**Politecnico di Torino**

I FACOLTÁ DI INGEGNERIA

Corso di Laurea Magistrale in Ingegneria Aerospaziale - Specializzazione in Sistemi Propulsivi

Master's Degree Thesis

# Preliminary optimization of an hollow Low Pressure Turbine blade


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**Anno Accademico 2018-2019**

*Ai miei genitori,*
*presenti in ogni momento*
*e a cui esprimo*
*la mia più profonda gratitudine*

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# Glossary

**AM** Additive Manufacturing

**CAD** Computer Aided Design

**CAE** Computer Aided Engineering

**SLA** Stereolitography Apparatus

**SOUP** Solid Object Ultraviolet Plotter

**SCS** Solid Creation System

**FDM** Fused Deposition Model

**SLS** Selective Laser Sintering

**PBF** Powder Bed Fusion

**DMLS** Direct Metal Laser Sintering

**SLM** Selective Laser Melting

**EBM** Electron Beam Melting

**DED** Direct Energy Deposition

**LENS** Laser Engineered Net Shaping

**DFA** Design For Assembly

**DFM** Design For Manufacture

**DFAM** Design For Additive Manufacturing

**NURBS** Non-Uniform Rational Basis-Splines

**LCF** Low Cycle Fatigue

**HCF** High Cycle Fatigue

**STL** Standard Triangulation Language

**HIP** Hot Isostatic Pressing

**SIMP** Solid Isotropic Material with Penalization

**DMLM** Direct Metal Laser Melting

# Literature

The first chapter provides an introduction to Additive Manufacturing technology, describing its history and the improvements made over the years. Due to the variety of AM machines, which differ from each other for several factors, including the type of material used, it has been given a description only of Powder Bed Fusion technology, which allows to produce metallic components through laser melting, electron beam melting or laser direct energy deposition.
The second chapter is focused on the analysis of the methodology that the designer has the task to follow in order to create a CAD model that fulfills certain requirements in terms of functionality, structural performance, manfacturability and similarity to the baseline real model; for this reason, it is also provided a brief description of the fundamental steps useful to obtain an effective 3D model.
In the third chapter the aforamentioned methodology is generalized and included into the Additive Manufacturing process chain, which starts from the conceptualization of 3D CAD and ends with the post processing of the printed component. Generally the potentiality of AM are exploited through the use of structural optimizations, which allow to study and to produce innovative, more complex and more performing geometries. Finally, the last chapter is characterized by an exercise of topology optimization, performed on an aeronautical turbine blade. The goal of this study case is to develop a strong methodology useful to conceptualize and to produce lighter and stronger blades, according to what presented previously.

# Introduction

The need for higher and higher performances of automotive and aerospace structures, and the parallel request for their lightening, are the reason why the conventional productive processes, characterized by a considerable amount of castable materials, are being progressively abandoned in favour of innovative technologies, which are usually referred to as rapid prototyping. This new way of designing and realizing components has its fundamentals on the massive use of 3D printing machines, which allow to build-up, by depositing material, geometries more complex than ever before starting from a model previously generated by Computer-Aided Design (CAD) tools.

Emerged in 1980s as a revolutionary technology based on a laser-induced photo-polymerization process, rapid prototyping has progressively evolved into a sophisticated process known as Additive Manufacturing, which allows to produce free-form metal objects with intricate lattice and honeycomb features, from which the final product can be eventually derived.

The applications of AM range from engineering to medical industry but, although the significant advantages coming from reduced material waste, time and costs associated with materials, in addition to the mentioned capability to manufacture parts with complex internal structures, there are considerable complications due to the limited knowledge and availability of materials, 3D printing machines performance and the stages that characterize the AM process, which includes also careful cleaning of the parts and post-processing such as sanding and surface preparation.

The aim of this work is to study and redesign an aeronautical engine blade taking into account the opportunities offered by Additive Manufacturing process and, subsequently, using innovative optimization methods, whose mathematical models allow to reduce systems which include a large number of degrees of freedom without losing important information of their behaviour.

The thesis has been developed in collaboration with Avio Aero, “a GE Aviation business that designs, manufactures and mantains components and systems for civil and military aviation”, which has reviewed and approved the elaborate. It is based in Rivalta di Torino and, thanks to research, development activities and partnerships with leading companies and universities, it has acquired a broad portfolio of knowledge on Additive Manufacturing processes.

# Chapter 1

# Additive Manufacturing

## 1.1 Introduction

As mentioned before, the Additive Manifacturing process chain embraces and expands rapid prototyping philosophy, which three decades ago produced the first remarkable results with SLA-1, the first-ever commercialized stereolitography system in the world, able to use a UV laser beam in order to induce the photo-polymerization of a particular resin and to cure it layer by layer. Although there were a good number of patents and demonstrations since 60s, the Stereolitography Apparatus was the first milestone of this revolutionary manufacturing approach, inspiring the development of new technologies which progressively put more emphasis on the functionality of the model created, considered initially as a baseline from which deriving further models, and now as a fully functional end-user part.

The photo-polymerization was also at the basis of some of these new systems, like the Solid Object Ultraviolet Plotter (SOUP) and the Solid Creation System (SCS); however, in the early of 90's, tecnhologies like Fused Deposition Model (FDM), Laminated Object Manufacturing and Selective Laser Sintering (SLS) defined new guidelines for AM development.

Given the enormous potential of the "additive" approach, the number of its applications is rapidly increasing as the processes and materials improve; one of the most impressive projects characterized by this innovative paradigm is, without doubt, the GE Advanced Turboprop, a demonstration engine which will power the all-new Cessna Denali single-engine aircraft and 35% additive manufactured, in order to reduce the weight by 5% and, at the same time, to improve significantly the specific fuel consumption (SPC).

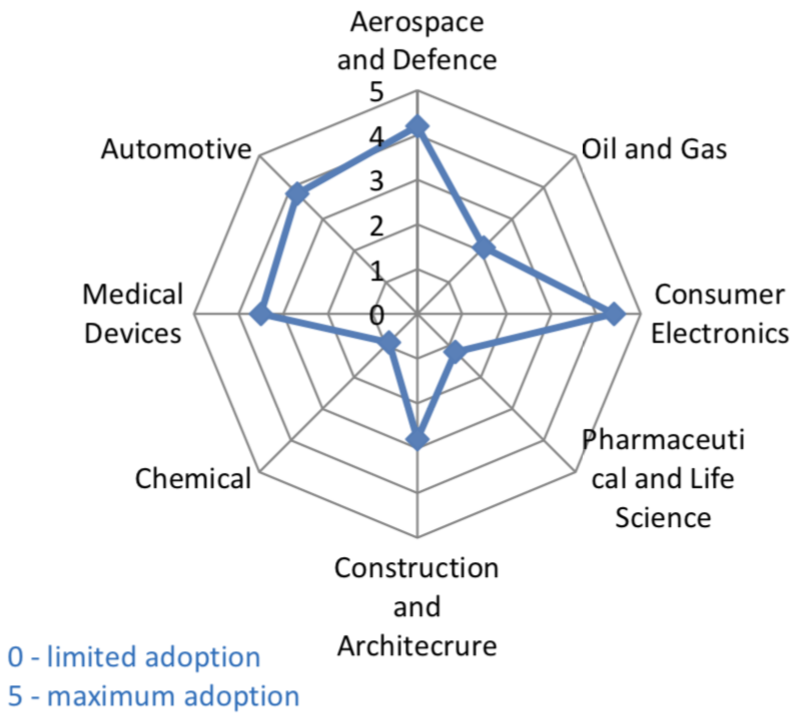



Figure 1.1: Impact of AM technologies on global industry

A key factor related to the correct AM processes development is also the study of materials properties, like metal alloys, ceramics and composites, each of which requires different productive strategies; this thesis is focused only on metal additive manufacturing technique.

