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Topology optimization for additive manufacturing

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ABSTRACT: Topology optimization provides design engineers the opportunity to create light and complex structural parts. Additive manufacturing produces parts easier than traditional manufacturing. Due to the above mentioned flexibility, parts that are designed for AM have the same structural load as the old parts but with reduced mass. This study utilizes topology optimization techniques, aiming to reduce the mass of the existing parts. Further weight loss is achieved by implementing lattice structure. The core of this thesis is to examine the workflow to include topology optimization in the process of design for AM. This was achieved by minimizing the mass of two parts of an electric scooter, neck and platform. The study produced new geometry for the existing parts. Cost analysis showed that the optimized design was cheaper to manufacture using the same AM method than the initial one. Within the context of the present work we came across the pros and cons of topology optimization and FEA through the Inspire software and proved that load conditions may directly affect the final result and product.

KEYWORDS: Topology Optimization, Finite Element Analysis, Additive Manufacturing, Traditional Manufacturing, Computer-Aided Design, Computer-Aided Engineering, Design for Additive Manufacturing, Design for Manufacture, Total Cost.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AP	Pre-processing cost per Part
BESO	Bi-directional Evolutionary Structural Optimization
BJ	Binder Jetting
BP	Post-processing cost per Part
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CP	Processing cost per part
DED	Directed Energy Deposition
DfAM	Design for Additive Manufacturing
DfM	Design for Manufacture
DLP	Digital Light Processing
DOD	Drop On Demand
EBM	Electron Beam Melting
ESO	Evolutionary Structural Optimization
FC	Fixed Cost
FDM	Fused Deposition Modeling
FEA	Finite Element Analysis
HDT	Heat Distortion Temperature
MOP	Multicriteria Optimization Problem
MP	Material cost per Part
PBF	Powder Bed Fusion
PC	Polycarbonate
PLA	Polylactic Acid
PVA	Polyvinyl Alcohol
SHL	Sheet Lamination
SIMP	Solid Isotropic Material with Penalization

SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	STereoLithography
TC	Total Cost
TM	Traditional Manufacturing
TP	Topology Optimization
UV	Ultraviolet
VC	Variable Cost

1 INTRODUCTION

Design engineers nowadays are facing new challenges such as the increasing complexity of designing parts. The structure of these parts should be getting lighter, smaller and stronger. This does not mean a conflict between the structure and the objective proposes, for instance, a car would benefit more from fuel consumption if it has less weight. Almost the same idea is behind every single vehicle and part that designers are going to implement. These kinds of problems which are considered as great challenges for design engineers, are becoming easier nowadays with topology optimization.

Generally, TO is the methodology that defines the best structure and material in order to get the optimal structure performance. This methodology has started to be used rapidly in the engineering field since the first introduction of the homogenization method according to M. P. Bendsøe, 1989a. TO connects shape and topology through the element. CAD allows the design of organic and complex features, but the problem begins during the manual optimization phase (mass, compliance, etc.) of these parts that can be proved to be a massive time consumption with not so good results (Diegel, Nordin, & Motte, 2019).

However, design engineers have proposed performance analysis through FEA and based on that the final design part can be improved. This leads to some suboptimal designs since the surfaces and topologies can be produced with the help of AM.

The TO algorithm takes the 3D model, boundary condition, loading, performance objectiveness as input to optimize the structure of the design part that is chosen (Silva de Siqueira, Mozgova, & Lachmayer, 2018). In most of the cases the objective goal is to reduce the mass of the part, so the algorithm will give us a lighter design part. The results of 3D for TO often cannot be manufactured with traditional manufacturing so the AM is coming to fill this gap (Brackett, Ashcroft, & Hague, n.d.).

Nowadays, AM is a growing market that counted in 2018 around 12,8$ billion revenue and it is expected to have 21$ billion in 2020. These numbers prove that AM is a rapidly growing market that will probably replace the traditional manufacturing methods of non-massive manufacturing production in the coming next decades ("3D Printing | Wohlers Associates," n.d.).

Complex shapes and structures can be produced by reducing time and material as well. Designing parts process is not as costly as it used to be in the past, additionally, it is possible to reduce the structure and eliminate some of the fixtures constrains. Therefore, low volume custom production, sometimes, is by far more financially profitable that traditional manufacturing (Frazier, 2014).

There are many challenges in this area among different types of AM due to the fact that every process uses different materials and printing parameters. Therefore, the parts can present different kinds of stress and anisotropy. The separation between the phases in microstructure is something that is mentioned because of the solidification of molten metal, which is also the characteristic of some methods (Wauthle et al., 2015). The creations of unstable phases, because of the high cooling rates, is something that affects negatively the mechanical properties of productive printed parts (Song, Mahon, Cochrane, Hickey, & Howson, 1997).

Among other advantages of AM is that it includes a complex design structure for more lightweight applications, such as cellular foams or monolithic foams. New ways of combinations are used to improve reticulated mesh structure and non-stochastic mesh structure. These complex shapes and structures would not be easy to be manufactured by casting, molding or other techniques (Schaedler & Carter, 2016). Observing the nature, cellular shapes combine high strength and stiffness as well, in very low densities. These kinds of cellular shapes and structures are related with the mechanical properties of the potential printing parts (L. J. Gibson, 2005).

Optimizing cellular structure under different stress conditions has developed the new approach of the lattice structure (Biyikli & To, 2015). The idea of a lattice model is based on the repetition of a unit cell through the whole material. There are many of these structural applications with lattice, such as biomedical and aeronautic industries, where the factors of being stiff and light are extremely important. We achieve high mass efficiency by reducing the structure's mass and using slim elements that contributes to the stress-bearing properties (J. Zhang, Wang, Niu, & Cheng, 2015).

Overall, the AM process through the lattice structure presents the opportunity to achieve optimization of structures. Moreover, 3D printed cellular parts are used to predict the structure mechanisms by two different concepts of lattice, the small one and the large one as well (L. J. Gibson, 2005).

This new capability of the AM is very useful in the aerospace industry and in car industry for saving fuel costs during the lifetime of the vehicle. An engineer can use TO for proposing a new design structure thought FEA. Moreover, one may check the results and based on the experience can improve the performance of the structure. After several attempts, the process gives the best design structure and AM process is able to be implemented. Overall, the field of TO offers designers or engineers a way to bypass much of the manual repetition. Often, the aim is to minimize the weight of the parts, as we will do in this study for a better and lighter design component. While this may not the best option in terms of structures and efficiency, however, offers to design engineers a chance for light weight and better structure.

1.1 Research area

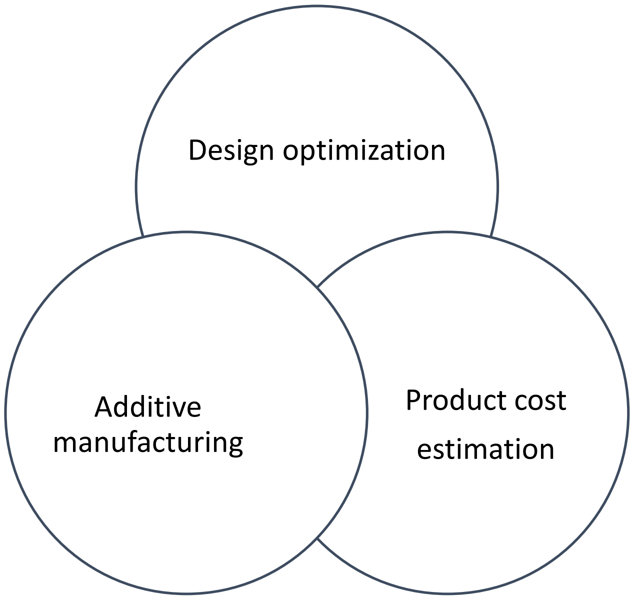


Figure 1. Research discipline

Innovation design is a wide research area that includes many definitions and aspects. For this thesis, the definition of innovation design includes redesigning the parts that manufactory is planning to produce. As a result, every product should be in the 3D model and follow the fundamental aspect of design. Therefore, the criteria of innovation design includes some other aspects as well, such as new CAD model, new CAE analysis and new CAM analysis.

The research area of this study is somewhere among TO, AM, and product cost estimation based on Figure 1. Research discipline. The current study also presents graphically the research area and which fields involved, such as (TO, efficient structure, FEA analysis, lattice structure, and AM process). All these methodologies and processes will be well analyzed in the coming pages.

The new component will represent all the above methodologies about the new structure and design discipline in TO and additive manufacture through the cost perspective. Product cost estimation involves many kinds of identifications such as assessment and prioritization of material. The new role of management is to synchronize the activities of a company in order to minimize the probability of unwilling events. In other words, how to maximize the opportunities through reducing the costs. This study will not analyze in detail the role of risk management but will emphasize the cost analysis since we all understand what it means and how is related with the production. Specifically, it will analyze how the cost is related to the market of traditional manufacturing versus 3D metal and other materials plus 3D printing machines.

1.2 Research questions

RQ 1 – What are the advantages of applying TO on metal parts?
RQ 2 – What are the barriers to the implementation of TO for AM?
RQ 3 – What are the pros and cons of producing metal 3D print parts?

All the above assumptions are included in detail in the next coming text of this thesis.

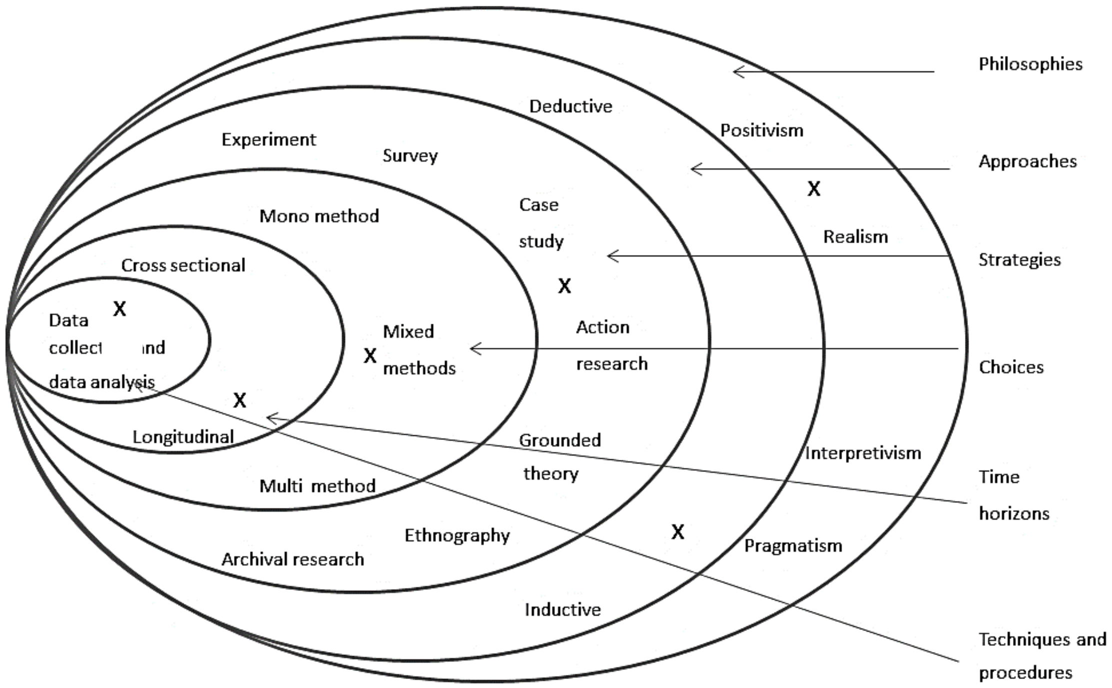


Figure 2. Presents some of the guides for this thesis

("Research Onion (Adapted from Saunders, M et al 2007) | Download Scientific Diagram," n.d.) Source.

Generally, it should be mentioned that this study is based on practical analysis of drawing CAD system and software and how to rely on TO and FEA through the AM process for better and more efficient component. The goal is to present something that will be fully accepted by everyone and drive to a new way of production. A collaboration of CAD and CAE analysis through some specific software is more than necessary. It is out of the scope of this thesis to give directions or trends that manufactories should follow, just a new perspective of structure design through the concept of TO with the collaboration of AM.

Taking every aspect one by one and trying to connect them with different goals, Figure 2. Presents some of the guides for this thesis. For instance, the philosophy of this study is realism, since it analyses and draws a real part from a real object, but at the same time, it approaches the aspect of interpretivism since the FEA method includes a kind of interpretation of the data that we receive through the simulation.

The approach seems that it is more deductive instead of the inductive since it produces a new part for the product which cannot be compared with the old one.

The strategy that the current research is following is, primarily, a cases study since it starts with a standard product and will analyse this one only. Furthermore, it briefly approaches an experiment since the results that will be presented later have arose after many repetitions and from this perspective, it is considered an experimental approach. The choice of methodology is an approach to the mixed methods due to the fact that we include a different methodology for the analysis. For instance TO theory, FEA methodology, AM process.

The time limit in this dissertation approaches the longitudinal since it is something that will take time to analyse and even more time for the results to appear in the market.

Last are the techniques and procedures, which are related to the data collection and analysis, but in our case, that is part of the vehicle. Based on this 3D model data we build all our methods and analysis of the thesis.

1.3 Research philosophy

All the above descriptions present that the objective goal of this thesis is to investigate the way that TO incorporates with designing workflow for AM. This is a rapid but effective way to present all the processes that should be followed from scratch to the final product. To achieve this goal we took an existing product such as an electrical scooter and started to apply all the methodology from CAD, TO, FEA, AM to improve some of the designing components. Based on those parts we applied stress force to check how it will react and which will be the deformation through the FEA analysis. TO occured also to help to create lighter parts through the improvement of the structure.

We could say that the aim of this thesis is to present the workflow based on TO (which means lighter, smaller complex structure) with the help of AM through the financial perspective which is the factor that runs the industries.

1.4 Structure of the study

This project is divided into 6 chapters.

Chapter 1 is the introduction of TO and AM. Introduction gives the main idea of this thesis, which includes the research area, research question and philosophy regarding the main concepts.

Chapter 2 relates to the theoretical framework of this thesis. In this chapter, the reader will become more familiar with TO, AM and product cost estimation.

Chapter 3 is the methodology, which includes all the methods that are used in the project.

Chapter 4 presents the software tools that will be used to achieve the results in optimization and analysis.

Chapter 5 includes the results and discussion. This part describes with details the steps that were followed in the project from CAD to analysis. This chapter includes the implementation of TO for the specific designing parts. Moreover, there are some quotes and details about prices.

Chapter 6 includes the conclusions of this thesis. This project ends with a suggestion for further research. Appendices contain details and extra pictures about topology details plus quotes price about traditional manufacturing and AM.

2 THEORETICAL FRAMEWORK

2.1 Design optimization

2.1.1 Topology optimization by isotopic material

TO is the methodology that allows the designer to have the best distribution of the structure and material according to a set of constraints. The structure can be optimized by creating some void and solid areas in the designing domain. Generally, an optimization problem starts with minimum compliance design. The aim is to improve a simple structure to gain maximum stiffness, or minimum compliance (c = k – 1). Undoubtedly, maximum stress will be applied when the shape of the structure is completely solid (Jie, Huang, & Zhu, 2009). To simplify the process and the methodology could be interesting to improve the weight of the shape while enhancing the stiffness properties.

This could be done by minimizing the mass of the object and satisfying the set of constrains, such as maximum stress or stiffness (Van Dijk, Langelaar, & Van Keulen, n.d.). In this project, we would like to minimize the mass of some scooter's parts by avoiding any kind of deformation and by increasing the stiffness while avoiding a detrimental range of natural frequencies. In more detail to set up an optimization method, the volume can be defined as boundary and the mechanical equation of the basic topology improvement that will offer a maximum stiffness could be: Max Stiffness

s.t. $m \leq mmax$ (1)

Assuming that there is a linear elasticity that allows to replace stress by compliance gives us a compliance optimization problem ("WB1440: Eng. Optimization: Concept & Applications at the TU Delft - StuDocu," n.d.).

Equilibrium	$Ku = f$	(2)
Compliance	$c = f^T u$	(3)
min_{design}	$f^T u$	(4)
s.t.	$Ku = f, \quad m \leq m_{max}$	(5)

In the above system, the aim is to minimize the compliance equation. This can be achieved with specific parameters that should be defined as design variables. Sometimes, TO appears like a free variable, so in this case density could be used as a design variable.

This kind of design and optimization can lead to something novel yet complex. A couple of years ago that kind of shape would be particularly impossible to manufacture because of the limitations of the traditional process. Currently, with new methods of AM is possible to have complex design parts and freedom in structure (Tanskanen, 2002).

The files that we received from TO software are in STL form and can collaborate with 3D printing software. However as we mentioned before, some of these shapes can be very complex and complicated, thus, difficult for manufacturing. Some topology software such as Altair Inspire, Ansys TO allows manufacturing even with constraints to basics tools. These constrains help to prevent generate the optimized shapes that would be extremely difficult to manufacture. But on the other hand with some software like Altair Inspire, Ansys Topology designers can use reverse engineer dimension parts from exported STL files. Overall we could mention that despite the fact that there are other methods for optimization tools, TO remains the most general and powerful tool for developing novel shapes and complexity part (M. P. Bendsøe & Sigmund, 1999b).

The stiffness of construction is one of the greatest requirements that engineers and designers should take into consideration during the design process. Is often required that this process is sufficiently distorted as long as it can be quickly traced to specific limits.

In order to approach the optimum structure, the method uses to define a void (0) or a solid (1) for determining the best solution. As a result, all the discretized points of element form the TO of the structure. In every optimization, the problem is similar: which is the best mesh to define and which one approaches reality better. That is why every sustained element should be discretized in a number of elements. Overall, this approach is known as mesh-refinement.

In general terms, the optimization of a part is made possible by specifying every point of a part that is included in the specific boundary, regardless of whether there is material to remove or not. Simultaneously, a discrete geometry with infinity elements exists where each element can be, either a blank point or one of its own parts and based on the above statement, the project is not abusive to the construction of topology. The proposed improvement is a cross-border change of the topology of construction, according to (Ding, 1986) and (Haftka & Grandhi, 1986) who have done more extensive study in this field to improve the above methodology.

Moreover, the method of change boundaries that can be applied in many ways, for example, in the very strict way of specific boundaries which define the shape of the designing parts. In this example, the parameters are the synchronizes of the control points of the defined model (Tanskanen, 2002).

The first ones who have developed the TO by the homogenization method were M. P. Bendsøe, 1989 and Suzuki & Kikuchi, 1990. In 1988 they presented the homogenization model for topological improvement, which has been the milestone until nowadays in the area of "structural improvement".

Mlejnek & Schirrmacher, 1993, proposed a different approach in TO, which utilizes the density of a part, in demand to minimize the distribution of the material limitations of the volume of construction. In addition, R. J. Yang & Chuang, 1994 proposed the use of normalized densities of the material for each element as a variable, which also reduces the number of factors in a case as TO. There are several analytical surveys available that are related to the changes in density and volume for TO (Johnsen, 2013).

Most of TO problems which are based on the densities of the data, use the volatility of the density as a basic element for improvement, while the volume remains a constraint. However, we can mention that several and different constraints in the volume of a component with the density method are quite reasonable to drive to different component blocks which means that it involves different trends of the stresses and displacements. Of course, with the cohesion of the structure which is achieved through the distribution of densities, the construction will either be strong or then unable to conform to the tenses limitations of the magnitude of the stresses and displacements.

This means that without the necessary limitation of volume utilization which can be used for improvement, the TO often fails to define the right topology when applying the major stresses and displacements (Outline, 2018). Many surveys were conducted in the field of algorithm development to find a structure that can respond to the limits of the stresses and displacements.

Deqing, Yunkang, Zhengxing, & Huanchun, 2000 consider the weight of the structure as a function of improvement and use of the displacement, the frequency and the unity of the construction as a limited. The results should not exceed a minimum and a higher level. Aiming to solve problems of TO, the logic of mathematical programs are integrated (R. J. Yang & Chuang, 1994).

It would be mathematically wrong if considered the stress or displacement as constraints on TO problems, which will imply in many numbers of variables. For this reason, an analysis of stress and deformation through the sensitivity functions is allowed. Eventually, it determines if some of the variables are related to one way or another with stress or deformation (Holmberg, Torstenfelt, & Klarbring, 2013).

A wide range of problems in design optimization of engineering systems involve multiple performance optimization. For instance, a typical bridge-construction might involve simultaneously minimizing the total mass of the structure and maximizing its stiffness (Carmichael, 1980). In mathematical notation, a "multicriteria optimization problem" can be posed as:

$$\text{“Min” } F(x) = \begin{pmatrix} f1(x) \\ f2(x) \\ \cdot \\ \cdot \\ \cdot \\ fn(x) \end{pmatrix}, \; n \geq 2, \quad \text{(MOP), where } C = \{ x : h(x) = 0, g(x) \leq 0, a \leq x \leq b \} \qquad (6)$$

F: $R^N \to R^N$, h: $R^N \to R^{\mathbf{n}_e}$, and $R^N \to R^{\mathbf{n}_i}$ are reliably distinguished twice mapping and

a $\in$ (R $\cup$ { -∞ })^N, b $\in$ (R $\cup$ { -∞})^N, N is the number of variables, n number of objectives, n_e and n_i are numbers of equality and inequality constraints.

Since it would generally not be possible to minimize every fi from a single x* at the same time, a concept of optimality that is useful in the multiobjective framework is known as Pareto optimality, as explained (Adali, 1983).

