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Master’s Degree Thesis

Methods for improved build feasibility in Additive Manufacturing

Supervisor
Prof. Daniele Botto

Candidate
Luciano Coniglio

Tutor
Ing. Edoardo Peradotto

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Ai miei Genitori, sempre presenti

ad ogni traguardo della mia vita

Index

Acronyms

AF	Additive Fabrication
AM	Additive Manufacturing
CAD	Computer Aided Design
CNC	Computer Numerical Control
DED	Direct Energy Deposition
DFAM	Design For Additive Manufacturing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
FE	Finite Element
FEA	Finite Element Analysis
FR	Frequency Response
HCF	High Cycle Fatigue
HIP	Hot Isostatic Pressing
HW	Hardware
LB	Lower Bound
LCF	Low Cycle Fatigue
LENS	Laser Engineered Net Sharping
LPBF	Laser Powder Bed Fusion
NURBS	Non-Uniform Rational Basis-Splines
PBF	Powder Bed Fusion
RP	Rapid Prototyping

SHS	Selective Heat Sintering
SIMP	Solid Isotropic Material with Penalization
SO	Structural Optimization
SLA	Stereo Lithography Apparatus
SLM	Selective Laser Melting
SLS	Selective Lase Sintering
STL	Stereolithography
SW	Software
UB	Upper Bound

Introduction

Additive Manufacturing (AM) is considered one of the most important emerging technologies in the last years and it is developing more and more in the industrial field, considered an important pivot of the industrial revolution 4.0.

The substantial difference from traditional technologies, considered subtractive, is that the part is built one layer at the time. Each successive layer is bonded to the preceding layer of melted or partially melted material. This allows lighter, more complex and more performing components, but at the same time the potential offered freedom is limited when complex geometries are printed. Additional support structures are often required in order to sustain overhanging parts but also to reduce the thermal warping, to minimize the residual stresses and to dissipate the heat generated during the melt. These structures are built with the part and at the end of the process they are removed, resulting an increase in manufacturing time and costs.

The aim of this thesis is to develop a methodology which allows to apply the concept of Topology Optimization in the design of the support structures for metal AM, defining a better distribution of the material, improving their structural and thermal behaviour, trying to minimize the amount of material dedicated to the support structures. The methodology is applied to the Rake component, used for diagnostic wind tunnel testing in order to determine the thermo-fluid dynamics conditions along the wall of a model or within the tunnel itself. In order to validate the goodness of the methodology, it has been considered a comparison made in terms of performance between optimized support structures and traditional support structures.

Many software are utilized in the definition of the whole methodology: a CAD software, a FEA software, a simulator of additive fabrication (AF) and MATLAB. The work has been developed in collaboration with Polytechnic University of Turin and GE Avio Aero, *"a GE Aviation business that designs, manufactures and maintains components and systems for civil and military aviation"*.

In the last years GE Avio Aero has become an important reference of innovative technological solutions, especially in AM. Just to cite some examples, Cameri plant (inaugurated in 2013), is one of the largest factory in the world entirely dedicated to additive manufacturing and in 2017 Avio Aero created, in collaboration with Polytechnic of University of Turin, the Turin Additive Laboratory (TAL), *"a joint lab created to collaborate on strategic research topics for the aviation industry, such as identifying new materials for this production technology."*

Literature

In this section it is provided a summary of what the different chapters deal with.

The first chapter includes a brief overview of the additive fabrication and it provides technical notions about the two main powder bed additive manufacturing processes: Selective Laser Melting and Electron beam melting.

The following two chapters provide notions about all the phases and the aspects to keep in mind during the design for AM. Starting from the study of the geometry and the functionality of the original component, up to the printing of the optimized component. At each step, the critical issues and constraints to be respected are analyzed in order to correctly execute the entire lifecycle.

The fourth chapter is a deepening of a topic already discussed in chapter 2: structural optimization. It provides a detailed description of the optimization concept and all the different methods of optimization.

The following chapter is an overview of all the conventional support structures. The advantages and disadvantages of these important structures are descripted, in particular the defects that can be generated and the techniques of removal of these structures are analyzed.

The last chapter describes the steps which led to the definition of the iterative procedure applied to realize the topology optimization of the support structures, with the aim of reducing the volume but at the same time guaranteeing a greater rigidity to the component to be supported. The steps of this methodology are applied to support the Rake. At the end of the iteration a comparison with traditional supports structures, shows all the benefits that could be achieved.

1 Additive Manufacturing

In this chapter a brief introduction of the history of Additive Manufacturing is firstly presented, in which the advantages and disadvantages of this technology are described. Furthermore, in the chapter there is a description of the main technologies applied on metal materials.

1.1 Introduction

The origins of additive manufacturing date back to the late 1980, noted under the name of Rapid Prototyping (RP). This term is used in industries to describe a process for rapidly creating a system on part representation before final release or commercialization [15]. The first commercial success was achieved in 1987 with the stereo lithography apparatus (SLA) by 3D System called SLA-1. Starting from there many technologies followed as the selective laser sintering (SLS) in 1992 by DTM company (today incorporated into 3D system).

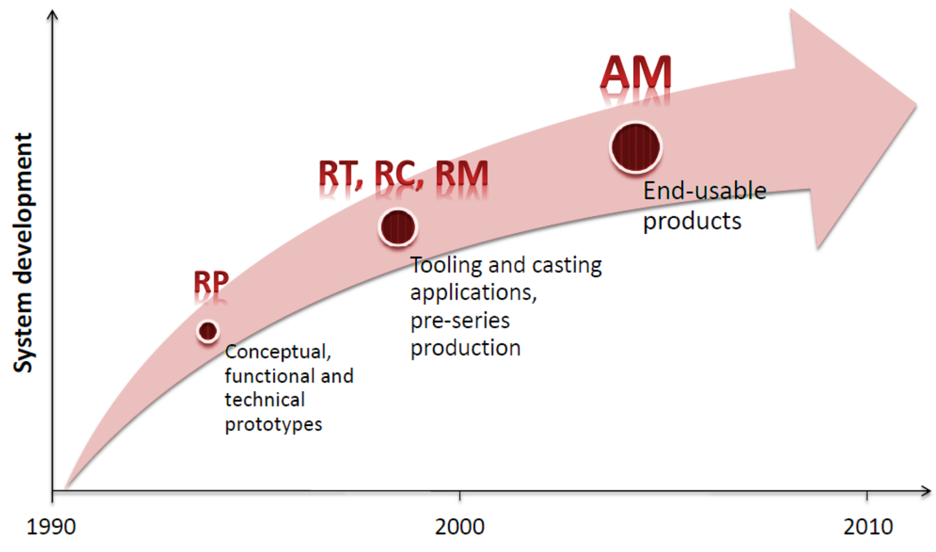

Figure 1.1 Historical Development of AM [20]

For the first time the AM terminology was defined in ASTM F2792 standard, but it was replaced a few years later by the ISO/ASTM 52900 standard which define AM as *"a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"* [35].

In the last twenty years, this technology has considerably evolved. New technologies and materials have been developed, while existing technologies continued to evolve becoming increasingly precise and fast. Although used in the industrial field since its inception, the AM was used specifically to create visualization models for products. They were being developed, as "model making". Models were employed to supply information about what is known as the "3 F": Form, Fit and Function. Now AM represents the present and above all the future of the manufacturing industry.

Today this technology has developed above all in medical field, for the production of jewels and mainly in the aeronautical and automotive fields, using polymeric, ceramic, metal and composite materials.

Among the advantages of Additive Manufacturing, surely the main one is the possibility of realizing complex shapes and geometries that cannot be realized with traditional technologies, creating assemblies, therefore reducing the number of joints and connections, and so decreasing the costs of the raw material and the manufacturing.

The technologies can be classified according to various criteria. The most used one is to distinguish the state of the basic material (powder, wire, foil) and then to classify the technologies according to the energy source used. The following paragraph describes the two most important technologies applied to metallic materials related to powder bed fusion technologies: Selective Laser Melting (SLM) and Electron Beam Melting (EBM).

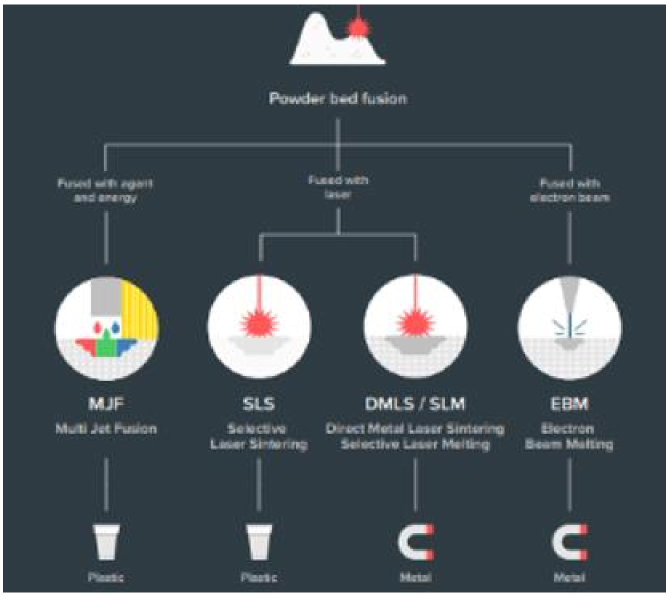

Figure 1.2 Examples of Powder Bed Fusion technologies

1.2 Powder Bed Fusion

PBF processes were among the first commercialized AM processes. There are several variants of this technology, but the working principle is almost the same. It includes the following printing techniques:

- Direct Metal Laser Sintering (DMLS);
- Electron Beam Melting (EBM);
- Selective Heat Sintering (SHS);
- Selective Laser Melting (SLM);
- Selective Laser Sintering (SLS);
- Laser Engineered Net Sharping (LENS).

In the powder form, the material can have a diameter ranging from a few tens of microns to a few hundred microns. The energy that induces fusion of the powder (melting or sintering) and links the following layer with the previous one, is entrusted by laser or electron beam.

The PBF methods provide for the feeding and spreading of the powder on the building plate or over previous layers, by a blade or a wiper mechanism. The space between the surface of the plate or the last layer built and the lower surface of the powder diffusion mechanism defines the layer thickness and the height. In general, for EBM technology, the average layer thickness is about 70-200 microns and 30-50 microns for SLM technology. Layer height is an important factor in the powder bed fusion process and is carefully selected and calibrated against other build parameters and factors in the system such as energy beam geometry, power, as well as powder particle size and size distribution [17]. Once the powder is placed, the laser or electron beam is focused on it and rasterize across the powder surface in a pattern to fill the area defined by one slice of the desired 3D model.

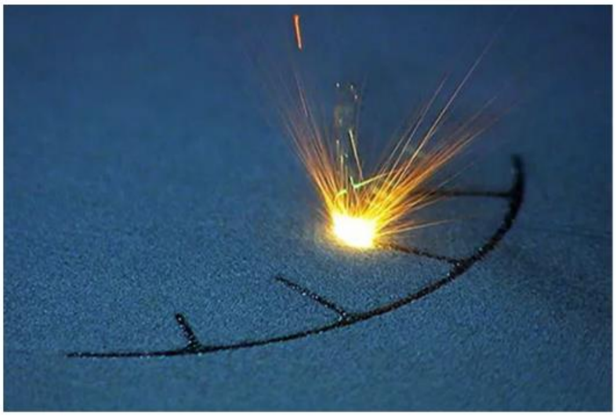

Figure 1.3 Power Bed Fusion

The raster pattern is a factor that determines the quality, the micro structure and the presence of defects. At each completed layer, the build platform drops down, allowing the creation of the next layer. For a good adhesion of the layers and to avoid layer delamination, the energy source must be able to re-melt a portion of the previously solidified layer. At the conclusion of the process the remaining loose powder is blasted away and, once gathered, it is re-used for the next project. The used amount of powder is in any case lower than the traditional techniques defined as subtractive.

In the following table, and in the paragraphs below, the substantial differences between the two main techniques of this category are reported: EBM and SLM.

Characteristic	***Electron Beam Melting***	***Selective Laser Melting***
Thermal Source	Electron Beam	Laser
Scanning	Deflection coils	Galvanometers
Atmosphere	Vacuum	Inert gas
Energy Absorption	Conductivity-limited	Absorptivity-Limited
Scan Speeds	Very fast, magnetically driven	Limited by galvanometer inertia
Powder pre-heating	Use electron beam	Use infrared heaters
Surface Finishing	Moderate to poor	Excellent to moderate
Feature Resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metal and ceramics
Energy Costs	Moderate	High

Table 1.1 Differences between EBM and SLM

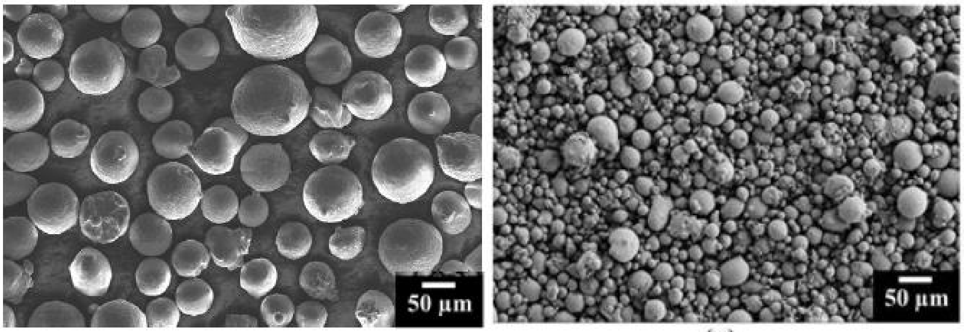

Figure 1.4 EBM powder (left) and SLM powder (right) [39]

1.2.1 Selective Laser Melting

Widely used in aerospace, automotive and industrial applications, it guarantees excellent mechanical properties to the produced parts. However, they are not always able to satisfy the requirements, so it is necessary to submit the parts to heat treatments in order to increase the performance. SLM compared to other PBF techniques, requires the use of inert gas, high energy costs with low energy efficiency (10%-20%), but as an advantage, it is definitely one of the fastest techniques.

SLM makes it possible to produce metal components, layer by layer, overcoming the design limits of the traditional methods, according to a 3D-CAD volume model. The whole process is controlled by an industrial computer that steers the laser beam, obtaining the melting tracks of the different layers that join each other through the fusion process. The laser beam scans across the top powder bed, exposing areas corresponding to the cross-section of the part at a certain height. The build platform will lower after the current layer has been exposed to the laser. The dispensing platform rises allowing the recoated blade assembly to sweep across from right to left, spreading a layer of metal powder across the powder bed. The collecting platform lowers to accommodate overflow powder as the recoater blade sweeps over top. This process repeats itself until the part is fully constructed, which may result from exposing thousands of layers that are microns in thickness [38]. The whole process takes place in a chamber in the presence of nitrogen or argon gas to provide an inert atmosphere to protect the heated metal parts from oxidation.

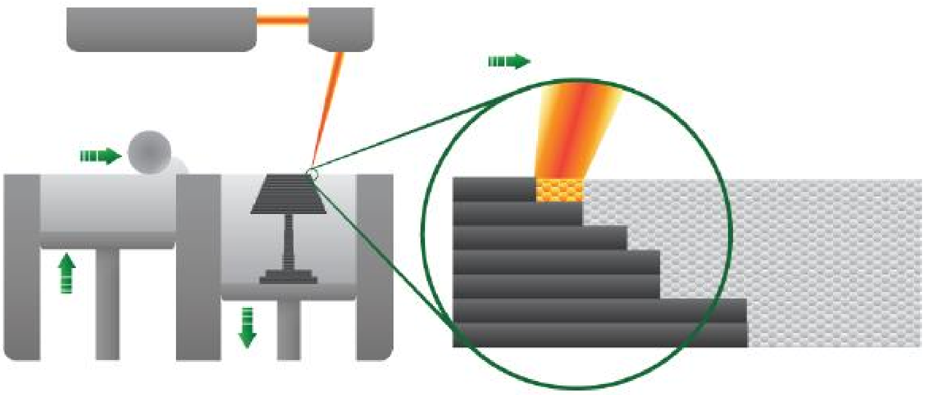

Figure 1.5 SLM process [39]

The parameters defined by the machine and by the part as point distance, exposure time, scanning speed, layer thickness, and building direction, affect the build time and the final quality, including surface microstructure, fatigue strength, hardness, density, and surface roughness. After printing, the excess powder is swept away and the part is separated from the building plate, through a band saw or a wire EDM. The Selective Laser Melting technique can use alloys (nickel alloy, Ti64 etc.) and single component metals such as aluminum.

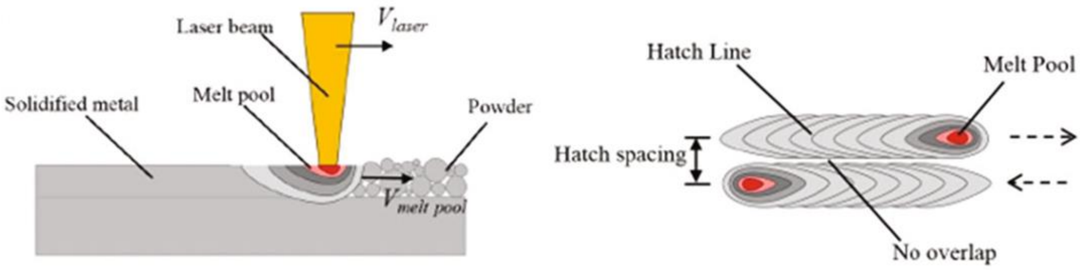

Figure 1.6 Example of SLM process parameters: laser power, layer thickness, scanning speed and hatch spacing [16]

Technical Data	***Selective Laser Melting***
Power	200W – 400W – 1KW
Pre-heating Temperature	Up to 200 °C
Inert Gas	N_2, Ar
Chamber dimension	Up to 400x400x400 mm
Laser speed	350 mm/s
Build rate	1,8 – 10,8 cm^3/h
Layer thickness	30 – 50 microns

Table 1.2 Technical data of SLM process

A particular phenomenon that can be generated during the SLM technique is the balling. It is a phenomenon that happens due to insufficient wetting of the preceding layer and to surface tension, which leads to the formation of material spheres, obstructing the blade passage, forming rough surfaces. In more severe cases, balling may interrupt the SLM process. This phenomenon can be reduced by applying high laser power and low scanning speed, keeping the oxygen level at 0.1%

A description of the advantages and disadvantages of this technique follows:

Advantages

- Very fine microstructure;
- Complex shape component;
- Absence of oxidation, thanks to inert atmosphere;
- Wide range of materials that can be used;
- Possibility of obtaining even density equal to 99.9 % of the theoretical density.

Disadvantages

- High cooling speeds that can lead to cracks in the material;
- Possibility of residual stresses (especially for complex geometries);
- Slow deposition rate.