## 1.2 Powder Bed Fusion Technology

At the current state of art the easiest systems to build up a component are powder-bed based, and, excluding some variations which characterize the different technologies such as process capability, conditions and part characteristics, they all share a basic set of working principle. The powder is fed into and spread on a build plate, which is in inert atmosphere or partial vacuum to provide shielding of the molten metal. An energy source, as laser or electron beam, is used to scan each layer of the powder and selectively fuse a section of the component. Once this process is completed, the piston of the building chamber goes downward and the one of the powder chamber goes upward, allowing a roller to deposit a new powder layer, with a desired thickness, which is scanned again. This cycle is repeated layer by layer until the part is formed.

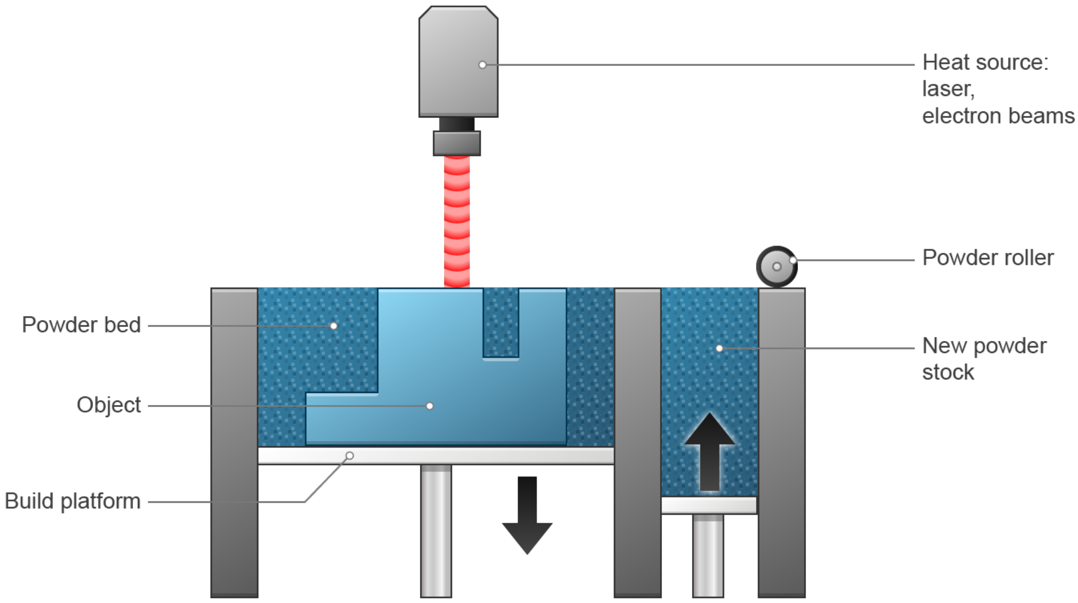



Figure 1.2: Schematic drawing of PBF technology

In order to ensure the absence of distortion, residual stress and other penalizing phenomena it is fundamental to evaluate the powder behaviour inside and outside the machine, as well as the correct thickness of the layers.

Due to the fact that only a fraction of the powder is used to build up the component, powder bed fusion processe haa a significant amount of unused powder that is subjected to some level of thermal history, which can modify powder properties; for this reason, an effective recycling strategy is necessary to guarantee that the material is within appropriate limits.

Also, the powder inside the machine can experiment different densities in the chamber, because the powder on the top compresses with its weight the powder on the bottom; this phenomenon can affect the amount of the material deposited at each layer.

The layer height is another important parameter which can influence the entire process, and need to be accurately set considering also other parameters such as geometry, power, powder particle size and size distribution.

PBF processes always require support of same material part, generated durig pre-processing phase and removed at the end of the process, in order to avoid collapse of molten matieral in case of overhanging surfaces; after support removal, post-processing treatments like peening,

polishing and machining can be done to improve component performance.
The most popular PDF based techologies which use laser or electron beam as energy source are respectively Selective Laser Sintering (SLS) or Direct metal laser sintering (DMLS) from EOS, Selective Laser Melting (SLM) from Renishaw, SLM solution and laser cusing from Concept Laser, and Electron Beam Melting (EBM) from ARCAM.

### 1.2.1 Selective Laser Melting

Selective Laser Melting (SLM) technique melt and fuse metallic powders by using a high power-density laser, which is focused through a system of lenses and mirrors and whose type can change from one machine to another, including $CO_2$, Nd:YAg, fiber lasers and disc lasers. During the SLM process, the building chamber is often filled with nitrogen gas or argon gas to provide an inert atmosphere to protect the heated metal parts against oxidation.

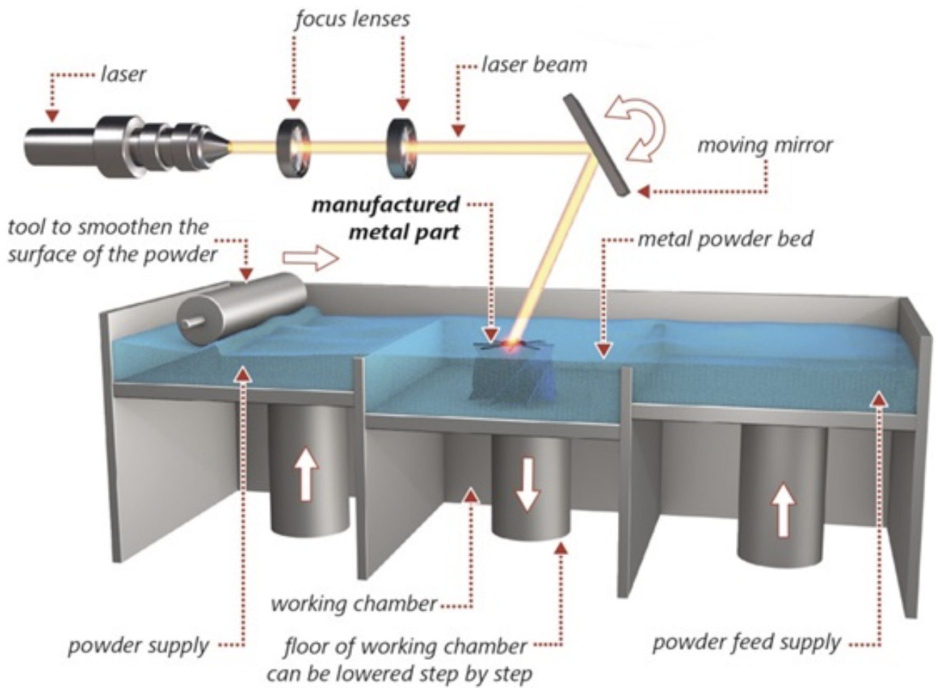



Figure 1.3: Representation of SLM process

Furthermore, some of the SLM machines are capable of providing pre-heating either to the substrate plate or to the entire building chamber. Laser power also ranges between 200 W and 1000 W, and its type has a relevant role in the consolidation of powders because its wavelength