Coming up to the latest methodologies that start to be used in the 21st century the TO can be achieved through a global search algorithm based on the genetic algorithm (GA). The total cost, like the component cost, is incorporated for function cost. To indicate the presence of each member, a topological algorithm is implemented. Based on the schematic theorem, it is shown that the use of the topological algorithm results in the rapid convergence of the solution to an optimal solution (Ohsaki, 1995).

The optimization of this kind of system can be categorized into a dual dimension problem for the designer. The first related to which algorithm should be chosen which would be appropriate for the system's correct application. The second was related to the algorithm's variety parameters that need to be tuned to the system's performance.

Genetic Algorithm is used to classify effective GA's for a series of numerical optimization problems such as Topology Optimization (Grefenstette, 1986).

2.1.2 Homogenization optimization SIMP

In the form of the optimum shape of components that are topologically equivalent to the initial design, reliable computational schemes involve some kind of remeshing of the finite element approximation of the problem analysis (Suzuki & Kikuchi, 1990). TO is an improved solution between void (0) and solid (1) regions and as mentioned already, this represents either full or hollow material.

However, there are some areas that range between 0-1 and are defined as a parts of an undesirable area (Rozvany, Zhou, & Birker, 1992). This method has to do with advanced techniques and consisted of calculating the optimal spatial distribution of an anisotropic material or Solid Isotropic Microstructure with Penalization (SIMP) (Munk, Boyd, & Vio, 2016). This space introduces a weak area of periodically distributed small holes in a given homogeneous “isotropic material” with the constrains that structure can carry the given loads and satisfy another design constraints (Dunning & Alicia Kim, 2013).

Moreover, with this method, the part presents small holes inside the structure, and the problem of TO, is to find out the best way to improve this shape, according to the constrains (Martin Philip Bendsøe & Kikuchi, 1988). With this method, the problem is converted into a problem of improving the holes inside the construction “sizing problem”.

Based on that, there are new holes in the structure, without knowing if they have preceded the construction. Consequently, it seems that the form and the topology of the model are optimized (Hsu, Hsu, & Chen, 2001).

However, in some cases, this method of planning structure should not reflect valid results. Many times it produces solutions which show that the inner side of the object have insignificant holes of resources that make the object constructively indefinite. Furthermore, the volatility generated by the algorithm when calculating the microprocessor does not produce real items, which are included into the structure and convert structure into more sensitive in different loads and stress (M. P. Bendsøe, 1989).

In order to solve these kind of problems, a large number of variants of homogenization methods get involved with the aim of smoothing the broker density that has been created (Mlejnek, 1992). Moreover, we could say that since the properties of the object are considered to be contiguous (isotropic materials), the transformation of the object can change the density of the elements (SIMP). However, the large percentage of volatility and the computational complexity occurred as the result of difficulties encountered in realistic requirement of the structures (M. P. Bendsøe & Sigmund, 1999b).

2.1.3 Evolutionary Structural optimization ESO-BESO

Xie & Steven, 1993, first presented the evolutionary structural optimization (ESO) method. The idea is based on a simple and empirical concept of a structure evolving into an optimal condition by slowly removing (hard-killing) elements with the lowest stresses (Xie & Steven, 1994a). In order to maximize the structure's stiffness, the stress criterion was replaced by the elementary stress energy condition according to Xie & Steven, 1994b.

This method achieved simultaneous optimization in shape and in structure which means a total TO (Xiaodong Huang & Xie, 2010). Until now there have been solved different kinds of structural problems with the use of the ESO model and the results totally agree with solutions of traditional models of optimization even with the method of homogenization as is mentioned earlier (X. Huang & Xie, 2008).

To accomplish the removal of the material values are given to the density of the items to be 1/106 of their initial values of density (Hinton & Sienz, 1995). The removed element is based on the method of rotation energy of Von Mises. This process of the method continues to run repeatedly until all the values of the elements are calculated. We should not forget to underline that removal of 1-2% of elements in any round of ESO toolkit can achieve satisfactory results, but a higher percentage of removal elements 2% >0, will give us different results even though it has a small cost (Hsu et al., 2001).

The ESO method is very easy to program in a software package. Furthermore, the topographies that have been produced have been accumulating with empirical results and presented as a promising method (Hinton & Sienz, 1995). We should mention that in this area have been developed different kinds of methods trying to improve more the algorithm in TO (Khakalo & Niiranen, 2020). However, we should underline that if that material is being removed from the beginning of the algorithm, the ESO is not capable of recovering elements that have been deleted in advance (Buonamici et al., 2019).

Bi-directional evolutionary model optimization (BESO) approach (X. Y. Yang, Xei, Steven, & Querin, 1999; X. Huang & Xie, 2008) is an extension of the first idea of (ESO) that allows the addition of new elements in the locations next to those elements with the highest stress. The stress energy of void elements was estimated by linear extrapolation of the displacement field for stiffness optimization problems using the stress energy criterion (Yang et al. 1999). ESO / BESO has been used in a wide variety of applications and researchers around the world have produced hundreds of publications (Zuo, Xie, & Huang, 2009). In this way, it is BESO which has greatly improved the potential of the process of solving a problem of optimization in conjunction with the ESO model.

2.1.4 Lattice

Lattice is a new design structure that presents the compatibility between weight reduction and efficiency increase. This structure is created by repeating the unit cell. Lattice offers functional parts of lightweight with superior characteristics and minimum material. Nowadays, AM is the process that helps engineers to use lattice structures to improve the performance of their design (Derakhshanfar et al., 2018). Lattice can be categorized into two and three-dimensional structures including a complex of nodes, cells, and beams (Wolcott, 1990).

There are thousands of lattice types available with different characteristics and aesthetics. Many of these structures, as is mentioned before, are inspired by nature. Because of the minor features lattices are almost impossible to process through traditional manufacturing. Lattice combination allows designers to try out more shapes by-rethinking the performance of their part (I. H. Song, Yang, Jo, & Choi, 2009). Overall we could mention that the lattice technique can reduce the total mass by 90% or more by adjusting the lattice parameter of stress on the designing part (OnuhY. Y. Yusuf, 1999).

With a lattice structure, in some critical areas of the component, we may remove material. The lattice structure does not reduce the strength of the structure, only the weight is reduced relative to the strength ratio (Kruth, Leu, & Nakagawa, 1998). One more factor that we should underline about lattice is that it eliminates vibration, which can be rough for users and machine performance. Lattice can be operative at eliminates vibrations due to the their low stiffness and ability to endure enormous strains.

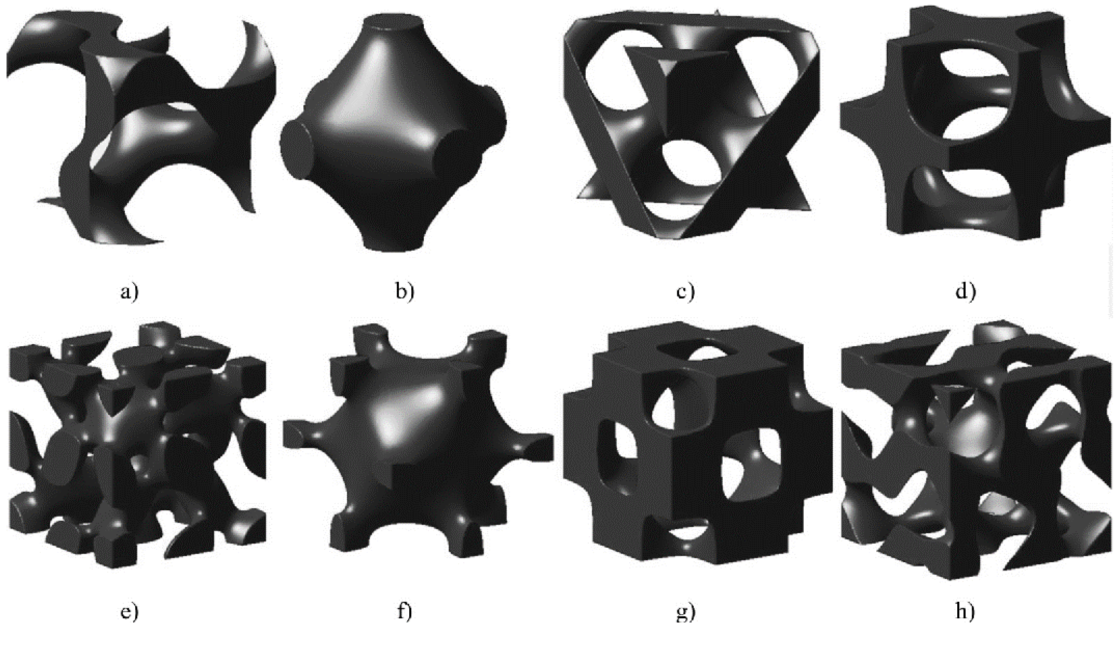


Figure 3. a)Gyroid b)Primitive c)Diamond d)iWP e)Lidinoid f)Neovius g)Octo h)Spilt (Panesar, Abdi, Hickman, & Ashcroft, 2018) Source.

Overall is accepted that design for AM (DfAM) helps engineers and designers to confirm their printed parts related to the design intention based on Figure 3. a)Gyroid b)Primitive c)Diamond d)iWP e)Lidinoid f)Neovius g)Octo h)Spilt. Some important features of DfAM include cell size, cell structure and density, of materials and cell orientation (Nguyen, Park, Rosen, Folgar, & Williams, n.d.)

Cell structure

There is a massive complex of the cell structure of lattice, but the most interesting and common include star, hexagonal, diamond, cubic, octet and tetrahedron. Some structures are more efficient, some others reduce energy better and there are also some with more pleasant aesthetic (Patil & Matlack, 2019).

Cell size and density

This kind of structure refers to the thickness and to the length of an individual unit clarifying the number of cells in a specific space. Large cells are easier to print but are also stiffer. On the other hand, a small cell allows a homogeneous response.

Material selection

To choose material for the structure of lattice, first should be defined which properties will be covered. Generally would be good to have a smaller and denser structure so it can reduce the sag during the printing (Wauthle et al., 2015).

Cell orientation

Have to mention that the cell orientation and the angle from which is printed it is important because it is related to the support that is required. Generally, a well-oriented structure is self-supported, so no need for any extra supports. Overall lattice makes complicated designing parts easier to create with the help of AM (Mahmoud & Elbestawi, 2017).

2.1.5 FEA

The main idea of this thesis is using the FEA analysis on this workflow to specify the maximum stress point of the structure between the model and experimental analysis as well as deformation during the test. Based on that, we can have a better idea and identify what are the differences in geometries that have been created during the load distribution in the part that it will be analysed.

The FEA or finite element method (FEM) is a computational method that subdivides the model into smaller areas or volumes which are called Finite Elements. These smaller elements from the same model may have different shapes as it is presented in the picture below. The main idea of this thesis is using the FEA analysis on this workflow to specify the maximum stress point of the structure between the model and experimental analysis as well as deformation during the test. According to that, is identifying better what are the differences in geometries that have been created during the load distribution, vibrations, in the part that it will analyse (Arabshahi, Barton, & Shaw, 1993).

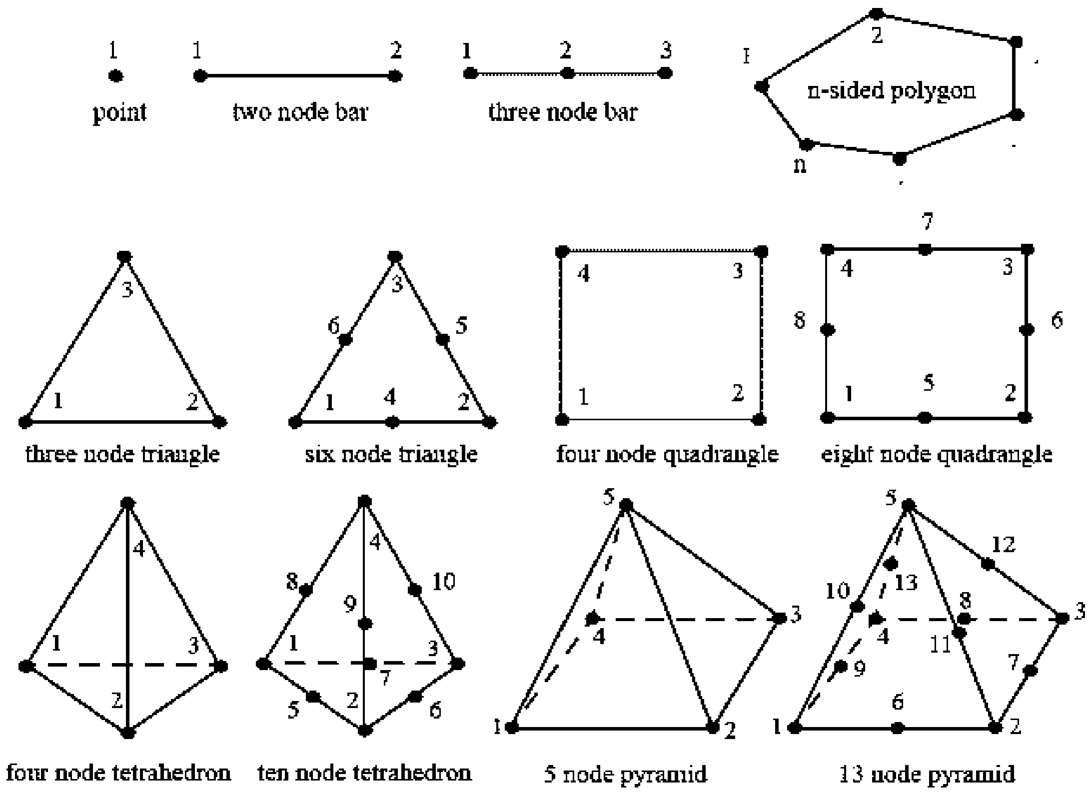


Figure 4. Different types of basic FEA elements

(“Habituating FEA: Types of Elements in FEA,” n.d.) Source.

Moving forward in FEA analysis one of the first things that should be defined is the material properties as seen from Figure 4**.** Different types of basic FEA elements. This is very important to define from the beginning (as in the results) because of the relationship between the stress (σ), the strain (ε) in the material of elements (σ = E*ε). Should be known how the structures will response to the applied forces, therefore, run the simulation (and this can be formulated in some basic principle of finite analysis, otherwise the detail analyzing of it will include a lot of mathematical approaches that are not the propose of this thesis) (*3.2 Experimental Investigation (a) (b)*, n.d.).

In mechanics, we have to define the equilibrium state, which means that the system load is balanced to keep the system at (V=0). This system is known as static analysis and when all finite element factors are solved, the formula will be,

$$f = Kx \qquad (7)$$

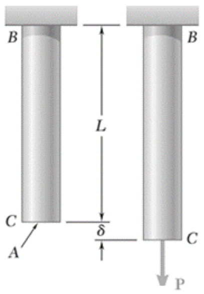
f: is the external forces vector applied to the structure

K: is the stiffness matrix

x: is the response of the projection vector to be determined

The entire math – calculation of mathematical formulas and matrixes, distortion and stresses of each component (or node) are then carried out. All of that happens while you are waiting for the analysis run to be completed.

It is very important to understand that the simulation analysis does not promise that the outcomes are always correct. The FEA is a “number cruncher”. Errors (i.e. simulation course is terminated) are reported if cannot be solved. For example, if the material is not defined or any other problem as well (Haftka & Grandhi, 1986).



$$\{f\} = [K].\{u\} \Leftrightarrow P = \frac{EA}{L}\delta$$

Truss Stiffness $k = \frac{EA}{L}$

Spring stiffness matrix

$$[K] = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix}$$

Truss stiffness matrix

$$[K] = \begin{bmatrix} \frac{EA}{L} & -\frac{EA}{L} \\ -\frac{EA}{L} & \frac{EA}{L} \end{bmatrix}$$

Figure 5. Linear stiffness in FAE analysis

(Dr. Matthias Goelke, n.d.) Source.

Above all, has to mention that in Inspire there is another very important type of analysis which is called vibrates model analysis as is seen from Figure 5. Linear stiffness in FAE analysis. This can be applied when designers or engineers want to have a structure that will resist in vibration discomfort or deformation of the structure. To be more specific any given model will have a tendency to vibrate at some discrete frequencies.

For example, if you hit the end of a plank beam, then the beam may start vibrating at 200 Hz, and then after a while it will fall abruptly to 180 Hz, for example, and vibrate at that lower frequency constantly. As the beam loses this energy, it will vibrate constantly at increasingly lower frequencies, causing discrete frequency leaps as the process goes on. Such distinct frequencies are considered the structure's natural frequencies, which a structure appears to vibrate.

Boundaries are another problem of FEA methodology since has to define these boundaries as often as it represents the physical structure. These variables are dependent variables that are defined by different equations (Ding, 1986).

Overall, should mention that it is very important to have a simple accepting of what stresses, distortion and strains represent in the FAE analysis since will apply all of these in the project of our scooter during the results.

2.2 Additive Manufacturing

TO offers to the various complex structures, the warranty that is required for AM to move on in the process (Toropov & Mahfouz, 2001). AM is a method of transforming the 3D model, usually layer by layer in contrast to the conventional subtractive manufacturing process that requires de-tailed CAM analysis and Gcode to define the geometry in order to organize which feature should be produced (Lei, Moon, & Bi, 2014).

Based on The American Society for Testing and Materials the AM process categories are seven. According to Frazier (2014), the difference between these categories is the manufacturing of layers and this affects the properties of parts, materials and the building speed of the structure.

2.2.1 AM technologies

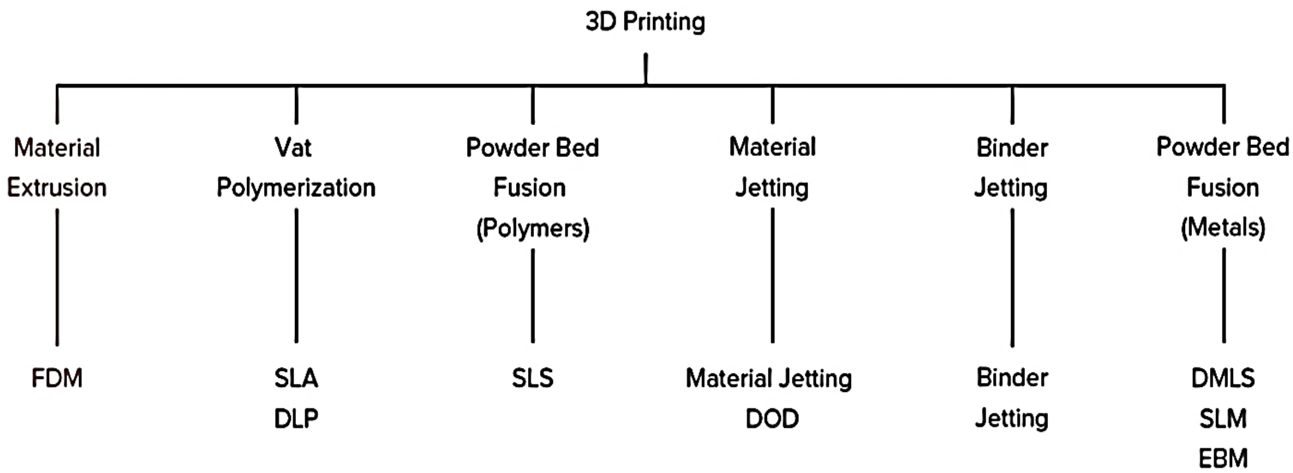


Figure 6. Different categories of AM

As we mentioned earlier, there are different categories that use different types of technologies in AM and we can arrange them as shown in Figure 6. Different categories of AM based on the American Society for Testing and Materials as shown below.

-Vat Photopolymerization (SLA, DLP)

-Bed Powder Fusion (SLS)

-Material Extrusion (FDM)

-Material Jetting (DOD)

-Binder Jetting (BJ)

-Sheet Lamination (SHL)

-Directed Energy Deposition (DED)

Vat Photopolymerization (SL) is a liquid photopolymer resin that is radiation-dried. Many machines use photopolymers that react to wave light's ultraviolet (UV) spectrum and some other machines use visible light to dry materials. The liquid material is solid when the radiation happens (I. Gibson, Rosen, & Stucker, 2010). Many industrial devices use photopolymers that respond to wavelengths of the ultraviolet (UV) spectrum, but some systems also use visible light-curable materials. The liquid content is solid when is radiated (Halinen, 2017).

Photopolymerization process, presents as the build platform moves down as the height of one build layer and the sweeper spreads the resin equally over the previous layer. Then the UV laser dried up the desired regions. This process is continuously repeated until the part is complete (Khajavi, Deng, Holmström, Puukko, & Partanen, 2018). As the produced component is connected to the construction framework and can be lifted from the liquid photopolymer, the system can change direction and operate upside-down. The light source is under the resin. This approach requires the liquid to have a shallow vat and is not limited in the process by the container depth (Halinen, 2017).

In contrast to other AM technologies, the main advantages of the vat photopolymerization process are the precision of the part as well as the surface polishing. This is a combination of mechanical transmission properties making photopolymerization an effective choice for structure and functional prototypes (Standard terms for AM-coordinate systems and test methodologies) (*Standard terminology for additive manufacturing-Coordinate systems and test methodologies (ISO/ASTM 52921:2013)*, 2016).

The method of Powder Bed Fusion (PBF) uses a thermal source to provoke fusion between powder elements. The powder fusion is limited to the area demanded for the essential layer to be created. Since the powder bed applying a new powder layer over the previous sheet, the roller spreads the powder.

Many different PBF process existed, such as Electron Beam Melting (EBM), Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), but they follow the same fundamental principles. They use different types of heat sources such as laser or electron beam, or various mechanisms of powder spreading as roller or blade. In available materials there are many differences (I. Gibson et al., 2010). For this reason, there is a wide range of available materials, including metals, polymers, ceramics and composites, as a process can use all the materials that can be melted and recrystallize. Because of the material properties, these methods can be used for the processing of final products since the properties of the materials are comparable to those of traditional parts (Halinen, 2017).

