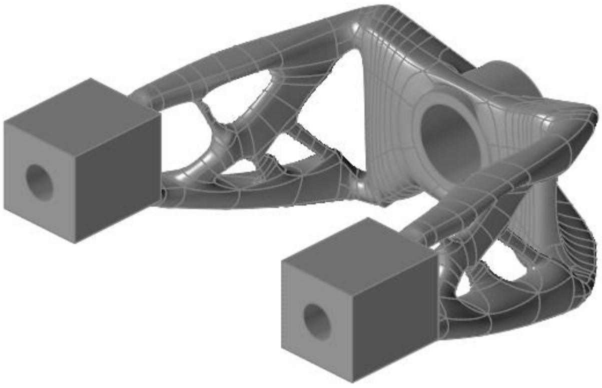
POLYTECHNIC OF TURIN

Department of Mechanical and Aerospace Engineering
Master course of Automotive Engineering

Master's Thesis

DESIGN FOR ADDITIVIE MANUFACTRUING OF CUSTOMIZED GRIPPERS FOR PART HANDLING



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Abstract

The recent application of Topology Optimization (TO) methods fulfills how to customize the industrial part respects to Mechanical rules, strength and endurance requirements in order to achieve the best structural performance and maximum geometric resolution for manufacturability by Additive Manufacturing (AM).

(AM) processes enable the production of functional parts with complex geometries, multi-materials, as well as individualized mass production. It comprises a family of different technologies that build up parts by adding materials layer by layer at a time based on a digital 3D solid model, allows design optimization and produces customized parts on-demand with almost similar material properties with the conventional manufactured parts.

In this thesis after reviewing the different technologies and materials used in metal AM and according to DMLS and SLM applications, HAND GRIPPER OF ROBOT is explained. Based on that development a sustainability analysis is performed consisting of the analysis of the environmental impacts, the production cost analysis . Nevertheless, what has been derived from the analysis is that despite the lower environmental impact compared with the conventional method of forming of metals, AM is costly for the production of a small number of industrial products and its impact needs further investigation. In fact, the cost depends on the complexity, production volume, the batch size as well as the high price of the material powders and the building rates of the machines. In the future, with more developed machines and cheaper material input the cost of metal AM is going to drop dramatically. In spite of all the progress, the application of metal AM is still not widespread.

Keywords: Topology Optimization, Additive Manufacturing, Convectional manufacturing, Direct Metal Laser Sintering, Cost Analysis, Sustainability Analysis.

Preface

This master's thesis is the final part of the master's program of Automotive Engineering. It is also my last efforts as students at Polytechnic of Turin. The work was carried out from July to December 2018.

Acknowledgements

I would like to thank everyone who has helped and contributed to this Master's thesis work. In particular, I would like to thank my supervisor at Additive Manufacturing by Topology Optimization, Prof. Paolo Minetola, for invaluable help and guidance during the work. The feedback and knowhow has helped me to continue my work in the right direction. In addition, I am also very thankful to the companies of CA.ST. S.a.S and INGENIA S.r.L to provided me the CAD files and all information about Material Price and Building Price of product.

Finally, I want to address thanks to Altair Engineering who has generously provided software licenses and given very helpful and appreciated courses in how to use the software (Hypermesh, Solidthinking Inspire).

Turin December 2018

Farschad Heydari Rouhi

Dedication

I sincerely dedicate this thesis to my parents for their support.

Abbreviations

3DP	Three Dimensional Printing
AM	Additive Manufacturing
CAD	Computer Aided Design
CM	Convectional Manufacturing
DMLS	Direct Metal Laser Sintering
EI	Environmental Impact
FE	Finite Element
FDM	Fused Deposition Modeling
LC	Life Cycle
LCA	Life Cycle Assessment
SLM	Selective Laser Melting
STL	STereoLithography (file format)
TO	Topology Optimization

List of Figures

List of Charts

List of Graph

List of Tables

Contents

1. Introduction

1.1. Background

In the industry, rapid prototyping (RP) is a term that describes a process that rapidly creates a system or a part representation, i.e. creating something fast that will result in a prototype. Additive manufacturing, AM, is a formalized term and was previously denoted rapid prototyping. Additive manufacturing works by creating the part from eg. CAD data adding the material in layers, contrary to the more traditional procedure where material is subtracted. This can be used to shorten the product development times and cost and can be manufactured using both plastic and a variety of metals (Gibson et al., 2015). [1]

Structural optimization focus on making an assemblage of materials sustain loads in the "best" way. The objective could for an example be maximizing the stiffness of a structure. A structural optimization problem consists of an objective function that classifies designs, design variables that describe the design and state variables that represent the response of a structure. There are different types of structural optimization problems and these are sizing optimization, shape optimization and topology optimization. Topology optimization optimizes the material layout in the design space allowing design variables to take the value zero (Christensen et al., 2008) [2]. The method is today used in the industry early in the product development to allow designers to investigate structurally efficient concepts it is integrated in some of the leading FEM softwares today such as ALTAIR (SOLIDTHINKING 2018) and AUTODESK (FUSION 360).

The ability of additive manufacturing to manufacture very complex topology, which often is the outcome from topology optimization, makes topology optimization a good design tool for additive manufacturing. In order to ensure manufacturability using additive manufacturing, support material is often necessary to overcome certain constraints such as overhang, minimum feature size, anisotropy to prevent collapsing during fabrication (Clausen, 2016).[3]

1.2. Aim

The aim of this thesis is to optimize the mechanical structure of HAND GRIPPER of ROBOT and to define the capabilities and opportunities of Metal AM. Therefore to investigate how AM fulfills and satisfy the Mass production in terms of sustainability, societal and environmental impact respect to product development.

1.3. Method

The thesis work starts with learning software used for Finite Element (FE) modelling. Subsequently, topology optimization (TO) tutorials are studied. These are followed by a literature study to increase the knowledge of how topology and shape optimization is used nowadays. Thereafter, Additive Manufacturing (AM) methods are studied which Metallic AM (DMLS – SLM) is applied for this thesis. Finally sustainability and societal and environmental impact analysis.

The commercial software used for pre-process FE modeling, both the linear and non-linear static finite element analysis, structural and Technology Optimization (TO) are solved using ALTAIR (SOLIDTHINKING INSPIRE) and AUTODESK (FUSION 360).Additive Manufacturing (AM) is used AUTODESK (NEFFABB PREMIUM 2019)

For AM in particular, there is little purpose in converting the topology result to CAD, although modifications to the geometry are easier to carry out in CAD software and it makes constructing assemblies with other components more straightforward. A modified workflow for topology optimization for AM is outlined in Figure 1 where the main differences compared with a traditional workflow are in the third stage. The main actions that need to be carried out following the optimization are to interpret/smoothen/modify the optimized topology and to reanalyze the performance with a more accurate FE analysis. It is common to generate a surface mesh from the thresholded isosurfaced topology, commonly a STereoLithography (STL) file. STL files are used as the standard geometry file format for AM and so if further tasks on the optimized topology can be carried out at the STL level it avoids the cumbersome and very difficult conversion to a CAD format. There are several software tools available specifically for handling STL files including MATERIALISE MAGICS, NETFABB STUDIO, and MARCAM AUTOFAB. These tools have other functionality, but of use for this task are the smoothening and remeshing functions.

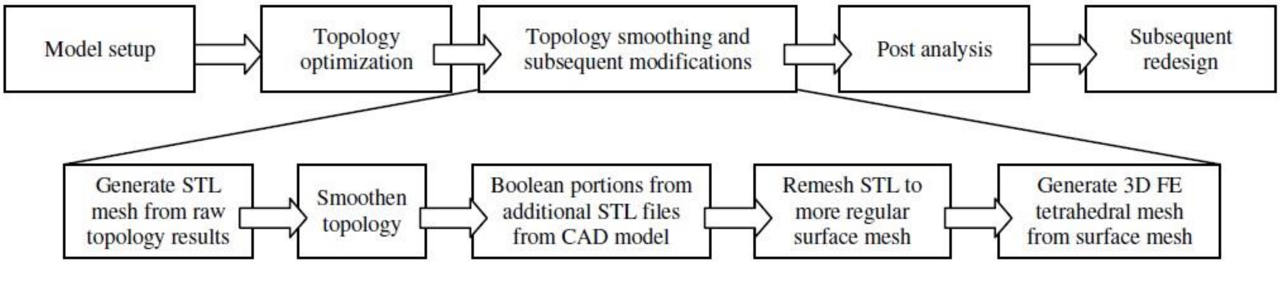


Figure 1: Workflow for topology optimization for AM, with sub-flowchart for the geometry

2. Additive Manufacturing (AM)

2.1. Rapid Prototyping (RP) to Additive Manufacturing (AM)

In the industry, RP or Direct Digital Manufacturing (DDM) is a term that describes a process that rapidly creates a system or a part representation, i.e. creating something fast that will result in a prototype. As of today, many parts manufactured using the rapid prototyping techniques are directly created and used and we should no longer label these as prototypes. Instead AM works by creating the parts from three-dimensional Computer-Aided Design, 3D CAD, adding the material in layers, contrary to the more traditional way where material is subtracted instead such as turning or milling. Each layer is a thin cross-section of the part from the original CAD data and the thinner the layer is the closer the result will be to the original. This can be used to shorten the product development times and cost and can be made from both plastic and a variety of metals (Gibson et al., 2015).

2.2. AM Technologies

The first method to create an object from CAD data was developed in the 1980s. As mentioned before it was mainly used to create prototypes, but as the technology has advanced, it is now used to create small series of products. The evolution of AM technologies leads to new solutions and methods, which also broadens the application areas (Gibson et al., 2015). The AM technologies can be divided into laser technologies, FLash technologies, extrusion technologies, jet technologies, and lamination and cutting technologies (Gardan, 2016) [4]. The laser technologies include Stereolithography (SLA), Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Direct Metal Laser sintering (DMLS). In SLA the models are defined by scanning a laser beam over a photopolymer surface. In SLM a thin layer of powder material is applied and a laser beam is projected on lines or points which fuses the powder together by melting the metal. SLS and DMLS works in a similar way as SLM but the sintering process does not fully melt the powder, instead the particles fuses together. In DMLS a laser selectively melts or sinter a thin layer of powder fusing them together and once the powder is fused the platform moves down and the powder bed is recoated and the process is repeated. A method similar to SLM is Electron-beam melting (EBM) as it also uses powder that melts layer-by-layer. EBM generally has superior build rate compared to SLM due to higher energy density and scanning rate (Gardan, 2016).

The flash technology is derived from the SLA technology in order to reduce lead-time and increase build speed. The laser is projected on the entire layer, which increases the building speed. Extrusion technologies include Fused Deposition Modelling (FDM), Directed Energy Deposition (DED), and Dough Deposition Modelling (DDM). FDM uses thermoplastic filament extruded from a nozzle to print one cross section of an object. DED is a more complex method usually used to repair or add additional material to existing surfaces and covers laser engineered net shaping, directed light fabrication, direct metal deposition and 3D laser cladding. DDM groups the processes which file different doughs, for instance are a few technologies based on the FDM method but uses a syringe to deposit a dough material. Jet technologies include methods such as Multi Jet Modelling (MJM) and Three-Dimensional printing (3DP) also known as Color Jet Printing (CJP). MJM uses two different photopolymers when building the part; one is used for the actual model and another for supporting. The supporting material is later removed. Similarly with MJM the 3DP uses powder, for instance metal, that are glued together. The part is later solidified by for example sintering where the glue is removed. Lamination and cutting technologies such as Laminated Object Manufacturing (LOM) is a process where the part is built from layers of paper and uses thermal adhesive bonding and laser patterning (Gardan, 2016).

2.3. Material and Process

A large variety of materials can be used in the different additive manufacturing technologies. Commercial additive manufacturing machines including sheet lamination can process polymers, metals, ceramic materials, paper, wood, cork, foam and rubber. Examples of different materials that can be used can be observed in Figure 2 (Clausen, 2016).

POLYMERS	METALS	CERAMICS
• Polyamide • Polystyrene • Polyether-ether-ketone • Polycarbonate • Polylactic acid • Epoxy resins • Waxy polymers	• Steel alloys • Titanium • Aluminum • Cobalt-chrome • Copper-based alloys • Nickel-chromium-based Inconel	• Calcium hydroxyapatite • Aluminum oxide • Titanium oxide

Figure 2: Commonly used materials in additive manufacturing.

Gibson et al. (2015) have divided the general process chain for additive manufacturing into eight steps. The process scheme can be observed in Figure 3 The first step is to obtain 3D CAD for instance through using a 3D CAD software. The next step will be to convert the 3D CAD data to a STL file format, which nearly every additive manufacturing technology uses. The STL format works by approximating the surfaces of the model with a series of triangular facets. As no units, colors, material or other features are saved as information in a STL file the "AMF" file format is now the international ASTM/ISO standard. The parameters mentioned above is extended to the STL file to be included in the AMF file. Step 3, step 4 and step 5 includes transferring the additive manufacturing ready file to the machine and setting up the machine software parameters and building the component. Step 6 includes removal and cleanup, where the part is removed from the build platform and sometimes removal of support structure is necessary. Ideally, the output from the additive manufacturing machine would be ready for use, but this is unfortunately usually not the case. In step 7 post-processing is the final stage of finishing the part, some of the processes involve chemical or thermal treatment or abrasive finishing such as polishing or application of coatings.

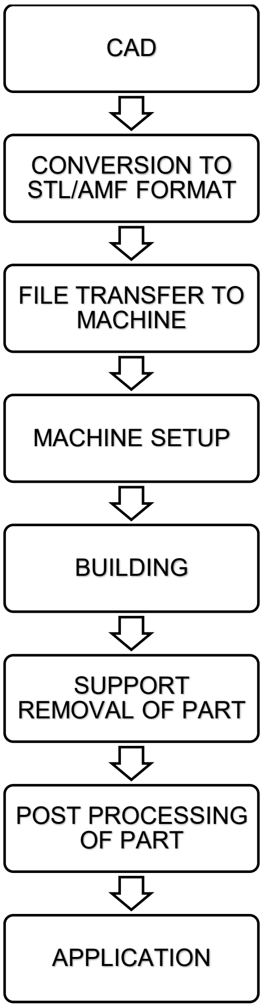


Figure 3: The process scheme for additive manufacturing

There is a wide application for additive manufacturing and the number of applications increase as the process improves. Historically the largest industrial sectors using the additive manufacturing technique are the automotive, health care, consumer products and aerospace sectors. The main reason for the usage in these sectors is the ability to generate complex geometries with a limited number of processing steps. This capability provides an opportunity to physical implement topologically optimal geometries, which are often highly complex (Gibson et al., 2015).

2.4. Manufacturing constraint

The main advantage of AM is its ability to create very complex geometries, which would not be possible with conventional methods such as casting. AM provides an opportunity with design freedom. Unfortunately, AM comes with manufacturing constraints. These include the digital and physical discretization of the parts to be produced, material capability, overhang, processing time, heat dissipation, the machine and material cost, enclosed voids, layer induced anisotropy, and minimum feature size (Thompson et al., 2016) [5].