1.2.2 Electron Beam Melting

It is another PBF-based AM process, with the difference that an electron beam is used to selectively fuse powder bed layer in vacuum chamber. Commercialized by ARCAM in Sweden in 1997, therefore it is a process very similar to the SLM one, where the substantial difference is the source of fusion energy. The operating principle is very simple: a heated tungsten filament emits electrons at high speed which are then controlled by two magnetic fields, focus coil and deflection coil. The first one acts as a magnetic lens, i.e. it concentrates the laser beam (diameters are even less than 0.1mm), and the deflection coil, steers the focused beam to the desired point of the fusion bed. When the electrons impact the powder layer, their kinetic energy is converted into thermal energy which gives way to the fusion of the powder.

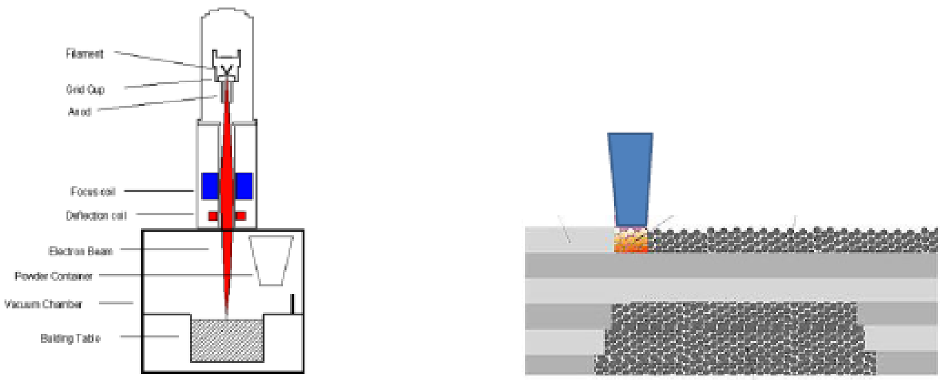

Figure 1.7 EBM process [39]

Each layer of powder bed first undergoes a preheating phase and then the melting phase. In the first one a high scanning speed is used to preheat the powder layer (up to 0.4 - 0.6 Tm) in multiple passes, while in the second stage, a low current beam with a low scanning speed is used to melt the powder. In EBM the powder bed must be conductive. Thus, EBM can only be performed with conductive materials (for example metals).

As in the SLM process, once the layer is completed, the building plate is lowered and is fed by other fresh powder that is distributed. Before the melting, the powder is disorganized with gaps and the layer thickness is about 2–3 times greater than it should be. When the powder is melted, it reduces itself to the correct layer thickness.

Table 1.3 Powder layer thickness before and after melting process [17]

The process ends when all the layers that form the required component are completed. The EBM process takes place under high vacuum of 10^{-3} to 10^{-5} mbar. Helium gas is also introduced to further reduce the vacuum pressure which favors the cooling of the part and the stability of the electron beam. Post-production work involves the removal of excess powder, further cleaning and CNC machining.

Technical Data	***Electron Beam Melting***
Power	3 KW
Pre-heating Temperature	Up to 1000 – 1100 °C
Chamber in vacuum	10^{-3} to 10^{-5} mbar
Chamber dimension	350x350x350 mm
Speed of EB source	8000 mm/s
Build rate	60 cm^3/h
Layer thickness	70 – 200 microns

Table 1.4 Technical data of SLM process

A description of the advantages and disadvantages of this technique follows:

Advantages

- Very fine microstructure, for the high solidification speed;
- High scanning speed which allows a high build rate;

- High power which allows the realization of high layer thicknesses, up to 200 microns;
- Possibility to work also with metals with high affinity with oxygen thanks to the vacuum working condition;
- Absence of porosity;
- Possibility of obtaining even density equal to 99.9 % of the theoretical density;
- Preheating at high temperatures (1000 – 1100 °C) reduces thermal shocks.

Disadvantages

- Possibility to process only electrically conductive materials;
- Limited life of the cathode emitter, that require the change out at intervals that may affect the maintenance and throughput of the AM processing of large pieces requiring significant beam powers and time;
- The high deposition speeds have a negative effect on the surface finishing and on the respect of the required dimensional tolerances;
- EBM not yet fully suitable to process low melting point metal powders, due to the tendency of the latter to evaporate, under vacuum conditions.

2 Design for Additive Manufacturing

The manufacturing industries have begun to consider AM as one of the technologies that will transform the paradigm of manufacturing [17]. In light of this it is necessary to study in depth not only the printing techniques or the different phases of the process chain, but also to acquire how these processes can be effectively utilized to realize designs and functionalities. This concept emerges due to the enormous design freedom provided by AM technologies and it includes three basic steps:

- Problem Definition;
- Design Optimization;
- Design Validation.

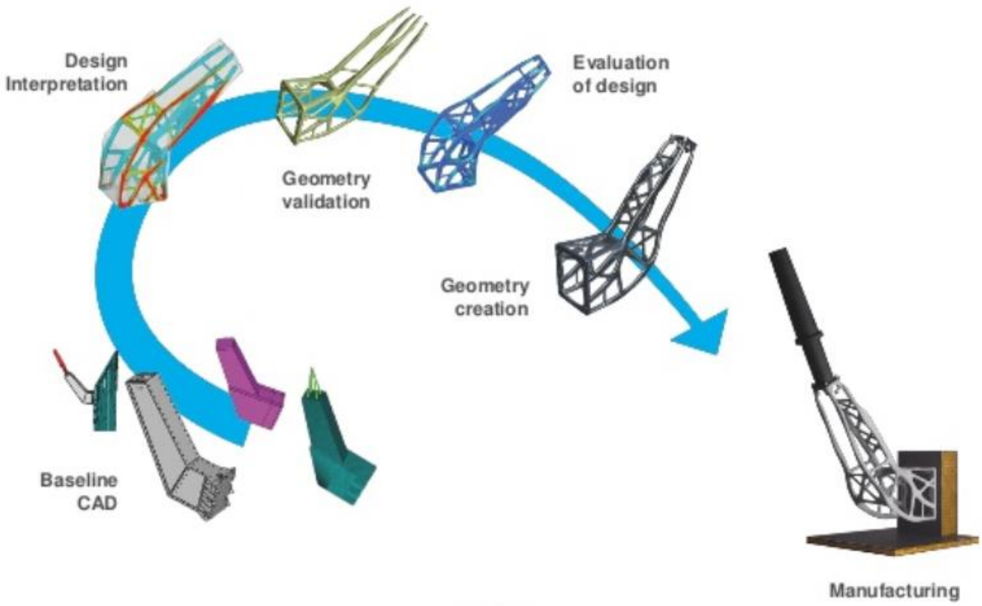

Figure 2.1 Design Process for AM

However, this freedom of design very often contrasts the limits of print production, for example for calibration structures with internal cooling channels, the production by AM is avoided due to the fusion of the powder bed, the powder could be trapped in the inaccessible channels, affecting the cooling performance. Another example is that support strategies are needed for parts with large overhanging areas. Consequently, they could lead to an increase of costs and production times and they might compromise the manufacturability of the parts since the support structures often require labor-intensive manual removal processes.

In the design phase process constraints related to the machine must also be considered. For the material deposition, the nozzle must stay parallel to the vertical axis and avoid collision to the part. The nozzle movement is related to the material deposition speed but also to the component design. To avoid acceleration and deceleration of the nozzle that can lead to manufacture interruptions, sharp angles are avoided and replaced by more curved surfaces. Another important aspect is the heat dissipation during the melting. Introducing support structures into the component design can be a solution (despite the negative aspects described above).

It should be added that additive production exploits more energy than conventional production techniques, mainly for the extraction and processing of the material. However, this use of energy is recovered due to the optimized design of the component and the best performance it can achieve during its operating life. In other words, the design leads to make the component more functional but with less weight and size. For this reason, this technology is structured in the aerospace and automotive sectors, guaranteeing greater efficiency and reduced consumption.

Design for Additive Manufacturing (DFAM) typically means that designers should tailor their designs in order to eliminate manufacturing difficulties and to minimize manufacturing, assembly, and logistics costs. Besides similarly to some traditional manufacturing processes such as casting and welding, many AM processes integrate the geometry generation and the functionality generation (e.g. mechanical and physical properties) in one single manufacturing step. Therefore, during the design of the AM structures, designers must consider not only how to optimize geometries but also how the geometrical designs influence the manufacturing qualities of parts [17].

Using additive manufacturing it is possible to reduce the number of parts of the component and to realize a single complex assembly, thus reducing the joints (screws, bolts, joints) and the production costs.

The figure below shows the construction costs depending on the complexity of the assembly, comparing the traditional techniques with the additive production. For low complexity, the AM is not convenient, but as mentioned above, the freedom of design and the possibility of reducing the number of parts, leads to a reversal of the trend for high complexity.

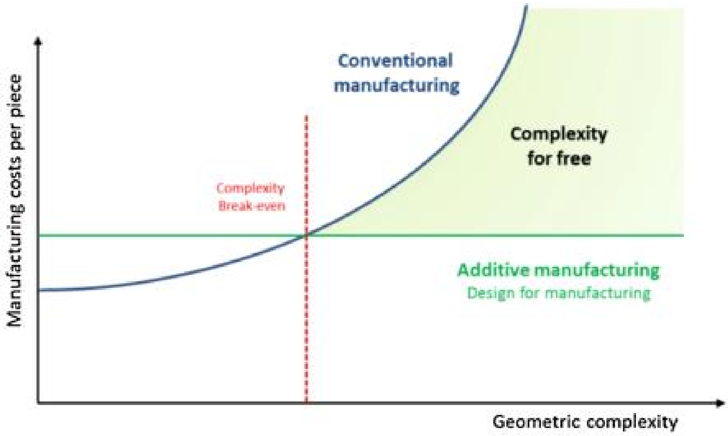

Figure 2.2 Cost per part and Geometry complexity

The main advantages of AM design are descripted [22]:

- *Material complexity:* possibility of a complex composition of materials and the application of different properties on different areas of the component;
- *Functional complexity:* in addition to the production of individual parts, there is the possibility to produce integral functional devices that reduce the number of parts;
- *Reduced material waste;*
- *Part and material variety:* possibility of manufacturing similar parts without investment in extra tools;
- *Low manufacturing skills:* no need for highly skilled professionals to make complex parts and features;
- *Design method:* improvement of the component performance;
- *Cost and geometry complexity:*
- *Hierarchical complexity*: possibility of design different shapes (honeycomb, lattice structures), to reduce costs and increase the stiffness to weight ratio;
- *Quality control;*

2.1 Problem Definition

In this first phase, the component to be optimized must be well characterized. This phase is very important and affects the subsequent steps, the outputs of this pre-processing allow the optimization of the component. In this first phase it is therefore important to understand the geometry of the component, its functionality and the constraints and loads to which it is subjected during its operating life. A FEM model is therefore required, containing all this information, which it is possible to submit the component to different analyses depending on the case: static analysis, HCF, LCF, FR (Frequency Response), modal analysis, and so on. These analyses allow to evaluate the performance of the component that in many cases represent a reference, to be improved for the optimized component.

Moreover, in some applications it is necessary to take in consideration several load cases. It is important to define them at this stage so as to highlight the dimensioning load case.

2.2 Design Optimization

The second phase is the Design Optimization, which has as input the considerations made during the definition of the problem and the output is the optimized part. This phase can be structured in the following steps.

- Definition of working domain;
- Optimization;
- Smoothing;
- Geometry reconstruction;

The working domain represents the component to be optimized and it's broken down in Design Space and Non-Design Space.

The Design Space identifies the work area to be optimized, in which the material can be removed. It is important that it is extended respecting the space constraints, i.e. avoiding interpenetration with the other components. This extension of the Design Space guarantees a certain freedom of the optimization software to dig the material and to realize the load paths. The Non-Design Space represents the area in which the optimization software must not act. They represent all the zones, whose modifications would compromise the component operation. Classic examples are nozzles, fluid-dynamic ducts etc. Both Design Space and Non-Design Space are parts of the component and the distinction of these two areas has a great influence on the final optimization result.

The next step is the optimization. There are different types of optimizations that vary depending on the objective to be achieved (for more information see chapter 4). For a correct optimization it is necessary to define the material of the part and the constraints and the loads to which it is subjected in operating conditions. Then it's necessary to define an objective function and the optimization constraints provided by the responses available for the optimization software. Classic examples of responses can be found in table 4.1. At the end of the iterative optimization process both objective function and optimization constraints must be satisfied.

Before launching optimization, other settings can be applied, for example two important settings in commercial optimization software are MINDIM (minimum size of 2D element) and DISCRETE (defined as $p - 1$, where p is the penalty factor). Beyond the optimization parameters, it's important also to define manufacturing constraints. These ones are considered in the re-building phase of the component, but changes of the optimization result can lead to a reduction in the performance of the component. For this reason, optimization software introduces some manufacturing constraints such as Draw Direction constraints, Extrusion constraints, Pattern grouping, Pattern repetition and the Printing constraint for the AM technology, to avoid overhang surfaces. Using these constraints, the re-building phase is simpler and does not compromise the performance of the component.

After the optimization the next step is the smoothing of the geometry. The smoothing process is a semi-automated design interpretation, facilitating the recovery of a modified geometry resulting from a structural optimization, for further use in the design process and FEA Reanalysis [13].

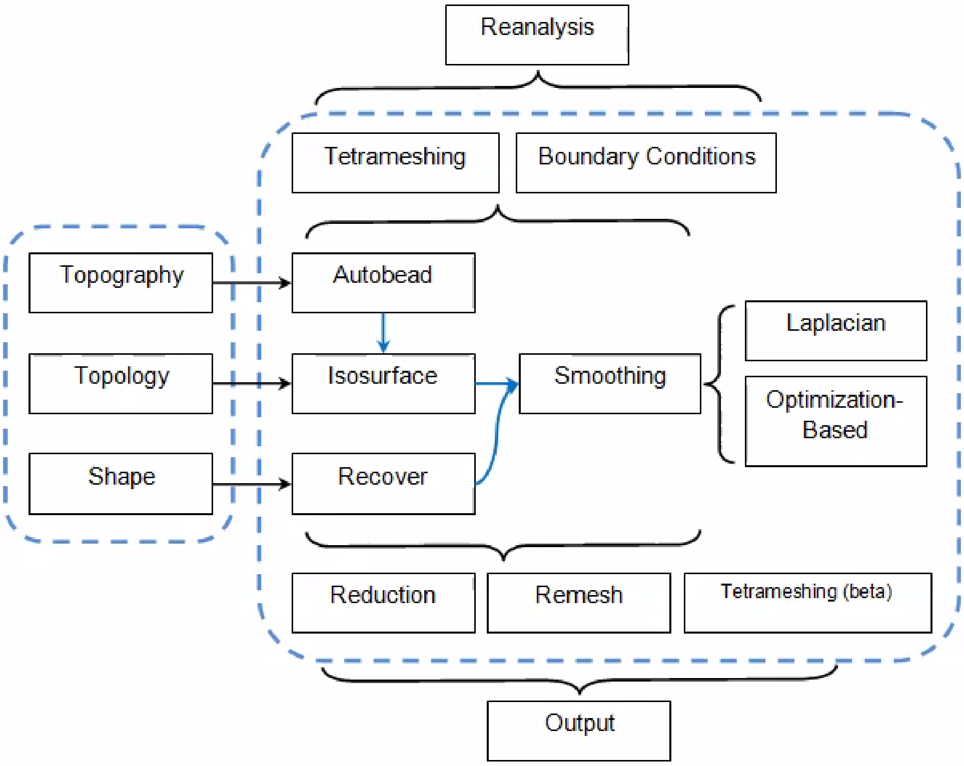

Figure 2.3 Reanalysis process scheme of an optimized component

Smoothing is used to export the geometry for the re-building phase or improves the quality of the component mesh for further analysis, such as topographic optimization. It is good practice to carry out analysis to the geometry optimized before re-building, in order to interpret the optimization results. The most common smoothing methods are Laplacian Smoothing and Optimization-Based Smoothing. The first is the simplest, and morph the different nodes of the Mesh through the following transformation:

$$v_i = \frac{1}{V}\sum_{j=1}^{n} v_j \tag{2.1}$$

Where v_i is the new position of the $i-th$ node, V is the number of adjacent vertices the $i-th$ node and v_j is the position of the $j-th$ adjacent vertex.

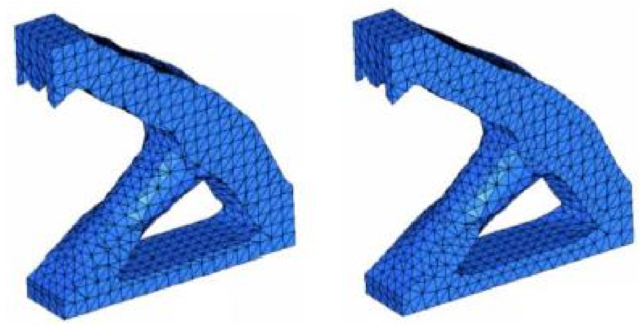

Figure 2.4 Iso-surface before (left) and after (right) Laplacian Smoothing

This smoothing process is very simple, and it is not possible to apply it when there are large distortions in mesh element. In these cases, the Optimization-Based Smoothing gives better results. The process consists of improving the quality of the individual elements of the mesh based on a defined parameter. This can be the minimum size, the maximum angle, the aspect ratio, the distortion. These mesh quality metrics are converted into objective functions, which must be minimized or maximized depending on the case. The relation is the following:

$$f(x) = min\, q_i(x) \tag{2.2}$$

Where f(x) is the objective function and q_i is the mesh quality metric.

The last step of the Design Optimization is the re-building of the part. This phase requires the important knowledge of DFAM, because as mentioned above, the modification of the optimized geometry can lead to a reduction in the performance of the component.

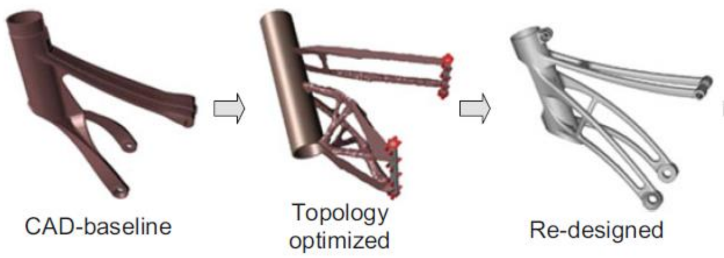

Figure 2.5 Design Optimization Process

Re-building is necessary because the optimized geometry is proposed as a polygonal geometry, it is therefore necessary to give greater continuity and regularity to the surfaces. The simplest method involves the use of simple features such as extrusion, trimming etc. In this case it is important to follow the load paths of the optimized geometry that is used as a simple background. The most complex method uses so-called NURBS (Non-Uniform Rotational Basis-Splines). They are a class of geometric curves used to represent surfaces. Moving the NURBS elements, it is possible to act directly on the optimized component, for the connection between the surface of the part and the NURBS elements.

2.3 Design Validation

After the Design Optimization process, the component has undergone important changes to its design. To validate the final design, it is possible to submit the part to many analyses. They serve to validate the optimized design in terms of mechanical performance compared to existing standard components.

The first structural analysis is a Static analysis, to evaluate the stress and displacement distribution on the part.

