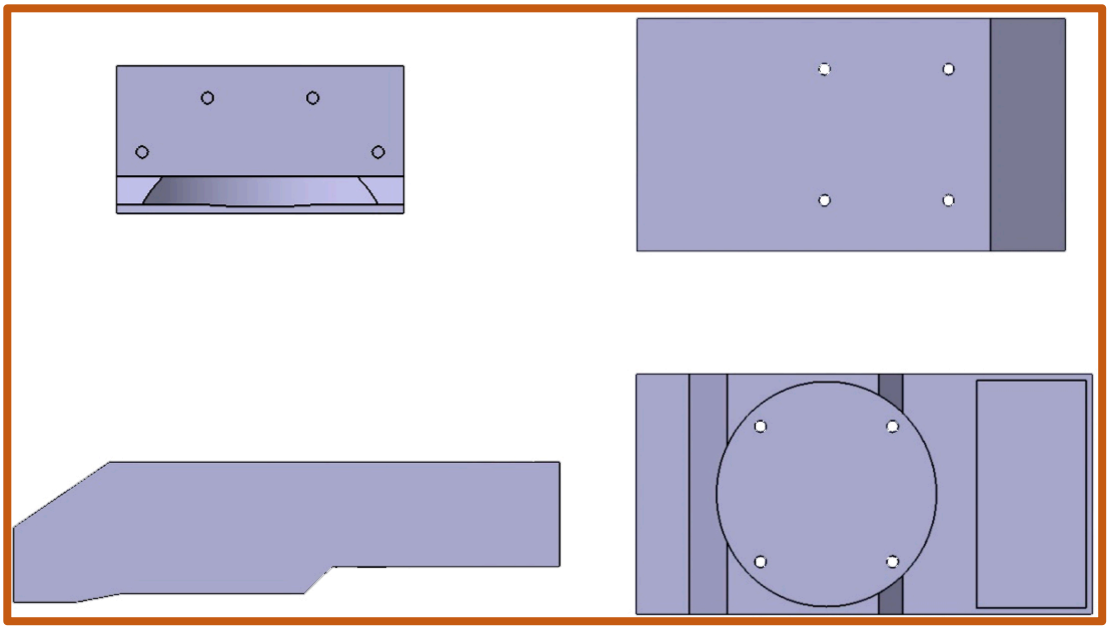


Figure 36 – Views of the support made in single Block

The support was subjected to loads of 14 kg and 10 kg, being the 14 kg load distributed in 4 holes in the center of the piece and the 10 kg load distributed in the front 6 holes, as seen in Figure 37. The support bracket is fixed at the back side.

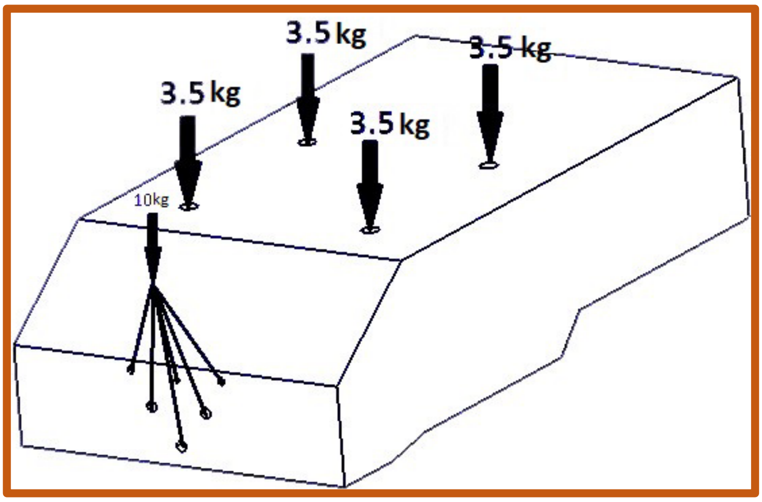


Figure 37 - Support with distributed loads.

The objective of this second case study was to do a topological optimization, so that the software choses a unique shape with the best distribution of material while keeping the same efficiency. The support was meshed with a tetrahedral mesh, as seen in Figure 38.