and energy density influence significantly the material absorptivity and the powder densification. Together with this parameters, laser power, scanning speed, hatch spacing, and layer thickness affect the volumetric energy density that is available to heat up and to melt the powders.
Compared to the conventional manufacturing methods, SLM ensures finer structures in the microstructure at very high cooling rate and, with a well monitored process, the absence of porosity and a material density close to 100%.
Iron, titanium and nickel are the three types of metal which most of the SLM research revolves around, due to their widespread application and their material cost, but recent researches are also focused on other metals such as aluminium, copper, magnesium and tungsten; however, the commercially available materials are: Aluminium AlSi10Mg, Cobalt Chrome, Maraging Steel, Stainless Steel, Titanium Ti6Al4V and Nickel alloys (Inconel 625 and 718).

### 1.2.2 Electron Beam Melting

Although the EBM process is similar to the SLM, it differs from it for the thermal source used, which in this case is characterized by an electron beam emitted by a heated tungsten filament; the electrons generated are collimated and accelerated to a kinetic energy of about 60 keV thanks to two magnetic fields, a focus coil, which is a magnetic lens that focuses the beam to the desired diameter, and a deflection coil, which deflects the focused beam to the desired point on a build platform. The entire process also needs to be done under high vacuum of $10^{-4}$ to $10^{-5}$ mbar, as even a small helium gas supply during the melting further reduces the vacuum pressure, allows part cooling and provides beam stability.
The EBM process consists of two different phases:

- Preheating: during this stage a high current beam with a high scanning speed is used to preheat the powder layer in order to regularize it and to prevent charging of electrons, also known as powder spreading, which can cause build failure during Additive Manufacturing process; Previous studies has proven the numerous advantages of prehating, which can increase the effective mechanical strength, electrical, and thermal conductivity of the sintered powder, improving the beam-matter interaction efficiency; it also allows to reduce the formation of balling and to lower the thermal gradient during melting, reducing distortion, warpage, and in-built residual stress [8]. On the other hand, this stage increases the overall build time and energy consumption and creates lightly sintered particles that are difficult to remove once the process is finished;

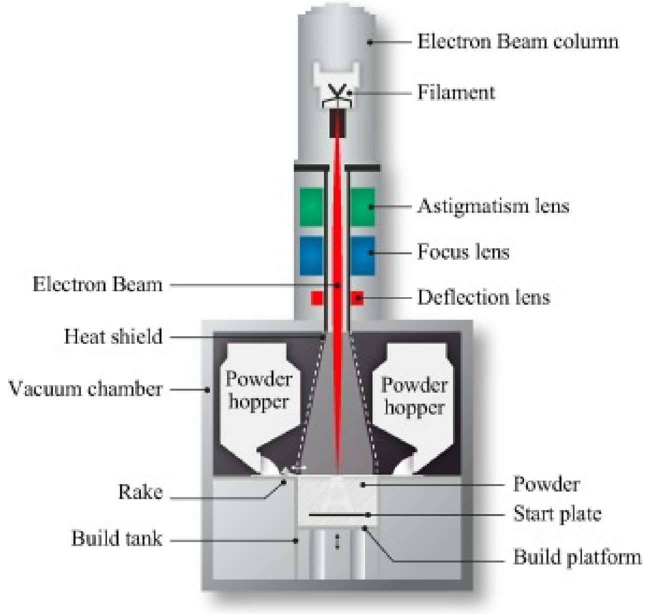
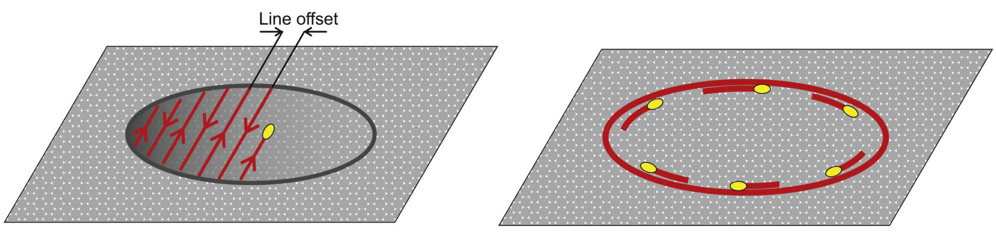



Figure 1.4: Schematic drawing of an EBM system

- Melting: this phase is characterized by a low current beam with a low scanning speed which is used to melt the powder; when scanning of one layer is completed, table is lowered, another powder layer is spread and the process is repeated till required component is formed [3]. The part cross-section is melted in two stages referred to as contouring and hatching. The first improves the surface finish of the part, melts the perimeter of the part cross-section using a constant beam power and velocity, and the second, which can follow or precede contouring, performs the majority of the melting using a beam with variable power and velocity to facilitate the heat dissipation and to prevent overheating. Different hatching strategies have subsequently been developed in order to improve this process.




(a) Hatching

(b) Contouring

Figure 1.5: Difference between hatching and contouring strategies

Another key factor which strongly affects the EBM process is the powder morphology, which influences preoperties such as powder packing and heat transfer process phenomena [6]. Generally, fine powder with spherical shape is used to ensure high flowability, high build rates and part accuracy; moreover, the material chosen has to be necessarily conductive to ensure interaction between the powder and the electron beam, and for this reason the adoption of ceramic materials is virtually impossible. Typical EBM metal powders are Titanium alloys, Cobalt-Chrome and Inconel 718.

| | **SLM** | **EBM** |
|---|---|---|
| **Power source** | One or more fiber lasers of 200 to 1000 W | High power Electron beam of 3000 W |
| **Build chamber environment** | Argon or Nitrogen | Vacuum / $He$ bleed |
| **Method of powder preheating** | Platform heating | Preheat scanning |
| **Powder preheating temperature (C)** | 100-200 | 700-900 |
| **Maximum available build volume (mm)** | 500 x 350 x 300 | 350 x 380 |
| **Maximum build rate (cm$^3$/hr)** | 20-35 | 80 |
| **Layer thickness ($\mu m$)** | 20-100 | 50-200 |
| **Melt pool size (mm)** | 0.1-0.5 | 0.2-1.2 |
| **Surface finish (Ra)** | 4-11 | 25-35 |
| **Geometric tolerance (mm)** | ± 0.05-0.1 | ± 0.2 |
| **Minimum feature size ($\mu m$)** | 40-200 | 100 |

Table 1.1: Technical specifications of SLM and EBM machines

### 1.2.3 Laser Direct Energy Deposition

Direct Deposition processes, using a focused heat source as a laser, an electron beam or an arc, create structures melting metallic material while it is deposited in a specific point through one or more nozzles mounted on a print head that can move along X, Y and Z axes. The powder delivered to the laser spot is consequently absorbed into the melt pool, thus generating a deposit that may range from 0.005 to 0.040 in. thick and 0.040 to 0.160 in. wide [13]. The entire process is often conducted in a controlled argon atmosphere containing less than 10 ppm oxygen.