In the presence of a high concentration of high stress (which greatly affects fatigue life), the part is submitted to a *"Design Fine Tuning Optimization"* (described in section 4), in order to optimize these local stressed regions.

According to business practice, other tests can be done, for example HCF, LCF, thermal analysis and so on.

Once the validation of part is obtained, the latter is ready to be printed and follow the process chain described in the next section.

3 Additive Manufacturing Process Phases

As any technology, the AM, has a process chain in order to generate a physical 3D part starting from its concept.

- Generation of CAD model of the Design;
- Conversion of CAD model to STL format;
- Transfer and manipulation of STL file on AM machine;
- Build process;
- Part removal and cleanup;
- Post-processing.

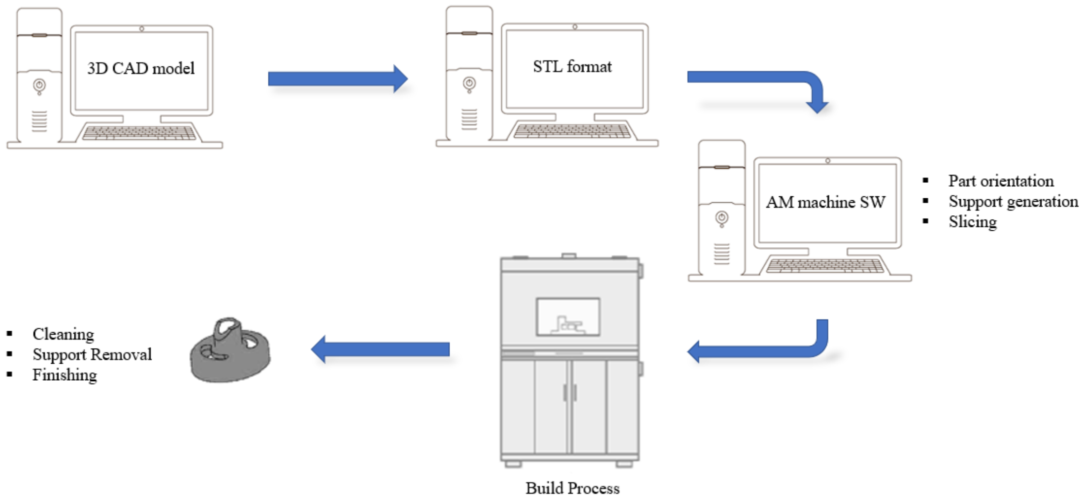

Figure 3.1 The AM process chain

This subdivision is not univocal, the different phases can be grouped or broken-down into other sections, even because the process phases are in constantly evolving and therefore can change. Although the process would look to proceed in one direction, in reality it very often is iterative.

3.1 Generation of CAD model of Design

The process starts with a software model that describes the geometry. This can involve the use of CAD solid modeling software, without them the AM technology wouldn't exist. Therefore, the first step consists to imagine, conceptualize the function and appearance of the product. CAD software are a critical enabler of a designer's ability to generate a 3D CAD model that can serve as the start of an AM process chain [17]. Very often, as explained above, process iterations due to missing feedbacks can lead to changes in the component design. The transition to this first phase of the process is in fact recurrent.

3.2 Conversion of CAD model to STL format

The STL (Stereolithography) is the generic file format for AM technology. It was developed by 3D System, USA in the late 1980. That was the first company to commercialize an AM technology. The STL capture the surface of the CAD model and interprets it as a distribution of triangular elements of different shapes. Each triangle presents a normal vector to allow AM pre-process programs to determine the spatial locations of the surfaces of the part in a build envelope.

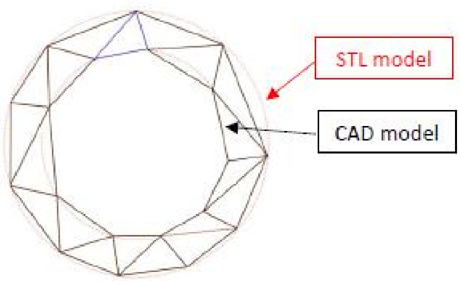

Figure 3.2 Comparison between CAD model and STL model

The STL file doesn't contain further information, these limitations lead to the adoption of a subsequent format: AMF file format. This format is now an international ASTM/ISO standard format [15], which extends the STL format to include, in addition

to geometry, information about material, proprieties, dimensions, color and other additional information.
Common errors in STL file can be the gaps between cells, internal wall, intersection of triangles and inverted normal.

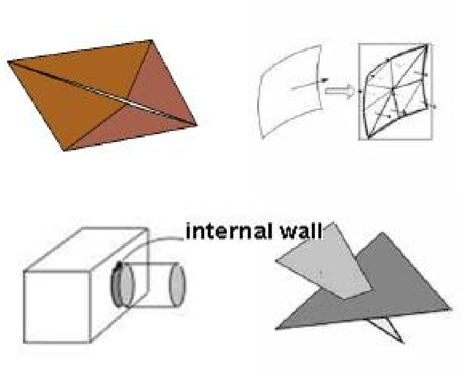

Figure 3.3 Errors in STL file

Currently, the actual use of the information stored in the STL file is still limited due to the capabilities of the current AM systems and the state of the current technology development [17].

3.3 Transfer and manipulation of STL file on AM machine

Before the print, some manipulation operations are applied to the STL file. Generally, the typical errors of the STL file, described in the last paragraph, are corrected in this phase. The user may change the orientation, unite more STL file, scale the component or repeat the same part by creating copies. The most important manipulations of the STL file are presented below:

- *Part Orientation:* it greatly influences the geometry and the final mechanical properties of the component, the amount of supports used to sustain the part and therefore also the surface finish of the piece and its quality. The building time is greatly influenced by the printing direction of the component and, from a certain point of view the process costs as well.

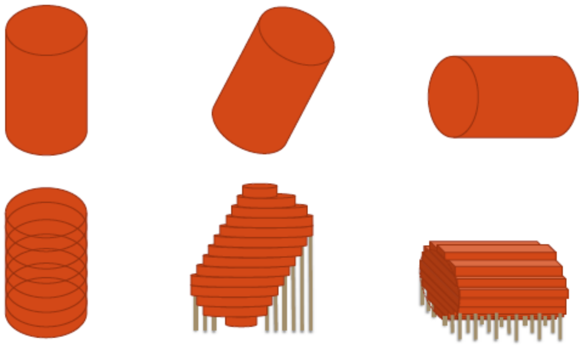

Figure 3.4 Part Orientation

- *Support Generation:* the primary function of the support structure is to extract heat from the model and to provide anchor surfaces and features to the building plate to avoid warpage due to the thermal stresses during and after the build [17]. Although the supports are very important structures in order to sustain the part, these are removed. Therefore, it is very important to minimize the amount of material used for the supports. Further details about these particular structures have been discussed in chapter 5.

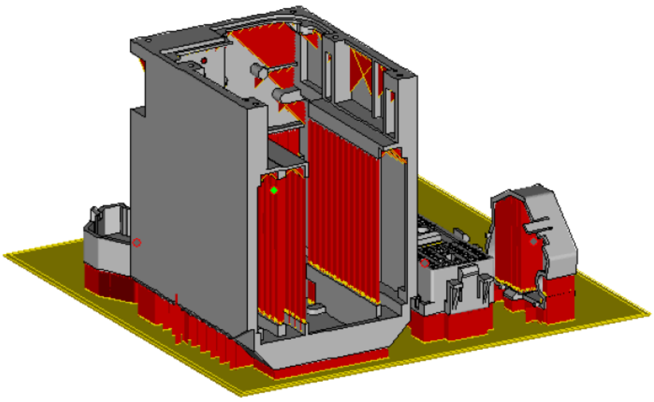

Figure 3.5 Support structures for AM

- *Slicing:* once the model CAD of the part with supports is ready, a slicer program is used to divide the part into different layers oriented by the printing direction. For power bed system typical thickness of the layer is about 25 microns for high resolution builds and 50–75 microns or higher for high-rate applications. The dimension and the distribution of the powder affects the thickness of the layer. The ideal thickness of the slicing would be slightly greater than the average diameter of the powder which would guarantee a complete fusion of the layers (including the previous one that is being re-melted) and the achievement of the high coupling of the laser energy input into the absorption.

Adaptive slicing is a solution to improve the quality of the component, but it is not applicable in all LPBF technologies and it becomes extremely complex in the case in which there are more than one geometry.

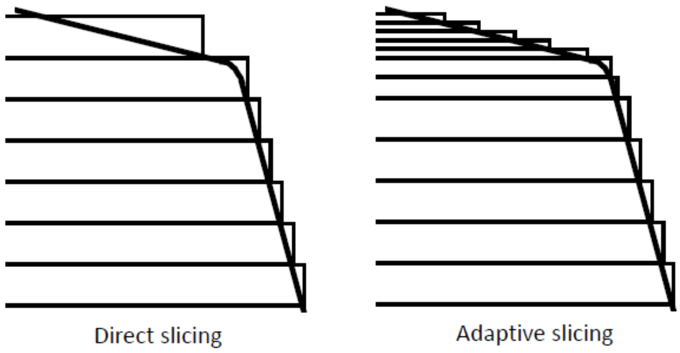

Figure 3.6 Direct slicing and Adaptive slicing

3.4 Build Process

This is the phase where the component takes shape starting from the stratification of the different layers. The machine preparation can be divided in two group: HW setup and process control. The hardware setup includes all the machine cleaning and the routine checks for example gas pressure, flow rate, oxygen sensors, etc. After this task, the AM system can accept the build file. In the process control the positioning of the construction part and some settings related to the material. Some process parameters of LPBF technology are showed in fig.3.7. Once the checks are made and the settings are set, the printing process starts. This is automatic and it is monitored by the AM system itself.

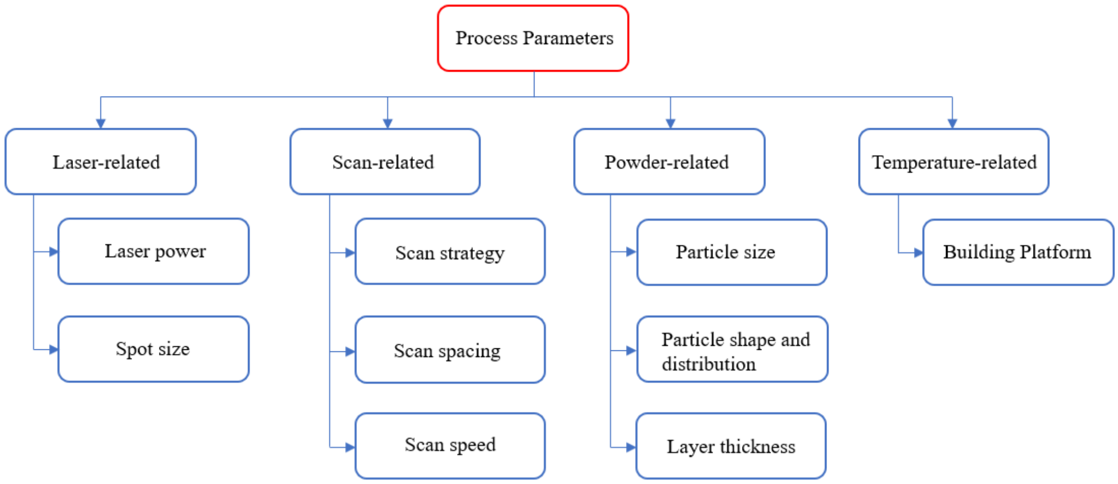

Figure 3.7 Process Parameters LPBF

3.5 Part removal and Cleanup

After the build process, the printed component is never ready to be used, but must undergo significant post-processing. Before dethatching the part from the plate, it is fundamental to perform a stress-relieving treatment to avoid bending or distortion of the parts. The component is subjected to elevated temperature (above 50% of the part material melting point) and isostatic pressure (above 100 MPa). This process is called HIP (Hot Isostatic Pressing).

The cleanup stage may also be considered as the initial part of the post-processing stage and in general the AM parts have different cleanup requirements. Usually there is an unpacking process and a removing activity of the part follows. The unpacking process typically involves the raising of the platform in the build chamber and the removing of the loose powder at the same time [17]. The loose powder is sieved in order to eliminate unwanted contaminants, that can be reused. Therefore the part is now clean but still welded on the plate by means of the supports. The removal is entrusted to cutting tools such as band saws, or wire EDM for a greater accuracy.

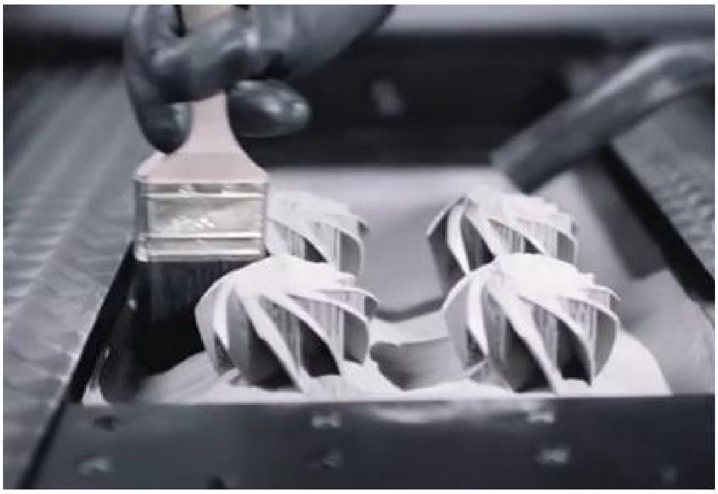

Figure 3.8 Part extracted from build chamber [17]

3.6 Post-processing

During the post-processing the part is detached from the plate and the supports are manually removed or by using some machines, such as a wire EDM machine, bandsaw, and/or milling equipment. At this stage the skills of the operator are very important as the part can be damaged. The techniques used as post-processing vary according to the application of the printed part.

The post processing is important in order to improve the part functionality, the dimensional accuracy, the finishing of parts, the increasing of mechanical properties and fatigue life of the component. Machining minimize the impact of process inaccuracies and the impact of the additive manufacturing process. This may involve abrasive finishing, like polishing and sandpapering, or application of coatings. Some post-processing may involve thermal or chemical treatment in order to confer determined proprieties to the part.

4 Structural Optimization

In this chapter a brief introduction of the structural optimization is firstly presented, which is followed by a description of the different technique of optimization, focusing the attention on the Topology Optimization and its main resolution method (SIMP method).

4.1 Introduction to the Structural optimization

Optimization is a concept that is increasingly developing in the last years, which the birth of structural optimization software has given an important contribution too. Its origins date back to the 60s, where the optimization problem was reduced to a system of differential equations that was solved analytically. With the advent of modern computers this technique has obviously been shelved.
Therefore optimization could be defined as a mathematical and iterative process and the basic principle of optimization is to find the best possible solution under given circumstances [10]. Structural Optimization is nothing but a subgroup of the latter one.

To formulate the SO, an objective function, the state variables and design variables need to be introduced:

- The *objective function* (f)*,* represents an objective that could either be minimized or maximized [14]. Classic objectives for SO could be the volume, the frequency, the stiffness of the structure etc. Structural design domain and state variable are associated to the objective function;
- The *design variables* (x) describe the design of the structure, so they may represent the geometry [14]. They can be changed during the optimization;
- The *state variables* represent the structural response as stress, strain, displacement. They are function of design variables.

So, the optimization problem could be formalized in the following manner:

$$\begin{cases} \min\limits_{x} f\big(x, y(x)\big) \\ subject\ to \begin{cases} design\ constraint\ on\ x \\ state\ constraint\ on\ y(x) \\ equilibrium\ constraint \end{cases} \end{cases} \tag{4.1}$$

State constraints can formulate a state function g(y) that can be incorporated as a constraint to the optimization. A classic example is to consider g(y) as a displacement function in a FE problem so g(u(x)).

$$u(x) = K(x)^{-1} f(x) \tag{4.2}$$

Where $u(x)$ if the displacements vector, $K(x)$ is the stiffness matrix (invertible) and $f(x)$ is the loads vector. The combination task can be expressed in this way:

$$\begin{cases} \min\limits_{x} f\big(x, y(x)\big) \\ subject\ to\ g\big(u(x)\big) \leq 0 \end{cases} \tag{4.3}$$

This formulation is usually called the nested formulation [7].

It is possible to define three classes of structural optimizations, associated to three different Design Variables:

- *Topology Optimization:* the design variable x, represents the connectivity of the domain. It involves features such as number and sizes of the holes in the design domain [10];
- *Shape Optimization:* the design variable x, represents the boundary of the state equation;
- *Size Optimization:* the design variables x, represents a structural thickness distribution.

The multi objective is defined as a vector of several objectives:

$$f(f_1(x,y), f_2(x,y), \dots, f_n(x,y)) \qquad (4.4)$$

The analytical relationship can be introduced through weights, whose sum gives the unit value:

$$f = \sum_{i=1}^{n} f_i \omega_i \qquad (4.5)$$

$$\omega = \sum_{i=1}^{n} \omega_i = 1 \qquad (4.6)$$

4.2 Structural Optimization methods

In the previous paragraph, a first classification of optimization techniques was mentioned. It is not wrong to think that in some cases it is necessary to rely on different optimization techniques to achieve the best result. In the description of the possible methods, Altair's guide has been used as a reference [11].

It's possible to make a distinction of the optimization methods:

- Concept Level Design, for preliminary optimizations;
- Define fine tuning, to refine the work done by the previous one.

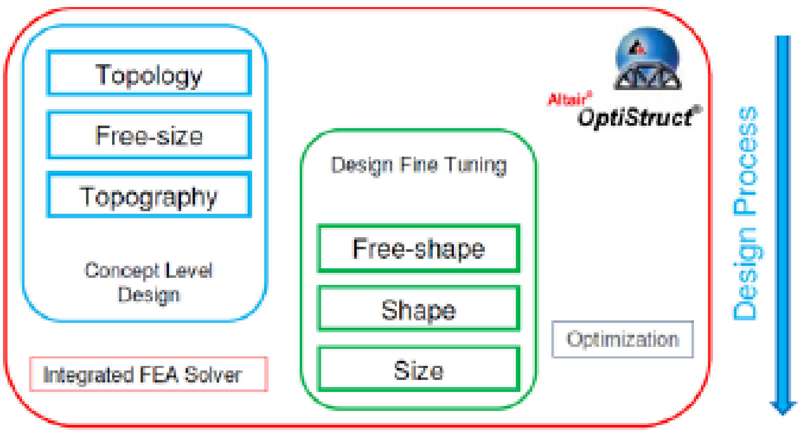

Figure 4.1 Classification optimization methods

Many responses could be used as objective or as constraint functions:

Mass	Volume	Center of Gravity
Moment of Inertia	Static Compliance	Static Displacement
Natural Frequency	Buckling Factor	Static Stress, Strain, Forces
Static Composite Stress, Strain, Failure Index	Frequency Response Displacement, Velocity, Acceleration	Frequency Response Stress, Strain, Forces
Weighted Compliance	Weighted Frequency	Combined Compliance Index
Function	Temperature	

Table 4.4.1 Responses for Optimization

4.2.1 Topology Optimization

Topology Optimization seek the optimal placement of the material, where the reference domain is partitioned into void and solid element by a finite element discretization [14]. With topology optimization the geometric results as shape and number of holes for example are not decided at the begin but they are consequence of the process.