Fused Deposition Modeling (FDM), is the most common 3D printer trade procedure (Wohlers & Wohlers Associates., n.d.). In this process, the material is melted and extruded from a nozzle to the construction base or on the surface of the previous layer. The material is either in a continuous filament or in a pellet or powder form in most systems (Gibson et al., 2010).

Fused Deposition Modeling is the most widely used extrusion technology that Stratasys produces and develops. We may conclude that FDM machines are more advanced worldwide than any other AM form machine (Gibson et al., 2010). FDM can generate plastic of any kind, but ABSplus becomes the most sealing material, which is a little more creative of ABS. FDM can process valuable property parts and is relatively cheap. One of the disadvantages is the low construction speed and the accuracy depending on the use of the extrusion (Attaran, 2017). The nozzle presents inertia that, for example, limits movement speeds to a laser-based system. The radius of the nozzle defines both the final quality and the accuracy of the part (Halinen, 2017).

Jetting material is very similar to two-dimensional printing because on the construction platform, the build material is thrown into droplets. The material jetting on the platform is either hardened by using UV light or by allowing it to cool down and harden. We manage to limit the available materials when we deposit the material (Akinlabi, Mahamood, & Akinlabi, 2016). Most of the time, owing to their skill and ability to form drops, we use substances such as polymers and waxes. However, the latest research types have shown that metals and ceramics also have potential. Jetting material is a process that includes high precision and makes it possible to use multiple colored materials under the same process (I. Gibson et al., 2010), (Halinen, 2017).

Binder jetting process is a method that distributes a layer of powder as a powder bed fusion machine does in a build frame. To create a layer for the part, a liquid connecting agent is selectively applied to this powder layer. The base then decreases and a new powder layer cover the surface and the process is repeated until the part is finished. The advantages of this method is that due to the powder bed and the way the part is in the powder, the process does not require any support structures. This also enables parts to fill the entire construction volume (Gibson et al., 2010). Jetting binder is a fast and cheap technology that works with many different materials, including metals, polymers, and ceramics. Unless further processed, the parts that are made with this process have some kind of minimal mechanical properties.

Sheet lamination (SHL) process involves sheets of material that use glue, thermal bonding, ultrasonic welding or clamping to tie together. When a surface is applied to the previous layer, either with a laser or mechanically, it is cut into the desired shape. Otherwise, the surface will be cut into form and then attached to the previous layer. We agree that one sheet is one layer of the part and defines the height of the layer. It requires the part to be extracted from the sheet material quantity after the process is over (Halinen, 2017).

Directed Deposition of Energy (DED) is a last AM method process. The nozzle is moving in three directions in a DED system. Nevertheless, it is possible to mount the deposition nozzle on a multi-axis neck. This makes it easier to maintain and repair existing structures as the material can be deposited in the process from various angles. The material deposits from the nozzle in the form of powder or wire and is melted with a laser or electron beam.

Generally, the DED process is used with metals but can also be used with polymers and ceramics. This method may be used to make similar structures in functional parts, high quality or repair. DED processes with a full-dense part can produce highly controllable microstructure-al features. Limited resolution and surface finishing is the key drawback of DED processes, while speed can sometimes be sacrificed for better surface quality and higher precision. The time may be very significant as the construction time is already very long (Halinen, 2017).

2.2.2 AM materials

AM process is a technology that we can use different kinds of materials, but the most important for industries and for AM technology is metal and plastic. We can also use ceramics, waxes, for many 3D models of these materials. Material property is definitely part of the AM area (Campbell, Bourell, & Gibson, 2012). While selecting AM and computers, it is very important to be able to understand the intended usage. The material alone does not guarantee good quality, particularly when compared to conventional production.
A wide range of plastic printed in 3D is available. Even in the same part, the properties of each plastic can vary from different machine printing, it is very important that plastics have different temperatures of resistance (Liu, Xu, Shi, Deng, & Li, n.d.). Plastic material's properties may not tend to be reported as properties as they may differ outside the given range. For these types of materials, heat distortion temperature (HDT) is good to report. Many materials decrease rapidly when the temperature is increased and some gradually decrease over a longer range of temperature, thereby increasing the material's usefulness (Halinen, 2017).

Some well-known plastics, such as acrylonitrile butadiene styrene (ABS), polyvinyl alcohol (PVA), polylactic acid (PLA), and polycarbonate (PC), are used in AM. ABS is the polymer's most popular type and can be found in many products. The advantages of ABS are good resistance to impact, strength, rigidity, and surface finish. The disadvantages of ABS are low incessant service temperature, very low dielectric strength and some diluent tolerance (Campo, 2006).

PLA is a thermoplastic biodegradable made from renewable resources such as maize starch or sugar cane. PLA is very sturdy and lightweight, but can be breakable and has a weak HDT. It is necessary to add fibers or filler materials to improve the mechanical properties of PLA. PLA parts are traditionally used primarily in biomedical and packaging applications. For example, in the automotive industry, reinforced material is used (Sharma, Mudhoo, Osswald, & Garcia-Rodriguez, 2011). As it is dissolvable in liquid, PVA is used as a form of support material in AM. As PVA absorbs water, for better results, the environment must be controlled for moisture. Higher than usual moisture makes the material softer and more durable than hard and brittle (Olabisi & Adewale, n.d.) (Halinen, 2017).

When extruded, polycarbonate (PC) requires a high-temperature nozzle that can be difficult for 3D printers. PC as a material has many advantages such as high impact strength, strong dimensional stability, wear resistance, and all thermoplastic methods can handle it. PC is constrained by relatively soft substrate, only good resistance to solvents and poor sensitivity to cracking pressure. For example, sports helmets and vehicle tail and headlights are common applications for polycarbonate (Halinen, 2017).

In all cases of a metal structure, the powder material is used as input (I. Gibson et al., 2010). Overall, based on Table 1. Commercial materials used in the manufacturing of AM, any metal that can be welded under normal conditions can also be printed as 3D. Some commercial alloys are also available that can be used in the AM process (Frazier, 2014).

Titanium	Aluminium	Tool steels	Superalloys	Stainless steel	Refractory
CP Ti	6061	Cermets	IN718	420	Alumina
ELI Ti	Al-Si-Mg	H13	IN625	347	CoCr
γ-TiAl			Stellite	316 & 316L M	Ta-W

Table 1**.** Commercial materials used in the manufacturing of AM

(*3D printing-increasing competitiveness in technical maintenance*, n.d.) Source.

Metallic parts of AM go through continuous melting, heating removal, and crystallization during the process, and sometimes even through transformations in the state process. Compared to traditional manufacturing methods in Table 1. Commercial materials used in the manufacturing of AM. The mechanical properties of metallic AM components are comparable with those of traditional manufacturing parts, certain defects such as microporosity, increases the fatigue of AM properties but can be enhanced with methods such as TO or post-processing behavior such as hot isostatic processing or machining (Frazier, 2014).

According to (Mani et al., 2015) recent presents a good look for properties of metal powder bed fusion. In this, a steel and aluminium axle and a case were made and participated in multiple tests. Those two pieces are very simple elements of the computer and are an example of working well together. For an axle, even after heat treatment for the application, the hardness surface was not adequate. It should be noted that the surface increased more than the necessary limit with nitration (Halinen, 2017).

The test showed that the hardness meets the die-cast criterion based on the SFS-EN 1706 norm. For aluminium, the elastic module was unusually lower than specified by the manufacturer (26.54 Gpa vs. 64 Gpa) and what a die-cast part (75 Gpa) would have.

This was due to the anisotropic design of AM parts and the variations in construction directions, according to the manufacturer. There were also some mistakes, as we described, during all the construction processes and measurement. The AM aluminium strengths of harvesting 84% and tensile 69% were unusually higher than that of the cast part. PBF manufacturing's accuracy was not so good for either the axle or the frame, but both needed some sort of additional surface machining (Halinen, 2017).

2.2.3 AM defect

There are so many articles and references available about the defects of 3D printing on the internet. We can easily realize the enormous data that appear as using keywords like ‘3D printer defects’, ‘3D model defects’, ‘Surface Defects in 3D models’ etc. These kinds of defects are measured in micro millimetres and with the help of some special device. These kinds of defects appear daily as we use 3D printing. In this thesis, we are very briefly presenting the main defect of AM which is (Wycisk et al., 2014).

WARPING: is a common problem in 3D printing, which happens when the first layers of the plastic part are cooling too fast and the layers are not properly attached with the other layers. To reduce warping is essential to use a heated bed platform (“Print Quality Guide,” n.d.)

ELEPHANT FOOT: mostly occurs as a result of the first layer. If the temperature of the print bed platform is too high or if we have some kind of insufficient cooling then we have this deformation on the surface in comparison with the other part ("Print Quality Guide," n.d.)

SHIFTED LAYERS: is a problem is when the layer of our print does not align properly and leaving a staggered "staircase" look behind. This is a visual defect and can easily notify since it is larger if compare with others ("Print Quality Guide," n.d.)

LOWER PARTS SINKS: this is also a visual defect that we can observe the sinking of the layer ("Print Quality Guide," n.d.)

LAYER MISALIGNMENT: this is a defect where we observe that a line is missing in the part ("Print Quality Guide," n.d.)

MISSING LAYERS: this problem is a minor defect where we can check the surface's roughness and depth ("Print Quality Guide," n.d.)

CRACKS IN TALL OBJECTS: this defect is a crack that can be measured with regard to the distance between layers, roughness, depth and length of the cracks ("Print Quality Guide," n.d.)

PILLOWING: it a defect which observes at the top surface of the 3d part, usually a lot of space is empty and filled up with infill material ("Print Quality Guide," n.d.)

STRINGING: it is a defect that can be prevented in a couple of layers and is related to the roughness and the quality of surfaces ("Print Quality Guide," n.d.)

2.2.4 AM future

The new release information about AM showed that in 2018 new companies beginning from more conventional manufacturing such as digital printing and photography entered in the market of AM. The list includes companies such as Hewlett-Packard, Xaar, Fujifilm-Dimatrix, Ricoh, Canon, Konica, Massivit, Minolta, Carbon, MarkForged, Rize, Desktop

Metal, Nano Dimension, Lumex Laser (Wu, Myant, & Weider, 2018) (Olabisi & Adewale, n.d.).

Moreover one of the most crucial factors for using a 3D printer, especially in the metal print area has been time and speed of the process. The latest news underline that Desktop Metal Company has overcome the time and speed factors. Desktop Metal Company has an exclusive position in the 3D market field. The feature to produce 3D products more quickly through the 3D devices has come for good.

Finally, we should mention that very few technologies have offered so much as 3D manufacturing has done in the concept of product in the last few years. The global market is impatient and price-sensitive so 3D AM technology is there to eliminate the costs of the product and add value to that.

2.3 Product cost estimation

Product costing estimation is one of the most important factors in the area of manufacturing and process in all industries. This crucial factor is used for estimating and evaluating the entire cost of the product. This estimation is important for companies and budgeting control. Based on that companies receive decisions about financial policy, prices, investment, etc.

2.3.1 Cost analysis

For a company to estimate the costs to manufacture a product is a very complex process but also very essential. This process is not only related to the initial capital required to produce the product but also involves the factors that are related to the market and price of the product. That is why it is mentioned above that “Product cost estimation” is very important and helps the company to specify that point.

Moreover, in this thesis, we will try to give a wide concept about the total cost product for AM and how it will be used in our project for approaching the calculation. Above all, there will be some definitions of the total cost and how this is related to additional costs and how it can be calculated based on other factors.

Total cost (TC), in production, is related to variable cost (VC) and fixed cost (FC). Total cost depends on variable cost since it is linked to the quantity of a product and that includes factors such as labor, raw material and etc. In contrast to variable cost, total cost is linked to fixed cost in independent way, since it includes factors such as buildings, machinery, etc.

As a result, it seems, from the below Figure 7. Costs related the total cost and the fixed cost starts from the same starting point since this point includes costs that exist despite any goods production. Afterwards, it can be mentioned, the total cost grows based on variable cost since it is related to the quantity of the product.

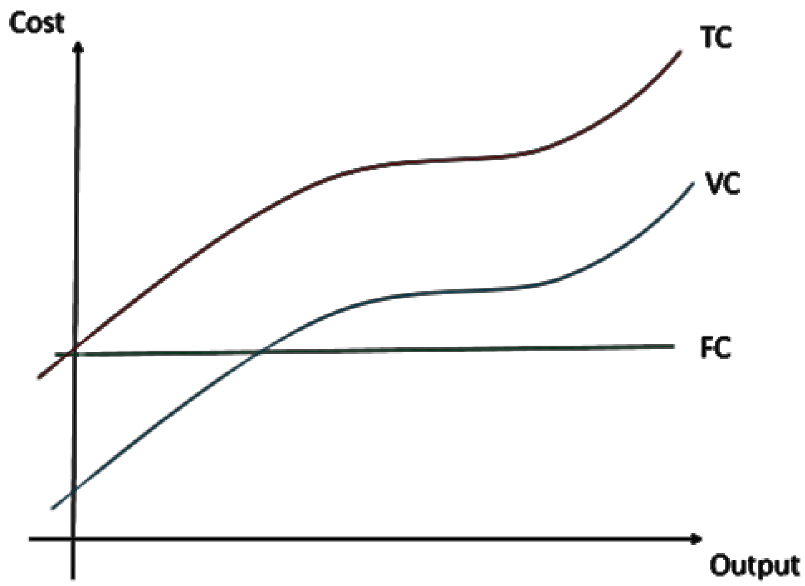


Figure 7. Costs related

The real meaning of the term 'costs' slightly depends on the content. For instance, when a factory has a production cost, these terms are related to variable cost plus fixed cost plus additional costs related to the production. That is a very fundamental measurement process for business owners and managers. Based on that they can define prices, revenue, and capital expenditures as it seems in Figure 7**.** Costs related.

Moreover, there are some other concepts of total cost such as investment cost, where its TC represents the cost opportunity which is related with choosing the best investment among another.

2.3.2 Cost of AM

Deciding which method of process is better for producing a designing part should face the factor of choosing between tradition manufacturing and AM and the question is always about cost. In product, line saving could be reached with different ways because every case is unique and different. For instance, saving could come from materials, or different concepts in designs, or from the smaller volume, even flexibility in delivery time and many other factors. Furthermore, 3D printing supports the production of small parts with a high level of complexity, as is mentioned in the picture below Figure 8. Costs – Complexity TM – AM

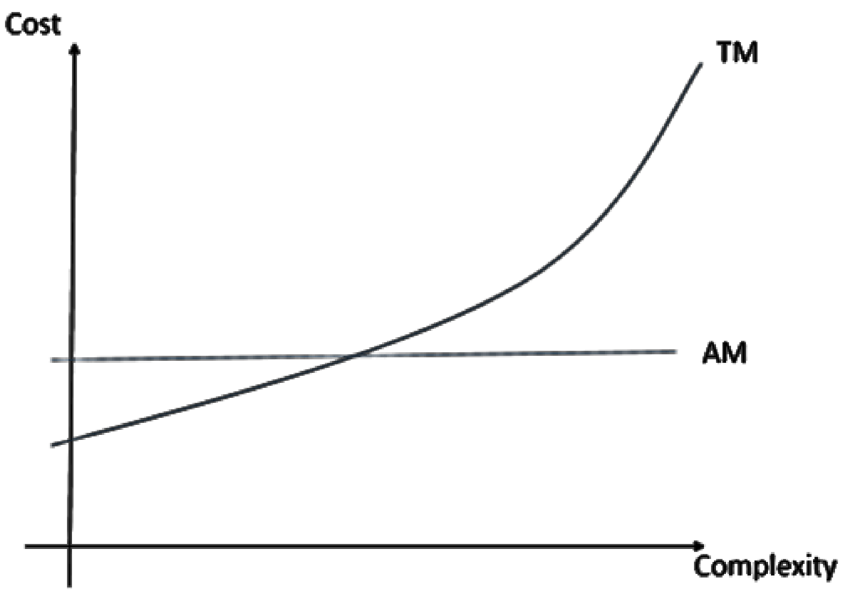


Figure 8. Costs – Complexity TM – AM

The cost is very important for every company and factory, consequently, for 3D printing and metal additive manufacture also due to the fact that every part should be customized with the flexibility of production. To be clear, in the next paragraphs two examples will be presented along with the effects of the production volume. First, let us analyse the case production of an iPhone case with a method of AM and traditional manufacturing which is injection molding.

The cost of designing is the same as for both processes. For a small quantity of fewer than 700 parts, AM is more economical as can be noticed from the Table 2. Price per unit from 3D printing to conventional manufacturing. But in the scale economy, the molding injection overlaps with the first advantages of AM and makes traditional manufacturing more profitable in a large number of parts. AM has a much higher cost for the raw material in contrast with traditional manufacturing.

Quantity	3D Printing	Traditional Manufacturing	Difference %
10	313,15$	1150,75$	-267
100	43,15$	115,75$	-168
250	25,15$	46,75$	-86
500	19,15$	23,75$	-24
750	17,10$	16,08$	6
1000	16,15$	12,25$	24
2000	14,65$	6,50$	56
4000	13,90$	3,63$	74
6000	13,65$	2,67$	80
8000	13,53$	2,19$	84

Table 2**.** Price per unit from 3D printing to conventional manufacturing

(*3D printing-increasing competitiveness in technical maintenance*, n.d.) Source.

In the above example, the advantages of 3D printing could have been more if small changes could be made in the shape and the need for less volume. In the AM process, it can be modified only the CAD file, for instance, if we have to produce a different size or to change some hole's dimensions. The model could be printed easily with no additional cost, but in case of injection molding would require a new model and new pattern which makes it more expensive as a single part (Atzeni & Salmi, 2012).

Another case that presents the real advantages of AM is, for instance, if a company needs a few spare parts for repairing a manufacturing air vent. The usual supplier demands to agree at a minimum of 250 parts when only few are needed and the delivery time would be around 4-5 months. In contrast with 3D printing, the cost will be extremely low since it can produce only few and the delivery time will be less than a couple of days, plus no need for stocking any extra parts, Table 3**.** 3D printing and conventional manufacturing for vent .

While is easy to notice that the cost for single part with traditional manufacturing is higher, on the other hand can easily be noticed that the gains from the overall costs are also lower, as it presents from the table below, since AM offers more flexibility and no storage cost since extra spare components are needed to be ordered.

	Traditional Manufacturing	3D Printing
Engineer Design	5 hours	5 hours
Initial Cost	60000-70000	<1000$
Minimum Order	250 units	1 unit
Lead time	4-5 months	<1 week
Warehousing Cost	Stocking an excess of 240 units	Order as needed
Labour Cost	500-2000	200$
Maintenance Cost	5000$	300$

Table 3. 3D printing and conventional manufacturing for vent

(*3D printing-increasing competitiveness in technical maintenance*, n.d.) Source.

In addition, to provide some of the old parts of a machine or assemblies it is not so profitable for companies, due to the fact that for manufacturing a single part is costly. Instead, they offer entire new machines for a better price. With AM is not more difficult to replace components that are missed or are broken.

For instance, let’s assume that we need to replace a slight sprocket wheel that breaks into an assembly. In this case, there are two choices, to order e new one from the original manufacturer, which, will reject the offer since it is expensive. The other alternative is to buy a new one (whole assembly part) which will costs much more plus installation and delivery cost. In contrast, AM gives us the opportunity to have the spare part in cheap price, in the right amount and in reasonable delivery time due to the fact that for 3D printing these parts are a straightforward process.

2.3.3 Cost of materials

It is usual that costs associated with new technologies change over time as innovation is widely adopted. That is something which is related also with AM and process materials. The prices of 3D printing materials from 2013, according to Wohlers & Wohlers, have changed and estimated to change even more in the coming years. More thermoplastics and photopolymers material for AM costs around 175-250 per kilogram and injection molding thermoplastics are usually priced at approximately $2-3 per kilogram.

This is a crucial factor that makes AM 58-125 more expensive than injection molding. For instance, Stratasys which uses its own material cost around 250$ per kilogram for ABS and Ultem 9085 the cost for PC varies around 500$ per kilogram and polyphenylsulfone. On the other hand, 3D printers use PLA and ABS that cost 15-50 per kilogram. Polyamide powders which is used for metal structure through laser sintering cost 85-100 per kilogram.

As can be noticed, the AM metal powder materials are more expensive compared to the materials that are used in the traditional manufacturing process. In general, stainless steel, tool steel and aluminum alloy powders are the cheapest in the metal list price, around 78-120 per kilogram. As for the Cobalt-chrome alloy powder the price range around 120$ per kilogram to 545$ per kilogram for some specific dental power grade. Nickel alloys cost around 210-275 per kilogram. Titanium and Titanium alloy prices range from 340-880 per kilogram. Of course, there are many variances or alloys that are not necessarily investing in the 3D printer manufacturing processes.