This process is typically used to repair or to add material to existing components creating a coating, or to build-up new ones printing also different materials sequentially, impossible with PBF technologies.

The elements that characterize a typical DED machine are:

- Deposition head: used to release the material, integrates a nozzle for powder or wire which can be placed in a tridimensional space, an optical system, inert gas pipes and, sometimes, sensors;
- Focusing system: it is characterized by a lens which focuses the laser beam on the part;
- Laser source: it is the device that produces the beam with the desired characteristics; some of the critical factors are power beam, radiation wavelength and continuous or pulsed emission.

There are generally two lower level processes of Direct Energy Deposition: Laser Engineered Net Shaping (LENS), which will be briefly described, and Electron Beam Freeform Fabrication.

**Laser Engineered Net Shaping**

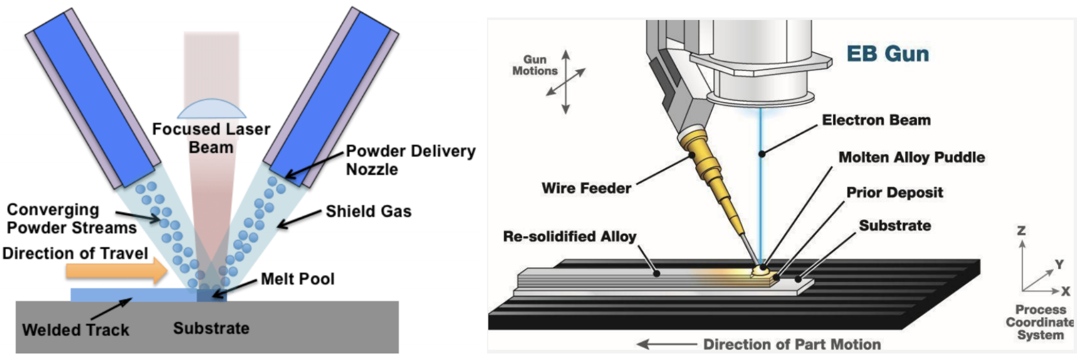



Figure 1.6: Directed Energy Deposition LENS and EBAM methods

LENS technology is being evaluated by medical industry, aerospace industry, as well as commercial industries that include electric power generation, oil/gas, chemical processing and mining because of the impressive versatility and flexibility of the process, whose applications include the repair of worn components, performing near-net-shape freeform builds directly form CAD files, and the cladding of materials.

Low heat input and minimal distortion are consistent deposit characteristics, in addition to a very fine grain structures, which may be one order of magnitude smaller in size than comparable wrought products due to a very fast cooling, up to 10,000°C/s, caused by the small melt pool and high travel speeds. For this reason LENS method can save more time and energy and can produce also ceramic parts with higher purity, density, and better mechanical behaviour.

Stainless steels, tool steels, nickel alloys, cobalt alloys, titanium alloys, and a variety of hardfacing or cladding alloys are some of the materials that are successfully being deposited utilizing this process [13].

# Chapter 2

# Design for Additive Manufacturing

The numerous advantages of Additive Manufacturing process allow to integrate, with some differences, methods, tools and rules proper to Design for Assembly (DFA), whose aim is to make product assembly easier and cheaper in terms of time and costs by minimizing number of assembly parts/components, and to Design for Manufacture (DFM), which concerns with reducing cost and complexity of manufactured parts without reducing quality or performance of the part by minimizing manufacturing operations complexity and number of tight tolerances [4].

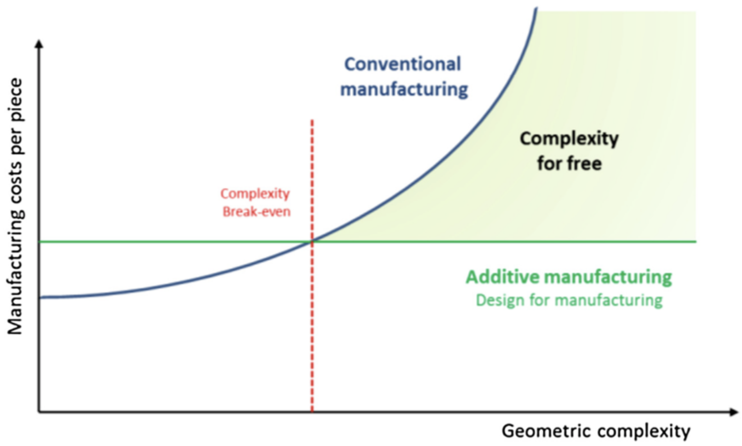



Figure 2.1: Costs vs. part complexity for AM technologies

These mentioned philosophies are used for conventional manufacturing, which cannot ensure all the benefits of AM technology listed below:

- Cost and geometry complexity: AM process depends only on production volumes and not on the geometric complexity of the component. Moreover, to achieve desired functionality, numerical simulation helps to place material only where it is required, ensuring weight reduction in aerospace and medical industry applications [4];
- Functional complexity: moving parts such as bicycle chain, chain mails, armor, crank slider mechanisms, gears, hinge, and various types of joints, can be manufactured directly using AM [4];

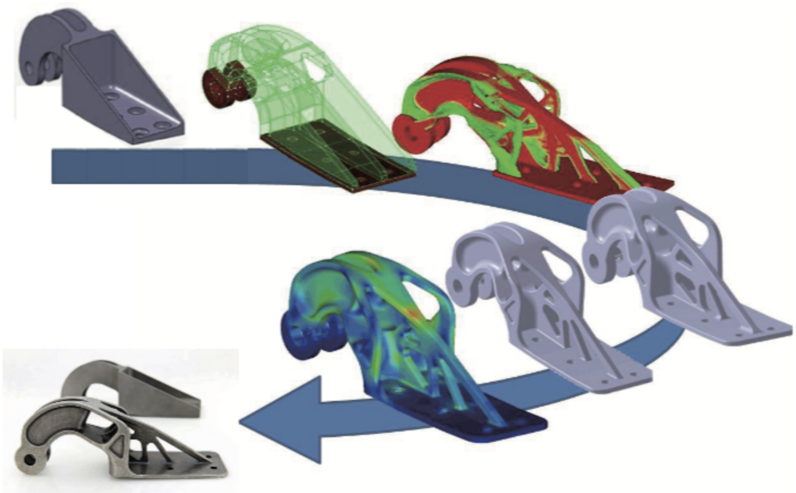


Figure 2.2: Airbus A320 Nacelle Hinge Bracket redesigned for additive manufacturing through topology optimization

- Material complexity: multi-material parts and products and complex composition of materials that provides different properties at certain locations can be manufactured in one operation [4];
- Hierarchical complexity: possibility of designing various shapes of internal structure (honeycomb, lattices or foams) to increase strength; properties like weight stiffness and weight ratio can be also improved to reduce material usage and cost [4];
- Low manufacturing skills;
- Reduced material waste;

- Part and material variety;
- Design method;
- Quality control.