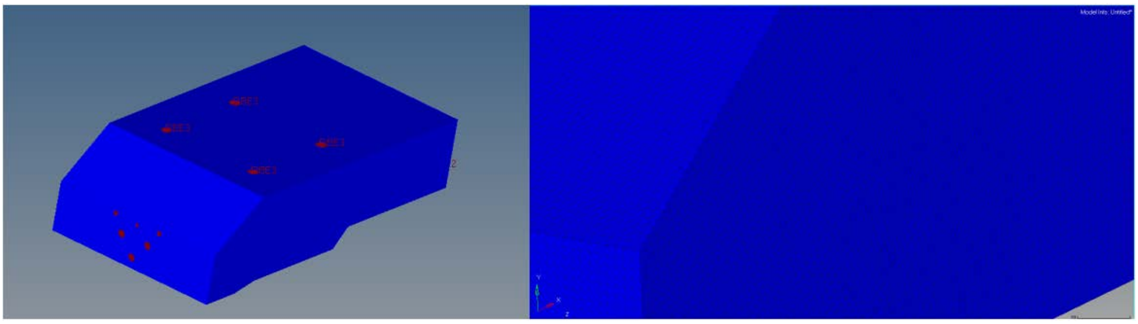


Figure 38 - Support with tetra mesh.

After the mesh is made, the loads are applied, one being 140 N divided into the four holes (35 N in each hole) in the center of the support (Figure 39). The other is 100 N divided by the six holes (16.67 N for each hole) in the front of the support and constraint elements in the back of the support (Figure 40).

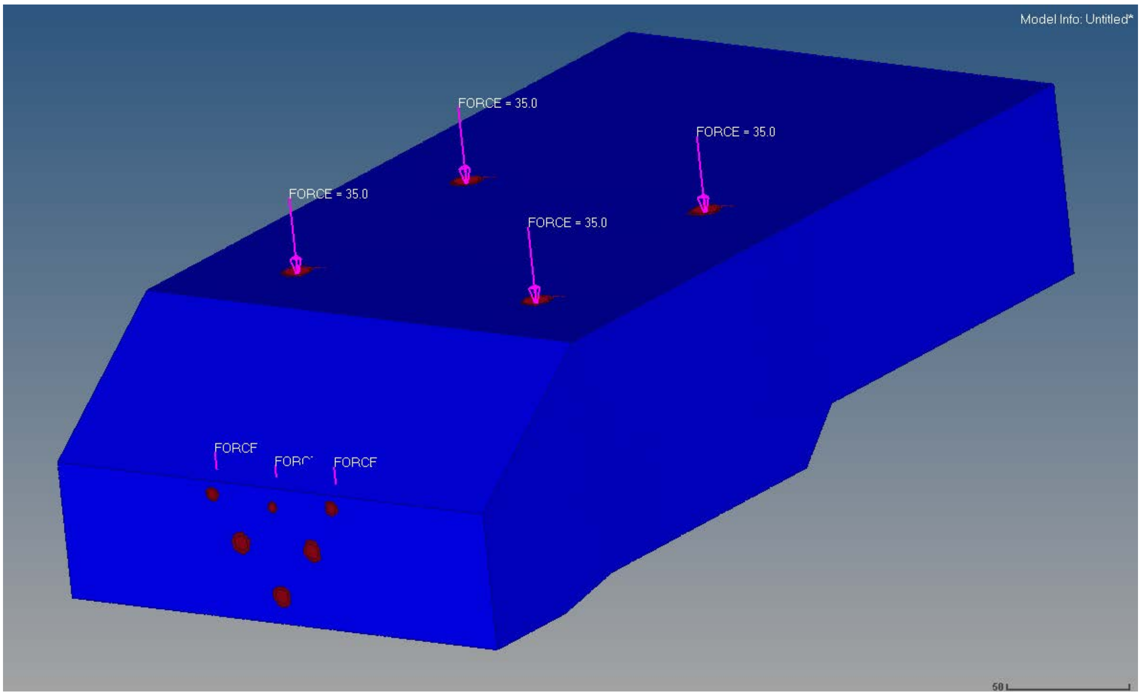


Figure 39 – Support with the Loads in front and superior holes.