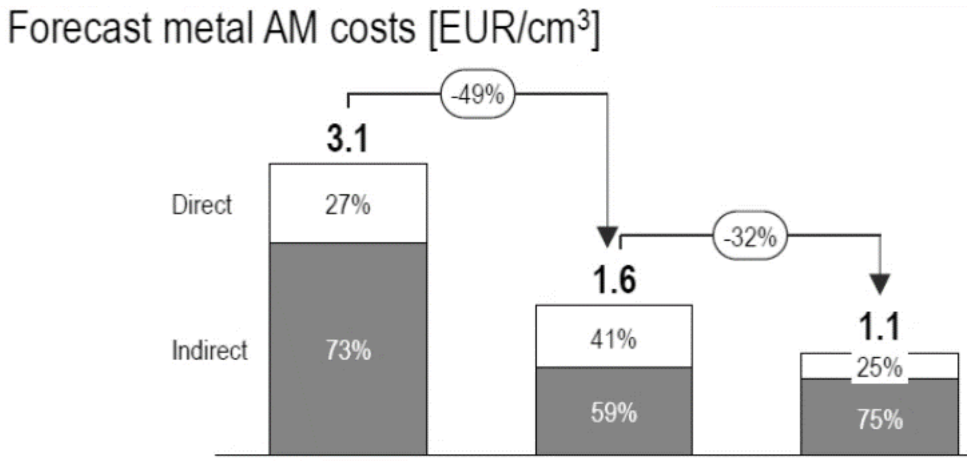
However, there are some applications that have comparative advantages for companies if they invest in 3D printing machines. Nevertheless, quick research in machine price for this kind of investment for professional-grade is arranged around 20000€ for plastic and begins from € 150 000 for a metal printer. The higher limit to purchase 3D printers is roughly EUR 1.7 million. More expensive 3D machines generally offer greater construction space and higher quality for finished parts (*Firpa*, n.d.).

In addition, it is important to consider the maintenance costs of the component, such as repair, tooling and retirement costs, for material and 3D printer costs. For example, tooling for injection molds, stamping dies or even machining fixtures may cost the traditional manufacturing methods. Therefore, the cost of service is always associated with fixing and replacing a part.

Equipment (tooling) is a big issue which is directly connected with the initial investment in the area of manufacturing. This means that it needs an initial cost plus supporting service for the product, but most importantly, should have a warehouse for offering all these facilities. In contrast with AM does not have to stock any tools that might be needed later.

The elimination of storages and hard tooling is a great advantage of AM technologies in many ways. Generally, they manage to save space, time, and money during manufacturing and mostly the durability of the product (Gibson et al., 2010). Costs occur later when a part is out of service and should be replaced.

Moreover, AM and metal printing manufacturing is a recyclable technology in comparison with traditional manufacturing. As for the plastic, there are a bit more different conditions. For instance, Nylon can be recycled but more difficult than other thermoplastic such as ABS. Furthermore, thermoset polymers, like photopolymers, are hard to recycle through the jetting process (Campbell et al., 2012). The future is very promising for materials prices since are expected to decrease more and the profit from using will go higher. The above can also be seen in the following picture which presents the tendency of the coming years.



PREREQUISITES	2013	2018	2023
Build speed	10 cm^3/h	40 cm^3/h	80 cm^3/h
Machine costs	EUR 500,000	EUR 700,000	EUR 800,000
Share of monitoring	5%	2%	0%
Machine utilization	86%	84%	81%
Powder price	EUR 89/kg	EUR 70/kg	EUR 30/kg
Post-processing effort	1.52 h/kg	1.05 h/kg	0.96 h/kg

Figure 9. Prediction costs for metal AM

(*3D printing-increasing competitiveness in technical maintenance*, n.d.) Source.

Overall, we should mention that the prices of metal material will be lower due to the competition between companies. According to Figure 9. Prediction costs for metal AM, the profit rates will get higher because of the development of technologies and machines. Prices for machines will increase because more lasers are involved in process. A reliable machine will reduce the process of AM for service, monitoring and troubleshooting to lower labour costs (*Additive manufacturing A game-changer for the manufacturing industry ?*, 2013).

3 METHODOLOGY

3.1 TO method

TO is a method that helps engineers to optimize the material under different constraints such as design space, boundaries and loads for achieving specific goals such as maximizing the abilities of the designing part.

This area of structural optimisation is divided into three categories as presented in Figure 10. Categories of optimization a) Sizing b) Shape c) Topology. The first one, related to size optimization, the second to shape optimization and the third one to TO (M. P. Bendsøe & Sigmund, 1999a).

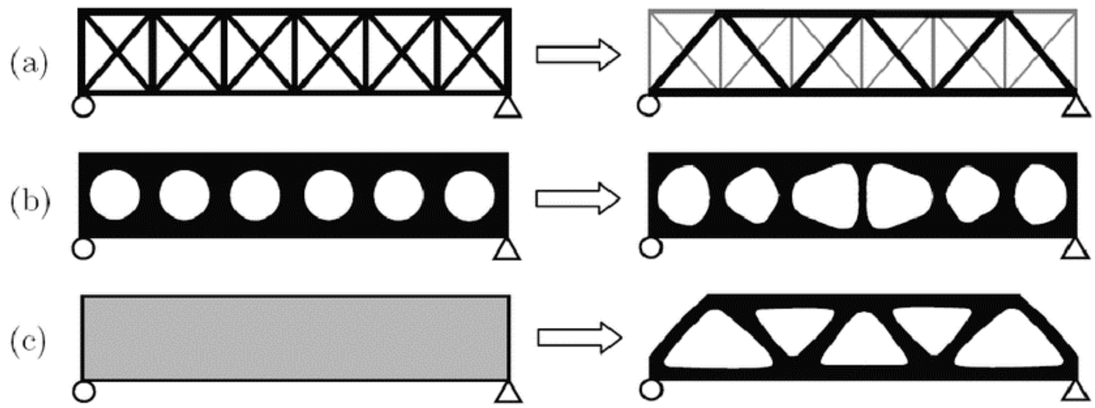


Figure 10. Categories of optimization a) Sizing b) Shape c) Topology

(Bendsøe and Sigmund, 2003) Source.

This study is focusing on TO and it is describing the designing space, loads and boundaries for our parts. TO applies FEA for verifying the performance of the designing part. The performance is optimized based on different genetic algorithms (Riaz, Ahmad, Alam, & Abid, 2013).

This method offers forms, naturally occurring and due to this factor, the manufacturing of that part is difficult, thus, we have to apply AM. Many engineers use TO in different concept design levels especially, in aerospace and automobile industries, the scooter where we applied this method is also part of those industries.

3.2 QuadDiametral lattice

In recent years the need to manufacture more complex and interesting shapes with lattice has been increased. Now is more possible to create lattice structure fabricated by direct metal laser sintering (DMLS) using even aluminum element. In the current study, we will try to develop a repetitive design of unit cell quadQiametral lattice with the aluminum element. This structure, it is believed to offer many advantages to the structure that we want to use for the scooter since it extends the use of DMLS for producing cellular lattice structures with a wide range of unit cell volume and size fraction. With this structure, we could achieve a range of size cells (3-7 mm) and volume fraction (7.5-15%).

These ranges can be manufactured by DMLS showing great suitability and flexibility for light part utility, which makes it really attractive for the aerospace industry and automobile industry as well (Yan et al., 2014). Let us underline here that the compressive modulus and the strength of the system of DMLS lattice structure rises the volume fraction while presenting special results using the Gibson-Ashby model.

Generally, the quadDiametral as it appears in Figure 11. QuadDiametral Lattice, planned to be applied in the aluminum scooter parts, shows that a similar lightweight aluminum structure can be designed to control volume fraction and unit size with the extraordinary controllability and predictability which appears in their mechanical performance (Mathew et al., 2017).

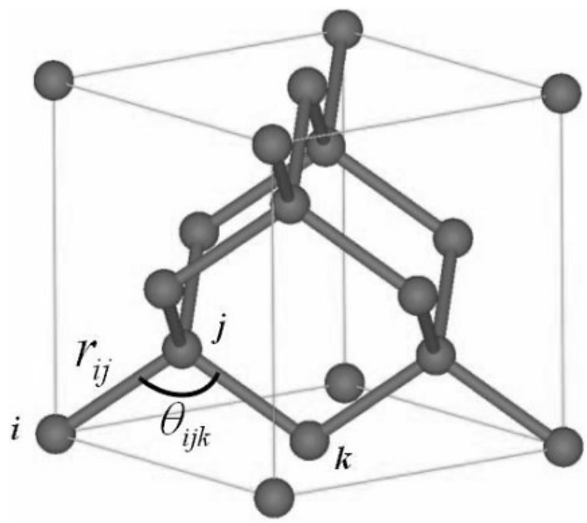


Figure 11. QuadDiametral Lattice

(Tae Jin Kim, January 2007) Source.

The above Figure 11. QuadDiametral Lattice, shows the structure of the quadDiametral that we will be used later in this project through the NX. The picture also presents some of the attitudes of the structure such as the edge length, rod diameter and angle of the structure. We can adjust these factors to something that approaches the constraints that we have set about the part.

3.3 Cost analysis method

Total cost (TC) for this thesis is the production cost, which is made of variable cost (VC) and fixed cost (FC). The first one (VC) depends on the number of products, costs of labor, raw material and some other variable factors like tools. As for the fixed cost that is independent of the quantity of a product and includes factors that cannot be variable short term.

TC = VC + FC = Kr + Lw (8)

TC = Total Cost

VC = Variable Cost

FC = Fixed Cost

K = Capital Cost

L = Labour Cost

r = Rental rate per Unit

w = Wage rate per Unit

Moreover, in the next pages, an effort is made to analyze the TC for traditional manufacturing and AM through some quotes and cost analysis. Concluding, a better view of the cost of components of the e-scouter that we had redesigned, will be presented.

4 SOFTWARE TOOLS

There are many software in the market for education and commercial propose in the area of CAD, as well as, for TO for engineers and designers. Every kind of CAD software has different capabilities and adjusts better with different kinds of problems that engineers have to solve. Some of the software packages that will be mentioned in this thesis, describe better the functionality of loads, contrary to others which describes better the simulation or the visualization of the problem.

To better define software optimization for our part, different software will be utilized. Moreover, all actions will be briefly analysed in the coming pages, yet, that does not mean that there is only solution to achieve the same result. As already been said, in the field of design and manufacturing the solution are so many and always depend from what perspective you approach the problem.

4.1 CAD / CAE

The CAD-CAE systems are characterized by the intensive interaction between design and analysis. Although there are various CAD software packages in the market and CAE software that are specialized in every field. It should be mentioned that CAD systems enable fast designing of the model and on the other hand, the CAE system provides the designer with the analysis results, cost of the manufacturing process and quality of a product. The advantage functionality of the systems CAD-CAE is still using a different interface to describe model since they run in a different environment. It is more than obvious that CAD-CAE is still not integrated.

To compensate the above mentioned disadvantage of CAD-CAE, analysis software provides building tools to users. However, they are not highly advanced as CAD software, providing only very limited drawing tools. Moreover, there are some CAD software that allows CAE analysis to run under their own environment, randomly can mention Solidwork, Unigraphics, Ansys, CreoParametric. The issue is that an integrated environment is created, but not an integrated system. Designers still need to construct their model, pass the model to research, and then determine their information related to the analysis model.

A lot of research has been done on this subject, attempting to examine this problem from different perspectives. An earlier scheme is about idealizing a CAD design for analyzing CAE and creating automatic mesh. Nonetheless, CAD design conversion to the CAE model supports idealization and automatic mesh creation in terms of geometry.

The derived idealization model also needs more information, such as material type, manufacturing process, boundary condition and many other variables, to complete the model with the correct CAE analysis information (Gujarathi & Ma, 2011).

There are also some studies that are focused on how these two systems can better integrate, but since they have addressed the issue of interaction design analysis, their emphases is on the specific issue of the algorithm for optimizing gate position. Ultimately, interaction is very critical for design-analysis and is a general problem facilitating the implementation of CAD-CAE (Deng, Lam, Tor, & Britton, 2002).

4.2 Altair Inspire

The Altair Inspire is software that gives to the potential designers or engineers a laidback feeling in the field of TO and simulation analysis. There is a wide variety of tools in this software, inspiring designers, engineers or architects even if they are not familiar with the simulation or TO concept to try it through a simple interface and build the structural model that they need based on the requirement of every case.

Overall with Altair Inspire, we are able to create and modify a solid model, generate a design model that is not very structurally efficient and improve their structure. Moreover, should be underlined that we are able to customize material and decide, which the best optimization is, defining the target such as the load, stress constrains, objectiveness (e.g max stiffness or min mass). Furthermore, with Inspire, we can achieve surface smoothing of geometry and performance using the FEA. Generally Inspire is a software that, with no previous experience, can achieve very good results in the TO, based on available simulations (“Powerful and Easy-to-use FEA and Optimization for Design Engineers | Inspire 2018,” n.d.).

5 RESULT DISCUSSIONS

In this step, we will go for further in details of design and TO for reducing the mass as much as possible in the parts of electric scooter. Firstly the initial design is edited and based on that we describe the results, for instance, shapes and the right structure for both parts that will be optimized.

5.1 CAD/CAE results

As mentioned before, in this current work an attempt will be made to redesign the part that has to be improved and later to apply the FEA analysis for checking the stiffness and the weight. As it seems from the coming Figure 12**.** First part of e-scooter during the modification, the part will be redesigned and modified in NX design software.

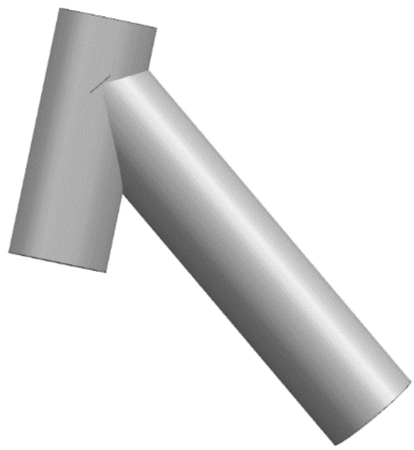


Figure 12**.** First part of e-scooter during the modification

After taking and modifying the mentioned part in NX, the process will continue with Altair Inspire software (“Powerful and Easy-to-use FEA and Optimization for Design Engineers | Inspire 2018,” n.d.). Our goal is to reduce the mass, although, to achieve that is needed to make some pre-optimization actions such as to define the design space which means the area from where the material will be removed and then apply the load on our part. On that point, we should clarify that the new part will be made from aluminium material which is lighter as metal material and it is possible to have it as a 3D print. So first things first, is to define the areas that will be considered as partition out and will not take part in the optimization.

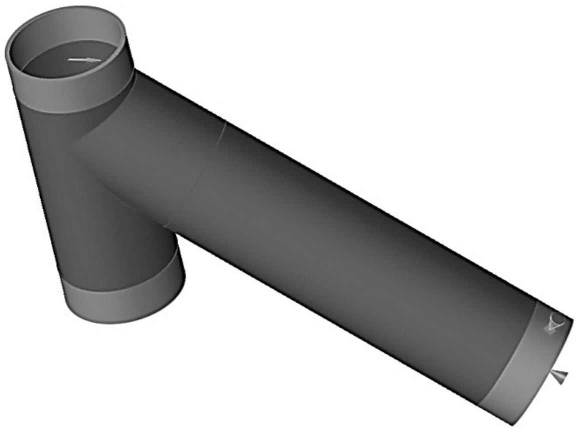


Figure 13. Define design space, material, loads and partition out

Since we have defined the design space, the material (aluminium) and the loads we are moving forward to define some fixers, which will only be on one side of the part and then will apply the load from both sides. The load will be 1500N. Applying the loads externally, will be generated for one moment in the entire part. This could be more realistic load scenario, as is depicted in Figure 13. Define design space, material, loads and partition out.

Different types of Optimizations

This part will analyse only the factors which are related to TO and not the topography. Gauge and topography are not related to the scope of this thesis.

0.132 kg	Objective of analysis	Values	Weight after optimization	Factor of safety
Optim1	Max stiffness	40% Total design space volume	0.079 kg	>1.5
Optim2	Max stiffness	Total target	0.086 kg	<1.5
Optim3	Min Mass	Total mass	0.083 kg	>1.5
Optim4	Lattice	NX	0.062 kg	>1.5

Table 4. Different types of optimization

The figures represent all the optimization and analysis that follows

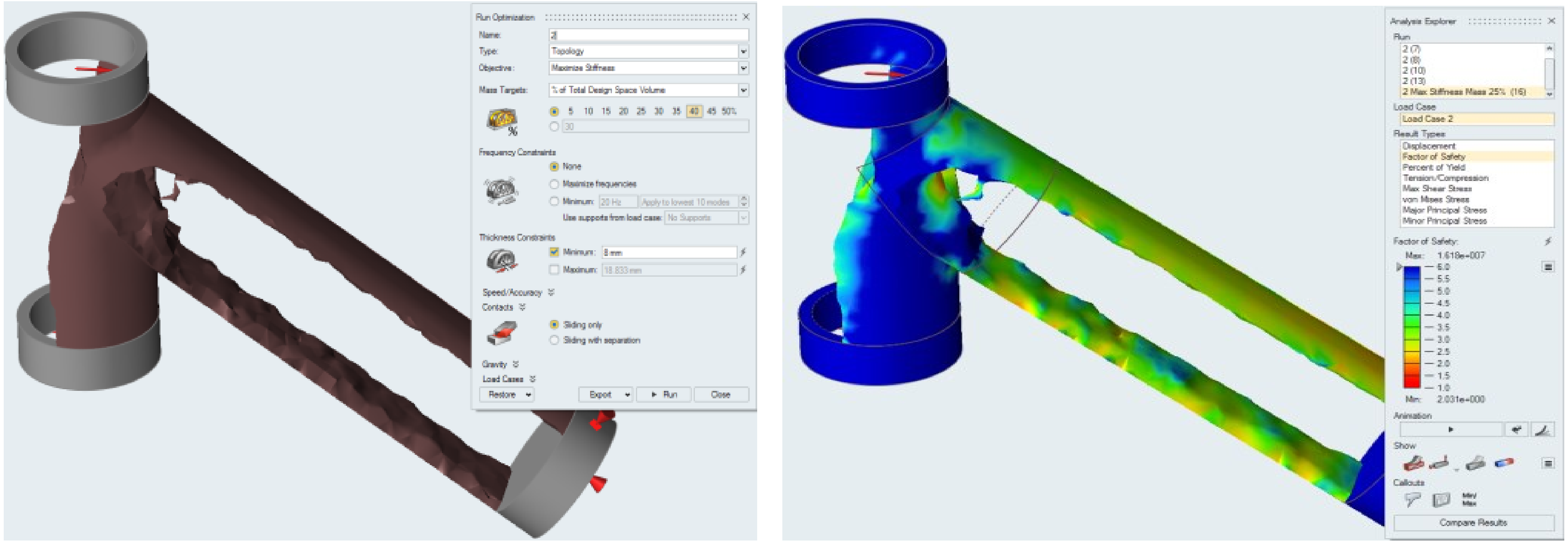


Figure 14. a) Optim 1, Max stiffness, Total mass to 40% – b) FEA

In this optimization, we will try to figure out how to make the neck part stronger, by reducing the weight. Through Inspire, as it seems from the above Figure 14. a) Optim 1, Max stiffness, Total mass to 40% – b) FEA, the software allows us to choose which kind of optimization is applied. In this first optimization, we go with the first option which is to maximize stiffness. According to that, we have the possibility to choose the mass of material that will be removed, based on the scale of percentages or customize it based on a specific target. We can check these options from Figure 14. a) Optim 1, Max stiffness, Total mass to 40% – b) FEA as well. As it seems from Table 4. Different types of optimization, in the first optimization our goal is mass target, by reducing 60% of the total volume space. The remaining volume space will be 40%. The total weight after optimization is 0.079 kg and is better than 0.132kg that we had initially. This can be noticed in Figure 14. a) Optim 1, Max stiffness, Total mass to 40% – b) FEA. The same component will run the analysis for checking the reaction of the part under loading. Based on Figure 14. a) Optim 1, Max stiffness, Total mass to 40% – b) FEA we define which load has to be applied and the result types that will be defined in the analysis. For instance, this project runs under the factor of safety 1.5. This is the limit of scale stress factor as it seems from Figure 14. a) Optim 1, Max stiffness, Total mass to 40% – b) FEA and is presented with red color. Inspire provides animation for better visualization of stress.

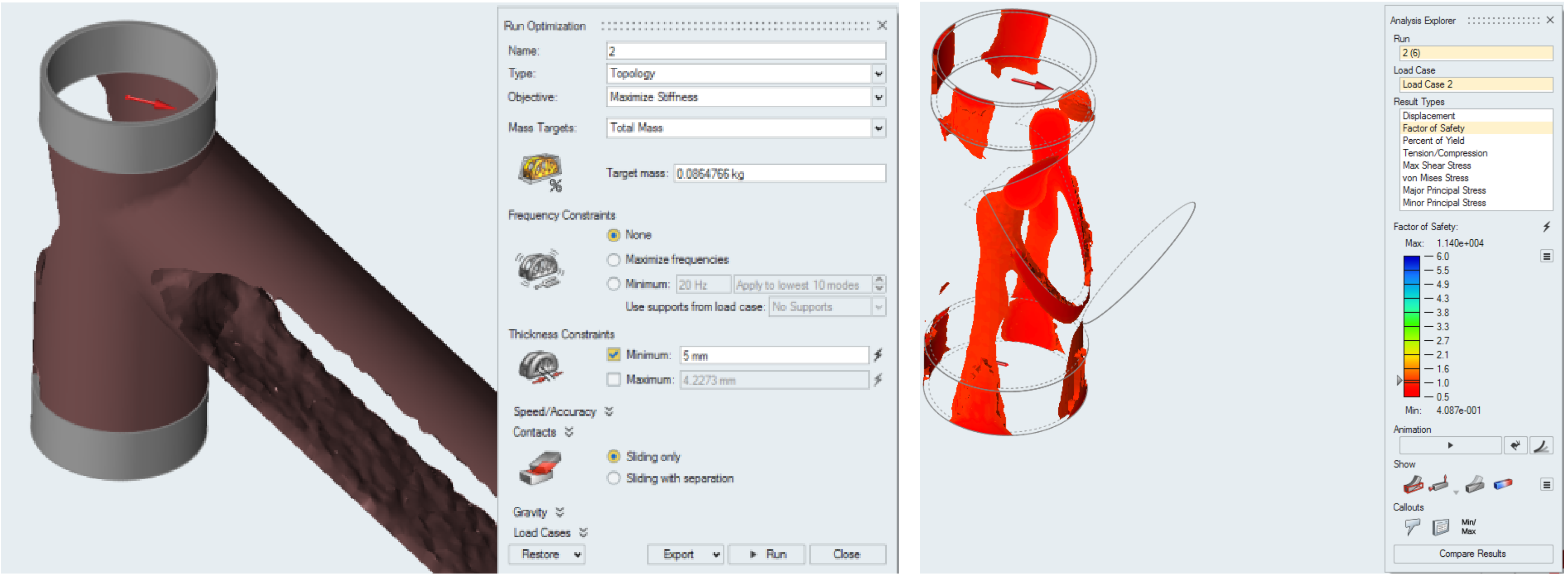


Figure 15. a) Optim 2, Min Mass – b) FEA

As for the second optimization, the idea is similar as the first one, the only difference is that it will run with the value of TO as total mass as can be seen in Table 4**.** Different types of optimization. Based on that the total mass will be reduced to 0.0864 kg. Of course there is an improvement compared to the first approach but the problem is that the factor of safety is low based, also, on the Figure 16. a) Optim 3, Max stiffness – b) FEA, and the visualization (too many red areas) that Inspire allows through analysis as it seems from Figure 16. a) Optim 3, Max stiffness – b) FEA.