Both polymer based processes and powdered metal-based processes require support material in order to ensure manufacturability for certain topologies. For example, the FDM method, the DMLS method and the SLM method require support structures in order to be able to manufacture certain topologies. In the FDM method support structures surround the part. It prevents the structural material from distorting for instance through curling because of residual stresses or sagging due to unsupported regions. The support material is removed in a post-print chemical bath. The usage of support structures increase the material usage, print time and require a chemical bath for removal (Vanek et al., 2014). Vanek et al. (2014) [6] defines the critical angle for the FDM process where support structures are needed to 45°, i.e. the printing faces may deviate up to 45° from the printing direction vector in order to be printable without support structures. It is however pointed out that the exact value of the critical angle varies from printer to printer and is not generally accessible.

Metal additive manufacturing, MAM, usually requires support structures to hold the part during the process. The thermal gradient from the selective heating and solidification processes creates residual stresses that leads to significant distortions such as curing and warping in the part (Thomas, 2010) [7]. It has been shown that overhanging surfaces warp easier when the inclined angle is smaller. Other parameters such as scanning speed and laser power also affect warping (Wang et al., 2013) [8]. The affect of the need of support structures for MAM is similar to when using polymers; it increases the material usage, the print time and the post-fabrication time. The support structures connect the build platform to the part, which provides structural resistance against distortion, and help with the heat dissipation. By preventing overhang features in the design, one might be able to be avoided support structures (Thomas, 2010). Thomas (2010) identifies the typical critical angle as to 45° in the DMLS process and Wang et al. (2013) identifies the critical angle to 45° in the SLM process.

2.5. Capabilities and Opportunities of AM technologies

2.5.1. Industries and Markets

In the recent years, substantial improvements in AM have enabled more and more applications and fields to use AM as a viable manufacturing method for industries. It started simply as a prototyping production, mould making and casting patterns application or complexly as a medical modeling creation for medical and surgery reasons. It used to be the solution only in highly specialized fields (usually early adopters due to the high profit margin and need of high customization). The main recent improvements have been in terms of production costs, material properties, part quality and accuracy. Considered as flexible and cost effective solution for the production of industrial demanding and complex products, AM is suitable for numerous industrial applications.

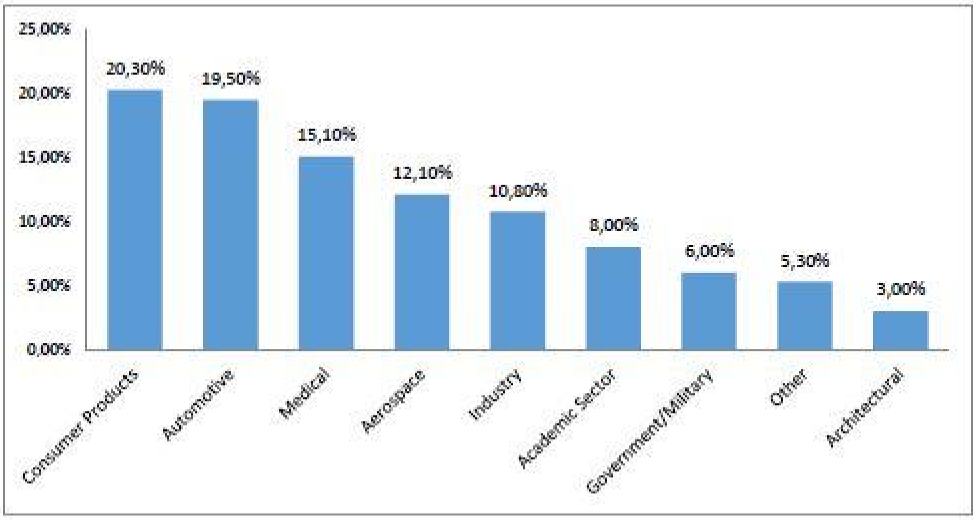


Chart 1: The distribution of AM applications within different sectors

2.5.2. Direct Digital Manufacturing (DDM) known as Rapid prototyping (RP)

RP creates those opportunities for manufacturers in a diverse range of industries to realize significant benefits. In this THESIS, those opportunities are explored through an investigation of RP, along with the advantages of AM in a mass production demanding industry as the Automotive. It is important to identify how the unique capabilities of AM technologies may lead to RP applications in automotive industry.

2.5.3. Additive Manufacturing Costs and Benefits

As discussed by Young (1991) [9], the costs of production can be categorized in two ways. The first involves those costs that are "well-structured" such as labor, material, and machine costs. The second involves "ill-structured costs" such as those associated with build failure, machine setup, and inventory. In the literature, there tends to be more focus on well-structured costs of additive manufacturing than ill-structured costs; however, some of the more significant benefits and cost savings in additive manufacturing may be hidden in the ill-structured costs. Moreover considering additive manufacturing in the context of lean production might be useful.

A key concept of lean manufacturing is the identification of waste, which is classified into seven categories:

a) Overproduction: occurs when more is produced than is currently required by customers
b) Transportation: transportation does not make any change to the product and is a source of risk to the product
c) Rework/Defects: discarded defects result in wasted resources or extra costs correcting the defect
d) Over-processing: occurs when more work is done than is necessary
e) Motion: unnecessary motion results in unnecessary expenditure of time and resources
f) Inventory: is similar to that of overproduction and results in the need for additional handling, space, people, and paperwork to manage extra product
g) Waiting: when workers and equipment are waiting for material and parts, these resources are being wasted

Additive manufacturing may impact a significant number of these categories. For example, additive manufacturing may significantly reduce the need for large inventory, which is a significant cost in manufacturing. Reducing inventory frees up capital and reduces expenses. The following sections will attempt to discuss some of the potential savings and benefits of additive manufacturing as well as its costs.

2.5.3.1. Ill-Structured Costs

Many costs are hidden in the supply chain, which is a system that moves products from supplier to customer. Additive manufacturing may, potentially, have significant impacts on the design and size of this system, reducing its associated costs.[10]

a) Inventory and Transportation

***Inventory*:** At the beginning of 2011, there were euro 460 billion in inventories in the manufacturing industry, which was equal to 10 % of that year's revenue. The resources spent producing and storing these products could have been used elsewhere if the need for inventory were reduced. Suppliers often suffer from high inventory and distribution costs. Additive manufacturing provides the ability to manufacture parts on demand. For example, in the spare parts industry, a specific type of part is infrequently ordered; however, when one is ordered, it is needed quite rapidly, as idle machinery and equipment waiting for parts is quite costly. Traditional production technologies make it too costly and require too much time to produce parts on demand. The result is a significant amount of inventory of infrequently ordered parts [11]. This inventory is tied up capital for products that are unused. They occupy physical space, buildings, and land while requiring rent, utility costs, insurance, and taxes. Meanwhile the products are deteriorating and becoming obsolete. Being able to produce these parts on demand using additive manufacturing reduces the need for maintaining large inventory and eliminates the associated costs.

Transportation: Additive manufacturing allows for the production of multiple parts simultaneously in the same build, making it possible to produce an entire product. Traditional manufacturing often includes production of parts at multiple locations, where an inventory of each part might be stored. The parts are shipped to a facility where they are assembled into a product. Additive manufacturing has the potential to replace some of these steps for some products, as this process might allow for the production of the entire assembly. This would reduce the need to maintain large inventories for each part of one product. It also reduces the transportation of parts produced at varying locations and reduces the need for just-in-time delivery.

b) Consumer's Proximity to Production

Three alternatives have been proposed for the diffusion of additive manufacturing. The first is where a significant proportion of consumers purchase additive manufacturing systems or 3D printers and produce products themselves. The second is a copy shop scenario, where individuals submit their designs to a service provider that produces goods. The third scenario involves additive manufacturing being adopted by the commercial manufacturing industry, changing the technology of design and production [12].

c) Supply Chain Management

The supply chain includes purchasing, operations, distribution, and integration. Purchasing involves sourcing product suppliers. Operations involve demand planning, forecasting, and inventory. Distribution involves the movement of products and integration involves creating an efficient supply chain [13]. Reducing the need for these activities can result in a reduction in costs. Some large businesses and retailers largely owe their success to the effective management of their supply chain. They have used technology to innovate the way they track inventory and restock shelves resulting in reduced costs. Walmart, for example, cut links in the supply chain, making the link between their stores and the manufacturers more direct. It also began vender-managed inventory (VMI), where manufacturers were responsible for managing their products in Walmart's warehouses. It advanced its communication and collaboration network. The management of the supply chain can be the factor that drives a company to market leadership. Additive manufacturing may have significant impacts on the manufacturing supply chain, reducing the need for supply chain management. This technology has the potential to bring manufacturers closer to consumers, reducing the links in the supply chain.

d) Vulnerability to Supply Disruption

If additive manufacturing reduces the number of links in the supply chain and brings production closer to consumers, it will result in a reduction in the vulnerability to disasters and disruptions. Every factory and warehouse in the supply chain for a product is a potential point where a disaster or disruption can stop or hinder the production and delivery of a product. A smaller supply chain with fewer links means there are fewer points for potential disruption. Additionally, if production is brought closer to consumers it will result in more decentralized production where many facilities are producing a few products rather than a few facilities producing many products. Disruptions in the supply chain might result in localized impacts rather than regional or national impacts. Figure 4 provides an example that compares traditional manufacturing to additive manufacturing. Under traditional manufacturing, material resource providers deliver to the manufacturers of parts and components, who might deliver parts and components to each other and then to an assembly plant. From there the assembled product is delivered to a retailer or distributer. A disruption at any of the points in manufacturing or assembly may result in a disruption of deliveries to all the retailers or distributers if there is not redundancy in the system. Additive manufacturing with localized production does not have the same vulnerability. First, there may not be any assembly of parts or components. Second, a disruption to manufacturing does not impact all of the retailers and distributers.

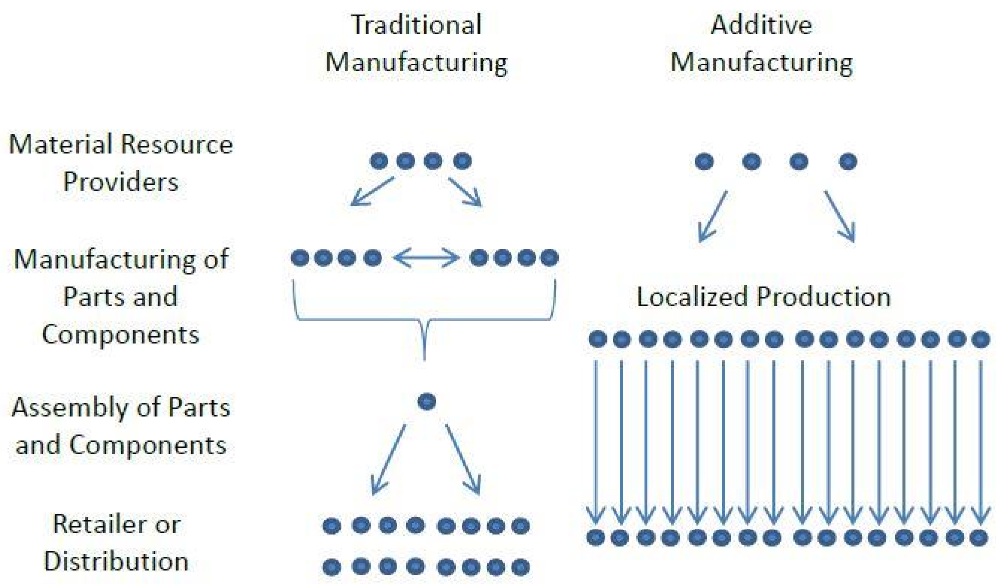


Figure 4: Example of Traditional Supply Chain Compared to the Supply Chain for Additive Manufacturing with Localized Production

2.5.3.2. Well-Structured Costs

a) **Material Costs**

With geometric freedom, additive manufacturing allows products to be produced using less material while maintaining the necessary performance. Products can be produced at the level of performance needed rather than significantly exceeding the necessary performance level because of limitations in traditional manufacturing. Currently, however, the price of materials for additive manufacturing can often exceed those of traditional manufacturing.

- Metal Material Price

Steel Powder	Price [€/kg]
MS1	120
PH1	80
316 L	125
CA	100
17-4PU	105

Table 1: Pricelist of AM metal powder

b) **Machine Cost**

In addition to material costs, machine cost is one of the most significant costs involved in additive manufacturing.

2.5.3.3. Build Envelope and Envelope Utilization

The size of the build envelope and the utilization of this envelop both have an impact on the cost of an additive manufactured product. The size of the build envelope has two impacts. First, products can only be built to the size of the build envelope, which means that it might not be possible to build some products using additive manufacturing technologies without enlarging the build envelope. The second impact of the build envelope is related to utilizing the total amount of build capacity. A significant efficiency factor lies in the ability to exhaust the available build space.

The build envelope is the maximum area for part production in an additive manufacturing system.

2.5.3.4. Build Time

Build time is a significant component about estimating the cost of additive manufacturing. In addition, a number of software packages are available for estimating build time [14][15]. There tends to be two approaches to estimating build time: 1) detailed analysis and 2) parametric analysis [16] . Detailed analysis utilizes knowledge about the inner workings of a system, while parametric analysis utilizes information on process time and characteristics such as layer thickness. Build time estimations tend to be specific to the system and material being used. Although this is an important factor in the cost of additive manufacturing.

2.5.3.5. Energy Consumption

Energy consumption is an important factor in considering the cost of additive manufacturing compared to other methods of manufacturing, especially in terms of examining the costs from cradle to grave. Energy studies on additive manufacturing, however, tend to focus only on the energy used in material refining and by the additive manufacturing system itself.[17]

2.5.3.6. Labor

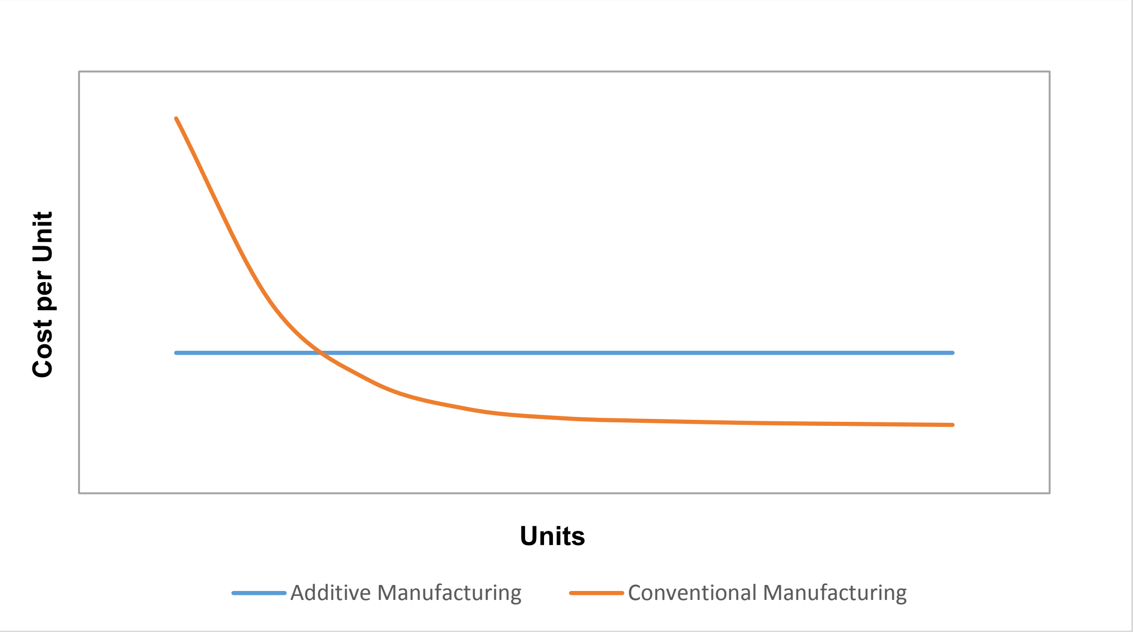
Labor tends to be a small portion of the additive manufacturing cost. Labor might include removing the finished product or refilling the raw material among other things.