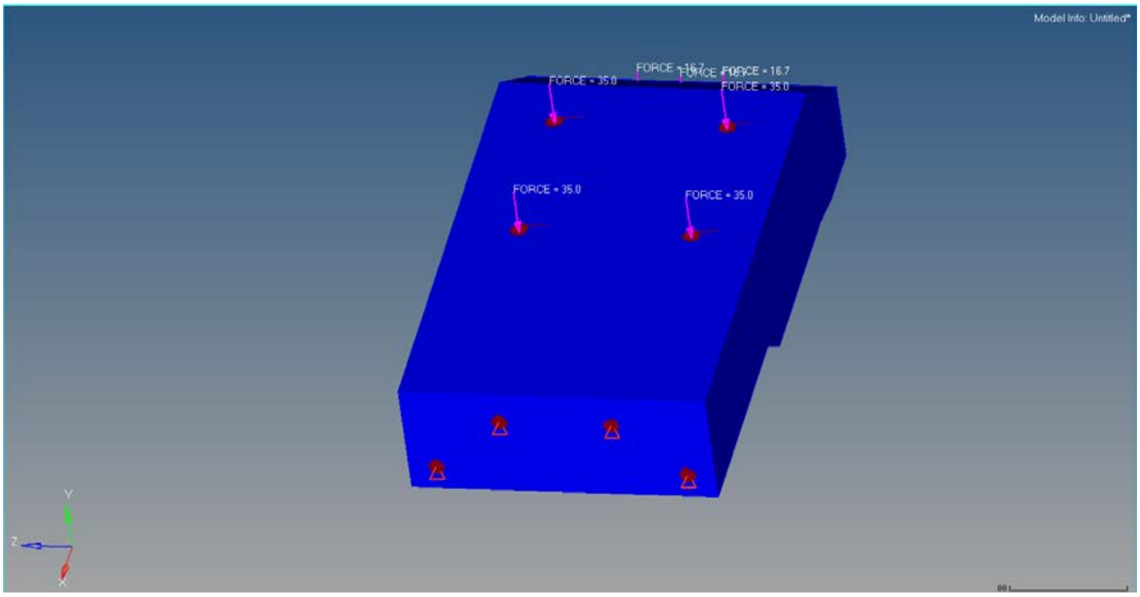


Figure 40 - Support with constraint and the loads in central holes.

With the application of the loads in the software, an initial analysis can be made to serve to compare with the future optimized design. In this case, one can view stresses only on the fixed elements, because the stress of these elements is so high that the program practically disregards stress in other elements (Figure 41 and Figure 42).

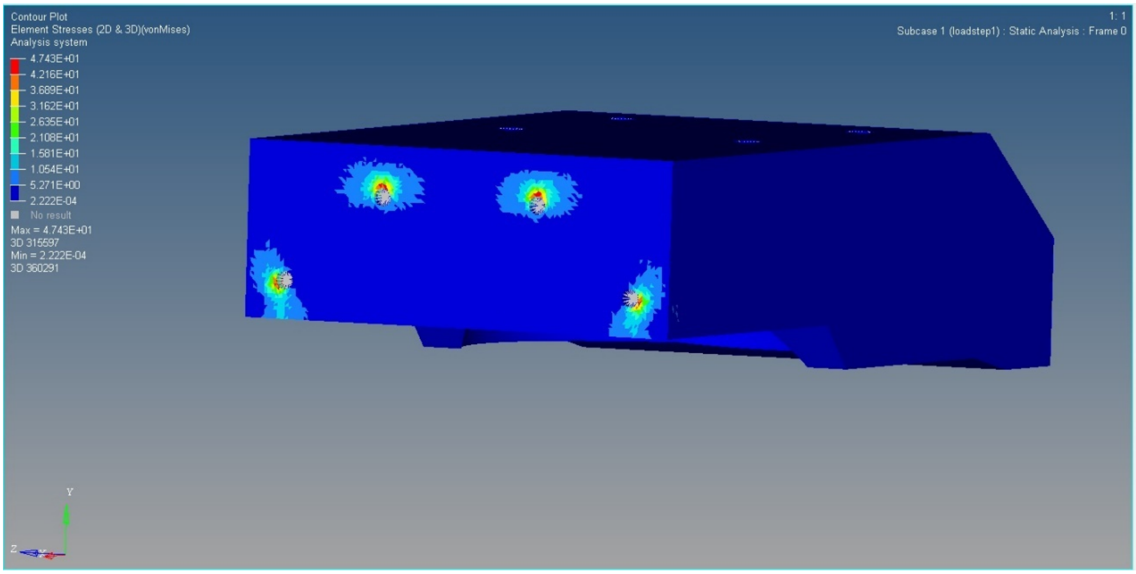


Figure 41 – Stress in the constraints.