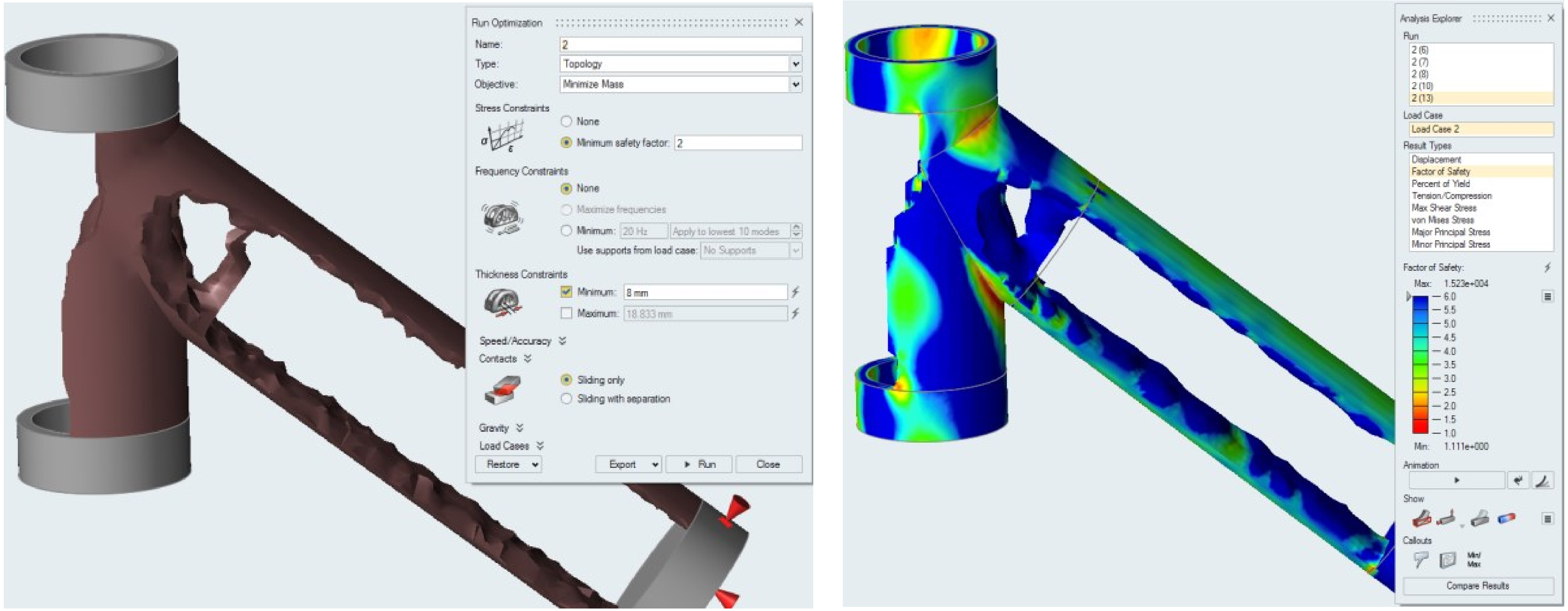


Figure 16. a) Optim 3, Max stiffness – b) FEA

The third optimization will continue with running Minimize Mass as an objective goal, which means less weight as it seems from Figure 16. a) Optim 3, Max stiffness – b) FEA. This optimization will apply the same load 1500N, and as a result, we get a weight of 0.083kg. After the TO analysis that was applied, we ran with the same load the FEA analysis. The results, as we can see from Figure 16. a) Optim 3, Max stiffness – b) FEA are quite interesting and the factor of safety is under 1.5. That makes us accept this optimization through topology as in Table 4. Different types of optimization.

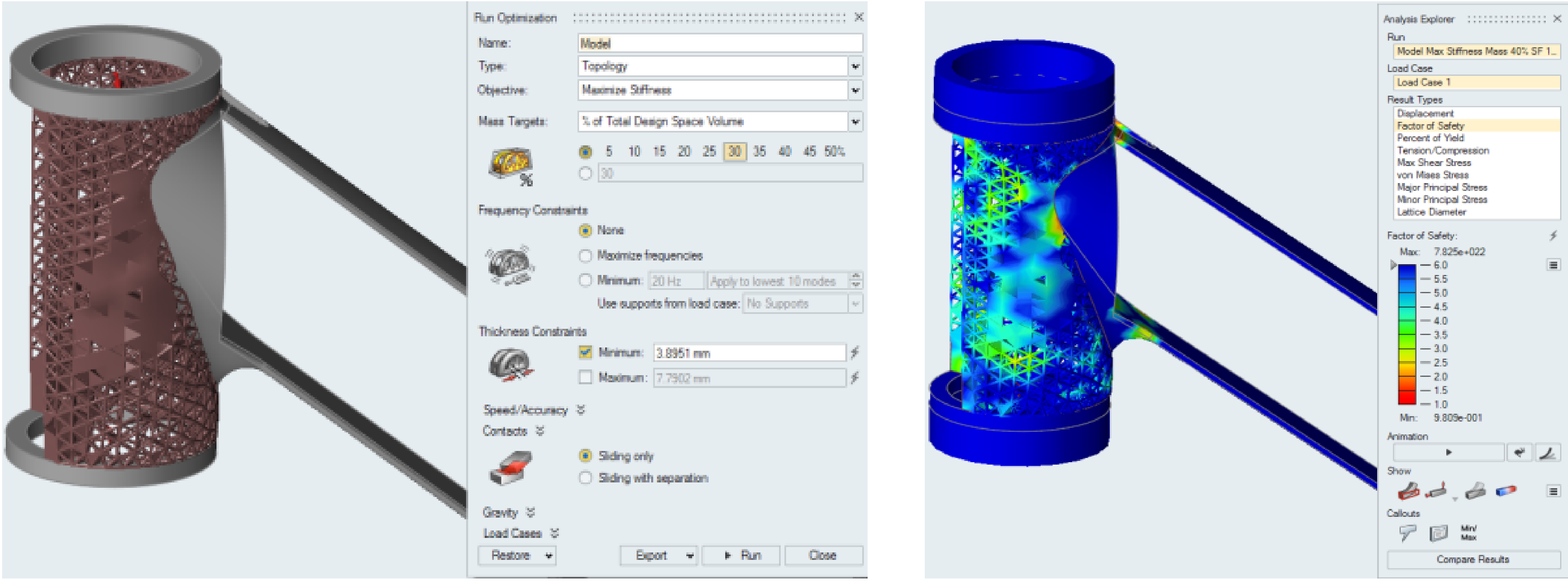


Figure 17. a) Optim 4, Lattice – b) FEA

For the last TO, we continued with the first well-performed part to improve it more by applying lattice. With the lattice, an attempt was made to reduce the weight and to increase the stiffness. As we can check from Figure 17. a) Optim 4, Lattice – b) FEA, we ran the simulation analysis to verify that the factor of safety is above 1.5 as we can see from Figure 17. a) Optim 4, Lattice – b) FEA, plus the color of the part (almost full blue). Once again we have to underline that, despite the fact of satisfying results of analysis, Inspire is just a software which runs analysis. This does not mean that it can replace the engineers, the software is designed to provide the basic information of what you need for a part but always have to take other factors under consideration.

Since we have decided the part model that we move in the next step of optimization, we are ready to build some polyNURBS. Altair Inspire ("Powerful and Easy-to-use FEA and Optimization for Design Engineers | Inspire 2018," n.d.), gives us the right to continue with this process, but since the 3D model of our component is very advanced there are two different shapes of cylinder with very weird optimization, as can be seen in Figure 18. Construction neck part PolyNURBS. Since we have this complicated part, we transfer the model again in NX to build the same structure faster with higher accuracy in thickness and shape.

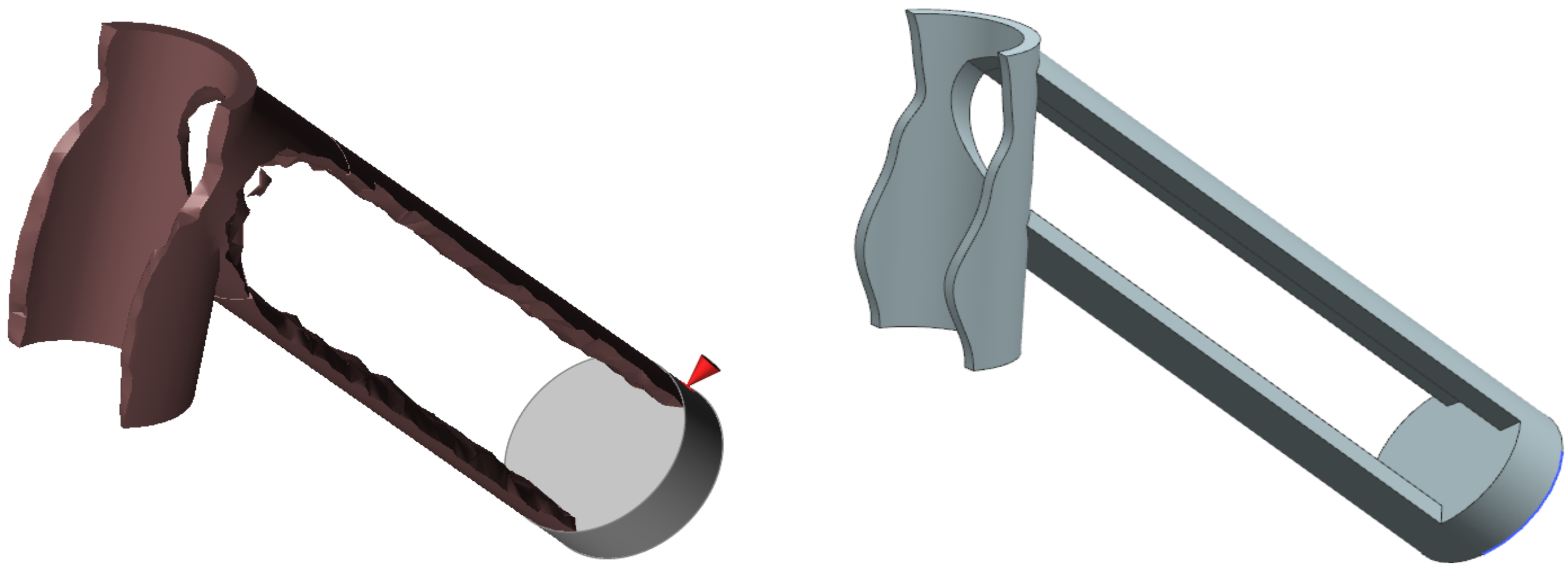


Figure 18. Construction neck part PolyNURBS

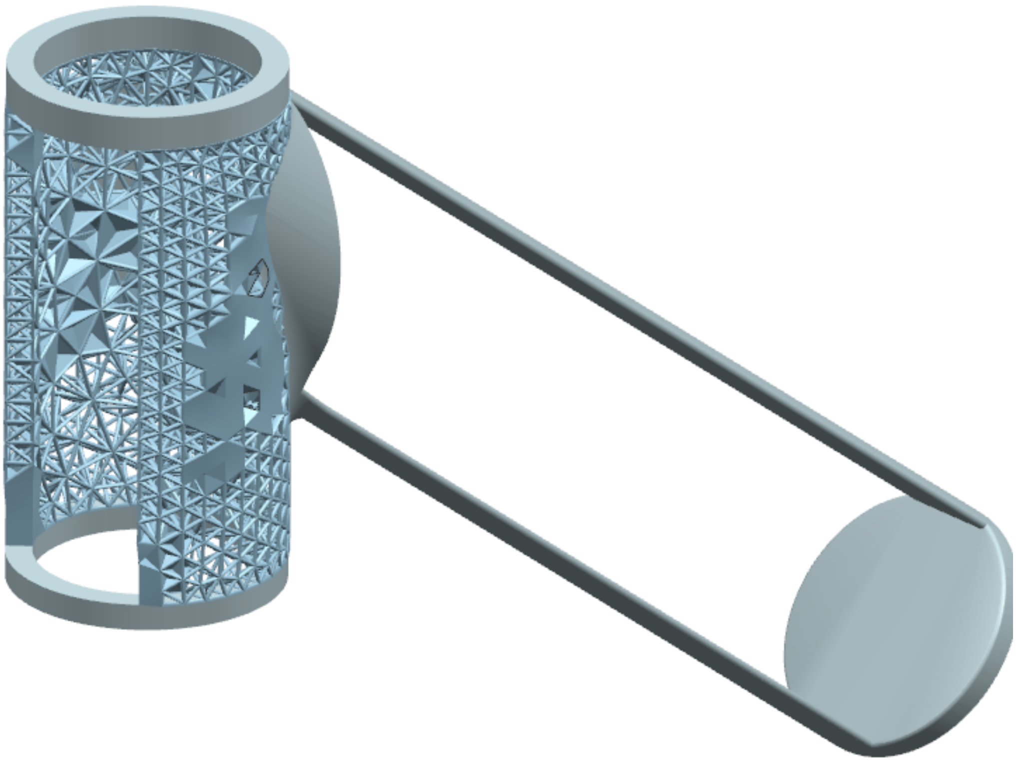


Figure 19. Lattice optimization

After we finished with polyNURBS we applied for lattice structure as it seems in Figure 19. Lattice optimization. The same process will be applied to the platform of the base as it seems from Table 5**.** Different type of optimization for the platform. The only difference, in this case, is that it cannot be applied for TO since the platform has the best shape already and should fit perfectly to the base. However, we try to optimize it as a lattice structure and to analyze it through FAE. The table below presents the attempts made to achieve the best results for the part.

0.235 kg	Objective of analysis	Values	Weight after optimization	Factor of safety
Optim1	Lattice	30% Total space/Lattice	0.165 kg	>1.5
Optim2	Lattice	Lattice	0.186 kg	<1.5
Optim3	Lattice	Lattice	0.177 kg	<1.5
Optim4	Lattice	Lattice	0.195 kg	>1.5
Optim5	Lattice	Lattice/NX	0.165 kg	>1.5

Table 5. Different type of optimization for the platform

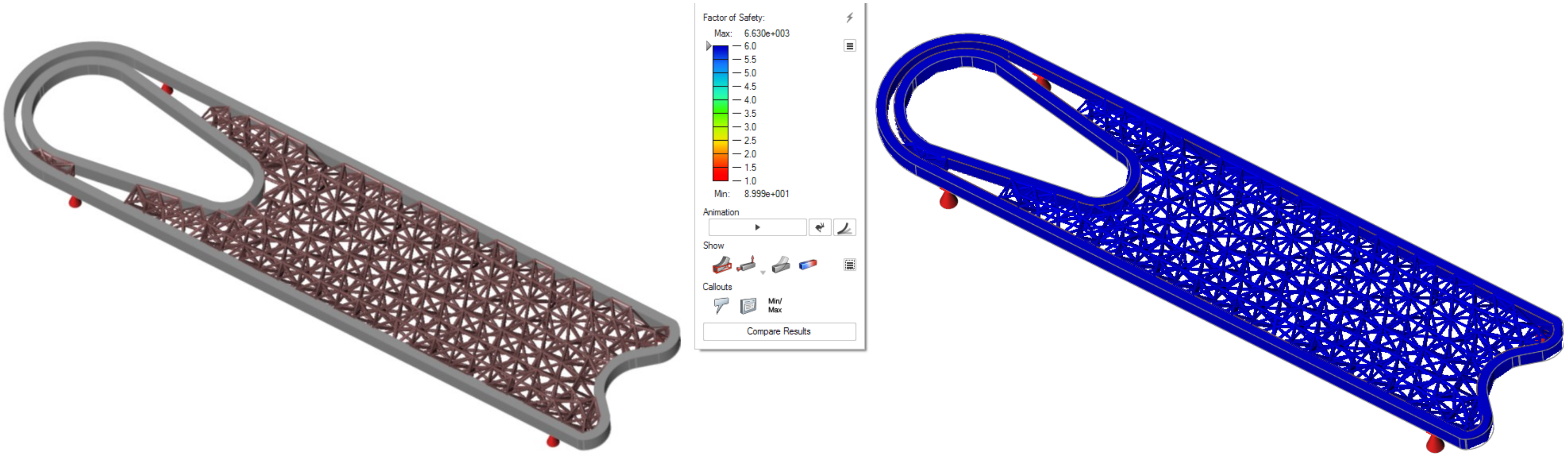


Figure 20. a) Optim 1, Lattice – b) FEA

In the case of the platform, we will not run TO since we do not want to have gaps in our part. We just wish to improve the base through the lattice structure. We run different lattice optimization analysis Table 5**.** Different type of optimization for the platform, until best lattice optimization for our case is found. As it can be easily noticed from Table 5**.** Different type of optimization for the platform, lattice is the objective of our optimization. In the first optimization, Figure 20**.** a) Optim 1, Lattice – b) FEA, we checked that the mass was reduced to 0.165, thus, the factor of safety is very high as can be seen from the color of simulation. The results are totally acceptable but will run some other simulations just to check which one reduces the weight more.

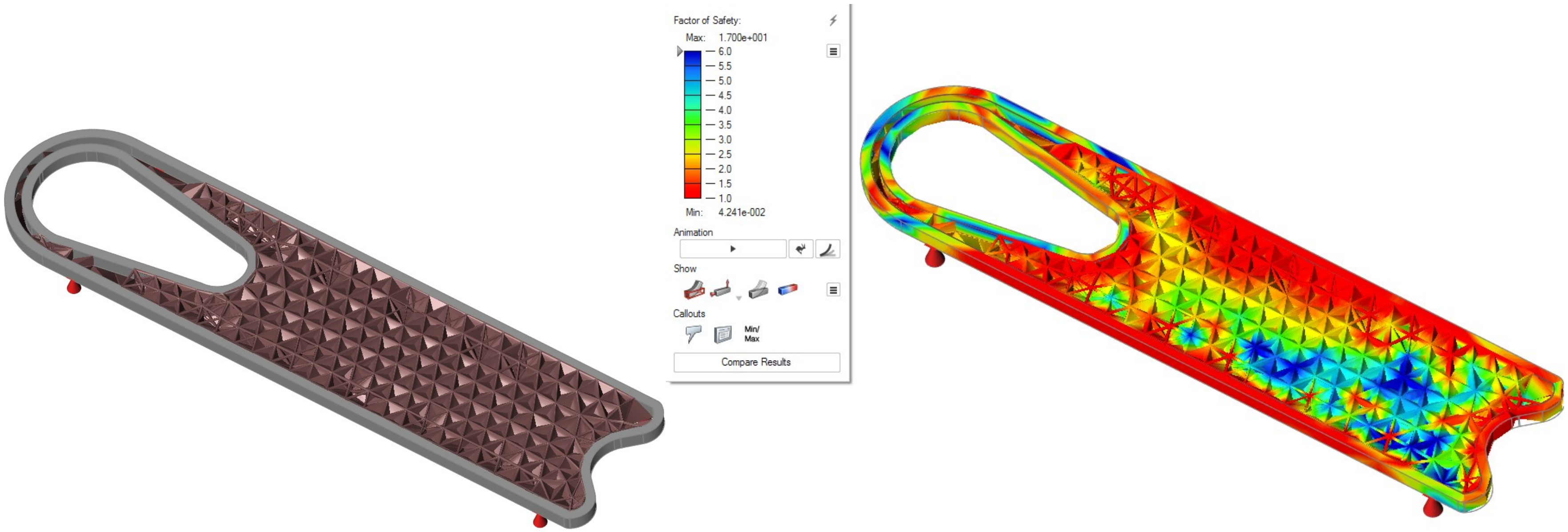


Figure 21. a) Optim 2, Lattice, Total mass – b) FEA

Through this optimization another lattice method was tried, as can be seen from Figure 21. a) Optim 2, Lattice, Total mass – b) FEA. Afterwards, an analysis simulation was ran to check how the component would react under the stress condition and loads. The results, as is presented in Figure 21. a) Optim 2, Lattice, Total mass – b) FEA, is not so satisfying since the factory of safety is below 1.5 and this is why the simulation gave us these results, which are not the desired for our parts. Additionally, the texture of surface it is not that we want for a platform.