2.5.4. Mass Production Stability

Behind the economic concept of Adam Smith, the production of scale was a key factor after the industrial revolution. The development of new production lines times larger than the small sized local firms, the innovations of more efficient processes, the more specialized workforce and distribution of them in definite tasks had a result the reduction of the cost per unit. Products such as cars and clothes that originally are extremely expensive due to the high fixed cost were afterwards affordable from every customer. Until the late 1970s, the higher productions achieved lower cost of production so it had lower prices as result; hence, the middle size companies became larger and more competitive gaining more market share. At the same time local firms, incapable to increase their production volumes and to follow the rhythm remained uncompetitive and mostly got disappeared [18].

Based in simple economic tails the cost of production is parted from the fixed cost and the variable cost. Fixed cost is originally independent of the production output and includes the buildings, the rent, the machinery, etc. Variable cost is more relative to the capital and labor includes wages, materials used, utilities etc. As the production increases the fixed cost can be shared more across the number of units, having as a result the cost of production per unit to follow a forward-falling curve.

On the other hand, in AM production, the fact that for the same result less processes needed implies to significantly less fixed costs comparing to the conventional production line. Therefore, the graph of the production cost per unit will follow a straighter – with a minor downwards trend – line.



Graph 1: Economy of scale – comparing AM with conventional manufacturing.

Comparing those two curves and considering the starting point of both productions, the inference is that AM would benefit more small to middle size productions, achieving cost values less than the more demanding conventional productions.

2.5.5. Product Variation

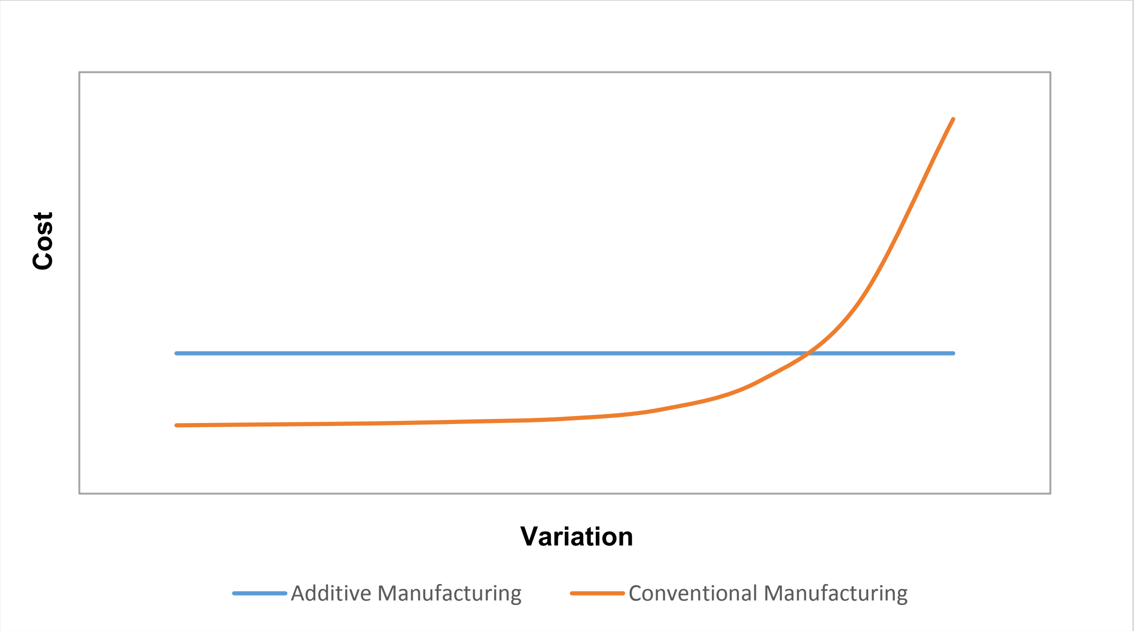
The economies of scale benefit a production in large number of units but transform them in inflexible mass productions. Every mass production appears a tradeoff between the cost per unit and variation. Traditional calculation of manufacturing cost of a certain unit includes a change - over cost from one unit to the other to set up the machine. Thus, the equation of the total cost is:

$$\boldsymbol{Total\ cost} = (\boldsymbol{Number\ of\ variable\ products}) \times (\boldsymbol{Number\ of\ set\ ups\ each}) \times (\boldsymbol{Change - over\ cost})$$

According to this calculation, it implies that the more variation in production drives to the higher total cost. Since in economy of scale the lower total cost depends on spreading the cost over the large number of units production, there are two ways to control this.

One way is to eliminate the *Number of sets ups* by producing in larger production in batches or sizes, but increasing the inventory same time. The other is to decrease the *Number of variable products* by making fewer rages of final products. Henry Ford summarized this dilemma and cost down the production of the cars by setting the *number of variable products* = 1 and he stated the following: "The customer can have any color he wants as long as it is black".

Over the years of attempts in productions, many improvements have been achieved. Especially firms such Volkswagen and Scania achieved to optimize the costs by applying methods of platforms and modularization. However those improvements the tradeoff between cost per unit and variation remain. According to EOS “Economies of scale are fading. Global markets are facing ever-shortening product life cycles. At the same time, product variety is on the rise. Manufacturing methods based on economies of scale are no longer in the position to meet these challenges” [19]. From the other hand AM is the unique technology that does not effect this tradeoff. AM production is able to give very different products from the fist to the second build. The reason is that there is of difference on changeover and no need of different set-ups in a production. The AM machine is controlled from a computer, which just sends the orders and monitors according to CAD files.



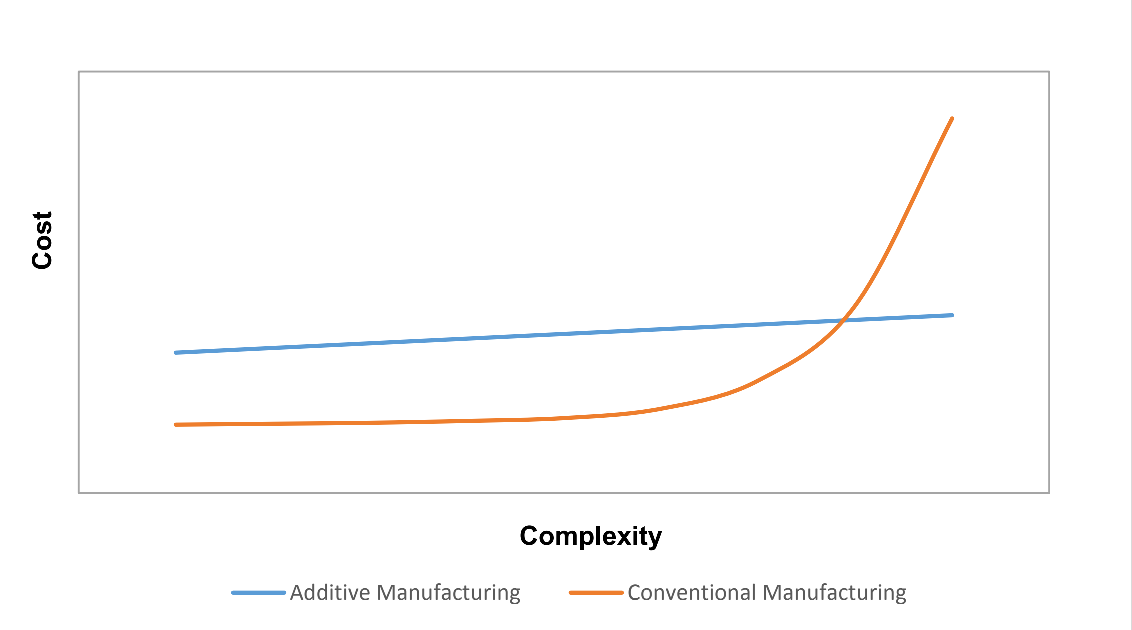
Graph 2: The correlation of cost and variation.

Comparing the two curves, obviously the contribution of AM in higher variation compared with conventional manufacturing is significant.

2.5.6. Design Freedom

Conventional manufacturing has limitations in production of different geometries. Some designs are impossible to be manufactured due to access limitations of tooling in techniques of machining for removing material and structures limitation of casting molds. Complex shape products usually are extreme time consuming in process planning and operation, as much as they demand specialized equipment and tooling. Therefore, those productions are extremely costly.

Opposite, AM by adding material becomes simple to manufacture complex parts without tradeoff between complexity and cost. The times for process planning, different setups and processes are combined in one single process time. AM can find easily application where there is no either way to produce individual and complex components because of their geometry.

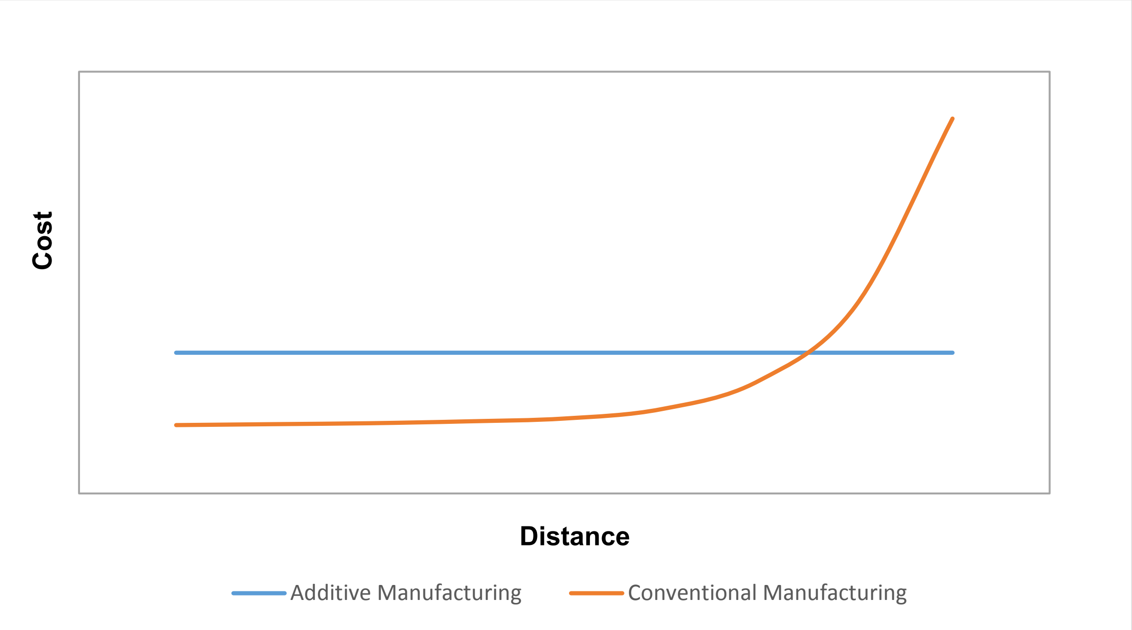


Graph 3: The correlation of cost and complexity.

Furthermore, another important capability of AM is appeared in the inner structure of a part. Tubes in complex shapes, cells and lower solidity can easily achieved though building layer – by – layer. Numbers of applications are benefited from this. Inner tubes are crucial element for inject molding in lubrication and reduction of heat. Cells increase the isolation and adjustable solidity reduces product weight. Structures with inner lower density are also fundamental improvement for the production, decreasing the raw material needed and the final cost relatively.

2.5.7. Process Improvements

A conventional production line is highly demanding management over supply chain and logistics. Industrial lines are very precise in lead times, process times, volumes and inventories in order to achieve the right materials to be available at the right place and the right time. AM however provides the opportunity to scope with time and space through a more distributed manufacturing. The orders can be sent as files electronically wherever the AM machine is located and the entire product can be manufactured directly, the right product at the right time without the complexity of supply chain and inventory procedures. The possibility will let the manufacturer to make the product more near to customer, so that the packaging, transportation, and lead-time will be decreased thanks to the decentralization of the production system. In widely distributed productions, usually the investment cost is higher than the centralized due to the multi times more distributed tooling and other sub – equipment. However, AM production is free of sub – equipment and extra tooling therefore is get befitted more by limited investment and transportation cost.



Graph 4 : The correlation of cost and distance

In addition, considering that every new development, new versions and new products that enters in the market should be developed according to a new process plan, that development requires specialized machines, new customized tooling, operation training and in general a large investment cost. In that case AM benefits the production providing an economical solution without any special changes and same time making the production more flexible in new developments and more competitive. [20]

2.5.8. Environmental Impact

Originally, conventional production systems are more energy consuming in total than an AM system. The manufacturing of a product requires a production system consisted from milling machines, heavy presses, melting machines. For the same production, AM requires a single machine using just a laser beam device. This difference in the total energy consumption in large unit production can be vital in the environmental footprint of an industrial line.

Another environmental factor is the waste. By definition, conventional production is more or less subtractive techniques that remove material, which often becomes useless. This waste is cost effect for an industry but it is eventually also a drag on the environment. AM having better environmental standing by applying an opposite concept, uses as much material as needed with less if any production of waste [20]. Furthermore the capability of AM to adjust the solidity of the parts according to the products functional demands, adds flexibility to production for reduction the material used and therefore effect positively to the environment.

The successful decentralized production system as is discussed previously, it can be a critical method to reduce the environmental impact switching simultaneously from conventional to AM production. The possibility to set the production location close to the material resource or to customer without need for significant investment cost is definitely an opportunity to reduce the distances and the transportation emissions respectively.

2.5.9. Ecological issues of AM

Sustainability characterization of AM as a part of industrial production chain is often difficult to do. The quantifiable dimension of such study should include ecological issues of AM, related to materials and energy consumption, health and safety, transport and waste management and emphasizes the correlation between sustainability and design quality. The main AM design aspects to consider include part strength, part flexibility, surface finish, enclosed voids, material cost, machine cost, and process productivity. AM processes must demonstrate their environmental-friendly potential, by considering the sustainability principles: efficient use of material and energy, industrial waste management, low manufacturing costs, avoidance toxic emissions and materials, health and safety issues, low environmental impacts, improvement of personnel health, safety, economical efficiency, reparability, reusability, recyclability, and disposability of the products made by AM.

2.5.9.1. Energy

Despite its potential to promote cleaner manufacturing, AM cannot be regarded as an ecological-friendly manufacturing method yet, due to the high energy consumption by using heat processes or lasers to melt plastic and metal or to cure resins. AM equipment is generally not designed to be efficient. Energy loss is considerable and the heat management is poor. At mass-manufacturing scale, AM processes have higher impacts per part than TM. However, this is not relevant, because they are replacing small batches of customized parts [21].