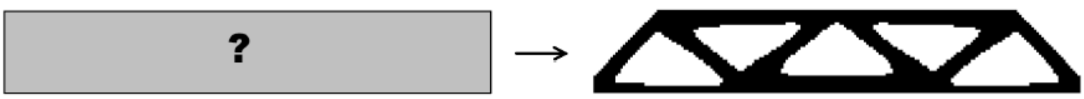

Figure 4.2 Topology Optimization

The domain is discretized, and in each element a density value ranging from 0 to 1 is associated. 0 means that the element is void, in reverse 1 means that the element is solid. Using a discrete variable instead of a continuous one can lead to complications.

The main methods for associating discrete values to elements are essentially two: *SIMP method* and *Homogenization method.* The first one solves the density distribution by introducing a penalty factor, while 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. This leads to a porous composite that has a density varying between 0% and 100% [10]. This can be appreciated in the following figure:

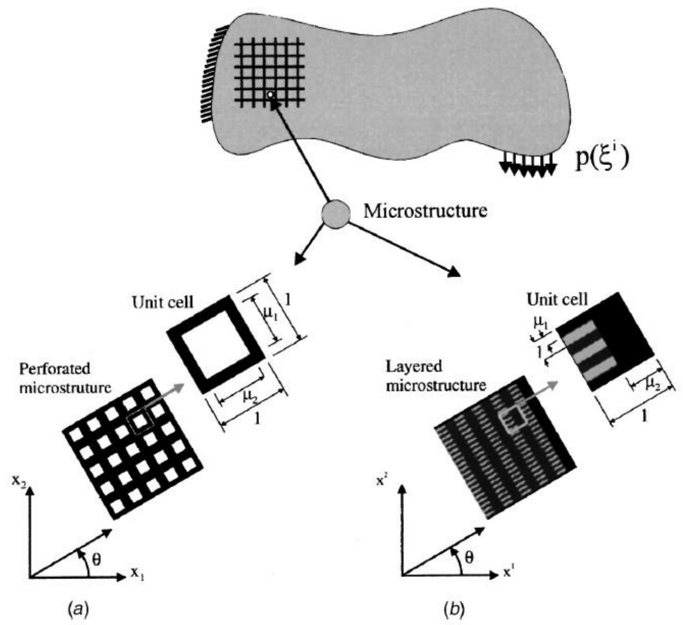

Figure 4.3 Example of microstructure: (a) Performed microstructure with voids, (b) Layered microstructure

During the topological optimization there are many variables involved and consequently there are several equations to be solved during each iteration. The computational cost is certainly high, but the topology optimization can lead to finite results, with the availability of compatibility constraints with the manufacturing processes.

An example of topology optimization process applied to a three-dimensional case is shown below.

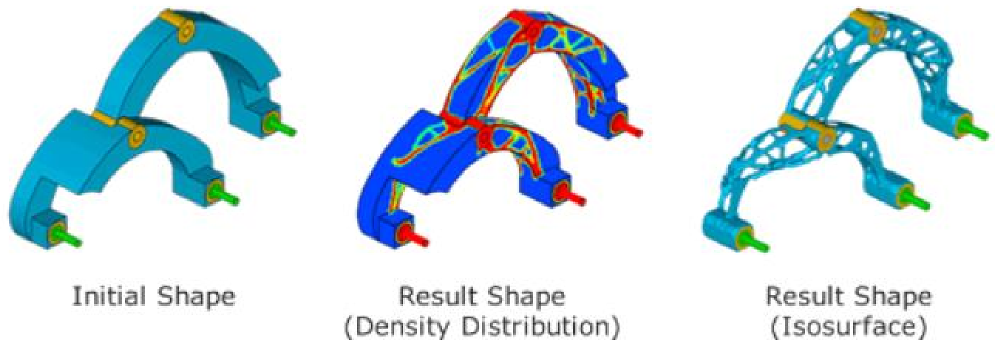

Figure 4.4 Topology Optimization process

4.2.1.1 SIMP Method

The SIMP (Solid Isotropic Material with Penalization) method, is the most used one in order to solve the topology optimization problem and in fact is widely used within Software. The method consists to introduce a penalty factor to steer the solution to a discrete 0-1 value building the final design with solid and empty elements. To approach this behavior, it acts on the stiffness through the Young's modulus of the element $E(x)$, that it depends on a variable interpreted as density variables $\rho(x)$. This choice allows the calculation of the gradients of the objective function for each variable within the FEM analysis. Generally, the relation is the following:

$$E = \rho E_0 \tag{4.7}$$

Where E_0 is the Young's modulus of the elements with unit density and $0 \leq \rho \leq 1$.

It is a linear relationship, but with the introduction of the penalty parameter the trend changes:

$$E = \rho^p E_0 \tag{4.8}$$

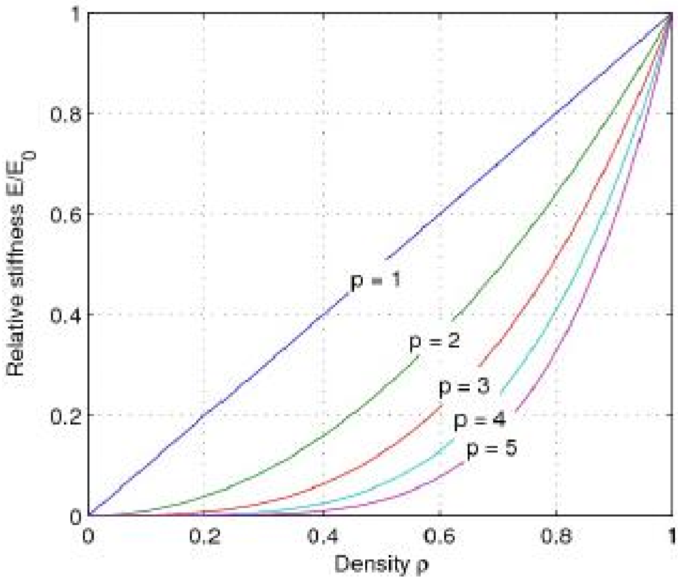

Figure 4.5 Relative Stiffness related to density and parameterized by penalization factor

A reduction of the Young's modulus leads to a reduction in the stiffness of the element. The penalty factor contributes to the reduction of the element stiffness. This factor greatly influences the result of the optimization; the optimal values are between 2 to 5 and high values of p lead to a strong penalization of the intermediate density elements, creating slimmer, lighter and more yielding structures, creating a phenomenon known as *Checkerboarding*. To solve this problem another variable called sensitivity (r) acts as a filter. This works by mediating, at each iteration, the density of each element with those of nearby elements within a radius of action of r times the size element average. In this way the solver forces the final configuration to create beams structures with a diameter of at least twice the average size of the elements. The effect of these two parameters is showed in fig.4.8.

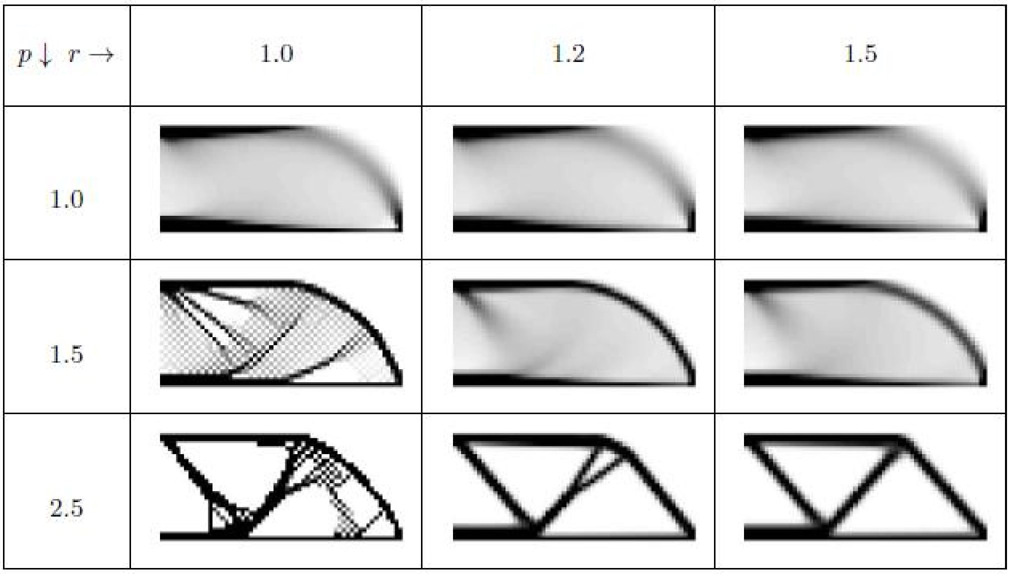

Figure 4.6 p and r effects on topology optimization

4.2.2 Topography Optimization

It is like the topology optimization but utilizes shape variables instead density variables, and at the same time it is more advanced than the shape optimization. During the iteration process, a large number of shape variables are involved, which allows to generate the reinforcement pattern that improves the component performance.

In fig.4.9, it is showed all the Topography process applied on a Plate in Torsion. In the first image there is the model with loads and constraints; the second image shows the different small areas of the Design Space created by the optimizator. During the process, the optimal reinforced shape is realized. The final shape is showed in the third figure.

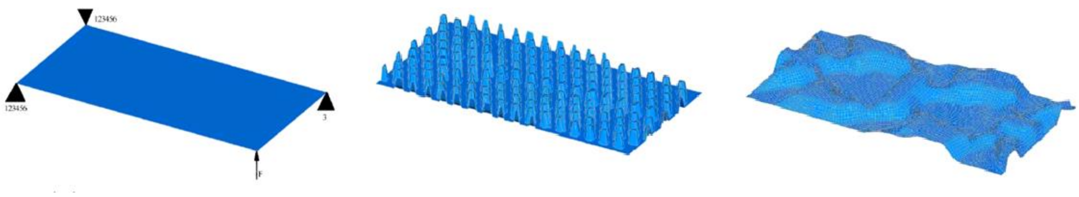

Figure 4.7 Topography optimization of a Plate in Torsion

Each topography shape variable has a circular domain with a hexagonal distribution on the design domain. Grids are perturbed as a group and for grids arranged between the different circular region, they are subjected to an average perturbation of the variables to which they are the nearest one.

4.2.3 Size optimization

It is the simplest form of structural optimization. The objective is to perform the sizing of the component without affecting the shape of the structure.

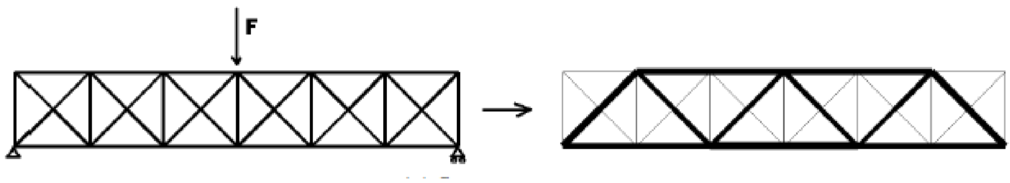

Figure 4.8 Size Optimization

In this optimization, the proprieties of the structural element (mass, stiffness, shell thickness) are opportunely modified in order to find an optimal design structure. Some structural elements have several parameters depending on each other; like beams in which the area, moments of inertia, and torsional constants depend on the geometry of the cross-section. The generic property p is not the design variable, but only a function of design variables d_i. The simplest function that can be defined between $p - d_i$ is a linear relationship:

$$p = C_0 + \sum_i d_i C_i \tag{4.9}$$

Where C_i are linear factors associated to the design variables.

This relationship must be specified before running the optimization. For a simple optimization of a shell structure, there is a simple relationship between the thickness T and the design variable:

$$T = d_i \tag{4.10}$$

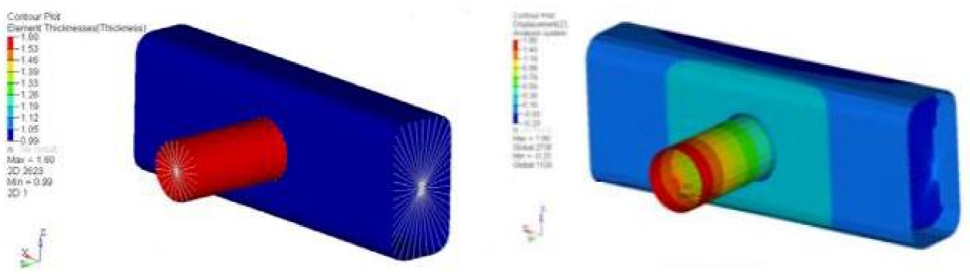

Figure 4.9 Rail Joint 2D: Thickness distribution before and after Size Optimization

4.2.4 Shape optimization

As the size optimization, the topology of the structure is known (number of holes, beams, etc.), and it does not change but the shape of the component, for example the shape or the diameter of the holes or the thickness distribution of a part could be the design variables of the shape optimization.

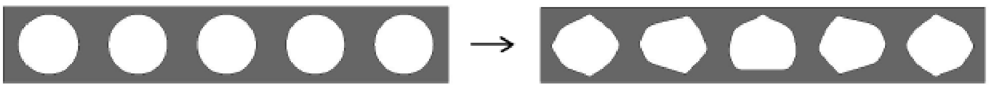

Figure 4.10 Shape Optimization

The shape of the structure is defined by a vector of nodal coordinates x. There are two different approach to define the mesh changes during the modification of the position of the nodal coordinates:

- *Basis Vector Approach:* the nodal position is a linear combination of basis vector b_i associated with the design variable d_i:

$$x = \sum_i b_i d_i \tag{4.11}$$

- *Perturbation Vector Approach:* the shape changes are defined as perturbation, so the node coordinates consider these contributions associated to the design variable:

$$x = x_0 + \sum_i d_i p_i \tag{4.12}$$

Where x_0 is the vector of nodal coordinates of the original design.

Figure 4.11 Cantilever Beam (a), Basis Shape 1 (b), Basis Shape 2 (c)

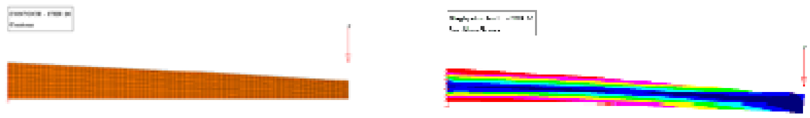

Figure 4.12 Shape Optimized Final Shape (d), Deformed condition with Von Mises stresses (e)

4.2.5 Free-size Optimization

This type of optimization is applied on 2D component like laminates and shells. The optimizator defines a map of the thickness distribution, so the most stressed areas are the thickest one. It's similar to the Topology Optimization, but the substantial difference is that the thickness varies in continuous way between two values, while the TO induces discrete thickness values.

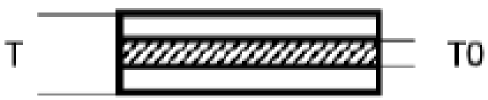

Figure 4.13 Thickness distribution for free-size optimization

Generally free-size optimization involved with topology in the same optimization is not recommended because it could lead to sub-optimal solutions due to possible bias produced during the process.

The next figure shows a comparison of these two optimizations of a cantilever plate:

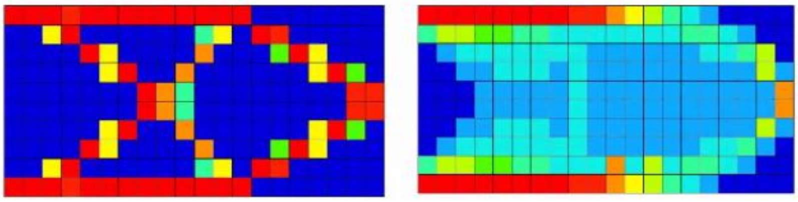

Figure 4.14 Topology results (a) & Free-Size result (b)

The results are similar, but the topology optimization is more aggressive, while the thickness distribution in free-size optimization is more gradual. It's important to note that size-optimization is limited to 2D elements, but this concept of thickness distribution can be implemented for the topology optimization on solid elements.

The fig.4.17 shows the free-size result on the cantilever plate and the TO on the 3D model.

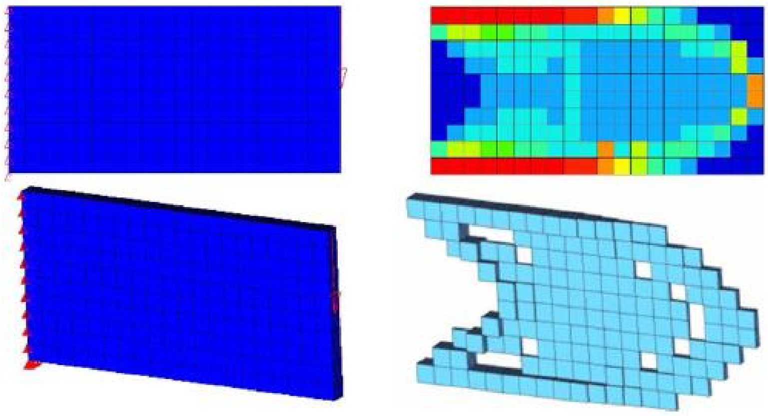

Figure 4.15 Free size result on cantilever plate and TO result on 3D model

4.2.6 Free-Shape Optimization

This is a different way to optimize the shape of a component. In this case a perturbation vector is not required, and the nodes can move totally free according to the objective and the constraints of the optimization.

Grid nodes can move in two different way:

- For shell structures, the direction is normal to the surface edge in the tangential plane
- For Solid structures, the direction is normal to the surface

The normal direction changes as the shape changes during the different iterations. A clear example is showed in fig.4.18

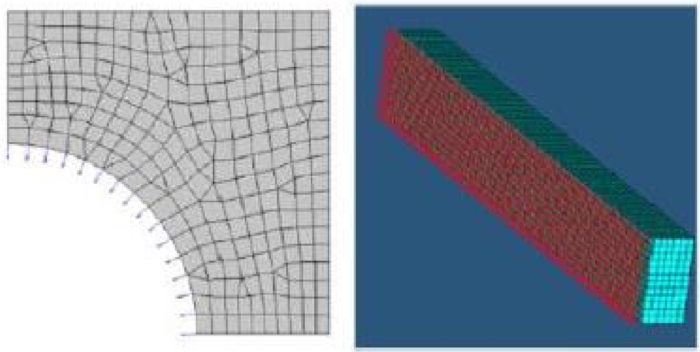

Figure 4.16 Grid Node movement in Free-Shape Optimization

Five parameters can influence and limit the progress of the shape:

- *Direction type,* constraint of the direction of the movement
  1. GROW the inside direction is constrained;
  2. SHRINK the outside direction is constrained;
  3. BOTH grids are free.