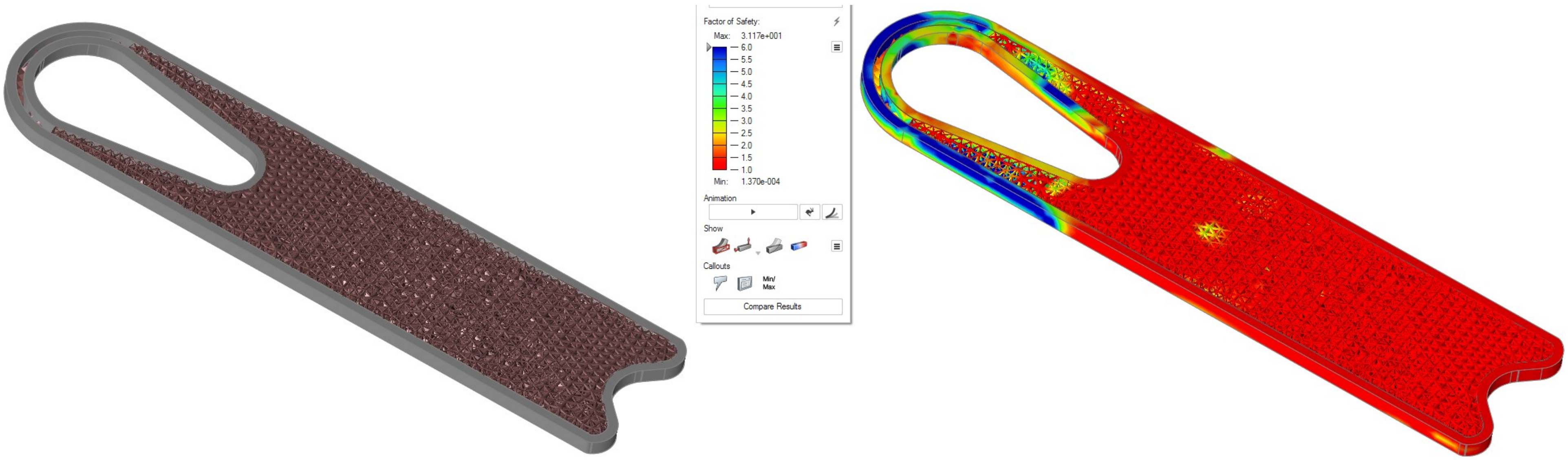


Figure 22. a) Optim 3, Lattice, Mass target – b) FEA

In this lattice optimization, we are constantly looking to improve the stiffness through the new structure for the platform, as is depicted in Figure 22**.** a) Optim 3, Lattice, Mass target – b) FEA. But the new structure of the lattice cannot improve the analysis simulation. Since the factor of safely is below 1.5 and that is why it is visualized with red color in Figure 22. a) Optim 3, Lattice, Mass target – b) FEA. We cannot move forward with this lattice structure.

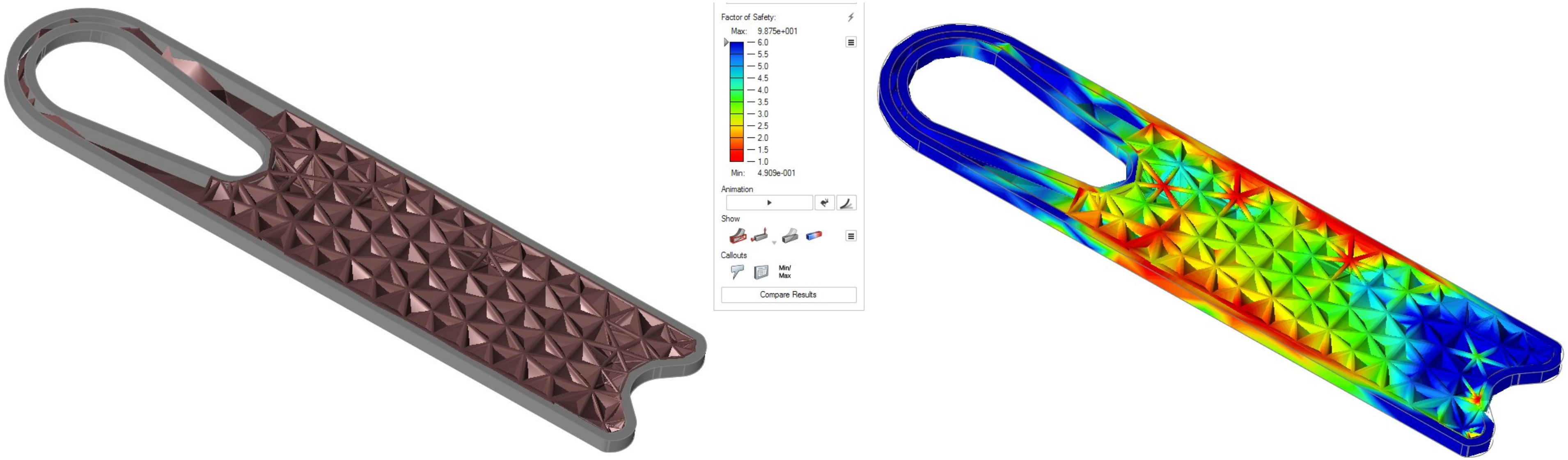


Figure 23. a) Optim 4, Lattice, Total mass – b) FEA

In this lattice optimization, we run different lattice structures and this time the results were satisfying as for the factor of safety. But as for the weight target, was not on the desired level since it resulted not as light as the other optimization that we run. Based on Figure 23**.** a) Optim 4, Lattice, Total mass – b) FEA and Figure 23**.** a) Optim 4, Lattice, Total mass – b) FEA this lattice structure is safe but didn't include all the criteria that we want. The Table 5. Different type of optimization for the platform, presents all the ideas and details of every lattice structure optimization, including the safe factor for every condition which is really important.

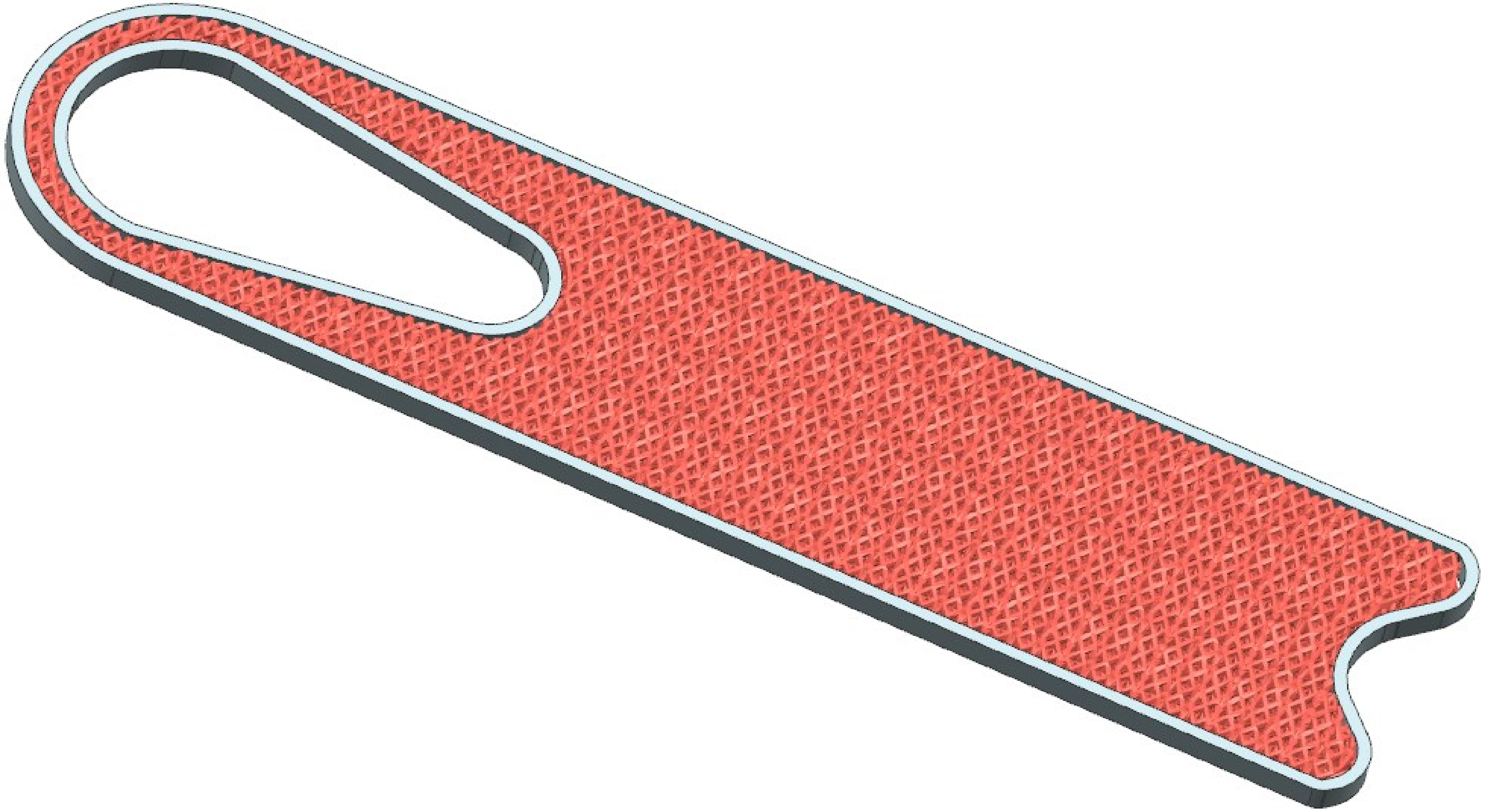


Figure 24. Lattice for platform base with NX

Based on the first lattice structure, we decided to move on with this part and to design a lattice structure based on the first one in NX and to improve it even more, as seen in Figure 24. Lattice for platform base with NX. This lattice is quadDiametral lattice and this is better than the first optimization because we increased the cell numbers and made it thicker; also the length of the structure was increased as it seems in Figure 24. Lattice for platform base with NX. The connection between the cells is now stiffer with higher density.

5.2 AM versus TM

At this point, we will analyze some of the advantages and disadvantages of AM in comparison to traditional manufacturing and plastic injection molding. Overall, we could say that AM produces less waste, smaller batches, mass customization and zero lead time.

5.2.1 Advantages/Disadvantages

In traditional manufacturing, we have so much waste, especially in metal production and it is estimated that around 90% of the original raw material ends up as waste on the factory floor. We know that the metal is milling the raw original mass of raw material to increase, not only the purchasing cost but also the waste cost. In contrast, an AM technology, like SLS, uses only the necessary raw material for the fabrication of the designing part. There are also some cases that need to work a printed object further but even that is significantly less than the milling part (Attaran, 2017).

Except for the cost issue, there is also the consideration of the environment. Removing the raw material and making it useable in traditional manufactories requires a lot of energy. The production of this energy most of the time leads to carbon dioxide emissions. There will be a significant issue in the coming years about reducing waste of energy consumption in manufactories according on Mosconi, 2015.

Small or single product has a very high initial cost with traditional manufacturing, therefore, are profitable only under massive production. The more parts the factory produces, the lower the cost becomes. This is known in the economy as the "economy of scale" (Dawson, 2006). For manufacturing, the initial cost comes directly from the tooling of machinery and when mention on plastic injection molding from mold material itself. It would not make sense for the economy of scale if we had to produce a single unit part because the cost for that will be massive according to Anderson, 2012. On the other hand, 3D printing is particularly for these kinds of manufacturing of small benches. Anderson declares that the AM economy does not change between one million or just one part, will remain the same. In addition, there is no penalty for dealing with just a few parts or making every part unique (Colosimo, Cavalli, & Grasso, 2019). Obviously, AM cannot be compared with traditional manufacturing production when we talk about the massive production of identical product design.

AM technology offers is the possibility to produce a complex structure of a design that would be very difficult and expensive to produce with traditional manufacturing due to the low demand of parts which means high cost (Lipson & Kurman, n.d.). Both Lipson and Anderson agree that 3D printing does not offer much to economies of scales and reminds that this kind of production is profitable only for companies whose strategy is to produce specific product with a defined margin of revenue.

Moreover, when a company or business is related to a unique design structure, based on customer needs, would be significantly beneficial for AM and would provide high margins to the company. A very brilliant example of a small company production is given by Barnatt, 2013. Apparently, it seems that makers of James Bond-movie Skyfall needed for some scenes three miniature Aston Martins to be blown up. These copies that were 1:3 scale of real models were produced using a 3D printer.

The production of a complex design structure has the same cost for the AM process. The cost of producing ten unique parts cost the same as making them customizing parts. The production of a decorative ornament has the same cost as printing of a plastic simple cube (Anderson, 2012). This ability of 3D printing is a great advantage for what we knew as mass customization. Nowadays there are many companies that offer 100% customization to their clients. Every single person has a different attitude and mass body structure which means full personalized design and products.

For instance, in dental industries, 3D printing products for customization are very common. This has created a market for personalized dental braces and crowns as well as prosthetics and hearing aids. Some years ago these processes were handmade production but today we are talking about personal customization based on 3D print (Lipson & Kurman, n.d.-a).

3D printing is a process with no time lean, especially for small batches where AM is more efficient and cost-effective for specific orders. There is no required time for retooling the design product as used to happen in traditional manufacturing. The new product can start printing very quickly after we have finished with the 3D model. In contrast with traditional manufacturing that we have to run 64 modeling in 3D CAM software for Gcode and adjust the right tool in the CNC machine. All of these systems might seem easy but are not because you have to take many factors into consideration. But with AM this happens easily, on demand, for every part that we have to print (Lipson & Kurman, n.d.-b). Moreover is by far more flexible and customized as we already said. This means that if the manufacture wants to make a change into the design part of the product the only thing that is needed is to change the 3D model, instead of changing the entire line production. The 3D machine is the same and the only thing that will change is the 3D model drawing (Anderson, 2012).

On the other hand, there are always some disadvantages even in 3D print technology compared to traditional manufacturing. Despite the fact that AM has some clear advantages especially for small production there are several limitations on this process as well.it seems that time, size, volume, material cost, machine cost are the most common drawbacks. Time is underlined as an equally important factor. Due to the fact that the actual production time of 3D printing is significantly longer in comparison with a mass-produced manufacturing line.

Even though we believe that 3D printing technologies will become faster eventually in the coming years, they will never reach the production speed of existing technologies such as plastic injection molding. The real fact is that there are limitations on the physical reality that is very difficult to over cover, such as friction and viscosity that are factors that would not allow 3D printing faster than plastic injection molding and mass production line overall (Barnatt, 2013).

Due to the lower production speed, would be impossible to convince manufacturers of mass-produced items to start moving in AM. For instance, if the company wants to maximize the quantity then it would require not only a huge number of 3D printers but also a large number of technicians to operate with them. That is why we assume that the cost of raw material will become cheaper and the cost of machines will become also cheaper for traditional manufacturing as well but the initial cost of 3D printing makes this technology less profitable in comparison to the mass production (Dawson, 2006).

Of course, there are many challenges of 3D printing such as the disadvantage of never being as good as current technologies in mass production. Although 3D printing is facing some challenges which at the moment are limiting the technology to move forward, solving them could lead to a more advanced and forward design structure in AM.

5.2.2 Advantages of 3D metal printing

3D metal printing has become a hot topic in the industry in the last years. A large investment has increased the intensity in R&D in this field of 3D printing. As we have already mentioned, nowadays, there are many companies that offer 3D printing parts. There are many companies which are interested to have this technique in their manufacturing process. However, this may not be the right move yet since the machine remains expensive as well as the raw material.

What are then the advantages of 3D metal printing? As we already have mentioned in the pages above, the advantages of 3D printing are closely related with the product that we plan to print, what material we are intending to use and the quantity and quality of the product. So, in a question like that, we cannot be naïve and claim that 3D printing has definitely great advantages and is better for all processes, but certainly, there are many advantages.

Of course, everything is related to the structure of the designing part, size, and the units, because, as we have mentioned already 3D metal printing is not for mass production, but for specific parts in real-time. We have analyzed the benefits and disadvantages in detail in the previous pages. Generally, what we could mention is that 3D metal printing is an expensive hobby for industries but with great potentials in the coming future.

5.3 SWOT of 3D printing

Swot analysis is something that every company should have done in order to deeply analyse what are the advantages and disadvantages of this specific area of the market. The SWOT process includes specific objective which involves many internal and external factors that are convenient or inconvenient with the process, as can be noticed from Table 6. AM SWOT analysis. As for 3D printing analysis, the swot method shows some of the external and internal factors that get involved through the process. That analysis would maybe be useful for managers that have to make decisions for the company and they are looking for details on this field (Gurung, 2017).

STRENGTHS (internal factors, positive)	WEAKNESS (internal factors, negative)
Low cost	Some machines are expensive
Available for all	Printing hours are longer i.e. production time
Positive market growth	Quality differs with the printers used
The efficiency of the manufacturing process	Learning to use of machine and software
Easy to build a custom model	Create and solve your problem yourself
High product quality	May need post-processing
	Problems printing with smaller details and
	Material selection limitation
	Requires controlled environment
OPPORTUNITIES (external factors, positive)	**THREATS (external factors, negative)**
Customization of existing design	Machine compatibility and upgrade
Active material development	Public safety
Recycled plastic garbage	Impact on environment
Printing with materials rather than plastic (metals, ceramics, wood, leather, textile)	Intellectual property rights
Smart materials (Introduction of the advanced machine)	Copyright
High speed and resolution	Patent
Multi-colour print	Trademark
Multi-material print	Software problems, hacking & cracking
Printing of micro details	Ethical issues
	Competitive industry, need to be con-stantly improving
Printing extra-large products	A threat to the traditional workforce

Table 6. AM SWOT analysis

(Gurung, 2017) Source.

5.4 Quotes results

At this point of the thesis, some quote analysis will follow the research on the prices of the metal printing process that we have received from ("3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days," n.d.). Trying to figure out the difference and how the prices fluctuated, based on the amount of ordering, especially between 1-100 parts as can be seen from Table 7. 3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days.

Checking now the differences between the prices for steel and aluminum parts that we received from ("3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days," n.d.) could be said that CNC machining and AM have many differences in costs.

This contrast takes into consideration the process that is necessary for finishing the steel part and the AM part respectively. For one neck part, the AM was 120,05% more expensive than the machining with traditional manufacturing and for 10 to 100 units the difference was 123,38% and 143,45% more expensive. Almost the same results we have for the base platform, 77,13% for one part and 81,51% for 10 parts and 134,39% for 100 parts (Appendix 2. Table 15**.** a) CNC prices for neck b) 3D metal prices for neck. and Table 16. a) CNC prices for base b) 3D metal prices for base.

This comparison can show that AM is still further expensive to metal parts instead of traditional manufacturing, however, we do not know what are the algorithms behind quotes and the costing methods. Moreover, we are assuming that the current cost analysis for 3D hubs does not take into account the storage cost plus delivery time if the customer demands to have the product faster.

	Parts number	CNC Price	3D Metal Price	Deference %
Neck part	1	271,25	596,89	120,05
	100	224,34	546,17	143,45
Platform part	1	211,47	374,58	77,13
	100	150,37	352,45	134,39

Table 7. 3D Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days

The table above presets just internet quotes from 3D hubs that are received on 12 August 2019 and it is very difficult to know the pricing algorithm as well as additional details that including the price of a company.

To double checking if the idea about the price that we received from the web quotes is indeed realistic, we started running our own cost analysis based on the factors that we believed are crucial for this thesis and are related with the cost analysis.

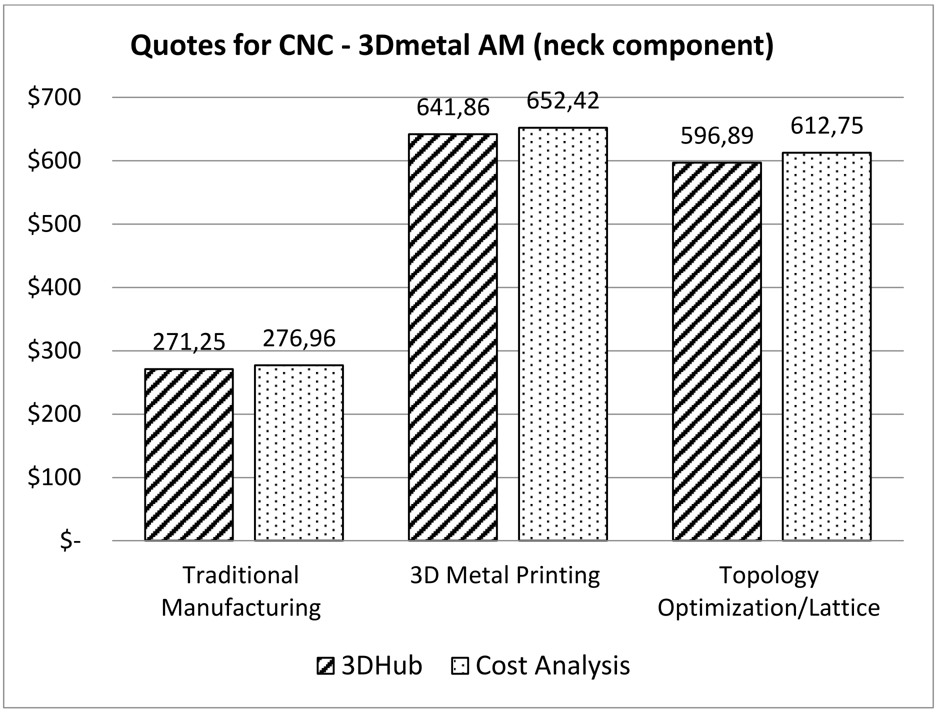


Table 8. Quotes of neck component for CNC – 3D metal (appendix 2-3)

TC of the system= well-structured cost+ Ill-structured cost	
TC of the system	$ 276,96

Table 9. TC for CNC neck part (appendix 3)

TC per assembly	EUR	P	MP+AP+CP+BP	652,42

Table 10. TC for 3D metal printing neck part (appendix 3)

TC per assembly	EUR	P	MP+AP+CP+BP	612,75

Table 11. TC for 3D metal printing Lattice (appendix 3)

Table 8. Quotes of neck component for CNC – 3D metal (appendix 2-3), presents the initial price of the neck part which was 271,25$ based on Picture 1. CNC price for neck part. This price is almost the same value as the price that we calculated according to our analysis 276,96$, Table 9. TC for CNC neck part (appendix 3).