## 2.1 Design method for Additive Manufacturing

The design process aims to take advantage of Additive Manufacturing benefits previously mentioned by providing new strategies, tools, techniques and methods, which can improve manufacturing capabilities. DFAM methodology follows generally five steps:

- Analysis of the specifications;
- Initial shape;
- Definition of a set of parameters;
- Parametric optimization;
- Validation of the shape;

### 2.1.1 Analysis of the specifications

Assuming to manufacture a part by a single additive manufacturing process, the design process starts with the definition of a set of functional surfaces, whose function is either to help assemble the part onto other parts, to transmit mechanical or thermal loads or to assure liquid or gas tightness and to prevent the part from colliding with other parts as well as to allow fluids circulation. Moreover, the material of the part has to comply with the manufacturing process, as well as behaviour requirement [14];

### 2.1.2 Initial Shape and parameters definition

The aim of this step is to obtain a single or multiple rough shapes through the definition of functional surfaces of the part made by the designer, taking into account Additive Manufacturing constraints and capabilities. For instance, if the part is destined to be manufacture on a layer-based process, the initial shape can not have any closed hollow volume (in the of case a single-process manufacturing) and the initial shape must make the powder removal as easy

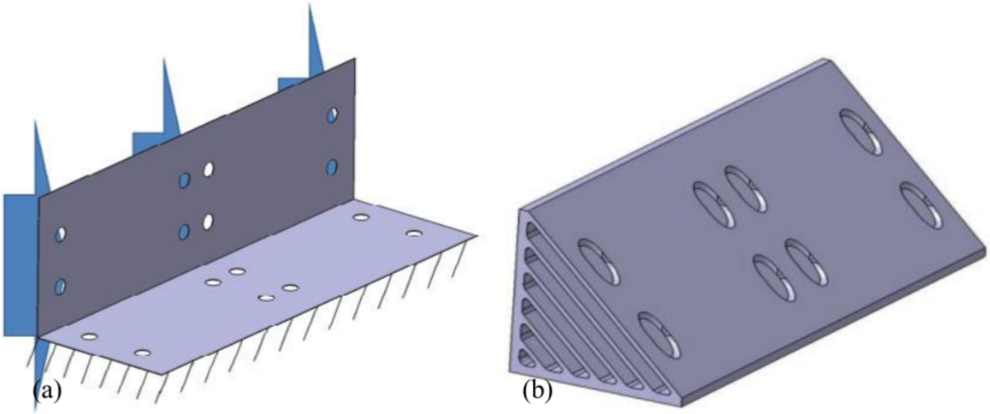



Figure 2.3: Functional surfaces and mechanical load (a) and new design manufactured in Ti6Al4 on an EBM machine (b)

as possible [14]. Moreover, these surfaces must be linked based on the specific part exposure to mechanical or thermal load.
During this step the designer also has to define a certain number of parameters and constraints with respect to the part specifications and to the manufacturing constraints in order to set up correctly the optimization analysis. Generally, for the correct addressing of any optimization is necessary to follow some preliminary steps:

- Design Space definition;
- Non-Design Space definition;
- Material Selection

**Design Space definition**

It is fundamental, during the pre-processing phase, to define and create the correct volume which the optimization algorithm can progressively manipulate or reduce in order to perform the analysis. The Design Space does not need a high level of detail during its creation because the designer has to give as much freedom as possible to the software while generating load paths; for this reason, the design area should be extended until there is an interference with other components or assembly of the part is no longer feasible.

#### Non-Design Space definition

The Non-Design Space is the complementary region of the Design Space, and represents the volume which can not be modified during the optimization in order to preserve the functionality of the component and of the assembly.

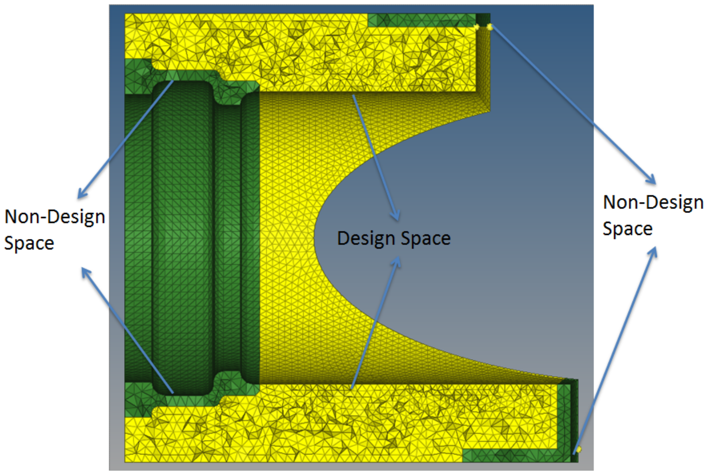



Figure 2.4: Example of Design Space and Non-Design Space definition

#### Material Selection

One of the factors that mostly affects the DFAM process is the type of the material chosen. Due to the lack of commercially availability of materials suitable for AM, it is currently difficult to select the one that complies with all of the productive constraints, making the research for innovative printing solutions absolutely necessary. The support strategy developed for overhanging surfaces represents in this sense a typical trade-off.
However, despite this drawbacks, AM allows to obtain lighter components with higher mechanical properties thanks to better materials such as Cobalt-Chrome, Ti6Al4V and Inconel 718.

### 2.1.3 Parametric optimization

The main objective of the optimization is to improve the performance of the component designed with CAD and CAE tools, generally in terms of weight, compliance and displacement reduction; different steps has to be followed in order to correctly address this type of analysis:

- Optimization method selection;
- Optimization responses definition;
- Optimization objectives and constraints function definiton;
- Optimization;
- Smoothing;
- Geometry reconstruction.

**Optimization method selection**

Several methods have been developed to perform different optimization, which are chosen in accordance with the characteristics of the problem and the results desired. In the next chapter a brief description of some of them will be given.

**Optimization responses definition**

Optimization responses represents a measurement of system performance; they are functions of the design variables and, during the optimization set up, it is possible to define more of them and subsequently to determine an objective function and constraint functions. Altair Optistruct gives the possibility to specify different responses, listed in the table below:

| | | |
|---|---|---|
| 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 |
| Weighted Compliance | Weighted Frequency | Combined Compliance Index |
| Function | Temperature | |

Table 2.1: Altair Optistruct responses

**Optimization objectives and constraints function definiton**

This step involves the definition of the role that every response previously chosen plays during the optimization.

The objective function is referred to as any response function of the system to be optimized, such as Mass, Stress or Displacement, which often are minimized. It is also important to remember that multi-objective optimization are currently not possible but, despite this limit, the designer can take advantage of different constraints function, which are the response functions of the system that need to be satisfied for the design to be acceptable. For example, if Compliance and Mass minimizations are both required, it is possible to define one of them as objective function and costrain the other with a chosen value. This methodology has without doubt an iterative nature, due to the fact that different values of the constraint function have to be tested, but, however, it can bring promising results. Moreover, a constraint is considered active if it is satisfied exactly, i.e. $g_j(x) = 0$; it is considered inactive if $g_j(x) < 0$ or violated if $g_j(x) > 0$.

$$\begin{gathered} g_j(x) \leq 0 \; with \; j = 1, ..., m; \\ and \\ x_i^L \leq x_i \leq x_i^U \; with \; i = 1, ..., n \end{gathered} \tag{2.1}$$

**Optimization**

Through a mathematical algorithm, the solver performs the optimization and defines iteratively the new geometry.