If the parts are manufactured by traditional manufacturing processes or by 3D printing, the most important factor for environmental impact is the way how these methods are used. Any of these methods manufacturing only a part per week, but left on the rest of the time, could have higher impact than the same machine at maximal utilization. [22][23]

For TM, material use and waste is the largest impact. For AM electricity use dominates environmental impacts, because the energy usage per item is still very high in the manufacturing stage. The best way to reduce impacts of AM energy use is to reduce the run-time by considering some simple strategies for that: orient parts for the fastest printing, print tubular parts rather than solid; and (if possible) fill the printer bed with multiple parts.

2.5.9.2. Materials

Reducing the amount of material printed is beneficial for AM sustainability. AM uses several raw materials to create prototypes, parts or functional products based on 3D digital models by printing layers of materials, but a substantial amount of unused raw materials left behind of 3D printers.

The variety of materials used in AM includes: metals, polymers, ceramic or composite materials in forms of powders, wires and liquids. AM works with several sorts of materials including powdered or molten polymers (plastics) which are not ideal for environment (even they can be recycled) regardless of what kind of manufacturing techniques is involved. Rarely plastic by-products can be reused, but often the material properties are corrupted, making these materials no longer suitable for parts manufacturing. Some plastics are less pollutant than others. Therefore, standardized scales of flammability, toxicity, and reactivity must be consulted for choosing appropriate materials. [21][22]

2.5.9.3. Life cycle

The environmental impact of products fabrication involves several stages through product life cycle, starting with natural resources exploitation to product disposal, beyond manufacturing process.[22]

The transport and end of life of the machines (both 3D printers and machine tools) represent a small portion of impacts, amortized by intense utilization, but, if only few parts are made every week, those embodied impacts can be significant.

AM can change the product life cycle by shortening the supply chains and by reducing the fuel amount consumed to ship products. Traditional production target the areas of low labor costs, often far away from the markets where the products are consumed. With AM, the production can be close to the product consumer. This shortening of the supply chain reduces the transport costs associated with it and with the pollution and roads congestion.

2.5.9.4. Waste management

The environment state and the growing of the global consumer economy should be well balanced. Nowadays AM technologies become more widely used in many industrial sectors. Their environmental impact will depend on how these manufacturing methods are used.

Compared to conventional manufacturing approaches, AM may have environmental benefits because it does not require tooling. Thus, innovative designs can be created without tooling putting limits on the shapes.

Unfortunately, the opportunity to print quickly a series of variations of a product design can encourage a new kind of pollution by rapid waste generation. A critical AM issue is reuse and remanufacturing of the parts/products.

There is almost no information about waste flows associated with polymeric and metallic AM processes. Some of these flows add actually no value to the part such as SLS powder refresh, FDM support structure materials, post-process heat treatment for reducing residual stresses or energy loss from inefficient laser and optical systems.

FDM machine can have negligible waste if the model does not need any support material while printing. The inkjet 3D printer wastes 40% of its ink without counting supports material. Depending on geometry and orientation, the support could be more mass than the final part, and this waste is difficult to be recycled.

3. Optimization

Here the basics of optimization in general and topology optimization in particular will be described; for a more in-depth look on mathematical optimization please refer to Rao and Ehrgott and for structural optimization see Bends_e and Klarbring and Christensen.

3.1. Mathematical optimization

The basic principle of optimization is to find the best possible solution under given circumstances [24] . One example of optimization is finding the quickest route when using the public transportation system or, as in the case of structural optimization, finding the optimal distribution of material that satisfies some given requirements. This is most often done by decisions made by the passenger or the engineer from their own experience and knowledge about the subject.

The objective of the optimization problem is often some sort of maximization or minimization, for example minimization of required time or maximization of stiffness. To be able to find the optimum solution the `goodness' of a solution depending on a particular set of design variables needs to be expressed with a numerical value. This is typically done with a function of the design variables known as the cost function Mathematically the general optimization problem is most often formulated as minimization of the cost function (which can easily be transformed to maximization by minimizing the negative function) subject to constraints, this can be expressed as [24] :

$$Find\ x = \begin{Bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_n \end{Bmatrix} which\ minimizes\ f(x)$$

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

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

3.2. Multicriteria optimization

In many cases, there are multiple objectives, which need to be taken into account. One example used by Ehrgott [25] is when buying a car; it is for example desired to have a car that is powerful, cheap and fuel-efficient. Obviously, it is not possible to find a car that is the best in every aspect; a powerful car is normally neither cheap nor fuel-efficient.

A concept often used in optimization with multiple objectives is Pareto optimality. A solution is said to be Pareto optimal if there exists no other feasible solutions that would decrease any of the objective functions without causing an increase in any of the other objective functions [26]. The set of the Pareto optimal solutions is called the Pareto front [6], for the case of two objectives; this can easily be visualized in a two-dimensional diagram. From the Pareto front interesting information about the trade-off between different objectives, and how they affect each other can be obtained.

One method of solving the multicriteria optimization problem is by scalarization, i.e., by transforming the multiple objective functions into a scalar function of the design variables. The simplest scalarization method is the weighted sum method:

$$\min_{x} \sum_{k=1}^{p} w_k f_k(x), \ \ where\ f_1, \dots, f_k\ are\ the\ objective\ functions$$

By varying the weights w_k , different Pareto optimal solutions may be found. Another approach is to consider one of the objective functions and constraining the other, the ε-constraint method [25]:

$$\min_{x} f_i(x)$$

$$subject\ to\ f_k(x) \leq \varepsilon_k, k = 1, \dots, p, k \neq j$$

The problem is then solved with different values on the constraints ε_k .

3.3. Structural optimization

Structural optimization is one application of optimization. Here the purpose is to find the optimal material distribution according to some given demands of a structure. Some common functions to minimize are the mass, displacement or the compliance (strain energy). This problem is most often subject to some constraints, for example constraints on the mass or on the size of the component.

This optimization is traditionally done manually using an iterative-intuitive process that roughly consists of the following steps [27]:

1. A design is suggested
2. The requirements of the design is evaluated, for example by finite element analysis (FEA)
3. If the requirements are fulfilled, the optimization process is finished. Else, modifications are made, a new improved design is proposed and step 2 - 3 are repeated

The result depends heavily on the designer's knowledge, experience and intuitive understanding of the problem. Changes to the design are made in an intuitive way, often using trial and error. This process can be very time consuming and may result in a suboptimal design.

According to Christensen and Klarbring [27] the problem of structural optimization can be separated in three different areas: *sizing optimization, shape optimization* and *topology optimization* see Figure 5.

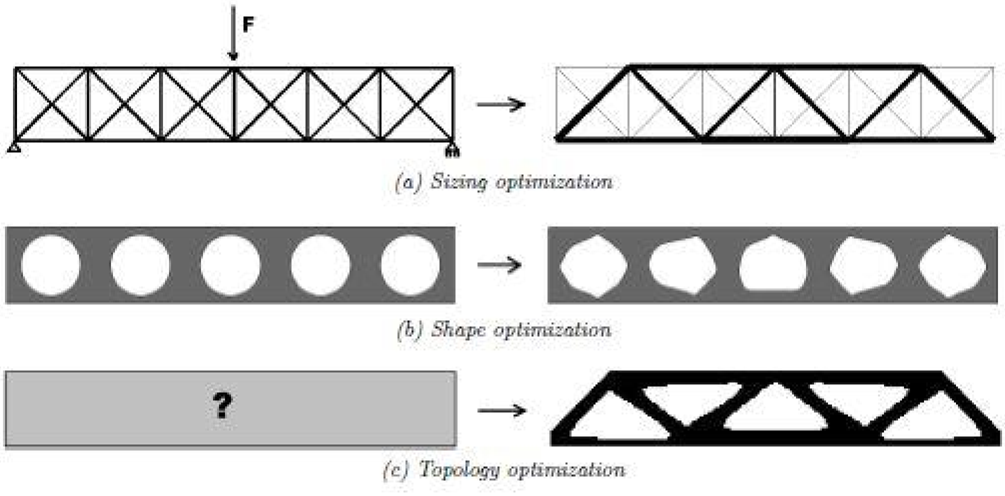


Figure 5: Different type of structural optimization

3.4. Sizing optimization

Sizing optimization is the simplest form of structural optimization. The shape of the structure is known and the objective is to optimize the structure by adjusting sizes of the components. Here the design variables are the sizes of the structural elements[27], for example the diameter of a rod or the thickness of a beam or a sheet metal. See Figure 5 (a) for an example of size optimization where the diameter of the rods are the design variables.

3.5. Shape optimization

As with sizing optimization the topology (number of holes, beams, etc.) of the structure is already known when using shape optimization, the shape optimization will not result in new holes or split bodies apart. In shape optimization, the design variables can for example be thickness distribution along structural members, diameter of holes, radii of fillets or any other measure. See Figure 5 (b) for an example of shape optimization. A fundamental difference between shape vs. topology and size optimization is that instead of having one or more design variable for each element the design variables in shape optimization each affect many elements.

3.6. Topology optimization

The most general form of structural optimization is Topology optimization. As with shape and size optimization, the purpose is to find the optimum distribution of material. With topology optimization the resulting shape or topology is not known, the number of holes, bodies, etc., are not decided upon. See Figure 5 (c).

From a given design domain the purpose is to find the optimum distribution of material and voids. To solve this problem it is discretized by using the finite element method (FEM) and dividing the design domain into discrete elements (mesh). The resulting problem is then solved using optimization methods to find which elements that contain material and which one do not. So this result is a so-called 0-1 problem, neither the elements exists nor not, which is an integer problem with two different states for each element, a so-called ISE topology (Isotropic Solid or Empty elements). [28]

The number of different combinations is 2^N, where N is the number of elements. As a normal FE-model easily results in hundreds of thousands of elements, this problem is out of reach to solve for any practical problem. The two main solution strategies for solving the optimization problem with an ISE topology are the density method and the homogenization method. Other methods, which will not be further studied, includes using genetic algorithms or heuristic methods such as evolutionary structural optimization (ESO)[28]. Rozvany [29] points out that “ESO is presently fully heuristic, computationally rather inefficient, methodologically lacking rationality, occasionally unreliable, with highly chaotic convergence curves" and that “ESO is now therefore hardly ever used in industrial applications".

3.6.1. Density method

One way to get a problem that can be solved is to relax the problem by letting the material density take any value between zero and one, i.e., 0% to 100% density. By making this relaxation, it is possible to use gradient-based optimization methods to find a minimum of the objective function. The design variable of the optimization problem is the density which is a function varying over the design domain. In the FE discretization the density is most often approximated to be constant over each element, the resulting problem thus has one design variable, the density, per element.

In practice, this also makes it similar to sizing optimization; here the sizes are the densities of the elements. This relaxation does not have a simple physical explanation. When considering elements in 2D the density could be represented as a varying thickness of a plate. In 3D, there is no similar counterpart; a solid with 50% material is neither physically reasonable nor very intuitive.

Two of the main advantages of the density method are that it does not require much extra memory, only one free variable is needed per element (the density) and that any combination of design constraints can be used.

3.6.2. Homogenization method

The main idea of the homogenization method is that a material density is introduced by representing the material as a microstructure. The microstructure is a composite material with an infinite number of infinitely small voids[30]. This leads to a porous composite that can have a density varying between 0% and 100 %. Some common types of microstructure are solids with square or rectangular holes or some sort of layered microstructure . Since the macroscopic properties of the microstructure are not isotropic, an orientation angle is also needed [31].

For a layered microstructure, the elasticity can be found analytically, but for most other types of microstructures, the elasticity needs to be calculated numerically by using the finite element method for different sizes and then interpolating between these values. The microstructures do by themselves provide some penalization on intermediate densities but this is most often not enough and some additional penalization needs to be introduced.

The optimization is then carried out similarly to the density method. The problem is discretized into finite elements with the design variables (hole sizes and rotation) assumed to be constant over each element.

One obvious disadvantage of the homogenization method is that more design variables per element are required than when using the density method. Also, and maybe even more serious is that currently the homogenization can only be used for optimization with the compliance as cost function or constraint. [28]

4. Case Study – Gripper for part handling

This chapter explains the component development process of a gripper using TO tools. It starts with a presentation of the current gripper and its structural performance, which is followed by the application of the gripper to the component development process using TO tools described in section 3 with two different software ALTAIR (SOLIDTHINKING INSPIRE) [32] and AUTODESK (FUSION 360) [33]. Thereafter, it is evaluated the FEM analysis of convectional part and the two optimized parts.

4.1. Presentation

As it mentioned before this thesis evaluated and compared the convectional manufacturing of a gripper of handling machine with Additive manufacturing technology according of TO application, this machine is a Robot hand, which works with a SCHUNK gripper **PGN-plus- 380-2-AS**. The considered component is a gripper used to hold an axle while handling it to the other place. The CAD data of Robot hand is shown as bellow:

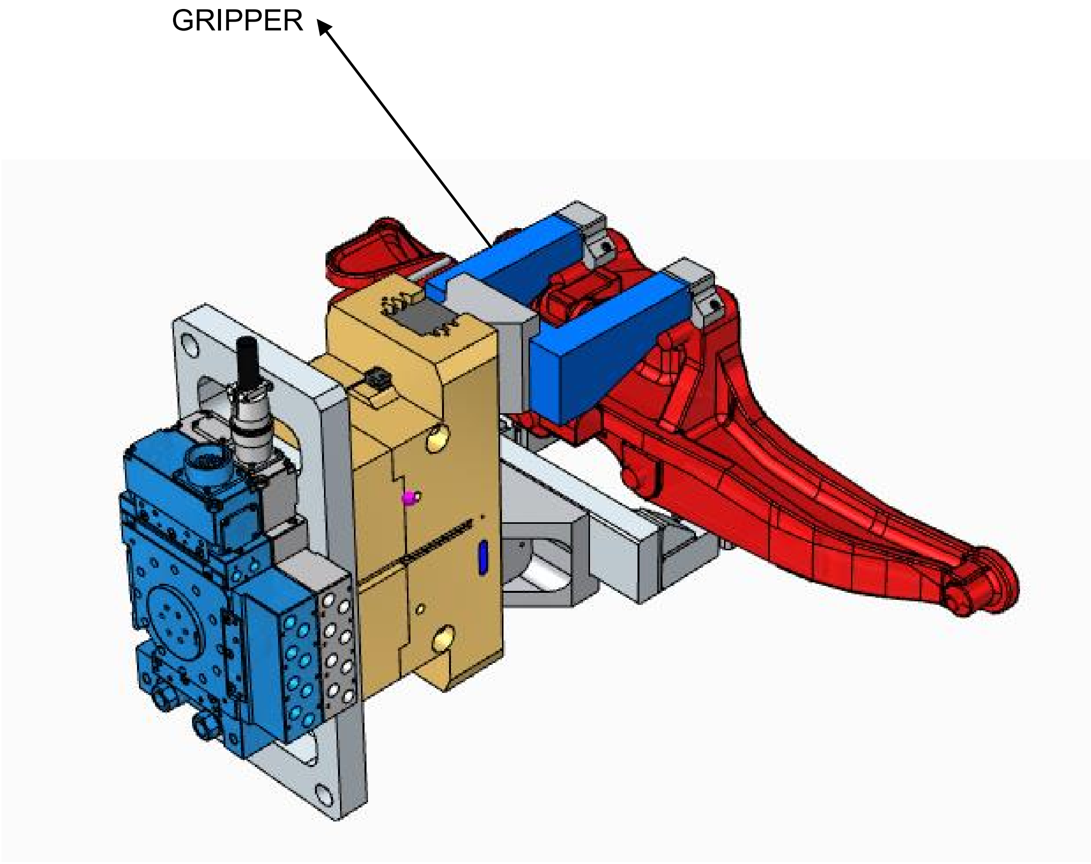


Figure 6: Assembly configuration of handling machine

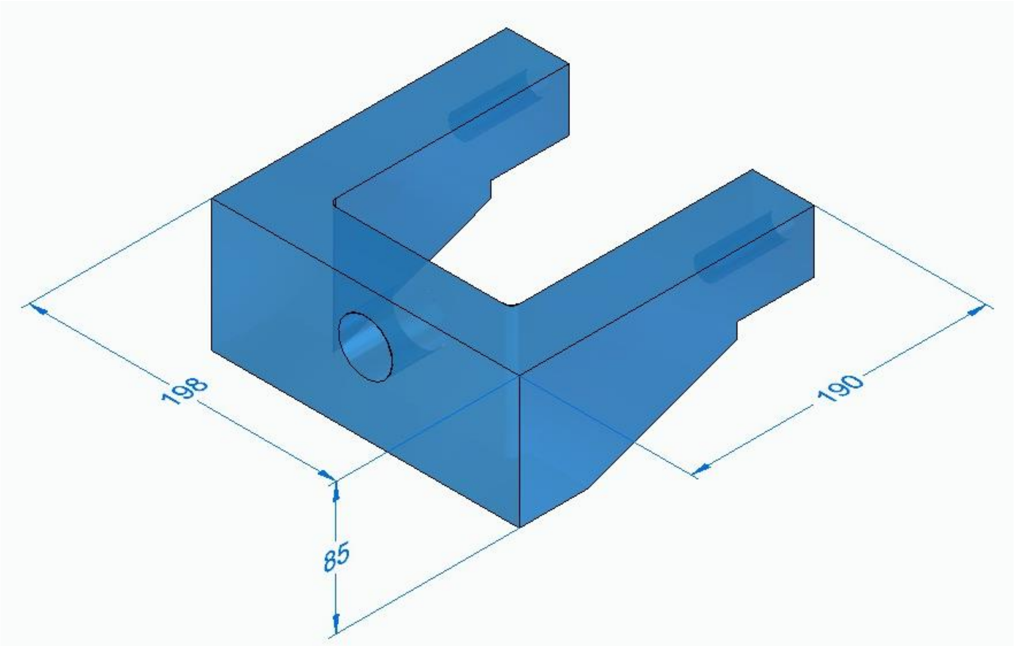


Figure 7: Gripper with convectional technology method

The material is assumed to be Iron with the following properties

Mechanical Properties	
Size (mm)	**198 x 190 x 85**
Volume (mm)^3	**1276257.195**
Material	**Fe360**
Yield strength (min) [MPa]	**225**
Tensile strength [MPa]	**360**
Young’s modulus [GPa]	**210**
Poisson´s ratio	**0.3**
Density (kg/m^3)	**7800**
Weight	**10 kg**

Table 2: Mechanical properties of FE360

4.1.1. Problem formulation

- **Loading and boundary:** This gripper in one side it fixed with a PIN at the middle of it to one jaw of SCHUNK gripper and in the other side it holded the product for handling. The Maximum forces of SCHUNK gripper is 18 kN for both jaws and obviously 9kN for each jaw. Due to the symmetric shape of evaluated gripper, the assumed force is 6kN in z-direction.
- **Objective:** The objective is to minimize the mass while keeping the stresses within safe levels. Safe levels are for simplicity assumed to be 80% of the yield stress of new material, which in this case is :

$$\sigma_{max} = 0.8\,.\sigma_y$$

There are also no constraints on the design due to the fact that the component should be feasible to manufacture in AM.

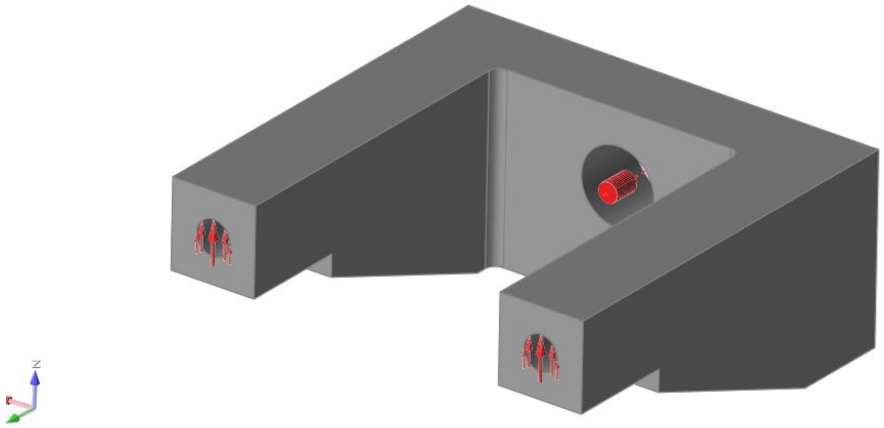
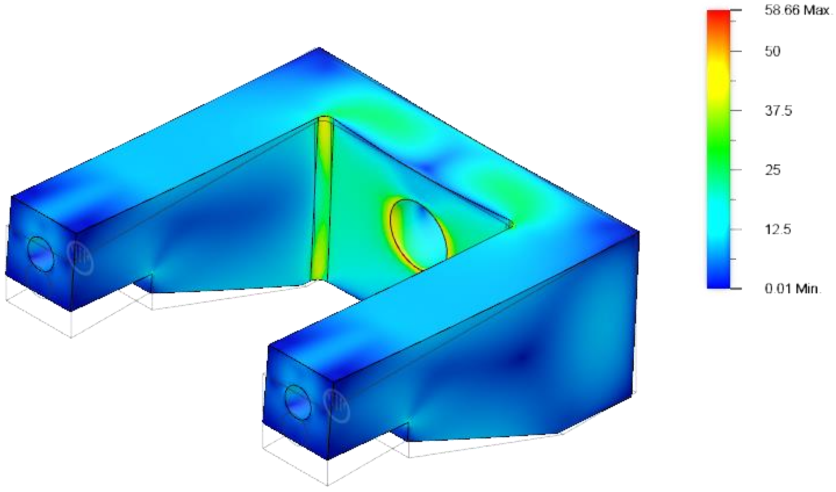


Figure 8: Loading and boundary conditions of Original Gripper

- **FE – Analysis (VON MISES ANALYSIS)**



$\sigma_m = 58.66\ MPa$ (a)

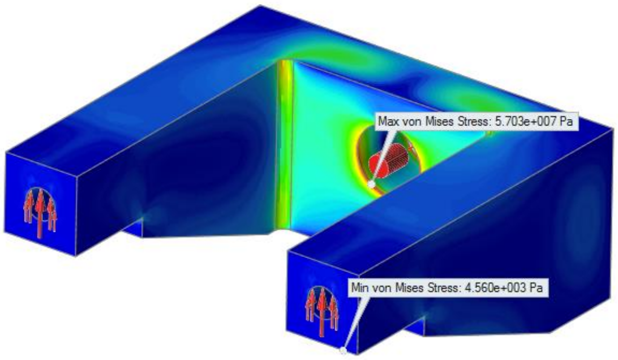


Figure 9: (a) FE model of the Original Gripper by Fusion 360. (b) FE model of Original Gipper by Solidthinking inspire

$\sigma_m = 57.03\ MPa$ (b)

FE360 $\sigma_y = 225\ MPa$ $\sigma_{max} = 0.8\ .\ 225 = 180\ MPa$ so $\sigma_{max} > \sigma_m$

- **Static analysis of original design**: As a first step a static analysis of the original component is performed. The FE-model, complete with boundary conditions and external forces can be seen in Figure 9.

4.2. Topology optimization of gripper

The optimization problem was formulated in SOLID THINKING INSPIRE and FUSION 360 as:

- Objective: maximize stiffness
- Stress constrained to a maximum of 1100 MPa based to **MaragingSteel MS1** material
- Minimum member size: 3mm
- Mass Targets: 30% of Total Design Space Volume
- Thickness Constraints: 3mm

MaragingSteel MS1 is a pre-alloyed ultra-high strength steel in fine powder form. Its composition corresponds to US classification 18% Ni Maraging 300, European 1.2709 and German X3NiCoMoTi 18-9-5. This kind of steel is characterized by having very good mechanical properties, and being easily heat-treatable using a simple thermal age-hardening process to obtain excellent hardness and strength, on the EOS. With the following properties:

Mechanical Properties	
Yield strength (min) [MPa]	**1000**
Tensile strength [MPa]	**1100**
Young’s modulus [GPa]	**180**
Poisson´s ratio	**0.3**
Density (kg/m^3)	**8000**
Thermal conductivity (W/m °C)	**15**
Specific heat capacity (J/kg °C)	**450**

Table 3: Mechanical properties of MaragingSteel MS1- As Built

Mechanical Properties	
Yield strength (min) [MPa]	**1900**
Tensile strength [MPa]	**1950**
Young’s modulus [GPa]	**180**
Poisson´s ratio	**0.3**
Density (kg/m^3)	**8000**
Thermal conductivity (W/m °C)	**20**
Specific heat capacity (J/kg °C)	**450**

Table 4: Mechanical properties of MaragingSteel MS1- After age Hardening

4.2.1. TO method with SOLID THINKING INSPIRE (ALTAIR)

MS1– As Built **MS1- After age Hardening**

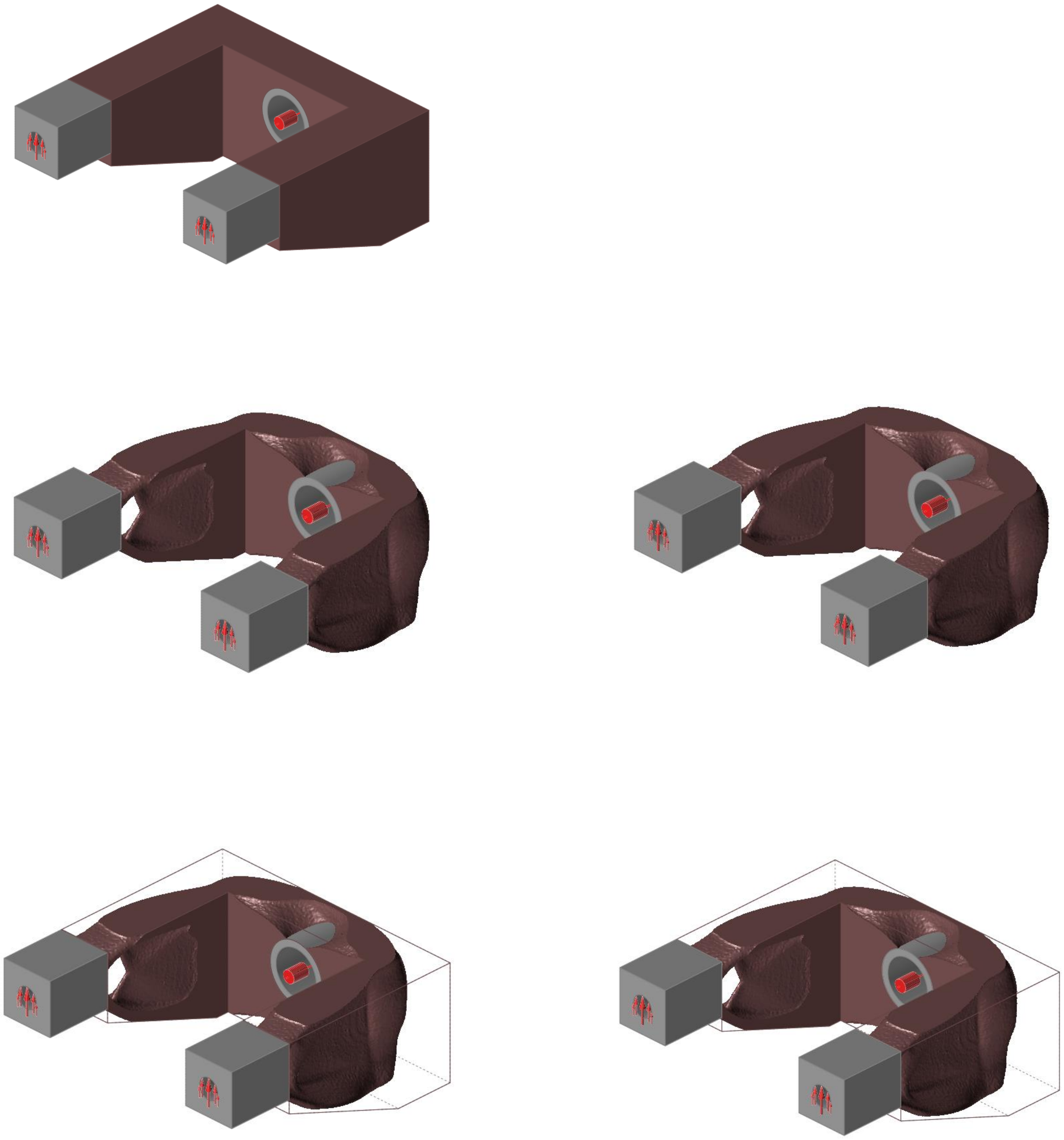


Figure 10: Results from topology optimization, red areas have high density and white areas

Original weight: 10 kg

Optimized weight: 3.92 kg

4.2.2. TO method by FUSION 360 (AUTODESK)

4.2.2.1. MS1– As Built

MS1- After age Hardening

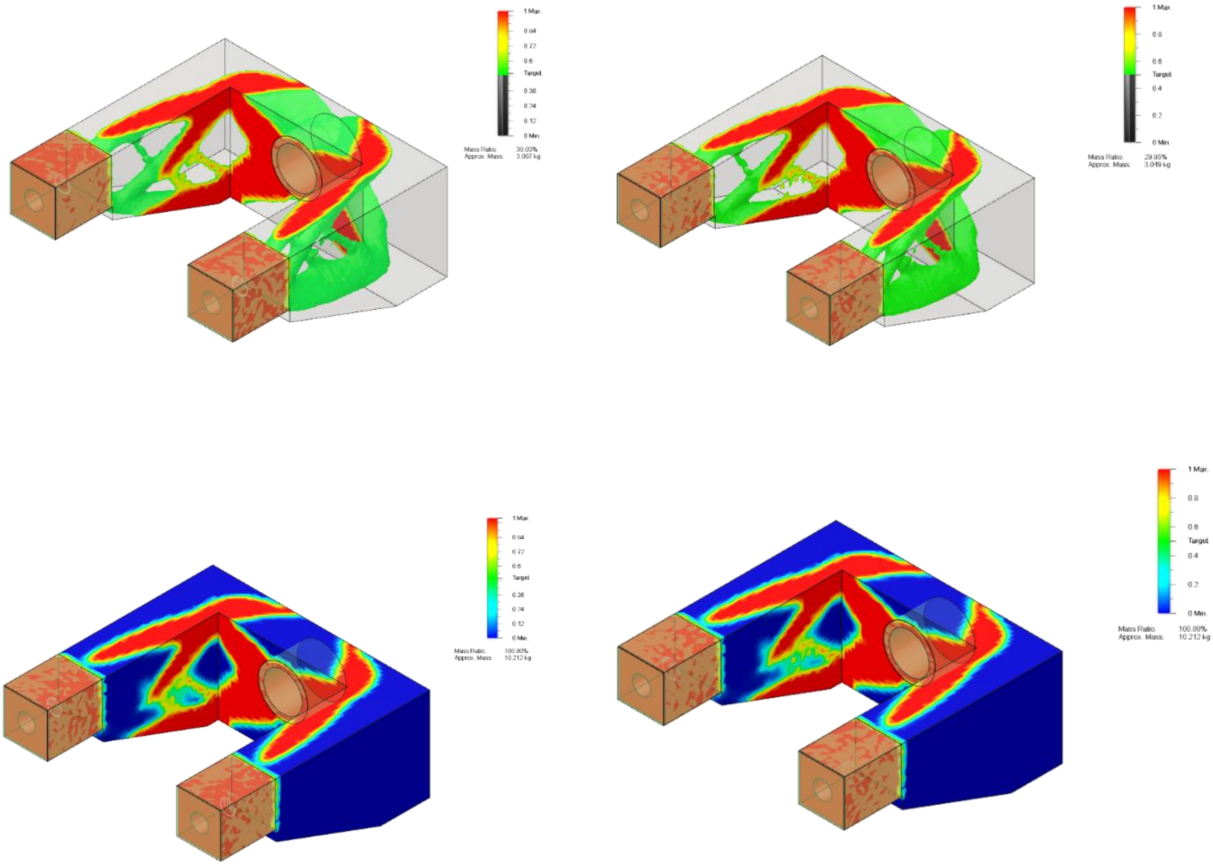


Figure 11: Results from topology optimization, red areas have high density and blue areas