Then we have the price about 3D print from 3DHub 641,86$, Picture 3. 3D metal price for neck part, and 652,42$, based on Table 10. TC for 3D metal printing neck part (appendix 3), from the analysis. Both prices are very similar to one another. Finally, we have the 596,89$ Picture 4. 3D metal price for neck part after optimization with lattice, from the 3DHub and 612,75$ from analysis accordingly Table 11. TC for 3D metal printing Lattice (appendix 3).

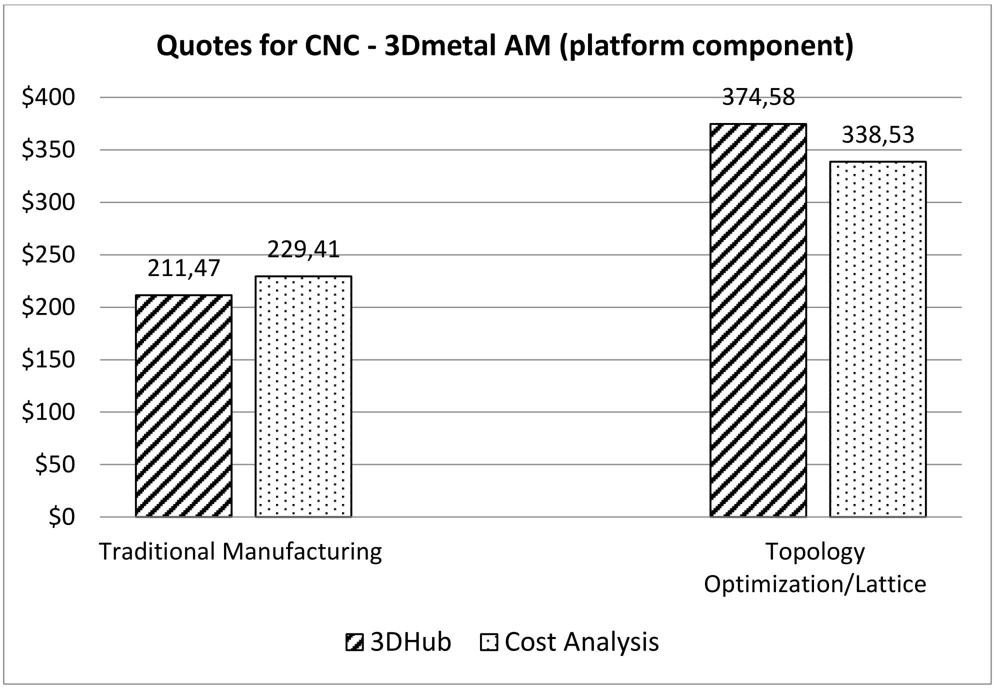


Table 12. Quotes of platform component for CNC – 3D metal (appendix 2-4)

TC of the system= well-structured cost+ Ill-structured cost	
TC of the system	$ 229,41

Table 13. TC for CNC base platform part (appendix 4)

TC per assembly	EUR	P	MP+AP+CP+BP	338,53

Table 14. TC for 3D metal printing base platform Lattice (appendix 4)

Same idea follows the second part which is the platform base of the scooter. First, we have the traditional manufacturing which costs 211,47$ according to Picture 2. CNC price for platform part, based on 3DHuB and 229,41$ from manufacturing analysis, Table 13. TC for CNC base platform part (appendix 4), followed by TO lattice 374,58$ from Picture 5. 3D metal price for platform part, 3DHub follow by 338,53$ from 3D printing Lattice for the platform of the scooter based on analysis of Table 14. TC for 3D metal printing base platform Lattice (appendix 4). Once more the prices are almost similar, which make our evidences about comparative advantages of AM stronger. This means that AM with lattice structure is not only better in 3D metal process but also cheaper in product cost if we compare with TM, under certain circumstances.

6 CONCLUSIONS

This thesis evaluates the state of the TO method and carefully present all the processes that collaborate to improve the designing parts. To put it differently, it presents the work-flow to achieve TO for AM.

AM is known as the technology that allows engineers to build easily complex geometry. Based on the form to optimized advanced structures that would not have been possible to construct through traditional manufacturing. The current study is also attempting to explain that efficient work flow requires the utilization of more than just one single soft-ware to achieve the goal.

Through the analysis was presented that most of the software used SIMP algorithm for TO, however, is engineers decision to choose the density threshold for the parts that will be optimized through the process. CAD program systems come with constraints that suit well for the editing manufacturing process, but when AM is involved then optimization constrains cannot be supported.

E-scooter parts were edited for design in NX Unigraphics and Altair Inspire for TO analysis. Altair Inspire improved the mass of both parts through FEA analysis and then reassembled all the parts back through NX in the same scooter to display the optimization that was achieved. Continuing a little further, was intended to check the cost production of each part and compare it with the new method of 3D metal printer. That was very crucial factor for our research since every single company has to take into consideration the cost pro-duction and choose the best solution through different processes and materials. Investi-gating the two design parts there are some advantages and disadvantages of AM through all the processes.

The above explanation provides answer to the first question of the thesis: What are the advantages of applying TO on metal parts? The results in our case show that TO could reduce material weight and increase stiffness while saving on material while reducing the cost for both parts.

Different boundaries and densities through different loads of applied conditions affect the optimization of our results and structures of both parts. This argument also answers the second question of our study: what are the barriers of implementation of TO on AM?

The present workflow of topology optimization to a component does not allow the determination of the mesh resolution before the analysis. Therefore, the complete usage of the advantages of AM that allows the production of complex geometry is limited.

Overall, it should be mentioned that the optimization process could be applied many times, even for a single part and every time designer engineers should take into consideration only one factor (e.g. mass, load, volume, stiffness). The results should always be analysed and balance should be found between the factors that aimed to be improved and design parameters.

Part of FEA should include lattice optimization since this structure offers the opportunity to achieve better results in maximizing stiffness through the lower mass output. Optimizing the topology with lattice structure reduces the appearance of stress, increases stiffness and minimizing the mass of the total part.

Prototyping the parts that have been designed, revealed some areas that should enhance the improvement of the workflow of TO for AM and especially in 3D metal printing. The benefits of 3D metal printing are indeed very important for small manufacturing, since a high level of customization could be achieved while reduces the cost of every optimized part. This also answers to the third question of this thesis: what are the pros and cons of producing metal 3D printing?

The advantage of the design process with an optimum structure is far better than a purely manual design process. Through the visualization results of TO and FEA process, engineers are more conscious for most crucial loads of the structure and can decide easily which are the required constraints for reducing the mass of the part and make it more easily for AM plus profitable for the company. As AM is continuously involved in the industry manufacture, similarly, TO will also be involved in supporting the process of AM.

6.1 Suggestions for further research

Further research towards this field should include direct collaboration between the TO algorithm and AM. One advanced idea would be to include AM in the TO algorithm and all under the CAD system software.

This would not be easy since there are many constraints that should be taken into consideration in both methods. For instance, minimization of distortion on the metal part during AM. Yet, until these difficulties are left behind, TO will still remain a powerful tool that can be used for AM. Commercial software do not support maximum size constrains that can optimize results for thinner parts, which will reduce distortion for 3D metal printing. In the long term will be necessary to understand how 3D geometry changes are connected with the optimization process.

As these two technologies are broadly used, hopefully in coming future the workflow of TO for AM will simplify the way that design structural components will become a fully automated process.

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Appendices

Appendix 1. Pictures of e-scooter

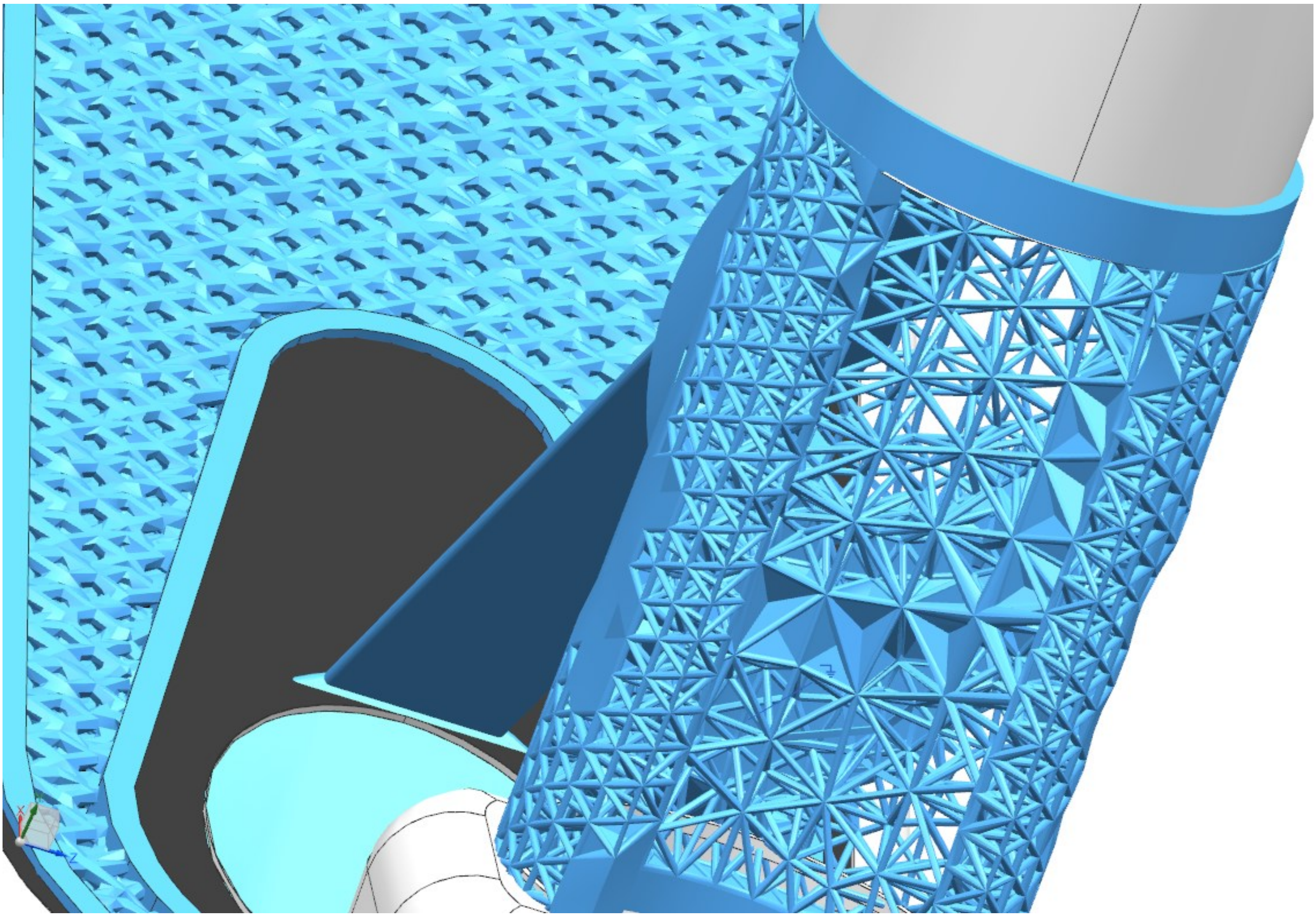

Figure 25. View 1 neck-platform base

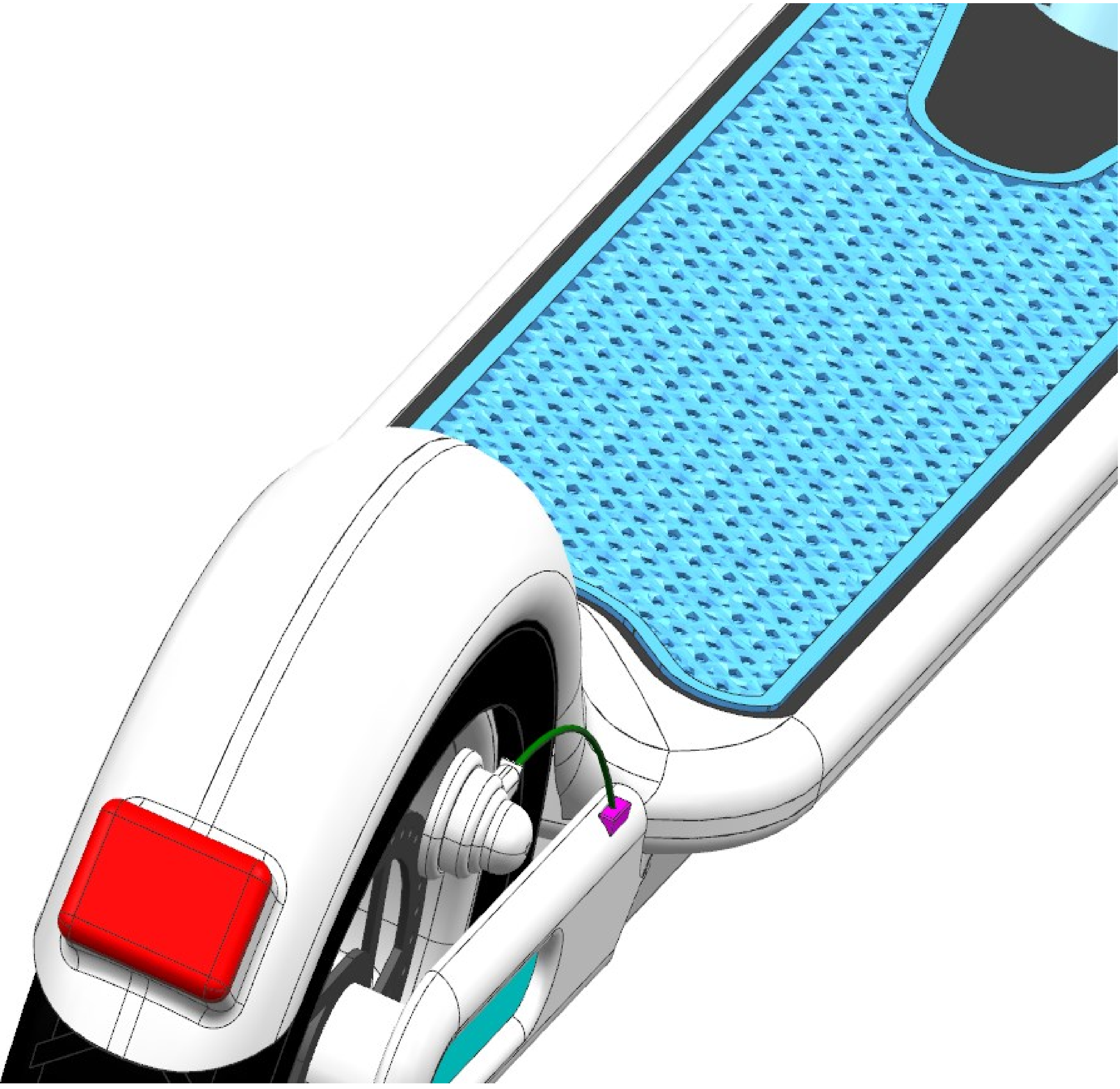

Figure 26. View 2 base

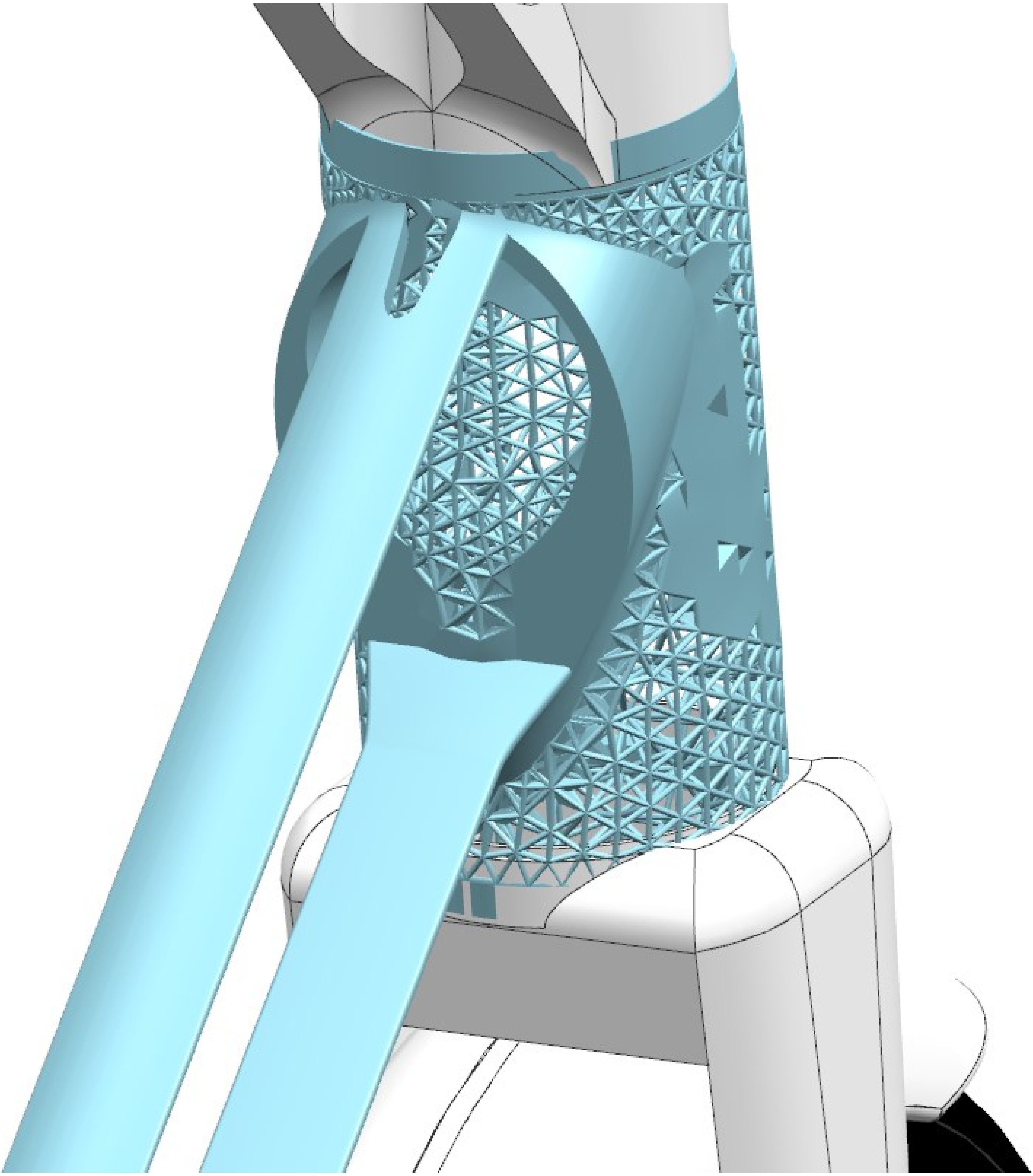

Figure 27. View 3 neck

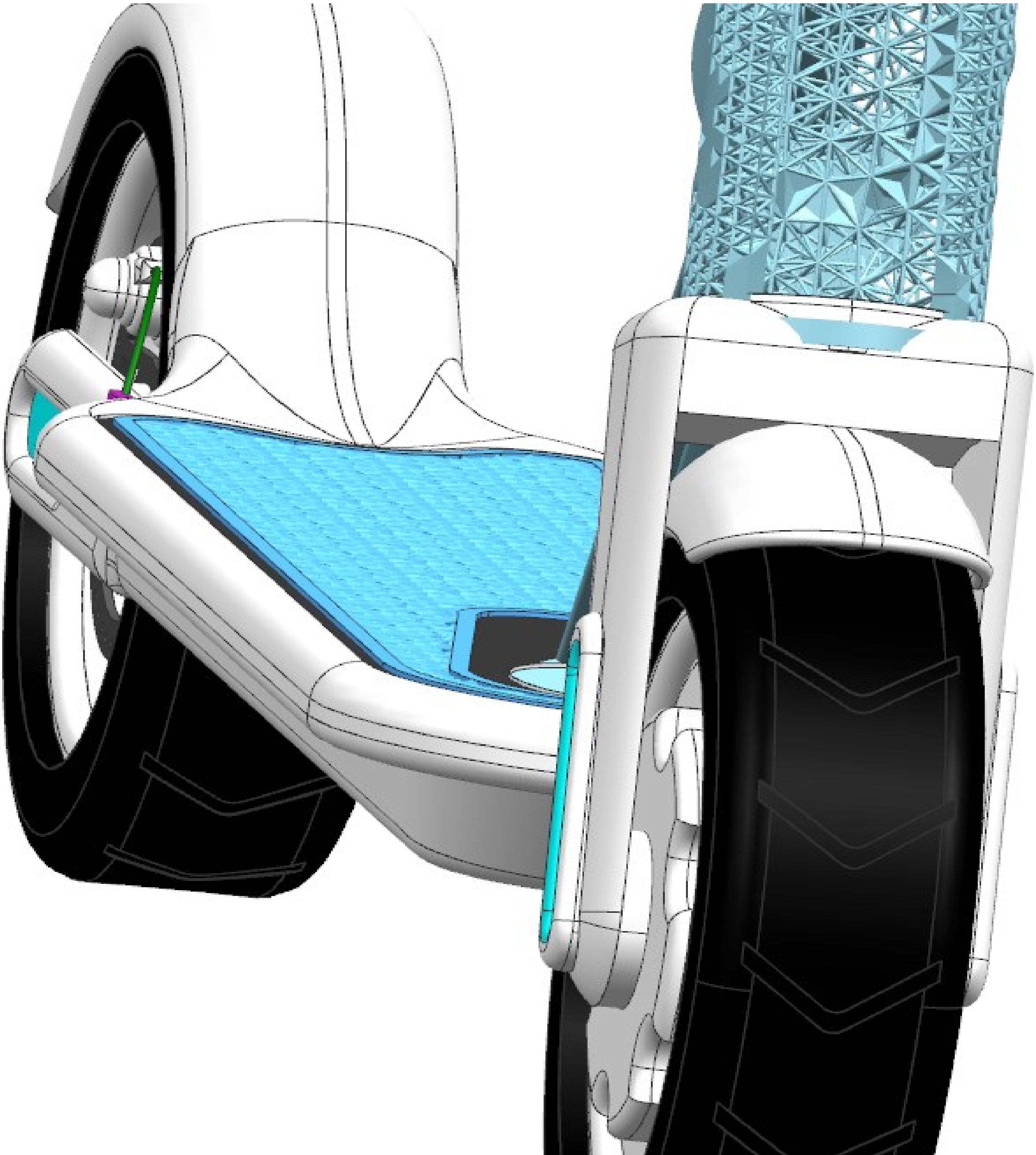

Figure 28. View 4 neck-platform base

Appendix 2. Wed quotes CNC/3Dmetal printing

Description		Specifications	Details	Qty	Price
	**1.0.stp** 30.0 × 111.9 × 1 26.7 mm	CNC machining Aluminum 6082 Smoothed (Ra 1.6μm, 63μin)	• No threaded holes ✓ Custom tolerances ✓ Description	1	$226.25 $226.25 / PART

https://www.3dhubs.com/manufacture/order/7045032c-37b2-4855-94b8-b0420b1ae70b/quote/788c7644-ab1f-4478-9395-9339db0178db 1/2