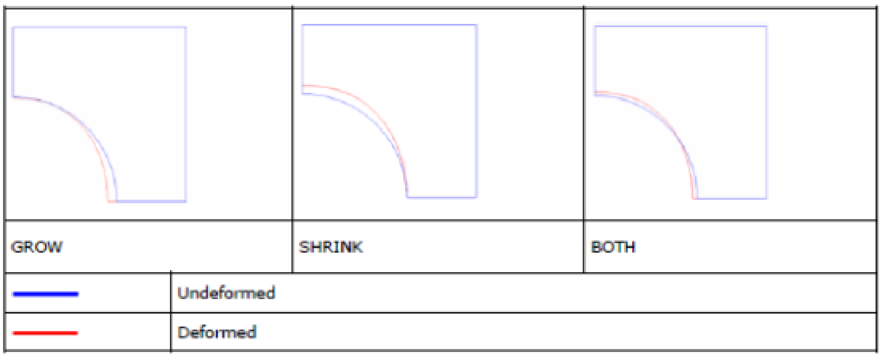

Figure 4.17 Direction type limitation in Free-Shape Optimization

- *Move factor,* represents the maximum allowable movement in one iteration. With a high value of the move factor, the process is faster but more unstable.
- *Number of Layer of Mesh Smoothing*. It avoids distortions mesh in the design areas, but the computational cost is higher.
- *Maximum Shrinkage and Maximum growth* limit the total amount of deformation of the design region. The first one limit the shrinkage direction and the second one the growth direction.

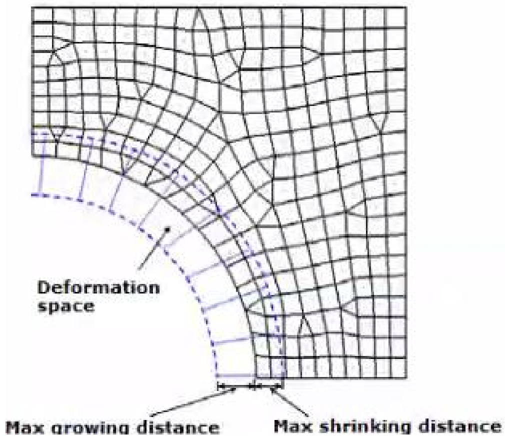

Figure 4.18 Maximum Shrinkage and Maximum growth

Other ways of the treatments to the grids can be acted like defining a Transition Zone between the Design Region and the Non-Design Regions, defining a Symmetry Plane Constraints or defining a Mesh Barrier Constraints and other kinds of physical, geometrical and technological constraints.

4.2.7 Lattice Structure Optimization

Maybe it is the most innovative one among all the optimizations presented. It utilizes lattice structures in order to achieve the final design, ensuring high reduction of mass and good mechanical proprieties. The optimization can be divided in two phases: in the first phase, there is a topology optimization with a reduced penalty factor. This involves a different distribution of density, hence the birth of some dense and some porous areas. In the second phase all the porous areas are replaced by lattice structures respecting constraints and the objective of the optimization. The final result is a solid part combined with lattice structures.

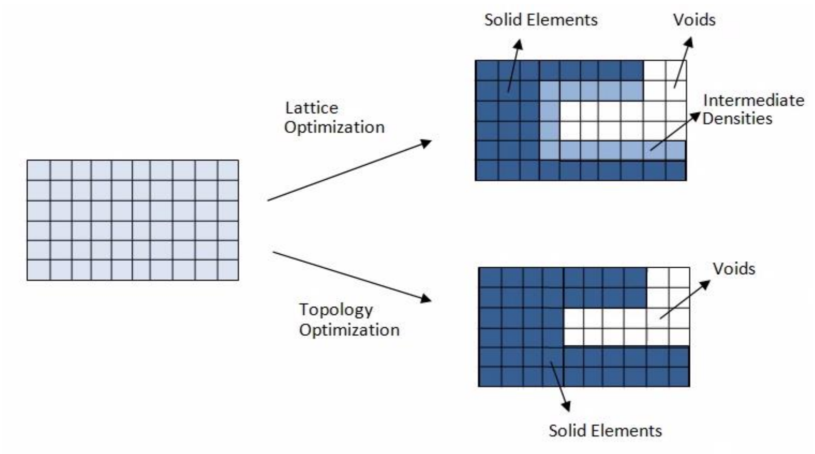

Figure 4.19 First phase of lattice optimization compared with topology optimization

For the same volume, the lattice structure is less dense than a full structure and for this reason it has a lower stiffness. For diamond and tetrahedron lattice cells the relationship of the Young's modulus is:

$$E = \rho^{1.8} E_0 \qquad (4.13)$$

Where E_0 is the Young's modulus of the dense material. The porosity parameter and the penalty factor rule the final design of the optimization and the design constraints can be defined for both the phases of the optimization.

Before starting the process, the user defines a lower bound (LB) and an upper bound of density (UB), and after the first TO this allows to define the voids, the porous areas and the solids elements. The lattice structures are developed with beam elements, following pre-established functions, respecting the defined volume fraction of a single cell.

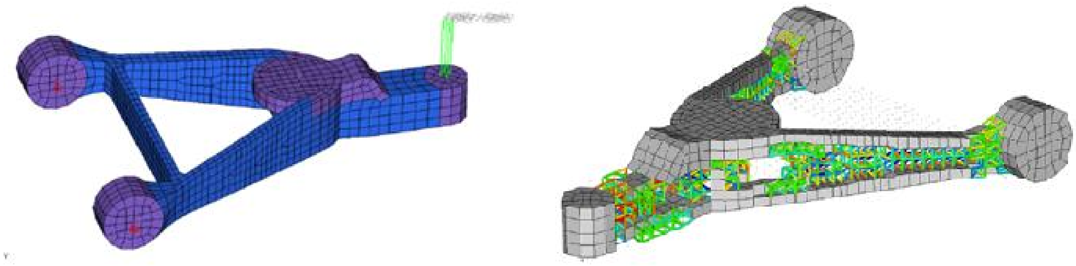

Figure 4.20 Example of Lattice Optimization

5 Support Structures

Support structures are an integral part for many AM process. They are necessary for many part designs, but at the same time they are undesired as they involve an increase in the costs and the material during fabrication. Furthermore, they also pose additional design constraints to the part.

Overall, the support structures can be categorized in three types:

- Heat diffuser and rigidity enhancer, for the processes which include high thermal gradients, that can induce shape distortion and residual stresses;
- Fixture Supports, able to sustain printed component, when unbalanced part or the raw material (powder for example) is not able to sustain the weight of that part;
- Support structure utilized to ensure that material is deposited at the intended height and the expected output is achieved [3]. For example, for DMD (Direct metal deposition), the material can be deposited only on the existing surfaces below.

The necessity of support structures is mostly linked to the type of technology used:

- For material extrusion process, gravity and thermal residual stress need support structure;
- For vat photopolymerization, support structures are needed to absorb the buoyancy force and the shrinkage induced to distortion effect during the photopolymerization processes;
- For powder bed fusion process, support structures are needed to counter the thermal residual stresses generated during the melting process that can lead to cracking, curling, sag, delamination and shrinkage;
- For material jetting process, in particular, for thermoplastics and metals that easily melt and solidify, structures are needed for printability functions and for anchoring the part on the build platform.

- For blinder jetting process, support structures are used, as for material jetting process, for printability functions and for anchoring the part on the build platform.

In these years the interest in AM has considerably grown, but as can be seen in figure 5.1, still few efforts have been directed towards the study of support structures that represent a land of conquest.

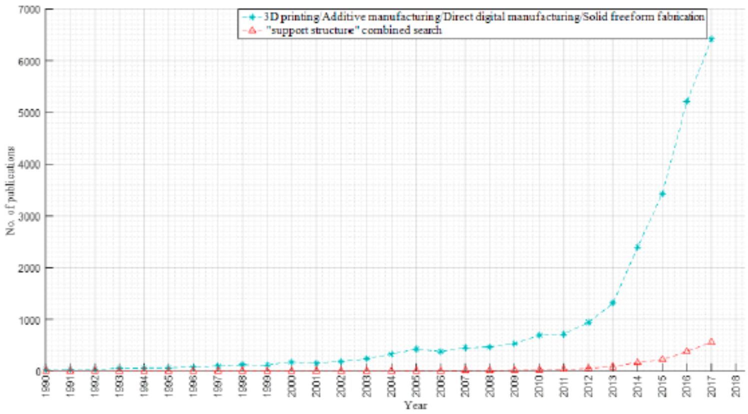

Figure 5.1 Number of publication papers with keywords "3D printing"/"Additive Manufacturing" combined with "support structures" [3]

5.1 Support Structure Design

The design of the support structures is a challenging process where many parameters must be taken in consideration. First of all, the role played by support structures has been discussed. In order to well understand how to define a correct support strategy, it is important that the designer takes into consideration all the disadvantages that these structures could involve:

- Accessibility in some areas for manual media removal can lead to constraints on component design;
- Once removed, in many cases the support structures are wasting material and are not recyclable;
- Removal requires a significant amount of manual work, especially for metal processes. different support methods lead to different surface finishes,

influencing the post-processing activity. Components that have a large amount of supports generally require a lot of labor and long production times;

- A support structure may be detrimental to the surface finish when the structure is removed;
- Extra time is required to design the part to accommodate the support structure and the design of the support structure itself. This implies a larger data file for the part. As the printing speed increases and the complexity of a single voxel increases by incorporation of information such as color and material, the speed of data transfer may become a limitation [3];
- The energy costs of the additive manufacturing process are linked to the volume of the material to be printed. The presence of support structures can lead to a considerable increase in the total volume and therefore in the energy costs;
- The STL file set-up requires the specification regarding part orientation and placement of the supports. These specifications must be manually dictated by a competent operator.

In many cases the design of support structures may be a trial-and error process and the skill, and the experience of the designer play a fundamental rule. In figure 5.2 it is possible to observe some important factors that the designer must respect in order to create efficient support structures:

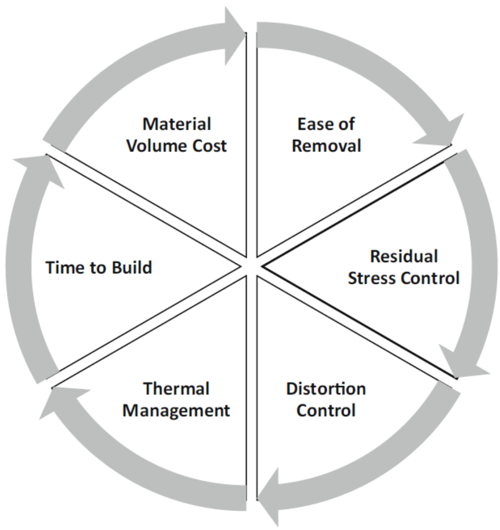

Figure 5.2 Design consideration for support structures [16]

Depending on AM process, different guidelines for the identification of the areas of the part to be supported are defined. In order to reduce the support structures, it is necessary to determine the optimal orientation on the building platform. In many cases the orientation which guarantees a lower quantity of supports, leads to very long fabrication times. The reason is that in these cases the dominant dimension of the component is aligned with the build direction. What has been said it can be valued in the following figure:

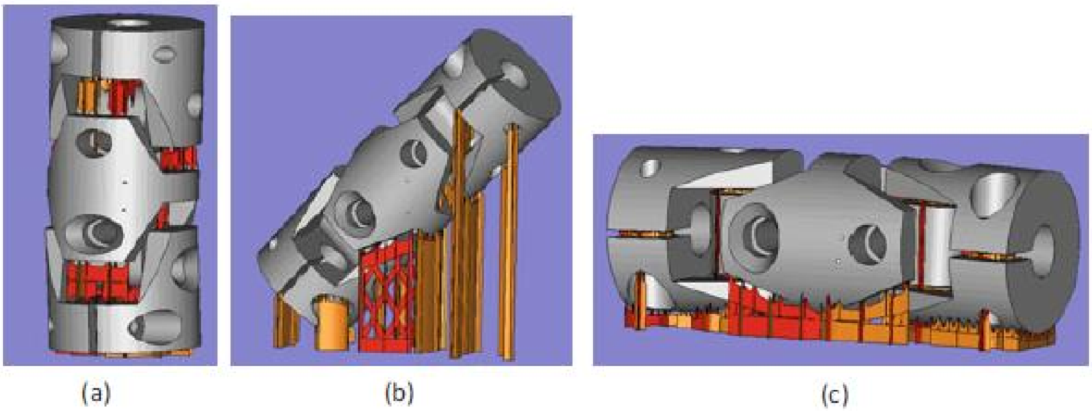

Figure 5.3 Strategy orientation for a universal joint [17]

The first image shows the solution that requires the smallest amount of support structures. The second solution is the best one in terms of easy removal of the supports, while the third solution is the fastest one in terms of manufacturing time but requires a great work of post-processing to improve the surface finishing of the final component. Among these three solutions, the optimal part orientation is the one that guarantees an intermediate angle to part, between the horizontal and the vertical direction. Therefore, in conclusion the part orientation affects the support contact area, the surface roughness and the final printed mechanical proprieties.

An important aspect to design a good support strategy is to prevent the part from collapse/warping, especially in the outer contour area which needs supports. In order to avoid the collapse of the part in the design phase and to reduce the amount of supports, self-supported surfaces are produced. The self-supporting angle is defined as the minimum angle of the part that will be built without supports. Beyond this angle the structure will be in overhang and it will need supports.

This angle is linked to the material. For example, compared to the horizontal direction, for cobalt chrome and stainless steel the minimum angle is 30°, for Titanium is 20-30°, while for Inconel and Aluminum the minimum angle is 45°.

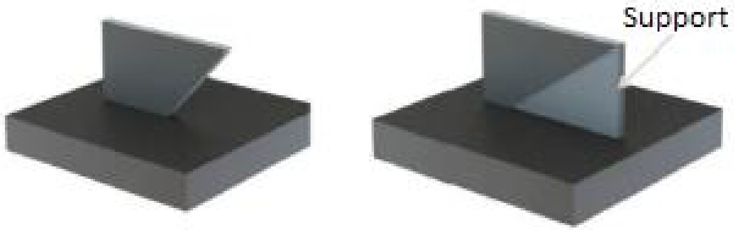

Figure 5.4 Part self-supported (left) and part which requires support (right) [25]

Always for metal processes, also angled surfaces need supports. Circular holes with large diameters (≥6mm), require support structures to prevent the part collapsing or becoming distorted during the build process.

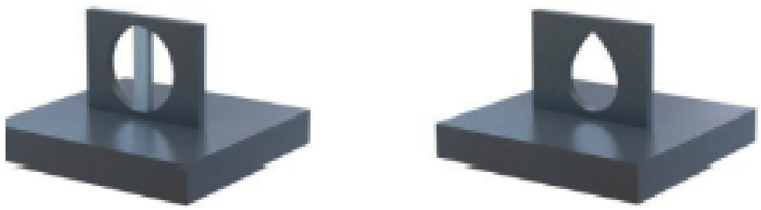

Figure 5.5 Support structure for large hole (left) drop-shaped to avoid support (right) [25]

Since the inner areas of the circle must be machined, in many cases the best solution is to carry out the compensation of the shape, creating particular geometries such as the drop-shaped profile, to compensate the collapse of the upper part of the shape during printing, guaranteeing a roughly circular shape at the end of the process.

Instead, for some special geometers, like concave and convex filet features, the gradual variation of the geometry helps to sustain the part, although there is a large overhang area. Also in this case there are limits beyond which the part needs support structures to avoid the formation of defects.

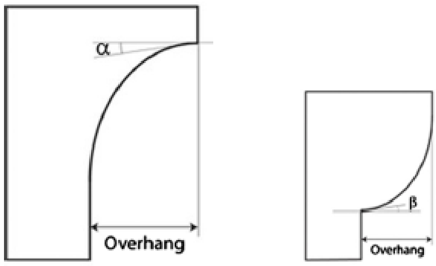

Figure 5.6 Concave radii (left) convex radii (right) [26]

It is important that the contact area between support and final part should be as small as possible in order to reduce the amount of material released after removing the support. Teeth structures are usually designed at the interface between support and component, in order to reduce the total contact. Many variables design can be considerate as tooth distance, tooth high, offset, base length, top length and also the melting strategy as hatch spacing for the laser passage.

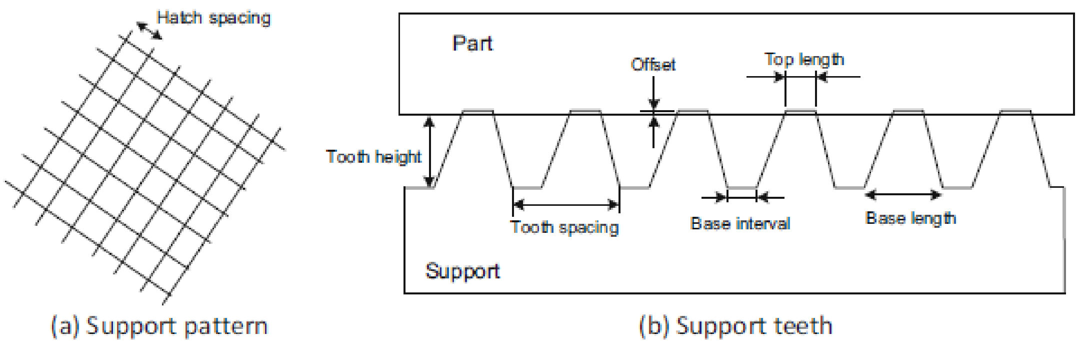

Figure 5.7 Typical design variables for block support [17]

5.2 Fabricating Defects

This paragraph refers to the fabricating defects of metal materials. For powder bed fusion, the metal powder is processed under a high temperature, usually over the melting point, so the residual stresses still remain after cooling and the thermal stresses inside the component become higher.

Rapid cooling can lead to a contraction of the material. So, this process can leads to many defects such as:

- Delamination of the layers;
- Cracks in the part;
- Warpage during the post finishing;
- Dross formation;
- Distortion.

Some of these defects can be minimized or avoided by shot peening, stress relieve process and/or heat treating.

Figure 5.8 Distortion and delamination in SLM processing [27]

It is necessary to spend a few words for the dross formation.

In figure 5.9, two areas of the part are identified: A, a solid supported zone and B a powder supported zone. For SLM process, when the laser irradiates the A region, the heat conduction rate is higher than that one of B region. The energy absorbed in the latter region is higher, and this leads the melt pool to become too large and to sink into the powder as the result of gravity and capillary force [26]. Dross will be formed, and its dimension will be related to the type of material and the extension of overhanging surface.