Original weight: 10 kg

Optimized weight: 3.02 kg

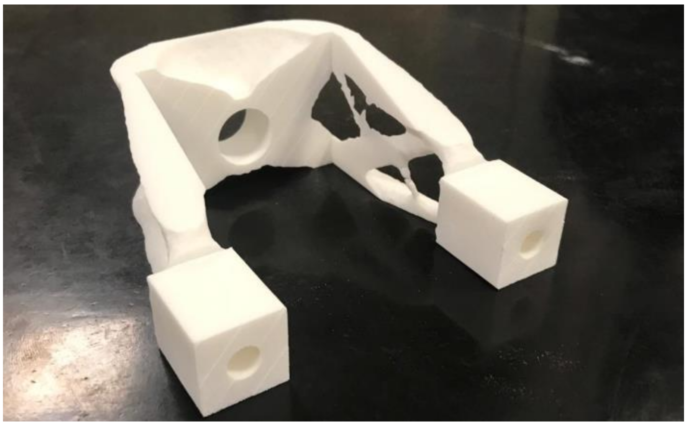


Figure 12: 3D Printed part modeled by Fusion 360

Figure 13: 3D Printed part modeled by Solidthinking Inspire

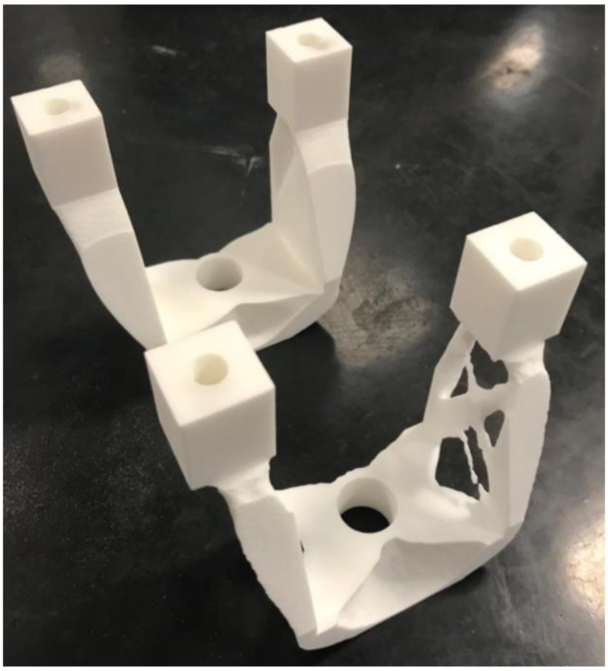


Figure 14: 3D Printed part with polymer Technologies

4.3. Realization of concept

The new modeling method in Solidthinking inspire (PolyNURBS) allows you to trace over optimized result with Precision, ease and efficiency.

Optimized shapes obtained in Inspire can only be exported in STL format to other CAD software. STL geometry is represented as triangulated polymeshes, which are great for concept design and 3D printing, but not directly compatible with subsequent CAD tools or manufacturing. NURBS are preferred in these use cases because they more accurately and efficiently represent curved geometry. However, converting third order meshes to NURBS is often very time-consuming.

At solidThinking, it is addressed this concern by developing a solution called PolyNURBS. This new modeling method allows you to easily trace over optimized results to create a smoother, watertight NURBS version of the STL geometry. The resulting model can be exported to other CAD systems and is readily usable for manufacturing.

The resulting Gripper has a mass of 3.09 kg, which is 30.9% of the mass of original design.

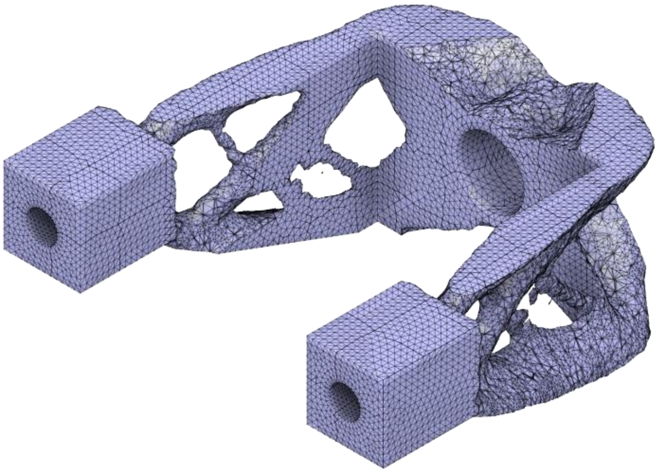


Figure 15: Mesh file of Optimized model by Fusion 360

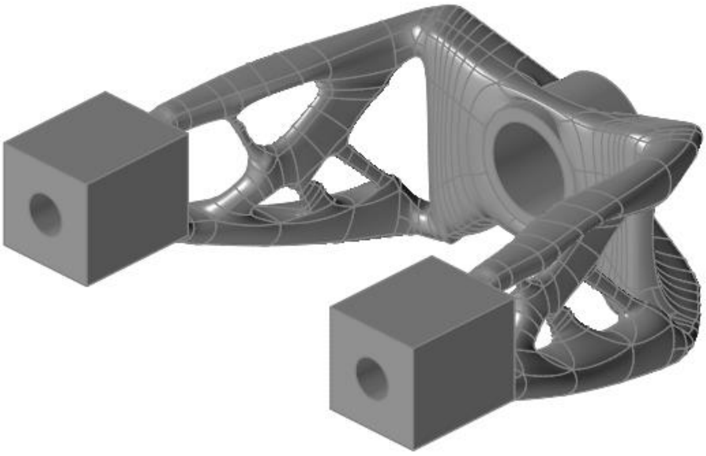


Figure 16: Realized model by Solidthinking Inspire PolyNURBS command

4.4. Static analysis of realized model

A static analysis is performed on the realized model, the Maximum Yield Strength of Material for MS1 – As Built is 1000 MPa (80% = 800 MPa) and for EMS1 – After Age Hardening is 1900 MPa (80% = 1520 MPa). In addition, according to Von MISES Stress analyzing the Maximum stress of realized model must be less than the Max yield strength of the material then there is no failure in our design.

4.4.1. FEM Analysis of Optimized Gripper

MS1– As Built

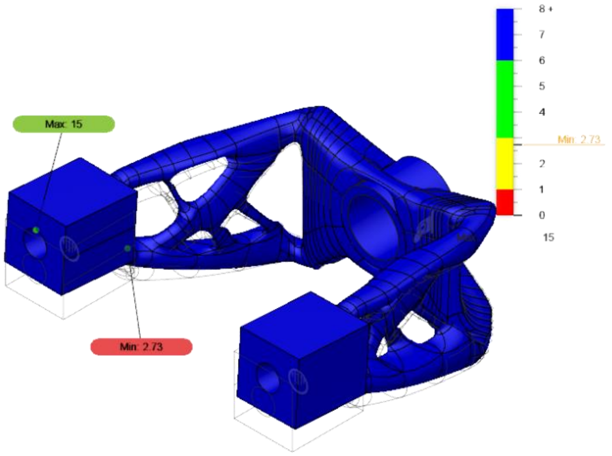


Figure 17: Safety Factor result of realized model

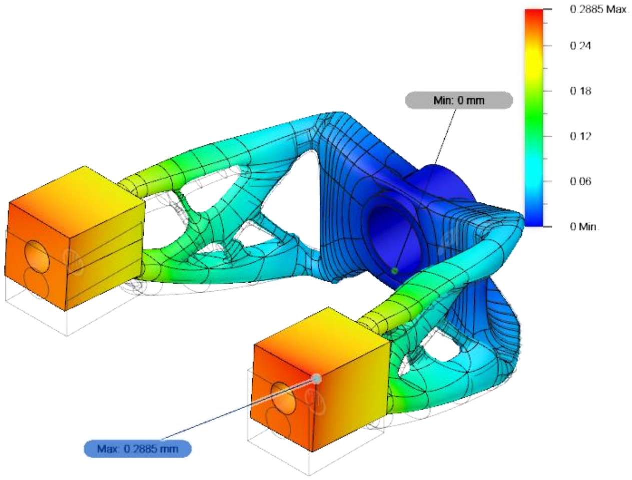


Figure 18: Displacement result of realized model

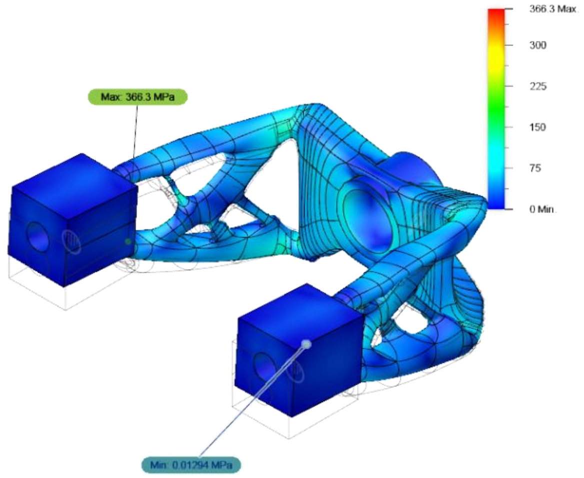


Figure 19: VON MISES result of realized model

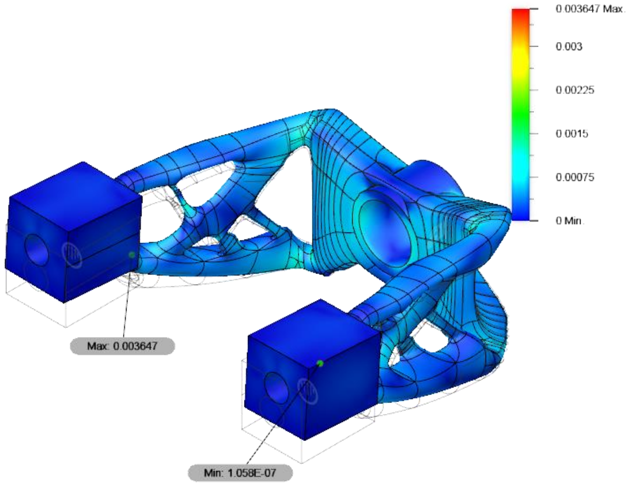


Figure 20: Strain result of realized model

MS1– After age Hardening

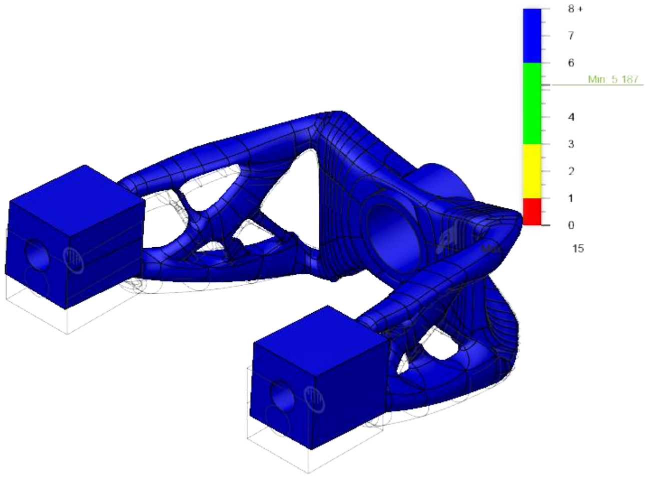


Figure 21: Safety Factor result of realized model

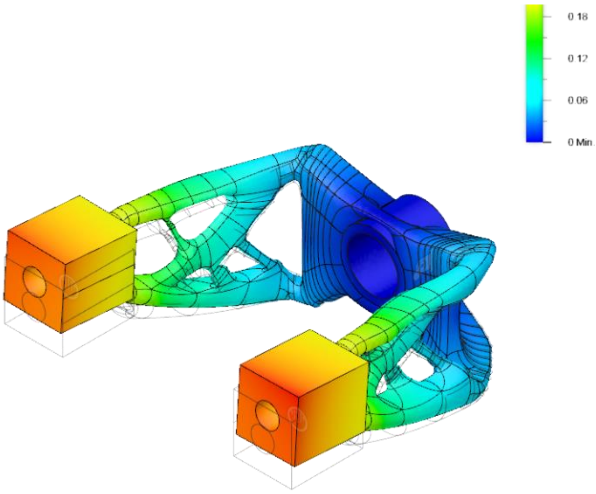


Figure 22: Displacement result of realized model

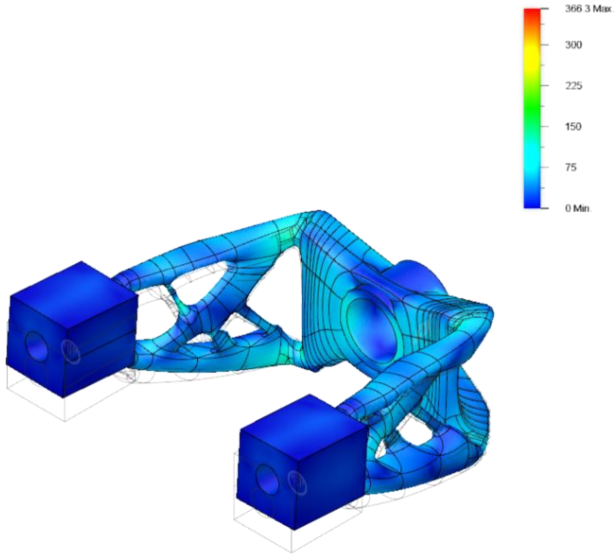


Figure 23: Stress VON MISES result of realized model

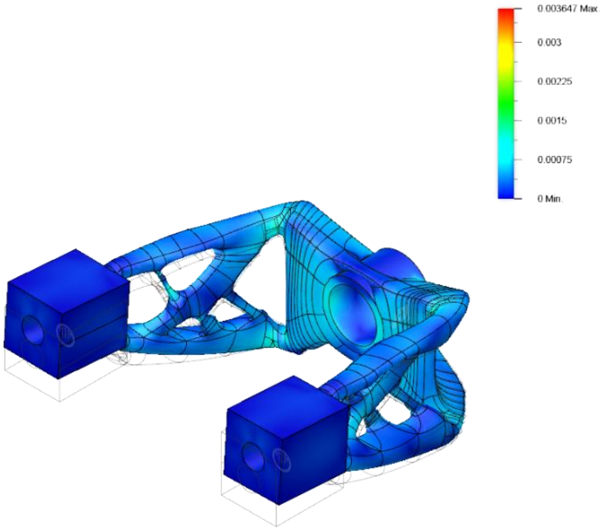


Figure 24: Strain result of realized model

4.4.2. CONCULOSION

- This procedure of optimizing the clip was straightforward and resulted in a design that was lighter and at the same time fulfilled the requirements.as it mentioned before the maximum stress with VON MISES method 366.3 MPa (Figure 19,23) that is less than 80% of max Stress Strength of material (800 and 1520 MPa).