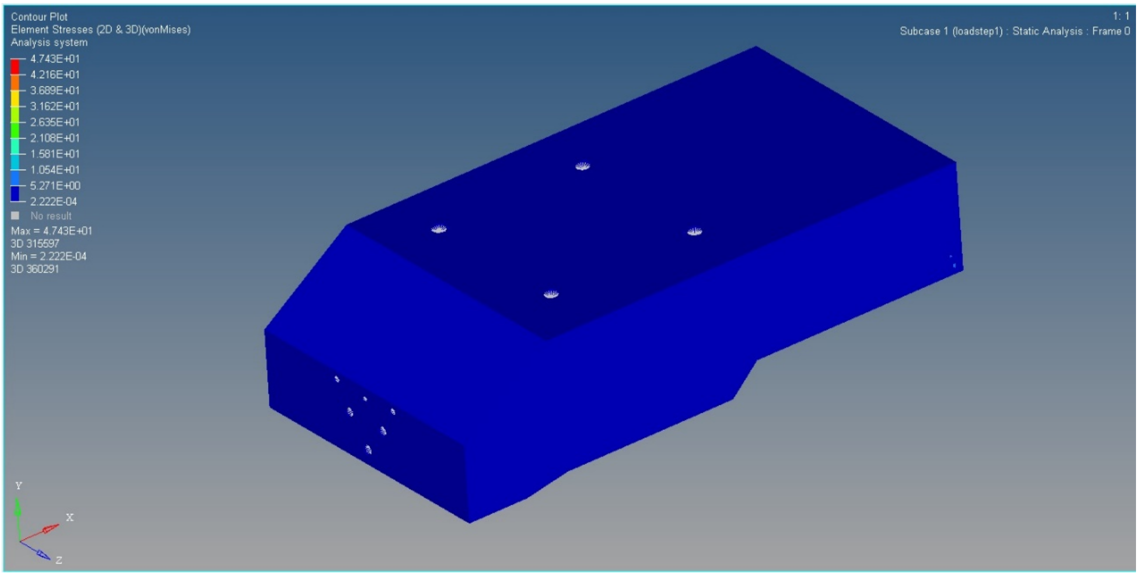


Figure 42 - Stress in the other holes

With the initial analysis done, the next step is to optimize the support design. The optimization proposal for the support was topological, with the response in mass and displacement and the objective to minimize mass. There was also a stress constraint regarding the yield strength of the material AL 7075 T651 (Annex 1). After everything was determined the optimization process was run in OptiStruct.

The result of the optimization can be found in Figure 43.