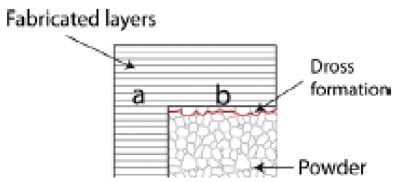

Figure 5.9 Dross formation [26]

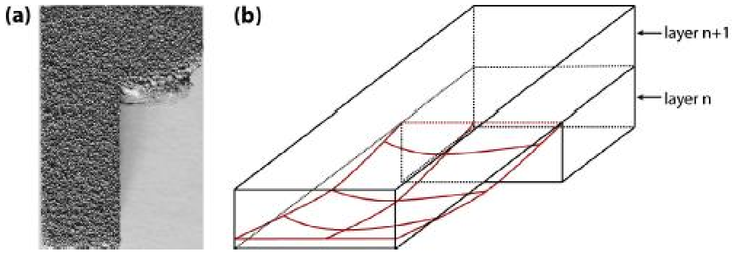

Figure 5.10 (a) Dross formation on the part (b) temperature gradient mechanism for the part [26]

The warping defect of an overhanging surface is often due to the lack of support structures. Previously it has been stated that concave and convex surfaces could be classified as self-supported. In reality the extension of the radius of curvature and therefore of the overhanging can lead to warping defect as can be seen in the following figures:

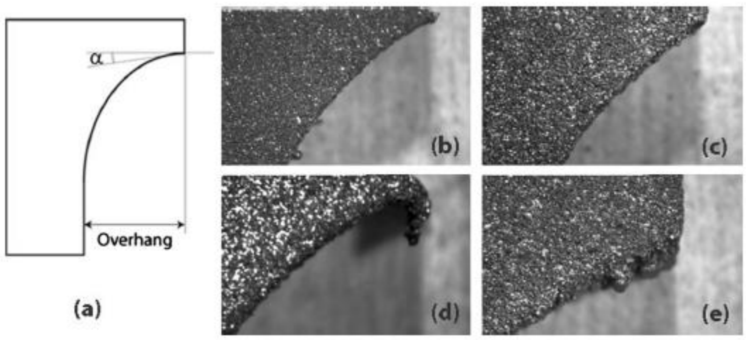

Figure 5.11 (a) Concave part (b) overhang of 9mm material A (c) overhang of 15mm material A (d) overhang of 9mm material B (e) overhang of 15 mm material B [26]

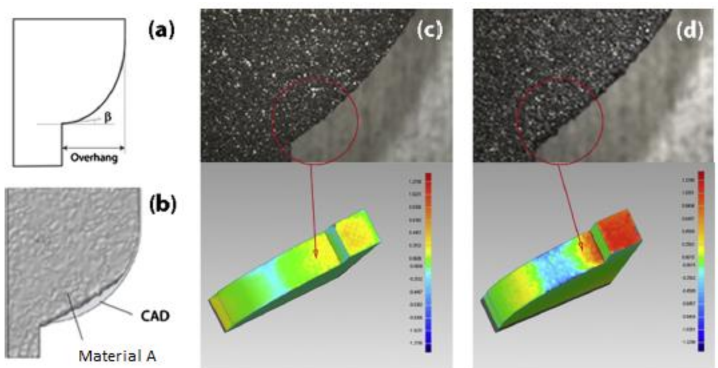

Figure 5.12 (a) Convex part (b) overhang of 15mm material A (c) overhang of 9mm material B (d) overhang of 9mm material A [26]

5.3 Support Generation

The first way to generate support structures is through software CAD, modelling and designing them. The alternative one is to generate support structures in the STL pre-process through software program. This second approach is more flexible in terms of being able to tailor the structures based on the needs.

Materialise Magics is one of the most widely used software tool, able to generate support structures on 3D models. Various types of support geometries are available within the database of these SW, such as web support, point support, block support line support and contour support.

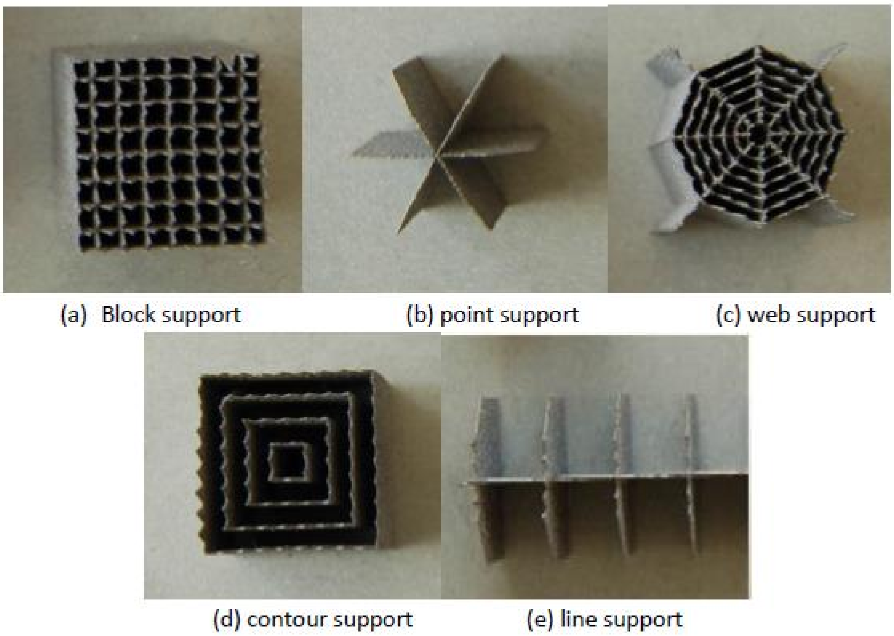

Figure 5.13 Typical support structures for metal AM [27]

Depending on the needs, surface-to-support contact can be a point a line or an area. The first one provides less resistance but greater facility of removal. Surface contact provides greater resistance but requires greater efforts to remove the supports. Block support is usually used for bulk structures while point and line supports are used for small features.

To further improve the ease removal and the efficiency of support structures, cellular structure has been developed. The contact between part and supports occurs trough points series. They represent lattice structures, whose performance is regulated by the volume fraction parameter. The 3-dimensional porosities could potentially achieve a better material efficiency, but especially for metal processes, low volume fraction of cellular structures may make support structures too fragile. A good compromise between cell size and volume fraction cold enable the future expansion of these structures.

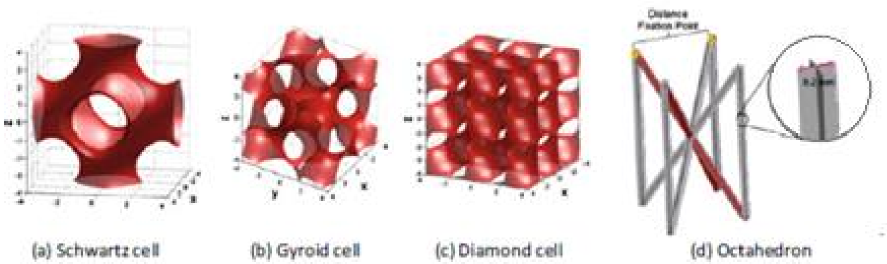

Figure 5.14 Cellular structures for supports [16]

Mathematical functions generate the cellular structures that are repeated in space to generate the final support. The most utilize cellular structures are Schwartz cell and Gyroid cell. Due to the fragmented cross sections in each layer of the cellular structures, printing time are considerably longer, especially for the laser-based powder bed fusion AM systems.

Chapter 6 deals with an even more different concept to support structures, that is to apply a topological optimization to the supports structures to guarantee a good thermal and mechanical behavior, saving the material and the energy costs.

5.4 Support Removal

In this section an overview of how to remove support structures for all process technologies in AM is descripted. Typically support material can be divided in two categories:

- *Natural supports*: material which surrounds the part as a naturally occurring by-product of the build process [15];

- *Synthetic supports*: rigid structures that have the task of supporting and fixing the part built with the build platform.

5.4.1 Natural support removal

Utilized for all PBF, blinder jetting and bond-then-form sheet metal lamination processes, the built part is fully encapsulated in the build material (powder material or sheet material). The part must be removed from the surrounding material before the use. In polymer PBF processes, after printing, the component is subjected to a cooling process. In order to minimize distortions, the part remains immersed in powder and the cooling time is related to the type of material and to the dimension part. There are several ways to remove the part, the manual work is the most popular one. Compressed air brushed and light bead blasting are the most used ways to remove the powder. Critical areas such as cavities and hollow spaces require more refined work. Recently automatic powder removal systems have been introduced and they can be integrated into the build chamber. For bond-the-form sheet lamination processes, the same considerations descripted preciously can be applied.

Figure 5.15 Automated natural support removal for PBF process [15]

5.4.2 Synthetic support removal

For PBF techniques for metal, synthetic supports are necessary to resist to distortion of the part. These supports can be made of the same material of the part or of a secondary material (generally a material with lower mechanical properties). Removing the supports can lead to the formation of the so-called *"witness marks"* that need to be removed through machining.

- *Support Made from Build Material:* for polymer parts, these supports can be removed manually. Included processes are vat photopolymerization, material jetting and material extrusion. After the removal, these surfaces may require subsequent sanding and polishing.
  The same concept applies to PBF and DED processes for metals and ceramics, but in these cases the removal cannot be performed manually. Thus, the use of milling, bandsaws, cut-off blades, wire-EDM, and other metal cutting techniques are widely used. With EBM process, less support structures are required, because the part maintains high temperatures throughout the process, without inducing residual stresses.
- *Support Made from Secondary Materials:* over the years several materials have been developed in order to facilitate the removal of the supports. They are common for material extrusion and material jetting processes.
  For polymers, the most common secondary supports are soluble polymer materials, which can be dissolved in a water-based solvent. The water can be ultrasonically vibrated or jetted in order to accelerate the removal process. For metals the most common secondary materials are lower-melting temperature alloys which can be chemically dissolved in a solvent, but it must not damage the part [15].

6 Exercise: Support Structure optimized for Rake component

In the previous chapters the importance of supporting structures has been analysed but at the same time also the disadvantages that they cause. Often the structures automatically generated by the software are not acceptable and high CAD modelling skills are required by the designer. The purpose of the thesis is to guarantee a different approach in order to automatically generate support structures, reducing the design time. This methodology allows the application of topological optimization, finding the optimal layout of the structure, changing the density distribution of the working domain, in order to create high-performance supports capable to reduce the distortions and thermal stresses caused by the melting process of the metal powders and to reduce the volume of used material as much as possible.

The logical scheme that explains all the steps of the methodology is represented in figure 6.1:

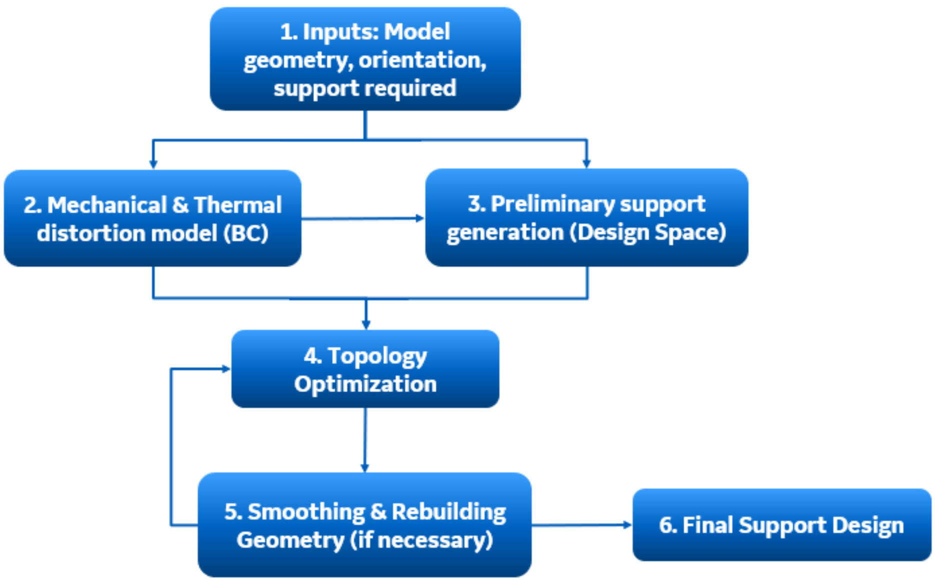

Figure 6.1 Logical scheme of the methodology in order to generate optimized supports

In order to define this scheme, first of all a very simple case has been analysed, whose part to be supported was L-shaped, with a horizontal overhang surface (Appendix A).

As industrial test case, the choice fell on the Rake. This component is used for diagnostic wind tunnel testing in order to determine the total pressure and the temperature of the fluid. The different probes are aligned with the direction of the fluid and this system offers the advantage of providing several separate simultaneous readings or a simple average of many readings. For this particular advantage, the Rake is used to evaluate the fluid conditions between two turbine stages, in order to get a complete mapping of the total pressure and temperature distribution, considering the non-uniform conditions of the fluid. Every Rake is custom designed and matched to the flow conditions of its particular application. Overall Rake length may vary from fraction of an inch to more than two feet, incorporating from two to several dozens of individual measuring elements.

Figure 6.2 Example of Rake

This component was chosen because it was printed, supported by traditional supports, modelled through the CAD software. They consist in a series of fins with teeth at the interface with the part, in order to reduce contact and facilitate remoulding (fig 6.4). However, the results obtained through this support strategy, shown in the following figure, were not satisfactory.

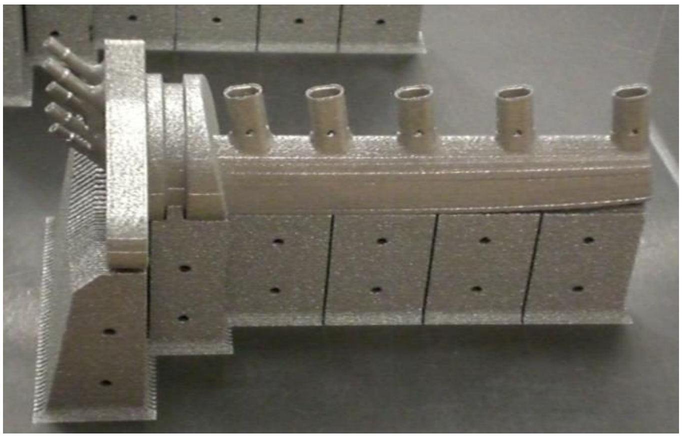

Figure 6.3 Rake thermal warpage after the AM print

As it can be seen from the figure, the support structures are not able to compensate the thermal stresses in the most critical area, letting the Rake free to deform. These critical areas are exactly the frontal area (on the right of the figure) and the two lateral areas of the flange close to the holes.

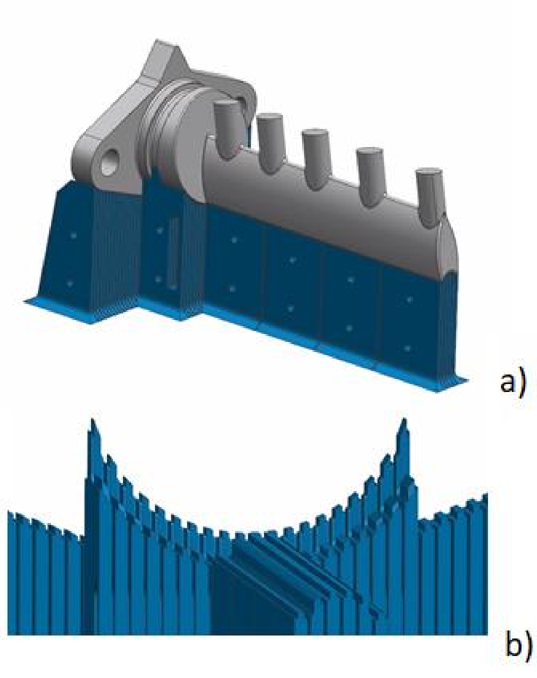

Figure 6.4 a) CAD of the supported Rake b) CAD of the traditional support structures

At least the presence of internal ducts has strongly influenced the printing direction which involves a larger area to be supported.

6.1 Application of the methodology

In this paragraph all the phases are explained in detail, leading to the final design of the support structure.

6.1.1 Input model

In order to apply all the steps of the methodology to evaluate the performed support structures, the starting point is the CAD model of the component.

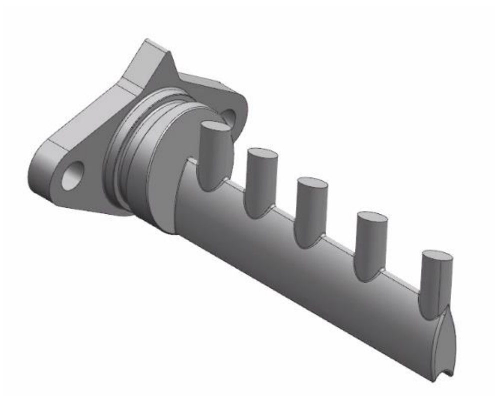

Figure 6.5 Rake CAD model

In the geometric model, the choice concerning orientation has already been discussed. In order to accurately evaluate the overhang surfaces to be supported, a draft analysis is used. It highlights the areas in which the surfaces have an angle of less than 45° with respect to the plane of the plate, which are therefore to be supported. In figure 6.6 it is possible to observe, in red the overhang surfaces and in grey the self-sustained surfaces.

Figure 6.6 Draft Analysis results

6.1.2 Mechanical and Thermal distortion model

During the set-up phase, the Topology Optimization requires, the loads to which the part is subjected during its operational life. In this case the part is the support structure and the loads represent the thermal and mechanical stresses that the Rake generates during the printing process. Having established this, a thermo-mechanical analysis is carried out that simulates the printing process in order to evaluate the nodal displacements that the Rake undergoes and that the support must contrast.

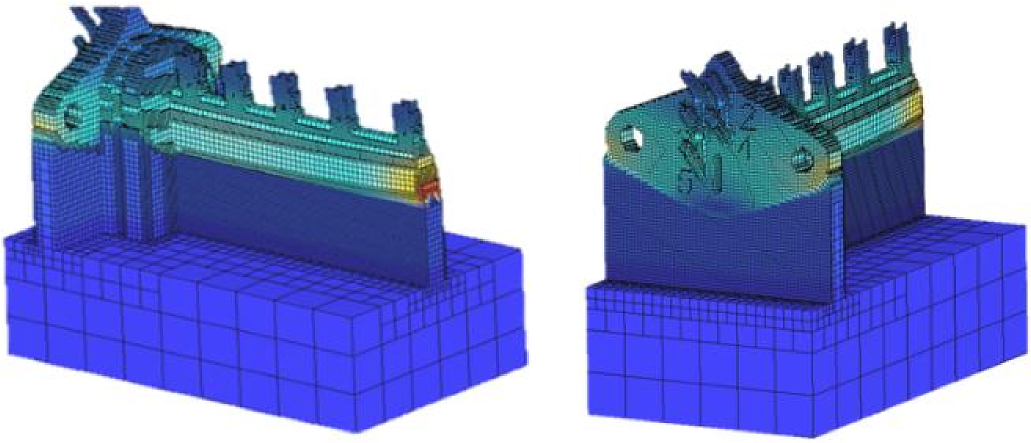

Figure 6.7 Rake thermo-mechanical analysis

This analysis should be conducted only at Rake, in order to analyze its way of deforming. However, in order to avoid contact with the building plate, a fictitious support is inserted, but its density and mechanical properties have been reduced by 95%. Therefore, it has no physical meaning. The outputs of this analysis, fundamental for the subsequent phases, are the nodal coordinates and displacements.