**Smoothing**

Mesh smoothing is one of the most important mesh processing operations, and allows to improve the mesh quality of not well-shaped automatic generated mesh in terms of faithfulness, manifoldness and uniformness.

Faithfulness is measured by how accurately the surface mesh preserves the original geometry and topology, and it is related to the accuracy of the numerical simulation and geometry processing. Manifoldness of a surface mesh means that each point on the surface has a neighborhood which is homeomorphic to a disk in a real plane. Uniformness includes the triangle shape, regularity, complexity and so on. [?]

Mesh smoothing is a significant research problem for scientific simulation applications and, during the years, different methods have been developed according to different approaches, classified as: geometry based, optimization-based, physics-based and combination of these.

Laplacian smoothing is a techique widely used due to its simplicity and effectiveness, and it is based on the simple relocation of a free vertex to the centroid of the vertices connected to that vertex. This smoothing operation can be described, for each vertex, by the following equation:

$$\bar{x}_i = \frac{1}{N}\sum_{j=1}^{N}\bar{x}_j \tag{2.2}$$

where:

- $N$ is the number of adjacent vertices to node $i$;
- $\bar{x}_j$ is the position of the $j$-th adjacent vertex;
- $\bar{x}_i$ is the new position of node $i$.

Although geometry-based methods like the Laplacian smoothing have the advantage of being fast, they have difficulties to improve the quality of severely deformed elements, and for this reason an optimization-based method, computationally more expensive but more accurate, has been used for the case study described in this work.

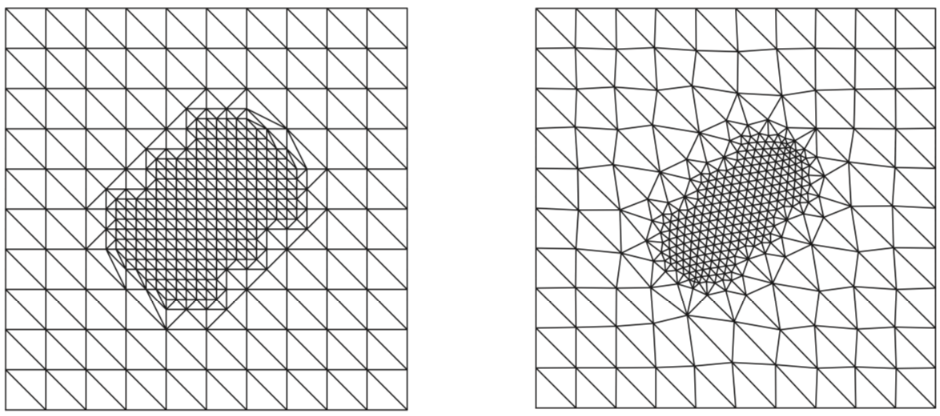


Figure 2.5: 2D mesh before and after smoothing

Differently from the Laplacian smoothing, the optimized-based smoothing aims to improve a mesh parameter, whether it is size, aspect ratio, minimum angle or the Jacobian matrix, by converting it into an objective function to be minimized, similarly to what happens with a real structural optimization.

Existing optimization-based smoothing techniques are relatively new and vary in relation to [1]:

- The type of mesh being smoothed (structured or unstructured);

- The element shape (triangle, quadrilateral, etc.);
- The optimization and search technique chosen;
- The distortion metric selected.

**Geometry reconstruction**

Reconstruction phase is fundamental to obtain a model ready to be printed; in fact, the smoothed geometry achieved through the optimization is characterized by polygonal surfaces, which have to be transformed into a regular geometry with greater surface continuity; the critical issues of this step come from the knowledge and the ability of the designer to model a component effectively printable.
Generally, two different approaches can be adopted to reconstruct a component. The first requires extrusions, revolutions and trimming in order to obtain a final geometry pretty similar to the starting one; on the other hand, the second is based on the construction of NURBS (Non-Uniform Rational Basis-Splines), which are a class of curves and surfaces defined by their order, a set of weighted control points, which determine the shape of the curve, and a knot vector, a sequence of parameter values that determines where and how the control points affect the NURBS curve.

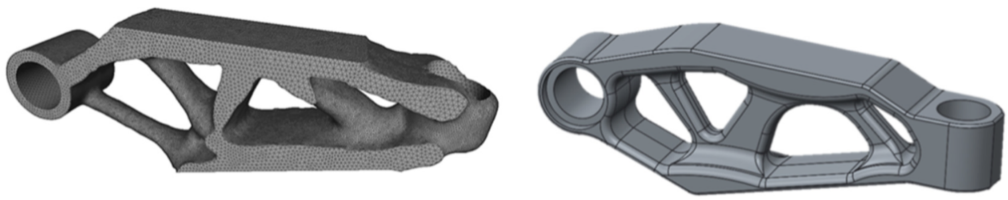


Figure 2.6: Optimized component before and after geometry reconstruction

### 2.1.4 Design Validation

The final step before the 3D printing is the validation of rebuilt geometry through different finit element analyses, such as static analyses, quasi-static analyses, dynamic analyses, LCF, HCF, in order to be certain of the goodness of the model properties.
Once the component is printed, further analyses are performed and compared to those coming from the simulations.

# Chapter 3

# Additive Manufacturing process chain

Although Additive Manufacturing techologies allow to produce effectively lighter and more performing components with a high level of freedom and customization, it is necessary to follow some steps in the process sequence to benefit of high quality results. The process chain is also constantly evolving and can change as the existing technologies develop and new technologies surface, and it can also change depending on the designer perspective, the equipment familiarity and the components used.

Neverthless, the process flow is generally characterized by the following key steps:

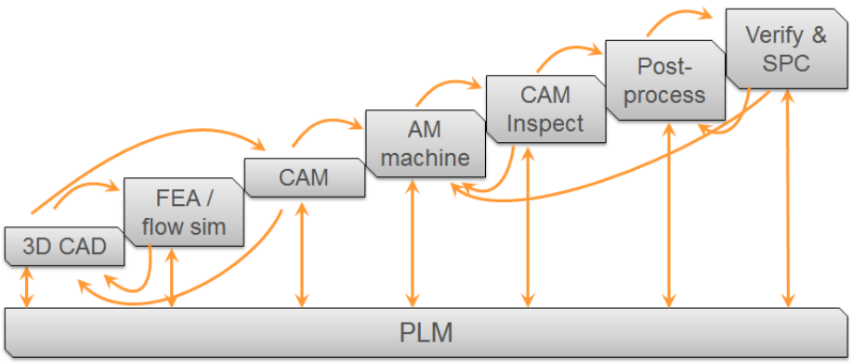



Figure 3.1: Schematic drawing of AM process chain

## 3.1 Conceptualization of 3D CAD model and conversion to STL

The AM process starts always with a Computer-Aided Design model imagined and generated by the designer through CAD programs as Autodesk Inventor, Solidworks, Creo and Siemens NX, which differ from each other for modelling principles, capabilities, accessibilities and cost. Initially, 3D CAD software were often afflicted by problems about the creation of models not mathematically enclosed and, due to their inaccuracy, AM machines were not able to perform a complete and correct work; nowadays, despite of critical feedbacks, which also come from significantly complex geometries with anisotropic materials and affect the optimal production of the model, CAD systems allows to convert 3D parts into AM machine acceptable format without issues.