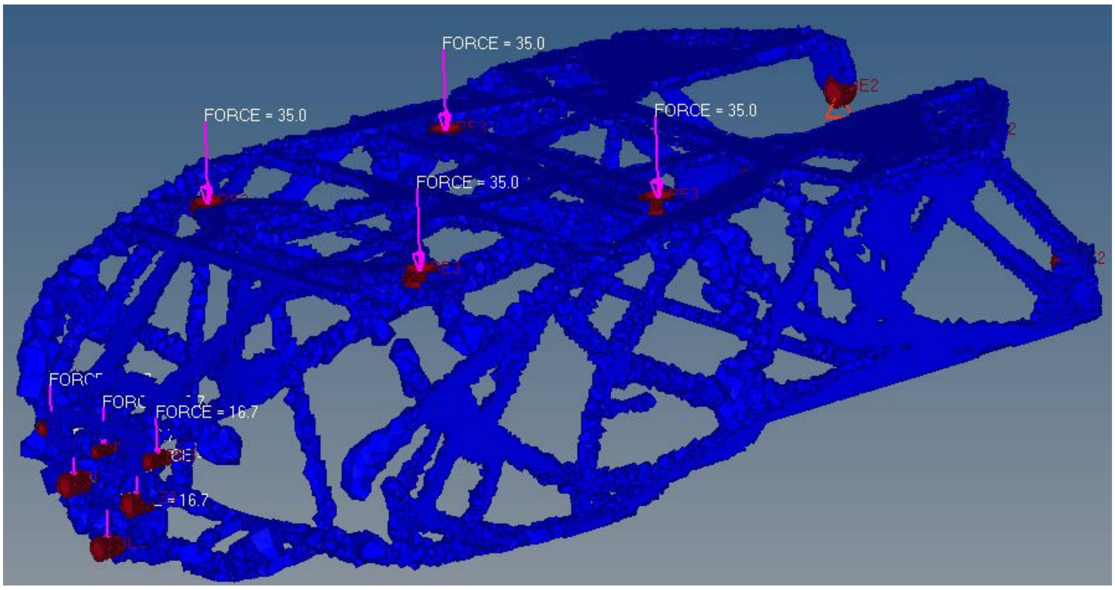


Figure 43 – Optimized Support

With the optimization done, the optimized support was re-analyzed to get the values for comparison. Figure 44 and Figure 45 show this analysis and values of stress.

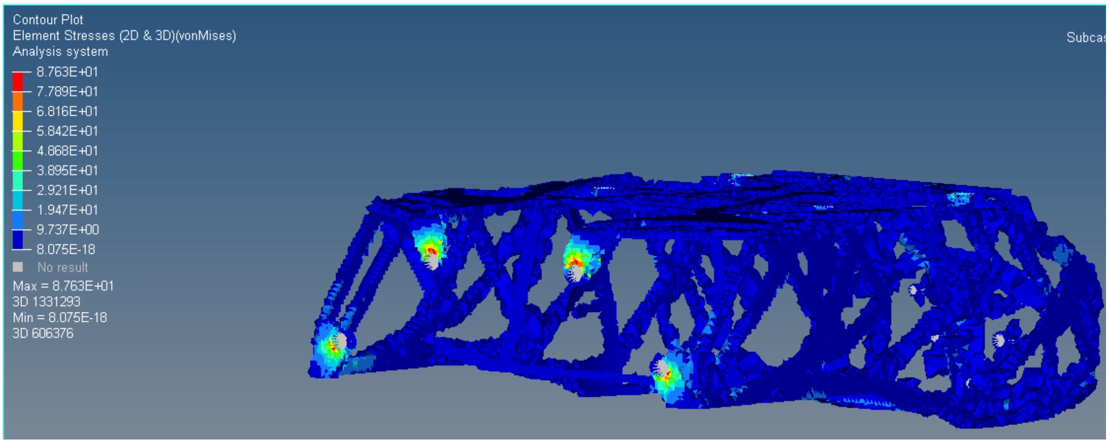


Figure 44 – Stress related to optimized support.