MaragingSteel MS1- As Built

$\sigma_y = 366\ MPa$ $\sigma_{max} = 0.8\ .1100 = 800\ MPa$ so $\sigma_{max} > \ \sigma_m$

MaragingSteel MS1- After age Hardening

$\sigma_y = 366\ MPa$ $\sigma_{max} = 0.8\ .1900 = 1520\ MPa$ so $\sigma_{max} > \ \sigma_m$

According to Safety Factor results (Figure 17,21) the Min SF of realized gripper before hardening treatment is less than 3 and after its treatment is higher than 3. So based to safety factor definition as bellow:

SF= Material Strength / Actual Stress

It can be derived that this realized model satisfied all requirement of problem definition with 30 % of mass of the original gripper.

4.5. Additive Manufacturing of Optimized Gripper

After realizing, the model based to Topology optimization result, as a next step in this thesis the Production method (AM) is discussed. As it can be found in the Chapter 2. There are many Technologies in AM and according to kind of materials (polymers, Metals, Ceramics) the Metal Technology is assumed due to problem definitions and requirements.

Metal technology is divided to several methods as bellow;

- SLS™- Selective Laser Sintering;
- DMLS™-Direct Metal Laser Sintering;
- SLM™- Selective Laser Melting:
- EBM™- Electron Beam Melting;
- SHS™- Selective Heat Sintering;
- MJF™- Multi-Jet Fusion

DMLS technology is defined from other techniques to this thesis according to the following advantages:

✓ Better finish and structures
✓ Bigger size of build envelope
✓ Already established in the automotive industry
✓ Many machine suppliers
✓ Can handle many different material
✗ Slower build process

With this as a background, a benchmark of many of the most well-known DMLS system suppliers was done to find the most suitable machine for the simulation.

These suppliers are the most famous and established companies in the industry. From this benchmark, Concept Laser, EOS and SLM solutions were the three best alternatives for the study parameters above. These three machines are checked in the software **Autodesk Netfabb 2019** [34] which is a software for build simulations. Concept Lasers machine was not available for software simulations so it was only two solutions left. These two machines are compared with the same component to check which performed best in fact of volume and build speed. the simulation of both machines is evaluated and compared together.

AM System Suppliers					
Supplier	Model	Technology	Build Size (X x Y x Z) MM	Deposition (cm^3/h)	Laser Power
3D Systems	ProX DMP 320	DMLS	275x275x420	Not available	500W
EOS	**M 290** **M 400**	**DMLS**	**250x250x325** **400x400x400**	**100**	**4x400W**
SLM Solution	**SLM 500 HL**	**DMLS**	**500x280x365**	**105**	**4x700W**
Phenix Systems	PXL System	DMLS	250x250x300	Not available	500W
Renishaw	RenAM 500M	DMLS	250x250x350	Not available	500W
Concept Laser	X LINE 2000R	DMLS	800x400x500	120	2x1000W
Realizer	SLM 300i	DMLS	300x300x300	37	1000W
Arcam	Arcam A2X	EBM	200x200x380	Not available	8000W

Table 5: AM System suppliers

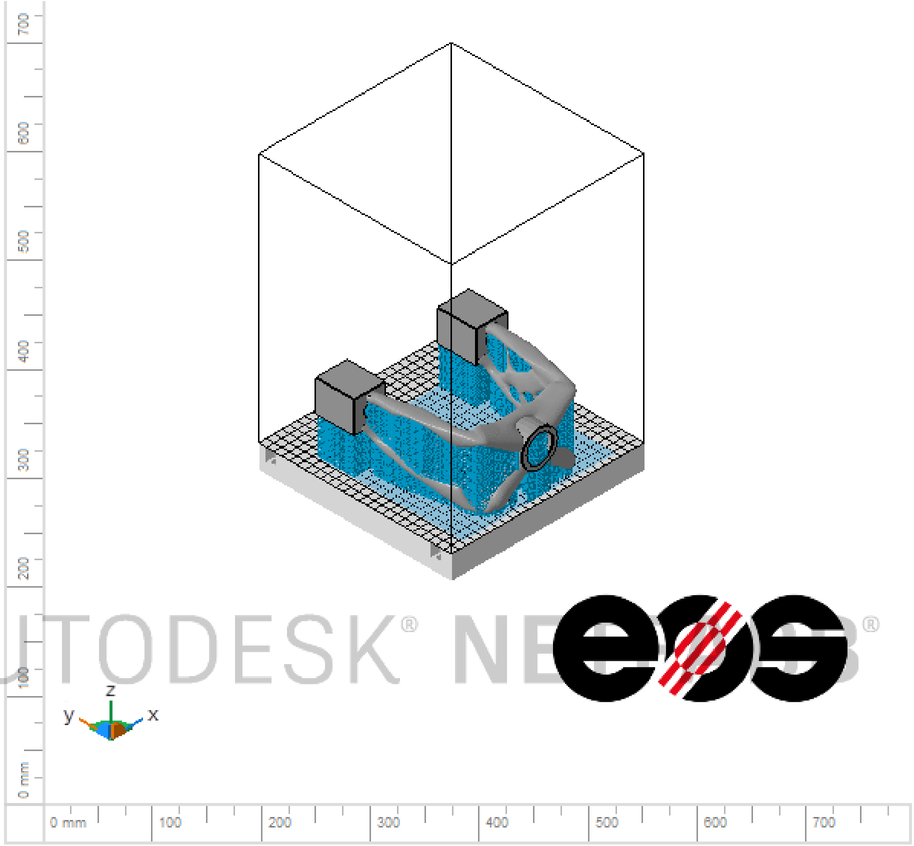


Figure 25: Realized Gripper in an EOS M 290

EOS M 290	
Gripper Volume (cm^3)	386.35
Support Volume (cm^3)	32.78
Build height (mm)	88.08
Build Time (h)	88:43:17

Table 6: Build properties of EOS M 290

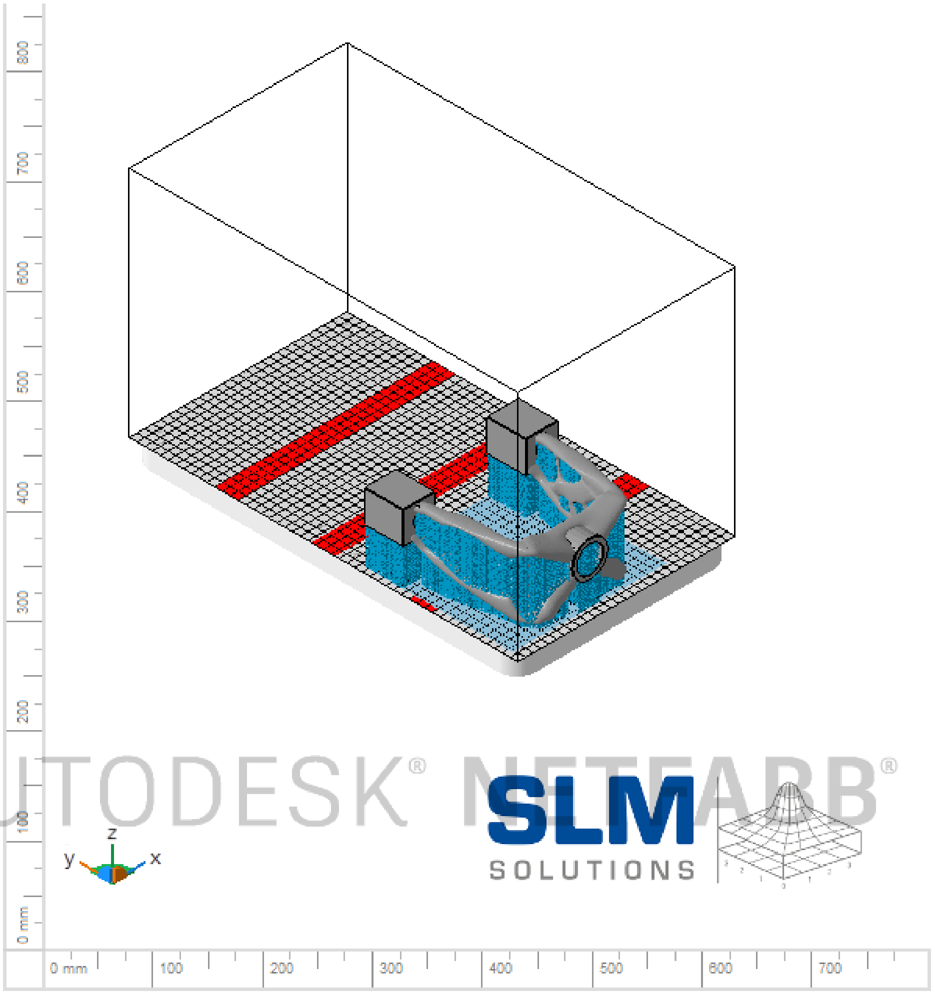


Figure 26: Realized Gripper in an SLM 500 HL – CASE (a)

SLM 500 HL	
Gripper Volume (cm^3)	386.35
Support Volume (cm^3)	32.80
Build height (mm)	88.08
Build Time (h)	76:52:22

Table 7: Build properties of SLM 500 HL – CASE (a)

The EOS machine could build Gripper in 88:43 hours and the SLM 500 HL [35] could print gripper in 76:22 hours. It gives the EOS m 290 a build rate of 12 hours higher than SLM 500 HL. Therefore, due to build speed and Cost evaluation SLM 500 HL had better performance so it is selected for all the simulations.

As it can be seen in Figure 25, 26 the gripper is planted on platform of machine while printing so in the next step it is tried to use change the orientation of printing in order to reduce time and cost of building.

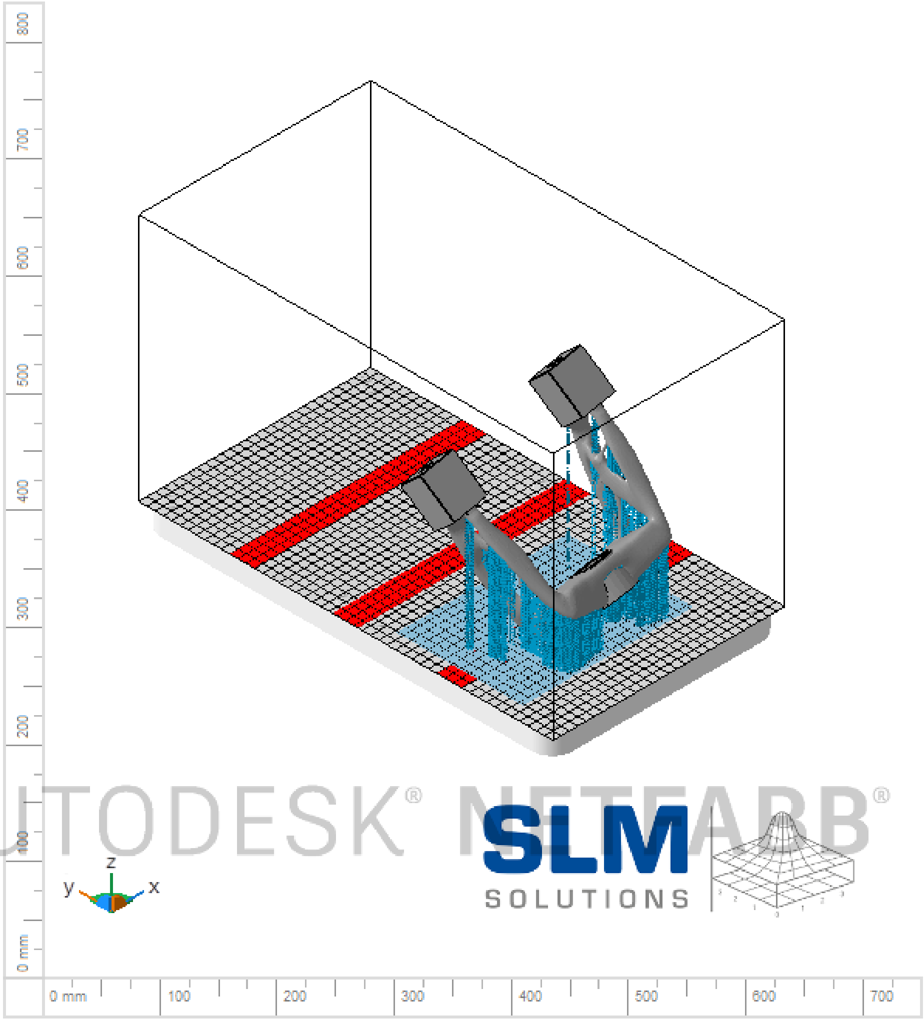


Figure 27: Realized Gripper in an SLM 500 HL – CASE (b)

SLM 500 HL	
Gripper Volume (cm^3)	386.35
Support Volume (cm^3)	14.35
Build height (mm)	218.03
Build Time (h)	85:52:38

Table 8: Build properties of SLM 500 HL – CASE (b)

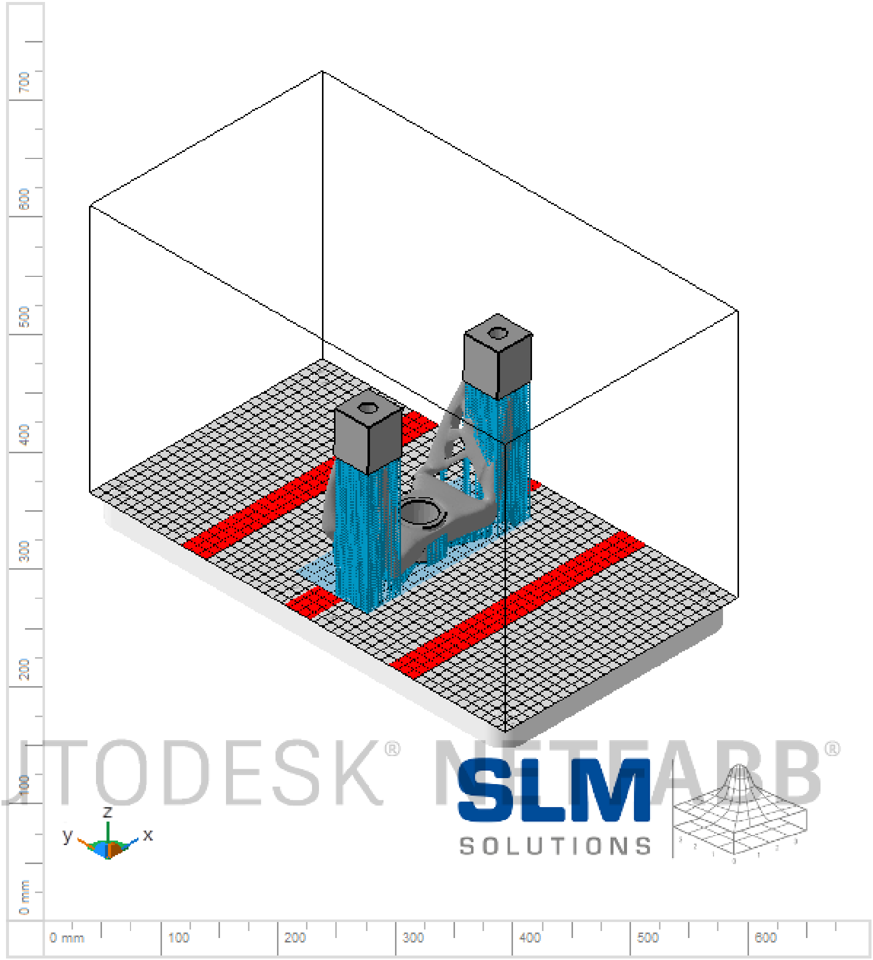


Figure 28: Realized Gripper in an SLM 500 HL – CASE (c)

SLM 500 HL	
Gripper Volume (cm^3)	386.35
Support Volume (cm^3)	24.09
Build height (mm)	194.40
Build Time (h)	85:17:13

Table 9: Build properties of SLM 500 HL – CASE (c)

According to the Table 7, 8, 9 CASE (a) had the minimum build time about 77 hours. However, it does not mean that case (a) it is a best orientation of printing of optimized gripper because it has to consider about post processing operations like leaving temporary supports which is helped during printing and clearing and creating smoothed surface and other criteria like this. In the next step it is evaluated the Cost and Sustainability of this product in order to find the best orientation of 3D printing in AM technologies and also it is compared the differences between CM and AM as a cost and sustainability point of view.