The standard format that transfers to AM machines the correct geometry to be printed is STL; it stands for Standard Triangulation Language, a file format created in 1987 by 3D Systems Inc. which describes an unstructered triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system. The minimum size of this triangles can be set once using the CAD software, which can eventually detect misalignments deriving from additionally, complex and highly discontinous geometry.

Moreover, recent studies have suggested the adoption of a new “AMF” file format, which overcomes the STL limitations including useful feature, such as dimensions, colors and materials.

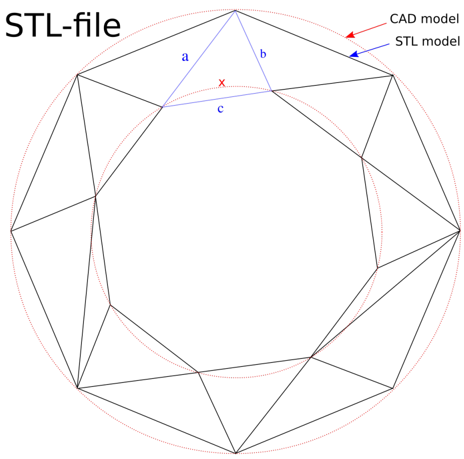



Figure 3.2: Difference betweenn CAD model and STL model

## 3.2 Part orientation

In order to make use of Additive Manufacturing technology full potential a detailed analysis of the build space and of the orientation of the component has to be done, since this last one can seriously affect the part quality.

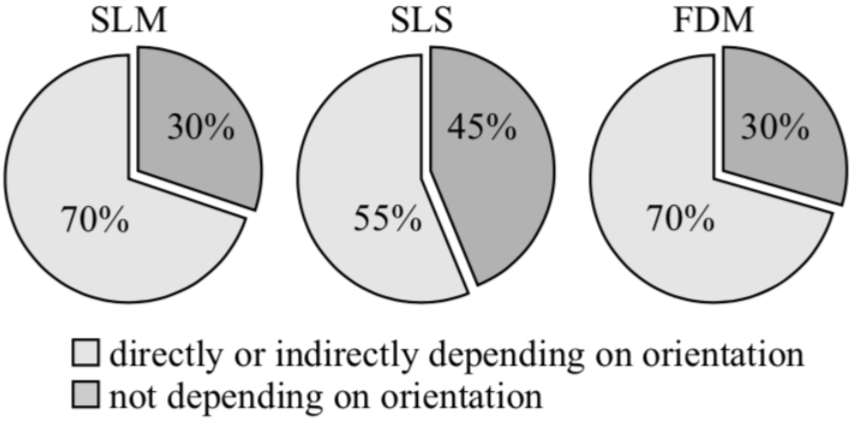



Figure 3.3: Dependency of part quality on part orientation related to AM main technologies

Due to the difference between the part geometry in building direction, which is discontinous in discrete steps layer by layer, and the geometry orthogonal to the building direction, produced continously, and depending on the AM process used (SLS, SLM, FDM), there are several quality features that need to be simultaneously optimized, such as:

- Dimensional accuracy;
- Surface quality;
- Shape accuracy;
- Building costs;
- Building time;
- Component warping;
- Stability;
- Support volume;
- Utilization of building space.

Given the considerable troubles the designer needs to overcome during the definition of the correct orientation thath the part must have, several methods have been proposed to simplify the design process as much as possible; one of these is based on the “early determination of the part orientation” principle, which states that the orientation should be determined before the final design of the part begins [9].

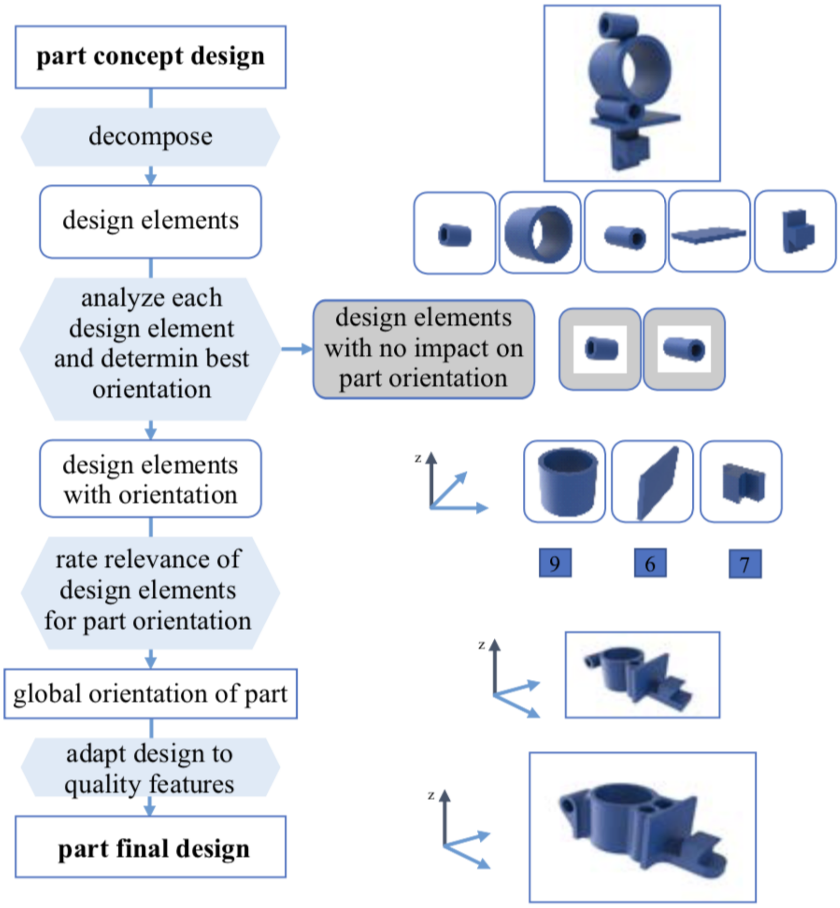



Figure 3.4: Process for defining part orientation in early design stage

According to this philosophy, the designer is able to avoid certain process restrictions by an appropriate design, conceptualized following different steps:

1. At the beginning, the concept part is decomposed into design elements, or rather surfaces, which fulfill a specific function in the component;

2. The designer has to specify which quality feature should be given higher priority and to evaluate how significant the influence of every single design feature is.

If the element has an influence, then the designer must determine the optimal positioning of the design element for the quality feature. If not, the design element can be neglected in the orientation of the part. This can cause orientation conflicts between the different quality characteristics, and a trade-off is often required.

3. Once the orientation is defined, it is possible to adapt the concept design in order to optimize the entire process.

## 3.3 Supports

One of the first issues that researchers and designers faced during the Additive Manufacturing methodology development concerned the printability of large overhang surfaces and the subsequent trouble to avoid the collapsing of the component.