6.1.3 Preliminary support generation

From the Rake CAD model, the FEM model is created, in which the displacements obtained from the thermo-mechanical analysis of the previous paragraph are applied. In reality these displacements are interpolated, since the elements of the surface of the FEM model, consist of three nodes arranged in different coordinates, respect to the previous mesh in which each element was constituted by four nodes. This detail can be appreciated in figure 6.8.

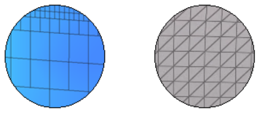

Figure 6.8 Mesh difference: four nodes elements (left), three nodes elements (right)

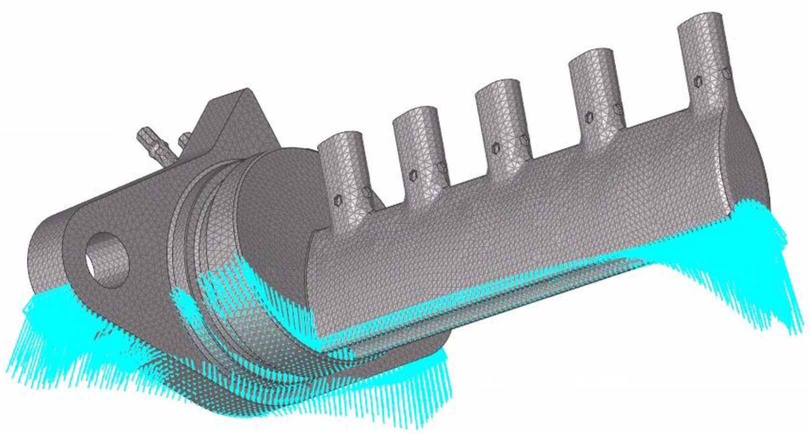

Figure 6.9 Displacement distribution on FEM model

The vectors related to the displacements in figure 6.9, as well as the results of the thermomechanical analysis in figure 6.7, confirm the most critical areas that have occurred during the printing of the Rake, which led to the failure of traditional supports. This distribution is an important information for a preliminary support generation.

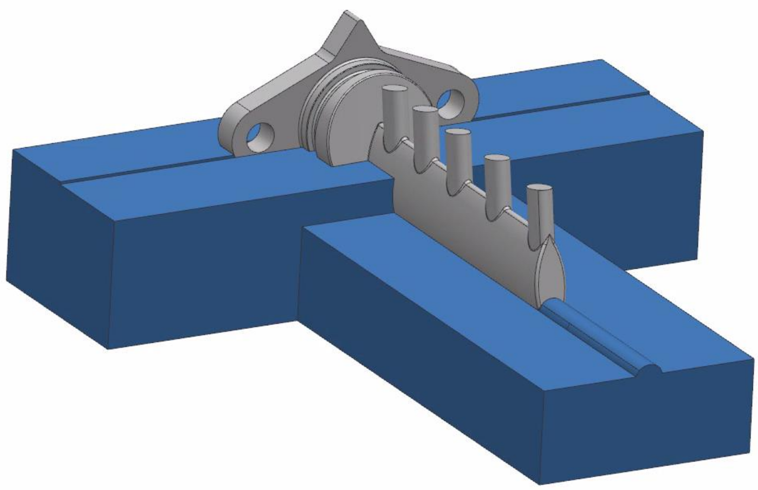

Figure 6.10 Preliminary support for Rake component

This preliminary support, which represents the design space for topology optimization, is very extensive in the first instance, especially in areas where the maximum displacements have been identified. The choice is dictated by the fact that in this way the optimization software has full freedom to dig the material and to create the most appropriate load paths in order to support the component respecting the directives indicated in the optimization set-up. The last step of this phase is to apply the displacements on the FEM model related to the preliminary support and to calculate the distribution of forces through a static analysis, because as said before, they are necessary in order to achieve the topological optimization.

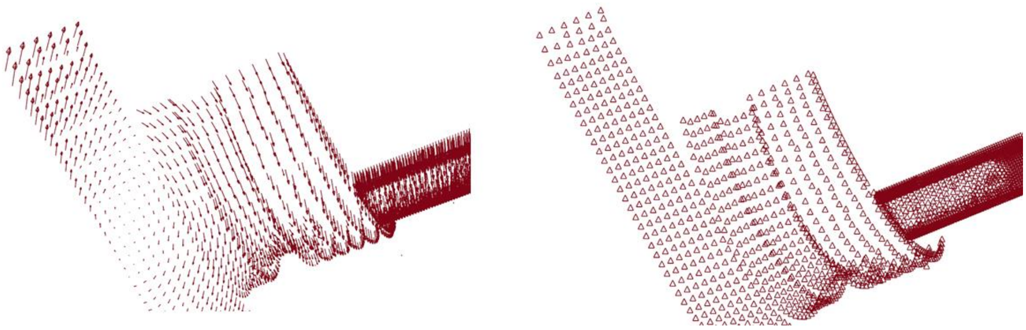

Figure 6.11 Displacements on support structure

in figure 6.11 it is possible to observe two different ways of understanding the displacements. On the left they represent the vector distributions of the magnitude displacements, while on the right they represent the constraints of forced displacements that are necessary in order to evaluate the static forces.

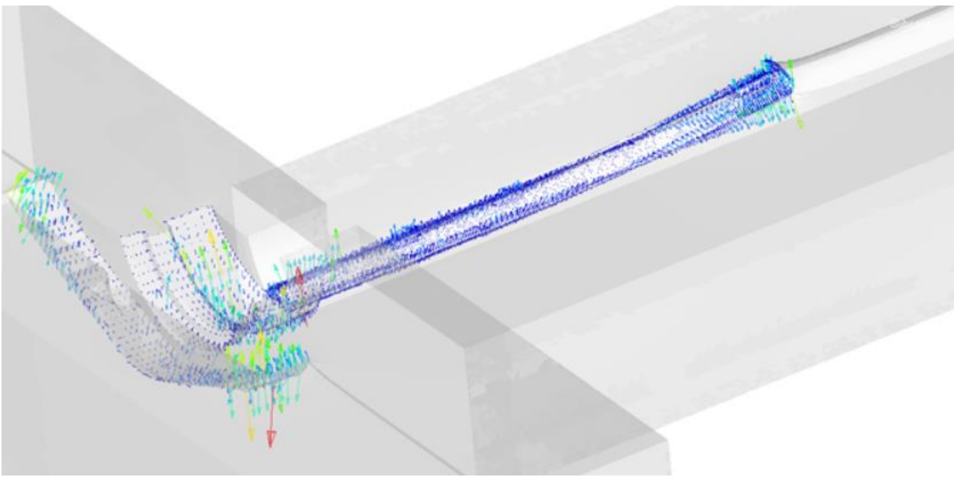

Figure 6.12 Force distribution applied on the support structure

6.1.4 Topology Optimization & Smoothing

Once the distribution of forces has been determined, it is possible to set up for topological optimization. Both for static analysis and for topological optimization, clamped constraints are placed at the base of the support structure, in order to simulate the fixing with the building plate.

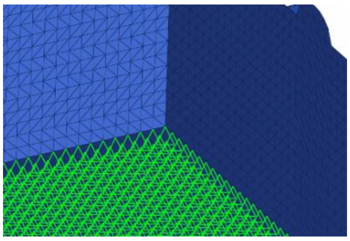

Figure 6.13 Clamped constrains at the support base

Once the constraints and the loads are arranged, the FEM model is the following:

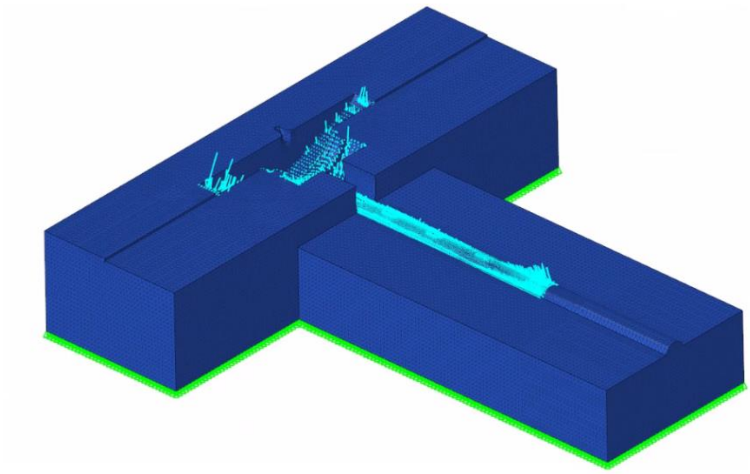

Figure 6.14 FEM model of support structure with loads and constraints

The response variables, of the different optimization cycles are:

- Compliance;
- Volume fraction;

The first one is the objective of the optimization and the second one represents the global constraint, defined as the ratio between the optimized final volume and the initial volume (≤ 1). The compliance C is calculated using the following relationship:

$$C = \frac{1}{2}\int \varepsilon^T \sigma \, dv = \frac{1}{2}u^T f = \frac{1}{2}u^T K u \qquad (6.1)$$

Where:

- C static compliance
- ε strain vector
- σ stress vector
- u displacement vector
- K stiffness matrix
- f force vector

For a structure with applied forces, the compliance can be considered a reciprocal measure of the stiffness:

$$C = \frac{1}{2}u^T f = \frac{1}{2}\frac{f^T f}{K^T} = \frac{1}{2}\frac{f^2}{K} \qquad (6.2)$$

Where $\frac{1}{2}f^2$ is constant. For a structure with applied displacements, the compliance can be considered a direct measure of the stiffness:

$$C = \frac{1}{2}u^T f = \frac{1}{2}u^T K u = \frac{1}{2}u^2 K \qquad (6.3)$$

Where $\frac{1}{2}u^2$ is constant.

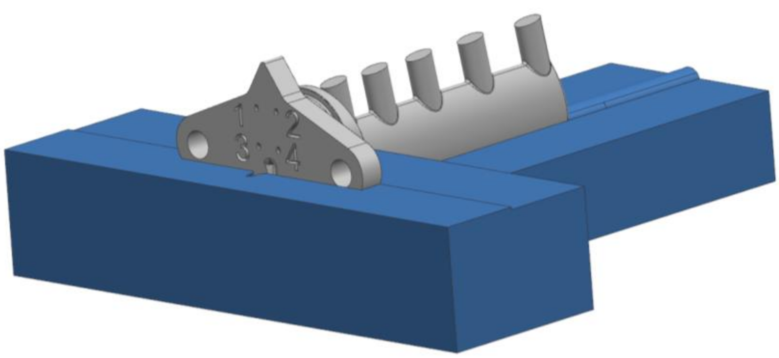

Figure 6.15 Initial Design Space of support structure

The printing constraint is also applied, in order to avoid non-self-supported surfaces, accepting a value of 45° respect the horizontal plane as the minimum overhang angle of the surface.

OPTIMIZATION 1

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.3*
Overhang Constraint	*Yes (45°)*

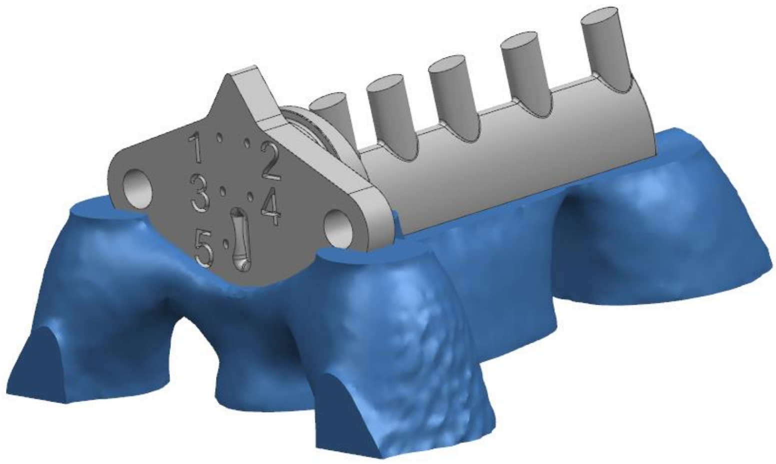

Figure 6.16 Results of Optimization 1

Iterations Number	*41*
Volume and Mass	*-70%*
Time	*5h*

The result of this first optimization represents the input model for the next one. As it can be seen in figure 6.16, the final result provided by the software cannot be used for further analysis, but it is necessary to apply a smoothing process (step 5 of the methodology) in order to carry out an FEA Reanalysis of the model. In this case the surfaces are more regular, and the new mesh that is automatically generated. In fig.6.18 it is possible to observe in detail the smoothing results.

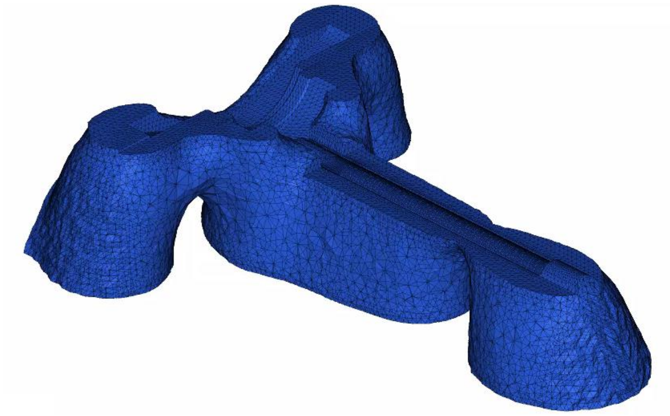

Figure 6.17 Optimization result before smoothing

Figure 6.18 Result of the Smoothing process

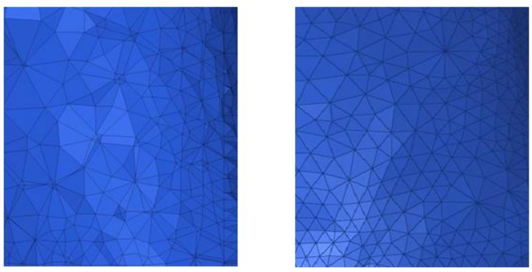

Figure 6.19 Comparison before and after the smoothing process

OPTIMIZATION 2

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.9*
Overhang Constraint	*Yes (45°)*

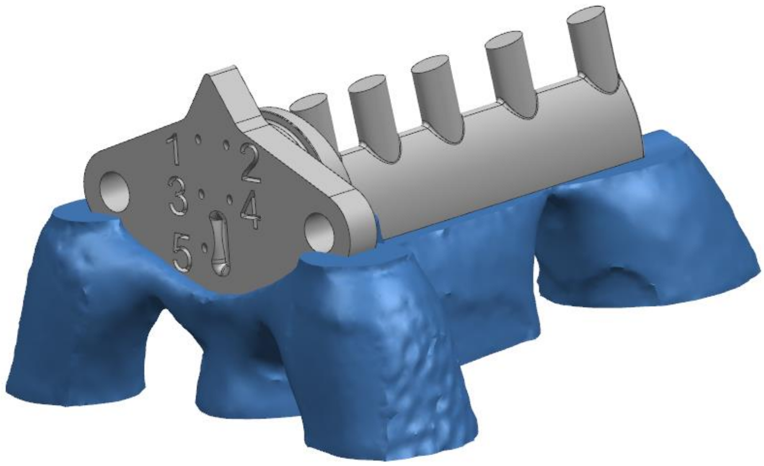

Figure 6.20 Result of Optimization 2

Iterations Number	*41*
Volume and Mass	*-10%*
Time	*7h 30 min*

OPTIMIZATION 3

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.8*
Overhang Constraint	*Yes (45°)*

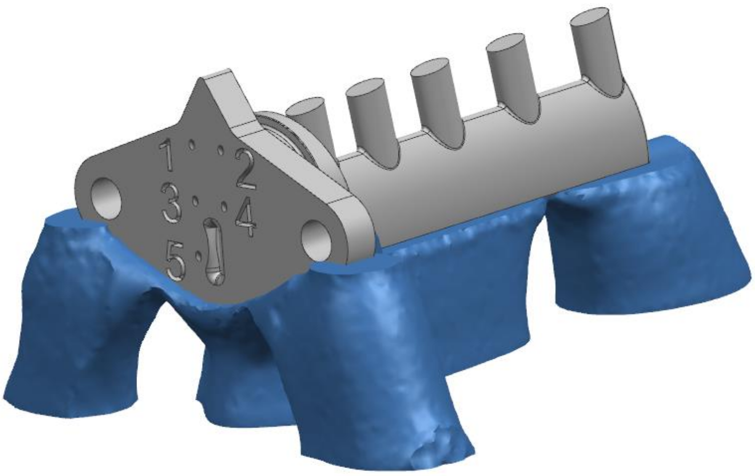

Figure 6.21 Result of Optimization 3

Iterations Number	*41*
Volume and Mass	*-20%*
Time	*7h 40 min*

OPTIMIZATION 4

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.6*
Overhang Constraint	*Yes (45°)*

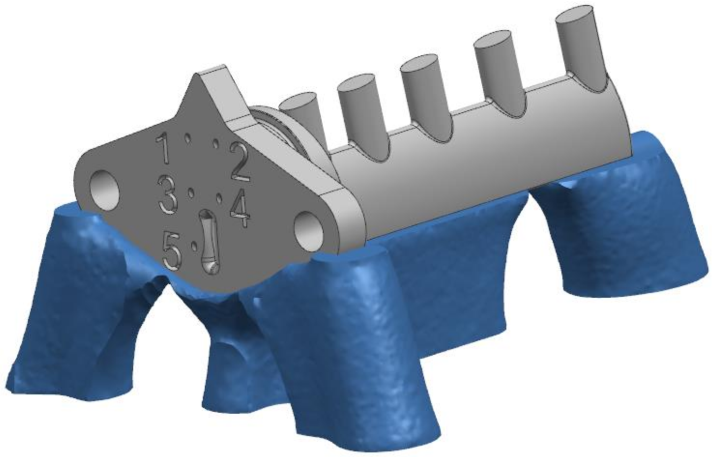

Figure 6.22 Result of Optimization 4

Iterations Number	*41*
Volume and Mass	*-40%*
Time	*21h 30 min*

OPTIMIZATION 5

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.7*
Overhang Constraint	*Yes (45°)*

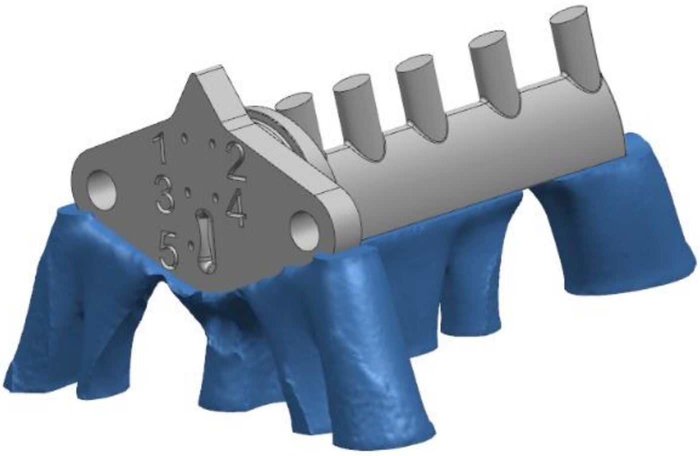

Figure 6.23 Result of Optimization 5

Iterations Number	*41*
Volume and Mass	*-30%*
Time	*49h 30 min*

6.1.5 Final Support Design and Results

As explained in chapter 2, the final solution provided by the software is almost never a finished product, but a reconstruction phase is required. In this case, this phase is not burdensome all, because it is only necessary to modify the frontal part of the support in order to guarantee a complete Rake sustaining. The CAD modeling software is used in order to perform this operation.