4.6. Cost and Sustainability of AM

4.6.1. Manufacturing Cost Analysis

AM building cost:

According to the pervious chapter result for Additive manufacturing by Autodesk NETFABB, three possible calculation are evaluated to understand the minimum cost of realized gripper. As it can be seen in Appendix (A) the Total Cost of building of optimized gripper with Additive manufacturing method for Case (a) is 3537.3 € for Case (b) is 3509.5 € and for Case (c) is 3734.2 € .

Therefore, Case (a) and (c) had a higher product Price than case (b).

Although in case (a) the building time is less than case (b) but as it mentioned before based to orientation of product during 3d Printing in order to create less support which made post processing work it has to be tilted the product.

In following it is compared the Cost of AM and CM method.

CM building cost:

According to the Appendix (B), the Total Cost of building of in CM is about 625 €.

As a brief comparison between to methods, it can be understood that the CM production method is better according to defined product of this project because of grade of complexity of my product.

4.6.2. Sustainability Analysis

The Eco-indicator values are intended to be applied by designers and product managers for the assessment of environmental aspects of product systems. The Standard Eco-indicators are numbers that express the total environmental load of a product or a process. These indicators are found in the "Eco-indicator 99 Manual for Designers, a damage oriented method for life cycle impact assessment", published by Ministry of Housing, Spatial Planning and the Environment, in Netherlands, in October 2000. The Eco-indicator methodology conforms well to the ISO 14042 standard on life cycle impact assessment.

The standard Eco-indicator values are regarded as dimensionless figures. As a name, the Eco-indicator point (Pt) is used. The unit millipoint (mPt) is used (so 100 mPt = 0.1 Pt). The scale is chosen in such way that a value of 1 Pt is representative for onethousandth (1 kPt) of the yearly environmental load of one average European inhabitant [36].

For the purposes of this study, the method of Eco-indicator 99 has been used in order to estimate the Environmental Impact (EI) of the manufacturing of a Gripper with conventional technologies (original scenario) and the EI of the same gripper AM using MS1 and the SLM 500 HL machine. The purpose is to compare the EI of these two methods.

The Eco-indicators of the production of the components are based to mPts per 1 kg so the mPts of each process is calculated by multiplying the indicator by the mass of each material.

The Eco-indicator manual does not contain any indicators for any AM technologies so the Eco-indictor of the SLM 500 HL machine must be calculated. A study performed at Loughborough University on the AM250 SLM machine by Renishaw (the study uses the former name MTT SLM 250 of the same machine) using the Stainless Steel 316L powder calculates the power consumption of the machine. The study focuses on the electrical consumption of the machine during the process. The average energy consumed per kg is calculated to 31 kWh [37]. Moreover, the EI of the SLM 500 HL machine is evaluated according to the following equation:

$$EI = fc_{electricity} \times ECR$$

Where ECR is the Energy Consumption Rate or massive energy use during the process such as :

$$ECR = \frac{P}{PP} = \frac{P}{q_{mat} \times \rho_{mat}}$$

In addition (=10 mPts/kWh) is the indicator which allows to convert a massive energy (ECR) to an environmental impact per kg express in mPts/kg. In the above equation, represents the electric power consume by the laser during manufacturing (in W), represents the process productivity (in kg/h), represents the quantity of powder fused per hour (in cm^3/h) and is the density of the material (in kg/cm^3) [38]

Consequently, since the ECR is 31 kWh/kg, the EI of the SLM 500 HL machine using MS1 as a powder material is calculated to 310 mPts/kg. This value is used as the Eco-indicator of the “SLM 250” process.

The table can now be filled in for each phase in the life cycle and the relevant Eco-indictor values can be recorded. The score is then calculated for each process and recorded in the “result” column. The results of the EI of each phase are added and result in the total EI of the life cycle of the Gripper.

The Table 10 shows the EI (mPts) calculated for every phase of the life cycle of the turbocharger together with the sum of them compared with the EI. The fully completed forms of both life cycles of the turbocharger can be found in the Appendix (C) and Appendix (D).

Phase	AM	CM
Production [mPt]	1194.8	2750
Processing [mPt]	4018.5	8000
Disposal [mPt]	-20.22	-148.7
Total [mPt]	5485.47	11165.3

Table 10 : The EI (in mPts) for each phase for both AM anc CM technologies

The phase of the production of each component has obviously the greatest impact on the environment. The development of the Gripper with AM technologies by Topology optimization reduces the EI from 11165.3 mPts to 5485.47 mPts. So based to TO for AM contributes to about 50.9 %.

It is significant that there are material production processes in the life cycle of the Gripper that contribute a lot to the total EI of the production phase.

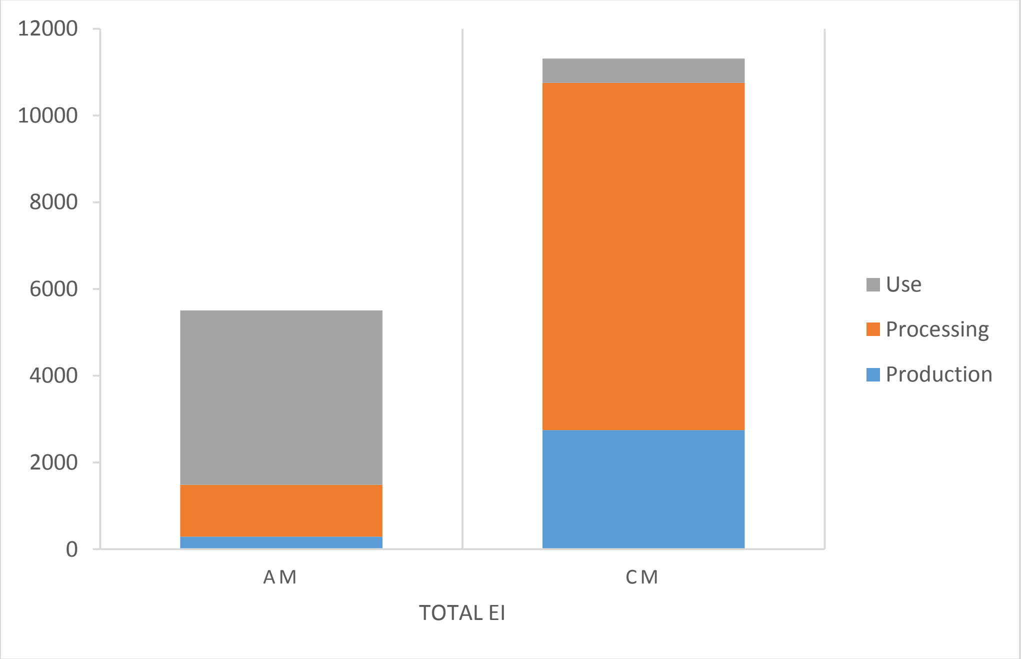


Chart 2: A comparative chart of the EI for the total LC of Gripper

A comparative Chart 2 illustrates the EI of the total life cycle of the gripper for both Technologies and the EI of just the phase of the production of the components of the turbocharger for both of them.

5. Conclusion and Discussion

5.1. Conclusion

Additive Manufacturing (AM) comprises technologies that create objects sequentially adding layers over each other. The technologies are grouped according to the material that they use. During the last few years there have been improvements in the metal technologies along with the metal materials used. Analysis over different technologies and machines of metal AM has shown that the technologies are not only different in terms of processes and machines, but also in terms of material, post processing and the desired accuracy. So one should carefully decide which technology should be chosen for each product type.

During the recent years the substantial improvements in terms of production cost, materials properties, part quality and accuracy of technologies, made AM a more competitive manufacturing way over different industrial applications. Benefited from flexible and low cost manufacturing solutions, AM production has been applied in several markets and industries such as Aerospace – Automotive – Customer product – Medical and … .

An optimized gripper with TO application reduced the mass of product with AM technology to 30% of original gripper, which was manufactured by CM technology. One of the development statements of the gripper with AM is the production with the necessary functional part resulting that uses much less material. The machine chosen for this development is SLM 500 HL which uses SLM/DMLS technology together with MaragingSteel MS1 as material input due to its high mechanical properties. It is worth mentioning that during the research of the metal material properties for the study of AM, it was unforeseen that parts produced with metal AM technologies have almost the same or sometimes superior mechanical properties with the conventional manufactured parts. Many advances have been made in the field of metall materials for the use in AM.

Furthermore, an analysis of the sustainability potential of the development of the critical component with AM is carried out. The results indicate that the SLM/DMLS technology has less environmental impact in comparison with CM. However, the analysis is based only on literature and estimations have been made due to limitations. There is no available software to use database for the environmental impact of any AM technologies. Besides these barriers the calculation and the comparison of the environmental impact of both ways of manufacturing was carried out following the Eco-indicator 99 method. For AM the impact of the production phase is based on the electrical energy which is used by the machine and estimations have been made for the impact that occurs due to the conversion of the metal bulk material to metallic powder. LCA attributed about 87.5

% less environmental impact to the use of AM for the production of the gripper. In addition, the production cost of the aforementioned development has been estimated. High material and machine prices and low built rates produce expensive products compared with the conventional manufacturing costs.

5.2. Discussion

The sustainability evaluation for new coming technology is necessary and it will help to provide improvement opportunities for the new product designers. The literature survey indicates that due to the variety of processing procedures and materials used, there exist both positive and negative opinions as for the environmental impact of 3D printing, and it is not easy to draw an exact conclusion. A reasonable conclusion is that the environmental impact of 3D printing is case-by-case depending on specific situation.

In order to better evaluate the sustainability of 3D printing processes quantitatively and better guide the decision-makers, this paper proposed a framework for 3D printing processes sustainability assessment. The integration of product CAD and LCA can realize the improvement in the early design stage, which is an essential step for 3D printing.

To realize the sustainable manufacturing is the goal in current industries, it’s unclear exactly how far we could go with 3D printing or if it will finally be marked as purely sustainable, but certainly it is a worthy study area now and in the future.

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Appendix

Appendix (A): Production Building Cost by AM

ADDETIVE MANUFACTRING			
	CASE (a)	CASE (b)	CASE (c)
Material	MS1	MS1	MS1
Part volume [cm^3]	386.35	386.35	386.35
support volume [cm^3]	32.8	14.35	24.9
Post Procecing volume[cm^3]	7.727	7.727	7.727
(Scale 2:100)			
Total post processing	40.527	22.077	32.627
Total volume [cm^3]	426.877	408.427	418.977
Density [kg/m^3]	8000	8000	8000
Total weight [kg]	3.415016	3.267416	3.351816
Material price [€/kg]	120	120	120
Material cost [€]	409.8019	392.0899	402.2179
Building time [hr]	76.5	85.5	85.2
Building price [€/hr]	35	35	35
Building cost [€]	2677.5	2992.5	2982
Post Processing time	9	2.5	7
Post Processing price [€/hr]	50	50	50
Post Processing cost [€]	450	125	350
Product Building cost [€]	3537.302	3509.59	3734.218

Appendix (B): Production Building Cost by CM

CONVECTIONAL MANUFACTRING	
Material	Fe360
Part volume [cm^3]	1276.2
Density [kg/m^3]	7800
Total weight [kg]	9.95436
Material price [€/kg]	2.5
Material cost [€]	25
Building time [hr]	12
Building price [€/hr]	50
Building cost	600
Product Building cost [€]	625

Appendix (C): LCI of AM

Addetive Manufacturing				
Production of ferro metals (in Millipoints per kg)				
Material	Amount	Unit	Indicator	Result
MaragingSteel MS1	3.4	kg	86	292.4
		mPt		292.4
Processing of ferro metals (in Millipoints per kg)				
Process	Amount	Unit	Indicator	Result
SLM 500 (50% Solidity)	3.4	kg	310	1054
Post processing	0.176	kg	800	140.8
		mPt		1194.8
Use (Electricity)				
Process	Amount	Unit	Indicator	Result
Electricity LV Ittaly 47	85.5	kWh	47	4018.5
		mPt		4018.5
Disposal (disposal processes per type of material)				
Process	Amount	Unit	Indicator	Result
Incineration Steel (22% in Europe)	0.748	kg	-32	-23.936
Landfill steel (78% in Europe)	2.652	kg	1.4	3.7128
		mPt		-20.2232
Total (all Phases)				5485.477

Appendix (D): LCI of CM

Convectional Manufacturing				
Production of ferro metals (in Millipoints per kg)				
Material or Process	Amount	Unit	Indicator	Result
FE360	25	kg	110	2750
		mPt		2750
Processing of ferro metals (in Millipoints per kg)				
Process	Amount	Unit	Indicator	Result
Milling, Turning, Drilling	10	kg	800	8000
		mPt		8000
Use (energy)				
Process	Amount	Unit	Indicator	Result
Electricity LV Ittaly 47	12	kWh	47	564
		mPt		564
Disposal (disposal processes per type of material)				
Process	Amount	Unit	Indicator	Result
Incineration Steel (22% in Europe)	5.5	kg	-32	-176
Landfill steel (78% in Europe)	19.5	kg	1.4	27.3
		mPt		-148.7
Total (all Phases)		mPt		11165.3