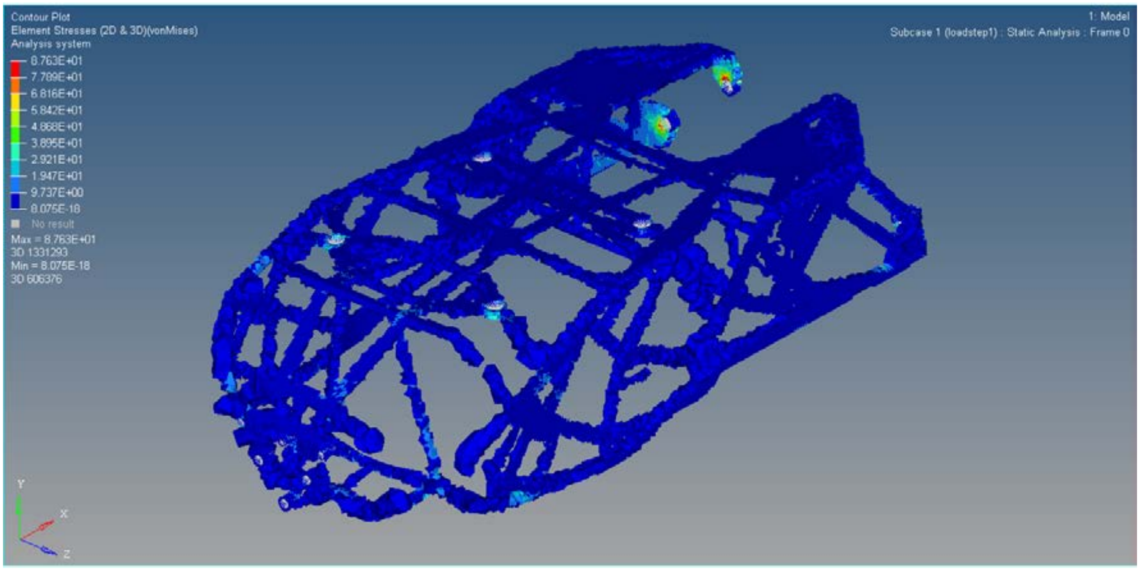


Figure 45 – Stress related to optimized support.

A comparison between values before and after optimization can be seen in Table 7.

Table 7 – Values of support

	Original	Optimized
Mass (kg)	9.23	1.073
Stress (MPa)	47.43	87.63

$$\text{Improvement in percentage} = \frac{(\text{Mass}_{\text{initial}} - \text{Mass}_{\text{final}})}{\text{Mass}_{\text{initial}}} \text{x}100$$
$$\text{x} = \frac{(9.23 - 1.073)}{9.23} \text{x}100 \qquad (5)$$
$$\text{x} = 88.37\%$$

The Software OssMooth was used as a post-processor and to generate a preview of the final part (Figure 46). Because the part was difficult to see, it was also processed in CAD software for better visualization (Figure 47).

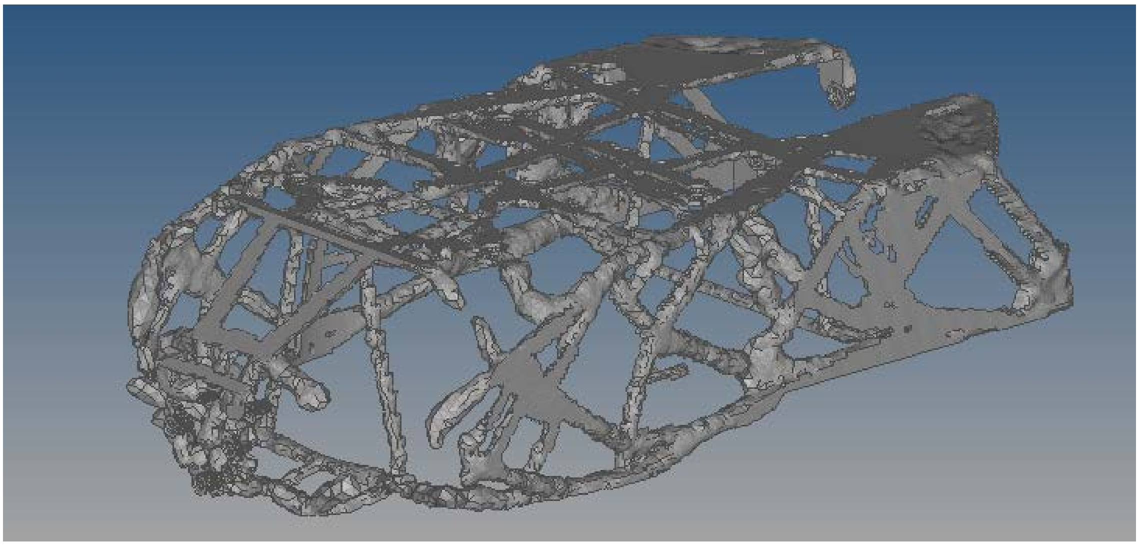


Figure 46 – Support generate by OSSmooth.