Figure 6.24 Support detail, before reconstruction (left) and after reconstruction (right)

The final support design is therefore obtained.

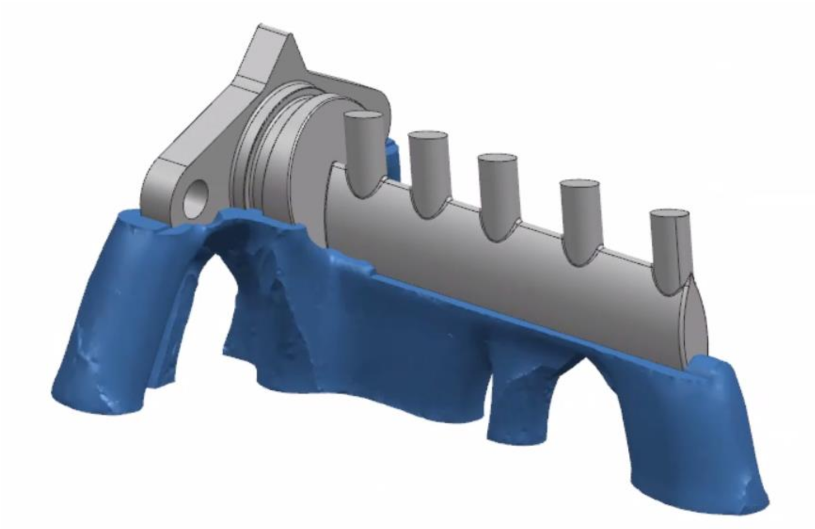

Figure 6.25 Final Support Design

As it can be seen from figure 6.25, topological optimization has created load paths, concentrating the material especially in the three most critical areas highlighted during the work. The methodological process was interrupted once the same volume of traditional supports was reached, in order to evaluate performance on equal terms. In order to validate the performance of this optimized support, a comparison with traditional supports is required, subjecting them to an analysis that simulates the printing process, similar to step 2 of the methodology. In this case the system is composed by supports and component. In figure 6.26 it is possible to observe the distribution of the displacements that the whole system undergoes, due to the effect of high thermal gradients. On an equal scale, it can be seen that the Rake, in the case of optimized supports, is less deformed, especially in the most critical areas where displacements have been significantly reduced.

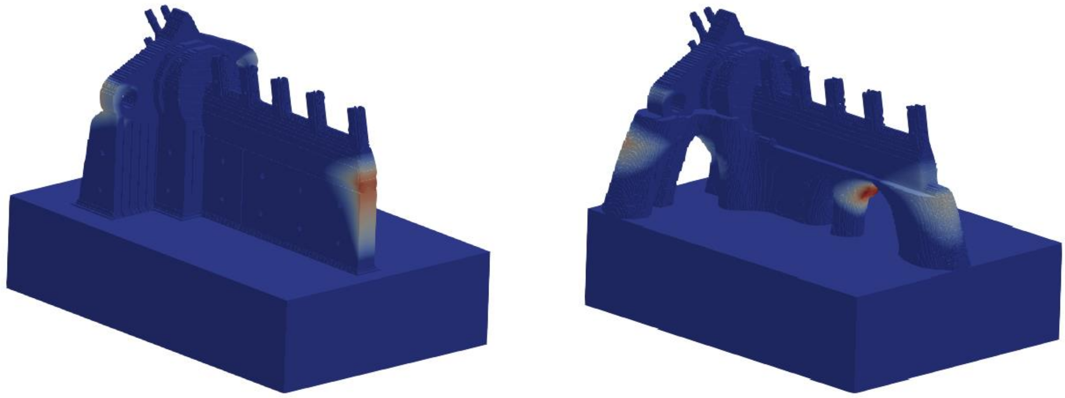

Figure 6.26 Comparison of magnitude displacement distribution between traditional supports (left) and optimized support (right)

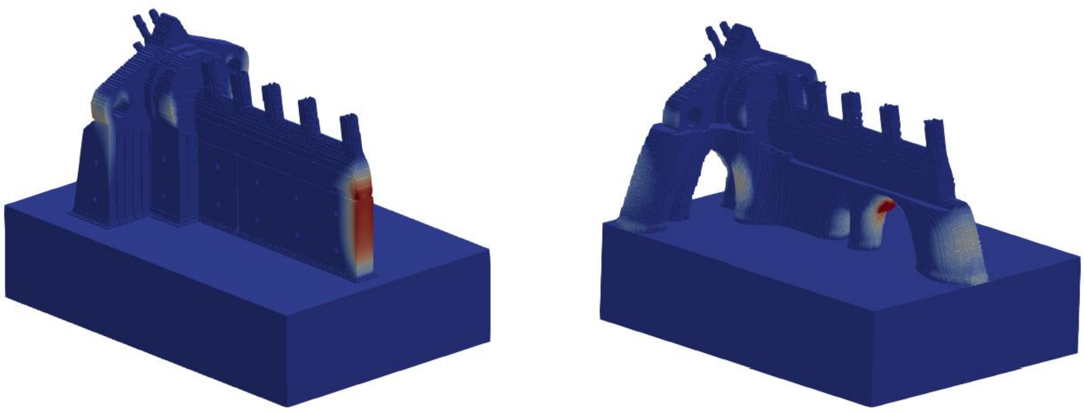

Figure 6.27 Comparison of z-displacement distribution between traditional supports (left) and optimized support (right)

The Rake is therefore relieved, and in fact, in figure 6.28 it is possible to observe the maximum displacements reduction in the three most critical areas compared to traditional supports.

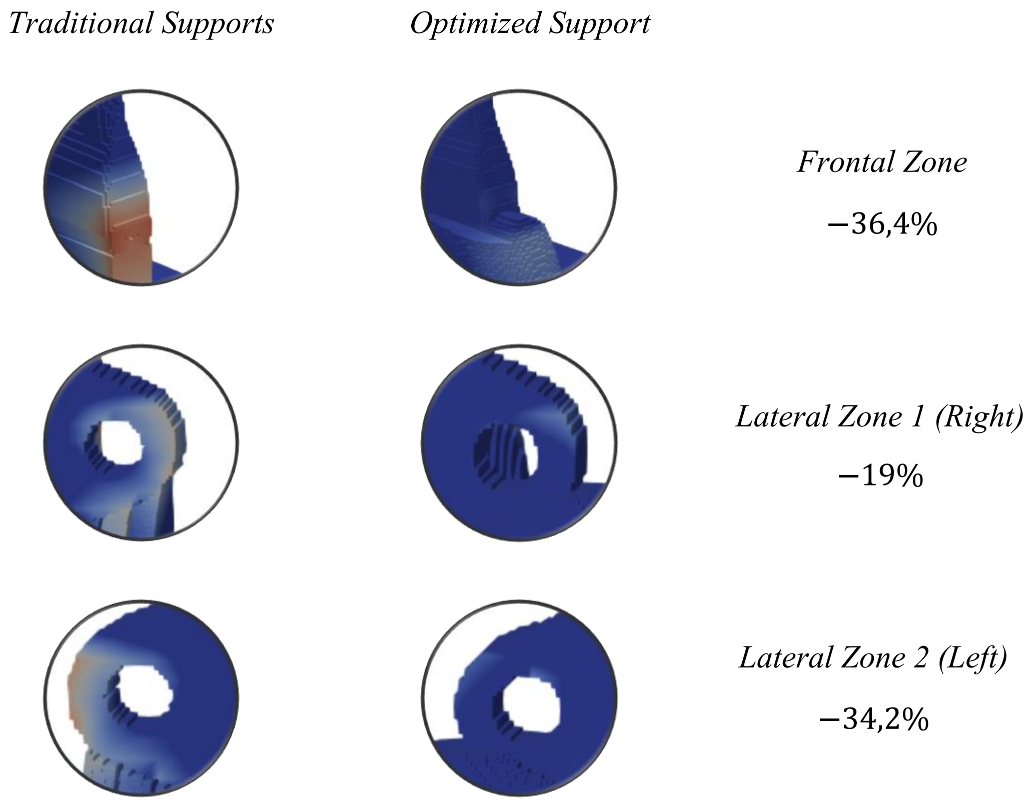

Figure 6.28 Detailed comparisons of displacements on the Rake between traditional supports (left) and optimized supports (right)

In figure 6.29 it is possible to observe the result of the final component after the removal of the system from the building plate and consequently after the removal of the supports. It is important to point out that no heat treatment was considered in the analysis. On the left of the image the results of the Rake sustained with traditional supports are showed, while on the right, the same results but with optimized supports. In blue the nominal conditions of the component are represented, while in gray, the conditions that can be reached by the printing process are represented, whose deformation however has been accentuated by 6 times its real value, in order to highlight once again the benefits that optimized support produce. In fact, it is easy to observe that the solution on the right shows results much closer to the nominal condition. The maximum Rake displacement, after the optimized support removal, is reduced by 24.8% compared to the solution with traditional supports.

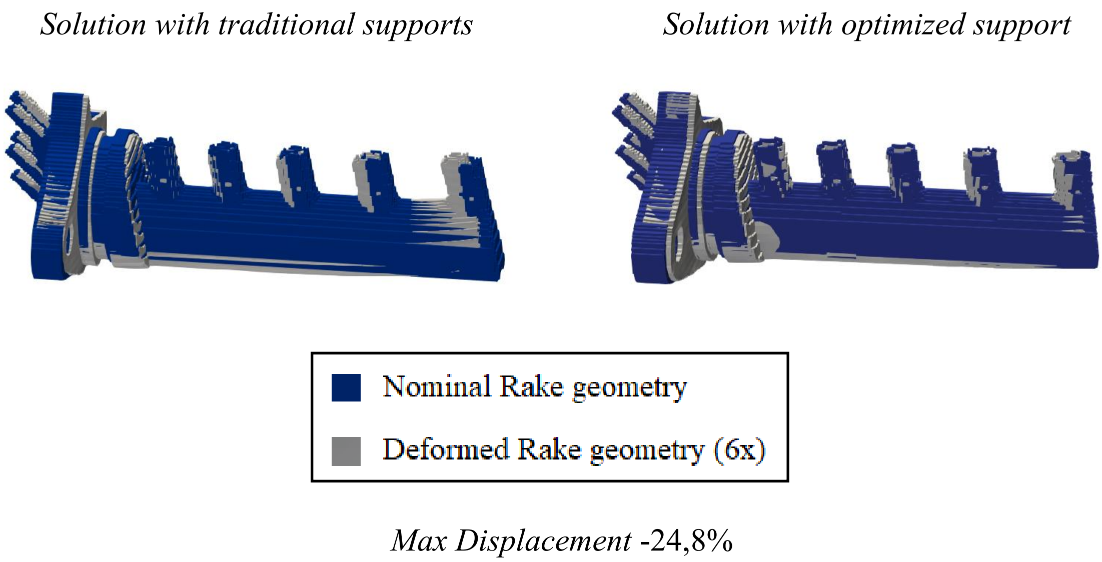

Figure 6.29 Comparison between nominal Rake geometry and deformed Rake after support removing

In reality it should be taken into consideration a further variable which was not taken into account in this first preliminary phase of the realization of the methodology, i.e. the ease of removal. It is clear that these optimized supports require more complex post processing operations. In any case, all these aspects have been clarified in the conclusions.

7 Conclusions

Additive manufacturing means innovation and the work of this thesis is in line with this philosophy. Support techniques are essential so that this technology can make its way and take over the other ones.

The results presented in this thesis, which include the formulation from scratch of the methodology and its application to the industrial component, are extremely interesting, but this should not be considered a point of arrival, but a significant goal and the process can still be improved with further developments.

As already mentioned in the definition of the process, the easiness of supports removal has not been taken into account, which however represents a variable of considerable importance. Currently it is also possible to associate this innovative support philosophy with the classic one, creating hybrid models that reduce the contact surface to the interface between support and piece or this optimized solutions with their load paths, can be used as guidelines for the designer in order to accurately create traditional supports.

Finally, it would be necessary to have a real feedback, making a print of the component sustained by these optimized supports.

Appendix A: Support Structure for L-Shaped geometry

Since the methodology was implemented from scratch, a very simple geometry was considered as the first application: the L-shaped geometry. It has a vertical self-sustained section in contact with the building plate, and a horizontal section in complete overhang [36].

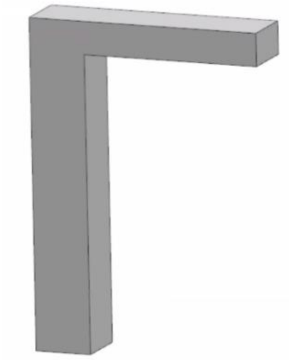

Figure A.1 L-shaped geometry

The methodology steps, for this test-case are illustrated below.

Mechanical and Thermal distortion model

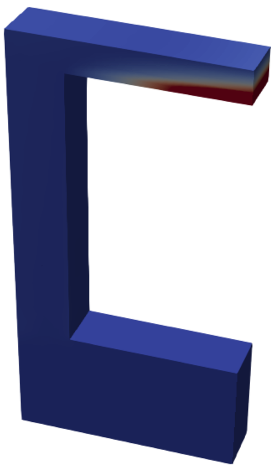

Figure A.2 Distortion prediction of the L-shaped part

Preliminary support generation

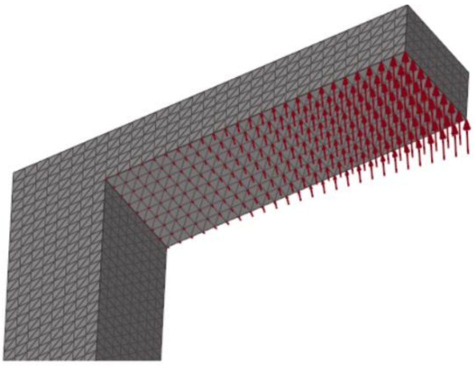

Figure A.3 Displacement vectors interpolated to the FEM part

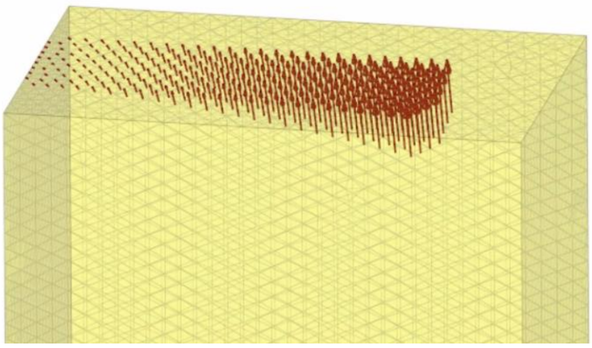

Figure A.4 Displacement vectors interpolated to the FEM of the preliminary support

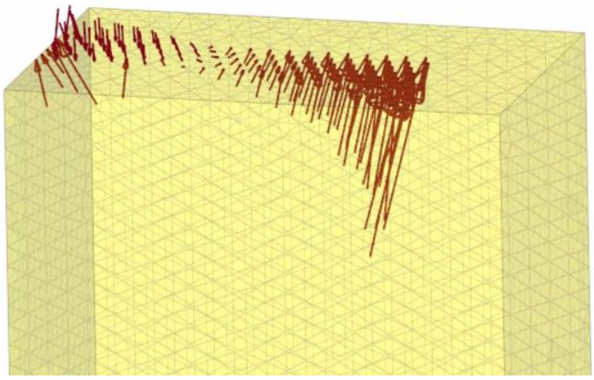

Figure A.5 Force distribution, evaluated through static analysis

Topology Optimization & Smoothing

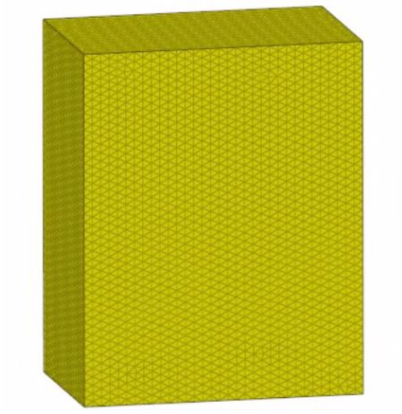

Figure A.6 Initial support Design Space

OPTIMIZATION 1

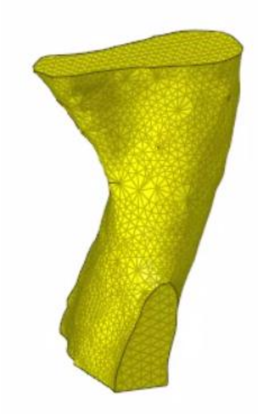

Figure A.7 Results Optimization 1

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.28*
Overhang Constraint	*Yes (45°)*
Volume and Mass	*-72%*

OPTIMIZATION 2

Figure A.8 Results Optimization 2

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.8*
Overhang Constraint	*Yes (45°)*
Volume and Mass	*-20%*

OPTIMIZATION 3

Objective	*Min Compliance*
Optimization Constraints	*UB Volfraction = 0.7*
Overhang Constraint	*Yes (45°)*
Volume and Mass	*-30%*

Figure A.9 Results Optimization 3

Final Support Design

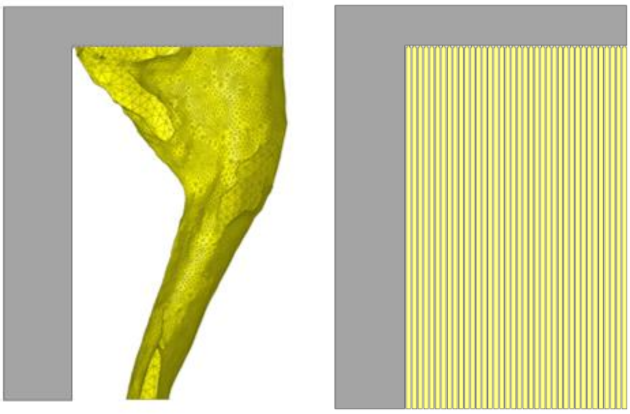

Figure A.10 Comparison between support optimized and traditional supports

Validation

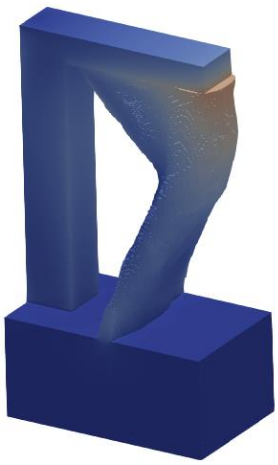

Figure A.11 Validation analysis of printing simulation

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