7/22/2019 Get instant CNC machining & injection molding quotes - 3D Hubs

3D HUBS

QUOTE OVERVIEW

Subtotal	$271.25
Total	US$271.25

Picture 1. CNC price for neck part

Parts & Pricing

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Description		Specifications	Details	Qty	Price
	**11.stp** 5.0 × 52.6 × 22 5.5 mm	CNC machining Aluminum 6082 Smoothed (Ra 1.6μm, 63μin)	• No threaded holes ✓ Custom tolerances ✓ Description	1	$166.47 $166.47 / PART

https://www.3dhubs.com/manufacture/order/cecc56ae-b41b-4ddd-9a45-08a76adb741d/quote/09f640bf-75bc-4a85-b682-7d1ba3f6bb37 1/2

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3D HUBS

QUOTE OVERVIEW

Subtotal	$211.47

Picture 2. CNC price for platform part

Description			Qty	Unit Price	Price
1	 fullneck.stp 126.7x30.0x111.9 mm	3D printing / DMLS/SLM / Aluminum / Default (Material color) / 50μm	1	$641.86	$641.86
Shipping					$0.00
			Subtotal		$641.86
			GST Export supply		$0.00
			Total		USD $641.86

Signature:

nikos koletsis

By signing or submitting a payment, customer agrees to the specifications of the quote (#2HRGMWPR) and the attached Terms & Conditions.

Picture 3. 3D metal price for neck part

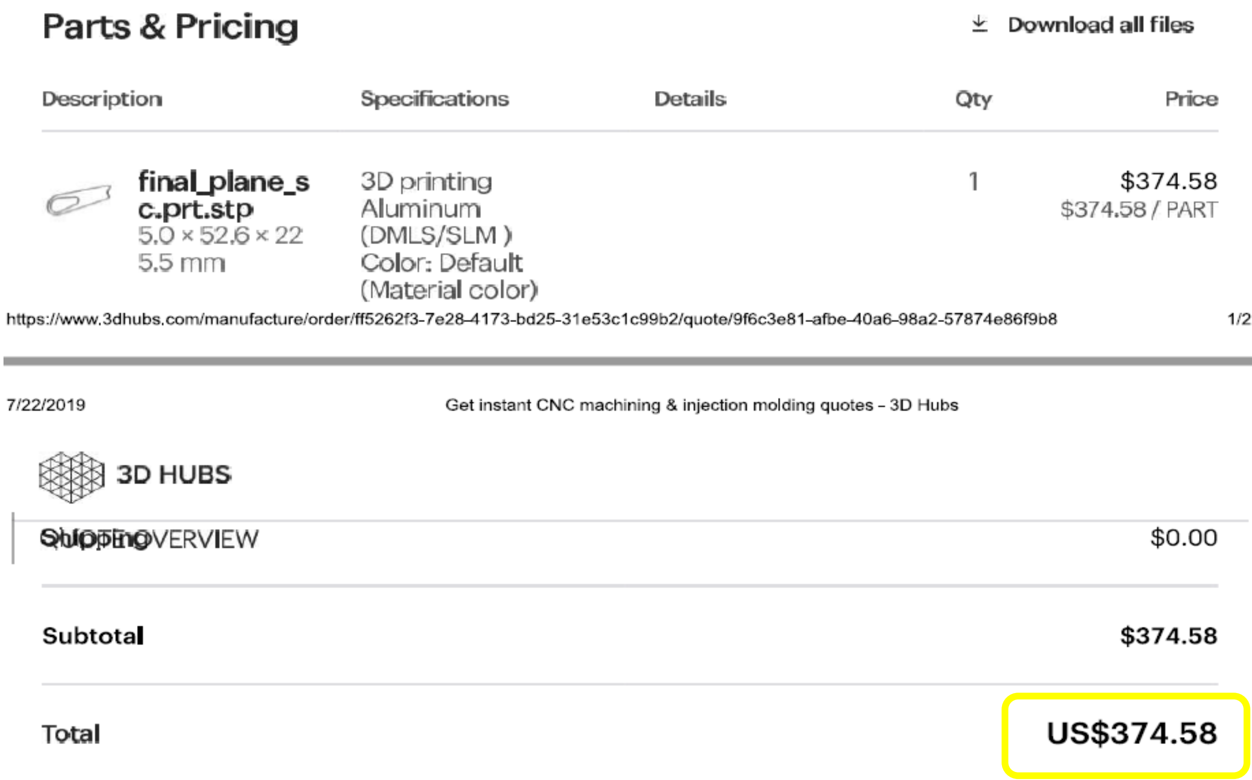
Description			Qty	Unit Price	Price
1	 1.2.2.final_neck.stl 136.6x31.9x111.2 mm	3D printing / DMLS/SLM / Aluminum / Default (Material color) / 50μm	1	$596.89	$596.89
Shipping					$0.00
			Subtotal		$596.89
			GST Export supply		$0.00
			Total		USD $596.89

Signature:

nikos koletsis

By signing or submitting a payment, customer agrees to the specifications of the quote (#2JV49JL2) and the attached Terms & Conditions.

Picture 4. 3D metal price for neck part after optimization



Parts & Pricing

Download all files

Description	Specifications	Details	Qty	Price
final_plane_sc.prt.stp 5.0 × 52.6 × 22 5.5 mm	3D printing Aluminum (DMLS/SLM) Color: Default (Material color)		1	$374.58 $374.58 / PART

https://www.3dhubs.com/manufacture/order/ff5262f3-7e28-4173-bd25-31e53c1c99b2/quote/9f6c3e81-afbe-40a6-98a2-57874e86f9b8 1/2

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3D HUBS

QUOTE OVERVIEW

Shipping $0.00

Subtotal **$374.58**

Total **US$374.58**

Picture 5. 3D metal price for platform part

Qty	Unite Price	Total Price
1	271,25	271,3
2	269,46	538,9
5	268,74	1343,7
10	264,23	2642,3
25	263,11	6577,8
50	254,45	12722,5
100	224,34	22434,0

Qty	Unite Price	Total Price
1	596,89	596,9
2	595,74	1191,5
5	594,43	2972,2
10	590,25	5902,5
25	583,87	14596,8
50	575,41	28770,5
100	546,17	54617,0

Table 15. a) CNC prices for neck b) 3D metal prices for neck

(12/08/19) 3DHuB

Qty	Unite Price	Total Price
1	211,47	211,47
2	210,15	420,30
5	208,25	1041,25
10	203,45	2034,50
25	194,25	4856,25
50	175,13	8756,50
100	150,37	15037,00

Qty	Unite Price	Total Price
1	374,85	374,9
2	373,45	746,9
5	371,23	1856,2
10	369,28	3692,8
25	365,36	9134,0
50	361,56	18078,0
100	352,45	35245,0

Table 16. a) CNC prices for base b) 3D metal prices for base

(12/08/19) 3DHuB

Appendix 3. Cost analysis CNC/AM neck part

Labour cost=(direct labour cost)+(Indirect labour cost)+(fringes)

		Item	Set Up (# of Min)	Run (# of Min)	Cost/Hour	Total Cost
Labour cost	Direct labout	1	10	35,00	$ 20,00	$ 38,89
		100	10	300,00	$ 18,00	$ 270,00
		1000	10	2 700,00	$ 15,00	$ 1 687,50
		10000	10	20 000,00	$ 12,00	$ 8 000,00
		100000	10	180 000,00	$ 9,00	$ 40 500,00
		tooling	10	10 000,00	$ 2,00	$ 111,11
		fixing material	10	10,00	$ 10,00	$ 2,78
		handeling	10	10,00	$ 5,00	$ 0,69
		inspection declines	0	0,00	$ -	$ -
	Indirect labour	1	0	0,00	$ -	$ -
		2	0	0,00	$ -	$ -
		3	0	0,00	$ -	$ -
		4	0	0,00	$ -	$ -
		5	0	0,00	$ -	$ -
	firenges					$ -
	Sum					$ 38,89

Material cost=(Direct material cost)+(Indirect material cost)+(ordering cost)

		Item	Unit cost for direct material	amout of direct material		Total Cost
Material Cost	Direct material cost	1	$ 0,88	3,5		$ 3,06
		2	$ -			$ -
		3	$ -			$ -
		4	$ -			$ -
		5	$ -			$ -
		6	$ -			$ -
		7	$ -			$ -
		8	$ -			$ -
		9	$ -			$ -
	Indirect material cost					$ -
	Total material ordering cost					$ -
	Sum					$ 3,06

Machine cost=Utility cost+maintanace cost+repair cost+insurance cost+property tax

Machine Cost	item	Machine	Utility cost of Machine per time	Total machine time	Maintanace cost	Time of maintanace	Repair cost	Total repair time	Insurance permimum rate	initial investment of machine	Property tax rate	Total Cost
	1		$ 10,00	0,2	$ 10,00	0,3	$ 50,00	0,3	10	$ 1,00	0,50 %	$ 30,01
	2		$ -		$ -		$ -			$ -	0,00 %	$ -
	3		$ -		$ -		$ -			$ -	0,00 %	$ -
	4		$ -		$ -		$ -			$ -	0,00 %	$ -
	5		$ -		$ -		$ -			$ -	0,00 %	$ -
	6		$ -		$ -		$ -			$ -	0,00 %	$ -
	7		$ -		$ -		$ -			$ -	0,00 %	$ -
	Sum											$ 30,01

Tooling cost= unit cost per tool*(total numbers of tools)

Tools cost	Tool name	Unit cost of tool type	Number of worn tool type	Number of broken	Cost
		$ 25,00	1		$ 25,00
		$ -			$ -
		$ -			$ -
		$ -			$ -
		$ -			$ -
		$ -			$ -
	Sum				$ 25,00

Floor space cost	Space cost per square	Manufacturing floor space	total cost
	$ -		$ 30,00

Computer software cost	software namer	membership fee for sotware	number of sofware types	total cost
		$10 000,00	1	$ 50,00
		$ -		$ -
		$ -		$ -
		$ -		$ -
	sum			$ 50,00

Machine depreciation cost	machine	depreciation cost
		$ 50,00
		$ -
		$ -
		$ -
		$ -
	sum	$ 50,00

well-structured cost=labour+material+machine+tool+floor space+computer software+machine depreciation

Total Cost of well-strictured cost	226,96

Total set up cost=set up cost for machine*set up time

Set up cost	Machine	set-up Cost	Total Set-Up time	Total cost
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
	sum			$ -

Waiting cost=Oppourtunity cost*total waiting time for parts produced

Waiting cost/ WIP cost	Number of process part visits	Cummulicattive waiting time	Oppourtunity cost per unit time	Total cost
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
	sum			$ -

Flexibility Cost

Idle Cost=Idle cost per unit time*total Idle time for equipment

Idle Cost	Machine	Idle cost /unit time	Total Idle Time	Cost
		$ 100,00	0,5	$ 50,00
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
	Sum			$ 50,00

Inventrory carring cost = Warehouse spacehouse cost+ Holding cost+ shortage cost

Inventory carring cost		item	cost of carrying raw material	Initial inventory of raw material	Amount of raw material obtained from supplier	Amount of raw material dedicated to production	Cost of carrying finnished products	Initial inventory of finnished product	Amount of finnished products on process	Demand rate of part	shortage cost of raw material	shortage cost of finnished produts	total cost
	Raw material		$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
	Finished products						$ -					$ -	$ -
							$ -					$ -	$ -
							$ -					$ -	$ -
							$ -					$ -	$ -
							$ -					$ -	$ -
	Warehouse space cost												$ -
	Total cost												$ -

Total cost of flexibility= set-up cost+waiting cost+Idle cost+inventory carrying cost

Total cost of flexibility	$ 50,00

	Quality Cost	Prevention	$ -
		Failure	$ -
		sum	$ -

Ill-Structured cos= total cost of flexibility + quality cost	
Total cost of ill-Structured cost	$ 50,00

'otal cost of the system= well-structured cost+ Ill-structured cos	
Total cost of the system	$ 276,96

Evaluation model of part cost for selective laser sintering				
Number of parts produced per job		N		1
Material cost per kg	EUR/kg	M		145
Part volume	(mm³)	V		0,06
Density of the sintered material	g/mm³)	D		2,68
Mass of material per part	kg	U	D*1.1 V	0,25
Material cost per part	EUR	MP	U*M	36,25
Machine operator cost per hour	EUR/h	O		20
Set-up time per build	h	A		1,2
Pre-processing cost per part	EUR	AP	O×A/N	24
Depreciation cost per year	EUR/year	C		
Hours per year	(h/year)	H		5000
Machine cost per hour	EUR/h	CH		35
Machine Cost	EUR	H*CH		175000
Build time	(h	T		54
Machine cost per build	EUR	CB	CH×T	1890
Processing cost per part	EUR	CP	CB/N	472,5
Machine operator cost per hour	EUR/h	O		20
Post-processing time per build	h	B		3
Heat treatment cost per build	EUR	HT		20
Post-processing cost per part	EUR	BP	(O×B+HT)/N	80
Total cost per assembly	EUR	P	MP+AP+CP+BP	612,75

Appendix 4. Cost analysis CNC/AM platform part

Labour cost=(direct labour cost)+(Indirect labour cost)+(fringes)						
Labour cost		Item	Set Up (# of Min)	Run (# of Min)	Cost/Hour	Total Cost
	Direct labout	1	10	2,00	$ 20,00	$ 2,22
		100	10	300,00	$ 18,00	$ 270,00
		1000	10	2 700,00	$ 15,00	$ 1 687,50
		10000	10	20 000,00	$ 12,00	$ 8 000,00
		100000	10	180 000,00	$ 9,00	$ 40 500,00
		tooling	10	10 000,00	$ 2,00	$ 111,11
		fixing material	10	10,00	$ 10,00	$ 2,78
		handeling	10	10,00	$ 5,00	$ 0,69
		inspection declines	0	0,00	$ -	$ -
	Indirect labour	1	0	0,00	$ -	$ -
		2	0	0,00	$ -	$ -
		3	0	0,00	$ -	$ -
		4	0	0,00	$ -	$ -
		5	0	0,00	$ -	$ -
	firenges					$ -
	Sum					$ 2,22

Material cost=(Direct material cost)+(Indirect material cost)+(ordering cost)						
Material Cost		Item	Unit cost for direct material	amout of direct material		Total Cost
	Direct material cost	1	$ 0,88	2,5		$ 2,19
		2	$ -			$ -
		3	$ -			$ -
		4	$ -			$ -
		5	$ -			$ -
		6	$ -			$ -
		7	$ -			$ -
		8	$ -			$ -
		9	$ -			$ -
	Indirect material cost					$ -
	Total material ordering cost					$ -
	Sum					$ 2,19

Machine cost=Utility cost+maintanace cost+repair cost+insurance cost+property tax												
Machine Cost	item	Machine	Utility cost of Machine per time	Total machine time	Maintanace cost	Time of maintanace	Repair cost	Total repair time	Insurance permimum rate	initial investment of machine	Property tax rate	Total Cost
	1		$ 10,00	0,2	$ 10,00	0,3	$ 50,00	0,3	10	$ 1,00	0,50 %	$ 30,01
	2		$ -		$ -		$ -			$ -	0,00 %	$ -
	3		$ -		$ -		$ -			$ -	0,00 %	$ -
	4		$ -		$ -		$ -			$ -	0,00 %	$ -
	5		$ -		$ -		$ -			$ -	0,00 %	$ -
	6		$ -		$ -		$ -			$ -	0,00 %	$ -
	7		$ -		$ -		$ -			$ -	0,00 %	$ -
	Sum											$ 30,01

Tooling cost= unit cost per tool*(total numbers of tools)					
Tools cost	Tool name	Unit cost of tool type	Number of worn tool type	Number of broken	Cost
		$ 15,00	1		$ 15,00
		$ -			$ -
		$ -			$ -
		$ -			$ -
		$ -			$ -
		$ -			$ -
	Sum				$ 15,00

Floor space cost	Space cost per square	Manufacturing floor space	total cost
	$ -		$ 30,00

Computer software cost	software namer	membership fee for sotware	number of sofware types	total cost
		$10 000,00	1	$ 50,00
		$ -		$ -
		$ -		$ -
		$ -		$ -
	sum			$ 50,00

Machine depreciation cost	machine	depreciation cost
		$ 50,00
		$ -
		$ -
		$ -
		$ -
	sum	$ 50,00

well-structured cost=labour+material+machine+tool+floor space+computer software+machine depreciation

Total Cost of well-strictured cost	179,41

Total set up cost=set up cost for machine*set up time

Set up cost	Machine	set-up Cost	Total Set-Up time	Total cost
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
	sum			$ -

Waiting cost=Oppourtunity cost*total waiting time for parts produced

Waiting cost/ WIP cost	Number of process part visits	Cummulicattive waiting time	Oppourtunity cost per unit time	Total cost
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
			$ -	$ -
	sum			$ -

Ill-Structured cost

Flexibility Cost

Idle Cost=Idle cost per unit time*total Idle time for equipment

Idle Cost	Machine	Idle cost /unit time	Total Idle Time	Cost
		$ 100,00	0,5	$ 50,00
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
		$ -		$ -
	Sum			$ 50,00

Inventrory carring cost = Warehouse spacehouse cost+ Holding cost+ shortage cost

Inventory carring cost		item	cost of carrying raw material	Initial inventory of raw material	Amount of raw material obtained from supplier	Amount of raw material dedicated to production	Cost of carrying finnished products	Initial inventory of finnished product	Amount of finnished products on process	Demand rate of part	shortage cost of raw material	shortage cost of finnished produts	total cost
	Raw material		$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
			$ -								$ -		$ -
	Finished products						$ -					$ -	$ -
							$ -					$ -	$ -
							$ -					$ -	$ -
							$ -					$ -	$ -
							$ -					$ -	$ -
	Warehouse space cost												$ -
	Total cost												$ -

Total cost of flexibility= set-up cost+waiting cost+Idle cost+inventory carrying cost

Total cost of flexibility	$ 50,00

	Quality Cost	Prevention	$ -
		Failure	$ -
		sum	$ -

Ill-Structured cos= total cost of flexibility + quality cost

Total cost of ill-Structured cost	$ 50,00

otal cost of the system= well-structured cost+ Ill-structured cos

Total cost of the system	$ 229,41

Evaluation model of part cost for selective laser sintering				
Number of parts produced per job		N		4
Material cost per kg	EUR/kg	M		85
Part volume	(mm³)	V		0,06
Density of the sintered material	g/mm³)	D		2,68
Mass of material per part	kg	U	D*1.1 V	0,17688
Material cost per part	EUR	MP	U*M	15,0348
Machine operator cost per hour	EUR/h	O		20
Set-up time per build	h	A		1,2
Pre-processing cost per part	EUR	AP	OxA/N	6
Depreciation cost per year	EUR/year	C		
Hours per year	(h/year)	H		5000
Machine cost per hour	EUR/h	CH		35
Machine Cost	EUR	H*CH		175000
Build time	(h	T		34
Machine cost per build	EUR	CB	CHxT	1190
Processing cost per part	EUR	CP	CB/N	297,5
Machine operator cost per hour	EUR/h	O		20
Post-processing time per build	h	B		3
Heat treatment cost per build	EUR	HT		20
Post-processing cost per part	EUR	BP	(OxB+HT)/N	20
Total cost per assembly	EUR	P	MP+AP+CP+BP	338,5348