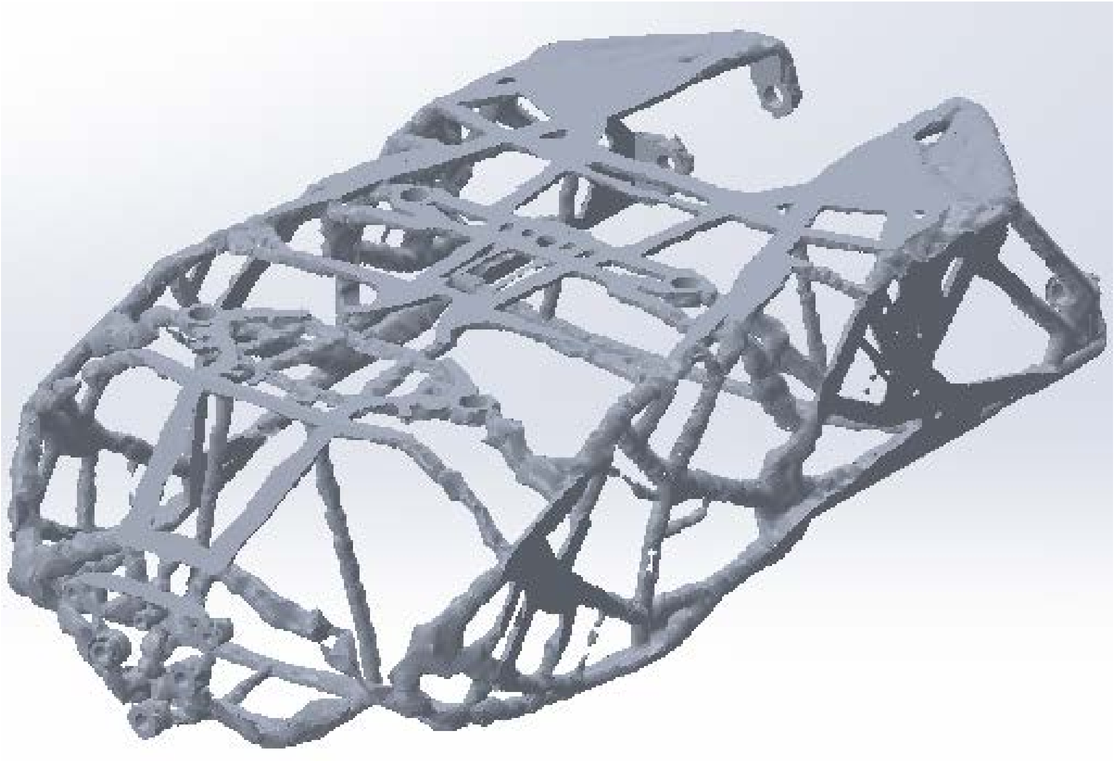


Figure 46 – Preview support in CAD Software.

CONCLUSIONS

4 CONCLUSIONS AND PROPOSAL FOR FUTURE STUDIES

4.1 CONCLUSION

The present dissertation was developed in the scope of the Master's Degree Course in Mechanical Engineering, Materials and Manufacturing Technology branch of the School of Engineering, Polytechnic of Porto. This report has made possible to carry out a vast bibliographic review regarding additive manufacturing and its respective techniques, as well as optimization tools to be used in conjunction with AM.

It was not possible to fulfill all the proposed objectives as the ALM machine was not ready in time for the completion of this dissertation. Nevertheless, it was important to deepen and better understand the area of optimization to gain knowledge on how the process is done and how important this tool is for several areas of activity.

In this particular dissertation, we can see the effectiveness of the optimization process as in the first case study, part 1, an improvement of 88% regarding displacement was achieved, since the software created a suitable structural reinforcement for the selected material and shape taking into consideration the applied load. In the second case study, the support bracket, a reduction of mass of 89% was achieved, allowing the benefits of using less material with the same efficiency and necessary form.

4.2 FUTURE STUDIES

As all the objectives were not been met, one of the proposals for a future research would be to print the parts in an AM machine and to perform laboratory tests to verify the real values of the optimized components and implement their design in their respective projects to enable the use.

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ANNEXS

6.1 ANNEX 1- AL 7075 T651

6.2 ANNEX 2- FLOWCHART

6 ANNEXS

6.1 ANNEX 1- AL 7075 T651

Table 8 – Properties AL 7075 – T651 (MATWEB, 2001)

Aluminum 7075-T6; 7075-T651	
Subcategory:	7000 Series Aluminum Alloy; Aluminum Alloy; Metal; Nonferrous Metal
Composition Notes:	A Zr + Ti limit of 0.25 percent maximum may be used with this alloy designation for extruded and forged products only, but only when the supplier or producer and the purchaser have mutually so agreed. Agreement may be indicated, for example, by reference to a standard, by letter, by order note, or other means which allow the Zr + Ti limit.
Material Notes:	General 7075 characteristics and uses (from Alcoa): Very high strength material used for highly stressed structural parts. The T7351 temper offers improved stress-corrosion cracking resistance.
Applications:	Aircraft fittings, gears and shafts, fuse parts, meter shafts and gears, missile parts, regulating valve parts, worm gears, keys, aircraft, aerospace and defense applications; bike frames, all-terrain vehicle (ATV) sprockets.

Component	**Wt. %**	**Component**	**Wt. %**	**Component**	**Wt. %**
Al	87.1 – 91.4	Mg	2.1 – 2.9	Si	Max 0.4
Cr	0.18 – 0.28	Mn	Max 0.3	Ti	Max 0.2
Cu	1.2 – 2	Other, each	Max 0.5	Zn	5.1 – 6.1
Fe	Max 0.5	Other, total	Max 0.15		

Physical Properties	**Metric**	**English**	**Comments**
Density	2.81 g’cc	0.102 lb’in^2	AA;Typical
Mechanical Properties			
Hardness, Brinell	150	150	AA; Typical; 500 g

			load; 10 mm ball
Hardness, Knoop	191	191	Converted from Brinell Hardness Value
Hardness, Rockwell A	53.5	53.5	Converted from Brinell Hardness Value
Hardness, Rockwell B	87	87	Converted from Brinell Hardness Value
Hardness, Vickers	175	175	Converted from Brinell Hardness Value
Ultimate Tensile Strength	572 MPa	83000 psi	AA; Typical
Tensile Yield Strength	503 MPa	73000 psi	AA; Typical
Elongation at Break	11 %	11 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Elongation at Break	11 %	11 %	AA; Typical; 1/2 in. (12.7 mm) Diameter
Modulus of Elasticity	71.7 GPa	10400 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Possion’s Ratio	0.33	0.33	
Fatigue Strength	159 MPa	23000	AA; 500,000,000 cycles completely reversed stress; RR Moore machine/specimen
Fracture Toughness	20 MPa-m½	18.2 ksi-in½	K(IC) in L-T Direction
Fracture Toughness	25 MPa-m½	22.8 ksi-in½	K(IC) in L-T Direction
Fracture	29 MPa-m½	26.4 ksi-in½	K(IC) in L-T

Toughness			Direction
Machinability	70 %	70%	0-100 Scale of Aluminum Alloys
Shear Modulus	26.9 GPa	3900 ksi	
Shear Strength	331 MPa	48000 psi	AA; Typical
Electrical Properties			
Electrical Resitivity	5.15e-006 ohm-cm		AA;Typical at 68ºF
Thermal Properties			
CTE, linear 68ºF	23.6 µm/m-ºC	13.1 µin/in-ºF	AA; Typical; Average over 68-212°F range.
CTE, linear 250ºC	25.2 µm/m-ºC	14 µin/in-ºF	Average over the range 20-300ºC
Specif Heat Capacity	0.96 J/g-ºC	0.229 BTU/lb-ºF	
Thermal Conductivity	130 W/m-K	900 BTU-in/hr-ft^2-ºF	AA; Typical at 77ºF
Melting Point	477 - 635 °C	890 - 1175 °F	AA; Typical range based on typical composition for wrought products 1/4 inch thickness or greater. Homogenization may raise eutectic melting temperature 20-40°F but usually does not eliminate eutectic melting.
Solidus	477 °C	890 °F	AA; Typical
Liquidus	635 °C	1175 °F	AA; Typical
Processing Properties			
Annealing Temperature	413 °C	775 °F	
Solution Temperature	466 - 482 °C	870 - 900 °F	
Aging Temperature	121 °C	250 °F	

6.2 ANNEX 2 – FLOWCHART