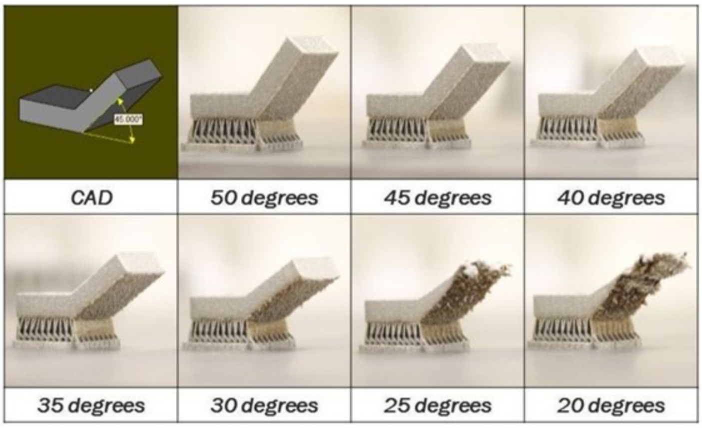



Figure 3.5: Overhang effects on 3D printed supports

Although the support structures principle aim is to improve the resistance to the deformation caused by gravity, their purposes are numerous and can be categorized into three types:

- Thermal gradient effects mitigation: metal processes are often characterized by high thermal gradients, which can lead to shape distortion and residual stress. A proper design of support structures is necessary to diffuse this heat and enhance the rigidity of the system;
- Local deposition processes can only deposit material on existing surfaces below. A support structure is, therefore, necessary to ensure that material is deposited at the intended height and the expected output geometry is achieved [?];

- Support structures can also be used to sustain the weight of an unbalanced part and, for this reason, bounded to collapse. Furthermore, a support structure can act as a tether in powder bed processes to stop any shift, especially layer shift during re-coating processes.

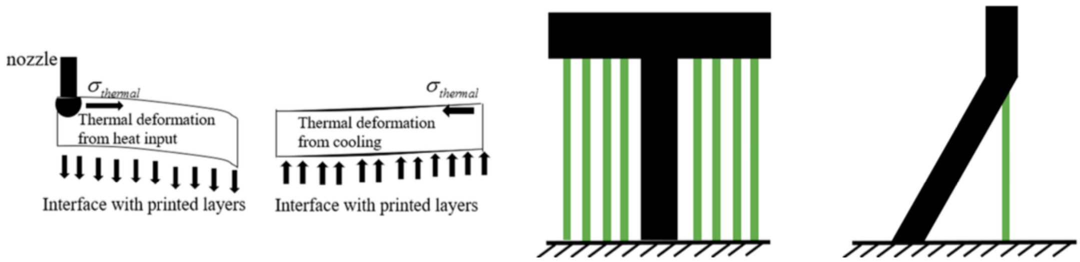



Figure 3.6: Advantages of support structures

However, the help supports give to solve the aforementioned problems is in contrast with the several drawbacks that make their use not as easy as it seems.
First of all, the removal of such sacrificial features can be onerous as the complexity of the component increases, affecting surface roughness with small defects; this manually operation needs also to be done with a high level of freedom and, consequently, extra time is required to design the part to accommodate the support structure and the design of the support structure itself.
Moreover, support structures result in wasted feedstock material which not always can be successfully reused. In addition to a larger data file for the part, that now contains also supports geometry, the energy used to produce the entire component increases, since Additive Manufacturing processes typically have energy costs that scale with the volume of material used [?]; Up til today, extensive efforts have been devoted in searching for innovative solutions to overcome this issues, and the many solutions explored are classified into the following categories:

- Slimming support design: it allows to reduce the amount of extra material used during AM process;

- Optimal build direction design: to avoid modifying the final design, another alternative seeks to optimize the building direction such that a minimum material usage shall be entailed [10];

- Non-vertical support design: experimental results showed that these supports assist well the fabrication of parts while reducing the material usage by averagely 30%;

- Self-support design.

Another support structure optimization method has been proposed, after perliminary studies, on lattice structures such as diamond and gyroid, which ensure successfully reduction of material and build time while fulfilling the structural demands.

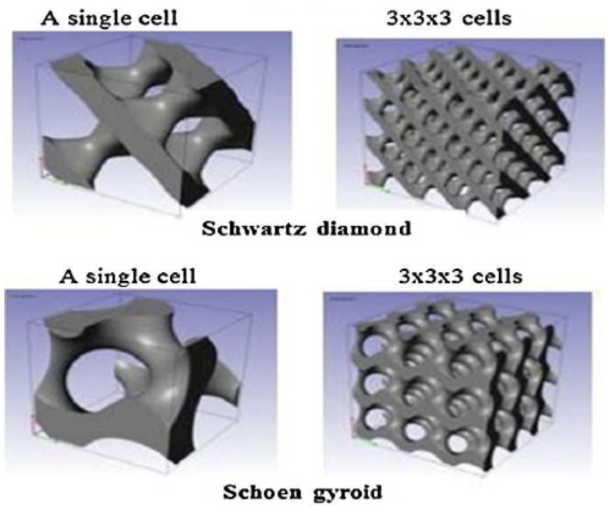



Figure 3.7: Example of lattice structures under development

## 3.4 Slicing

After the design and the orientation of the part is defined, it is fundamental to convert the 3D model, which is in STL format, into printing instructions for the 3D printer. In current 3D printing practice the software pipeline cuts the model into horizontal layers, generates toolpaths to fill them and calculates the amount of material to be extruded [7].
There are also two kinds of methods to slice the geometric model of a part into layers: the STL-based slicing, which can be uniform or adaptive, and the direct slicing.
In uniform slicing, the STL file is sliced by a fixed layer thickness whose height can be increased with a reduction in the build time but also a deterioration of the surface quality. The adaptive slicing is currently more difficult to implement in the productive process because it needs a specific 3D printing system to achieve the desired results but, on the other hand, allows to obtain better surface finish.

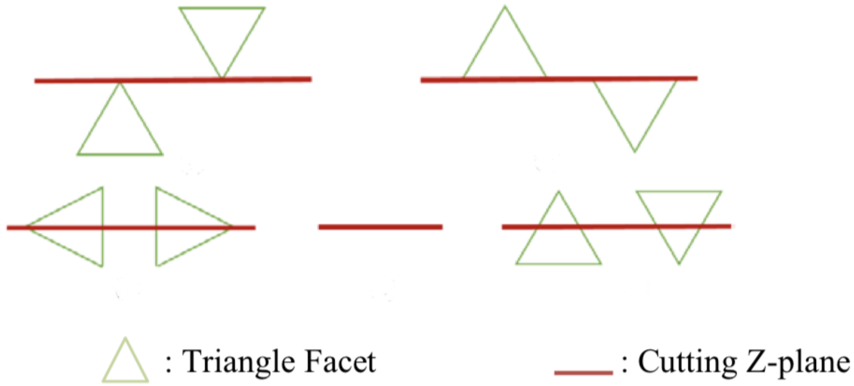



Figure 3.8: The possible cases of facet-plane slicing

Direct slicing can generate precise slice contours from original 3D models and obviates the error detection and the repairing process of STL files, but it can only be used for a specific set of software and machine.
Moreover, slicing process leads to staircase effect, a particular condition that makes the quality of the part worse at the increasing of the thickness and at the decreasing of the surfaces angle of inclination. This effect can also be reduced with a correct orientation strategy and a smaller size of the metal powder.

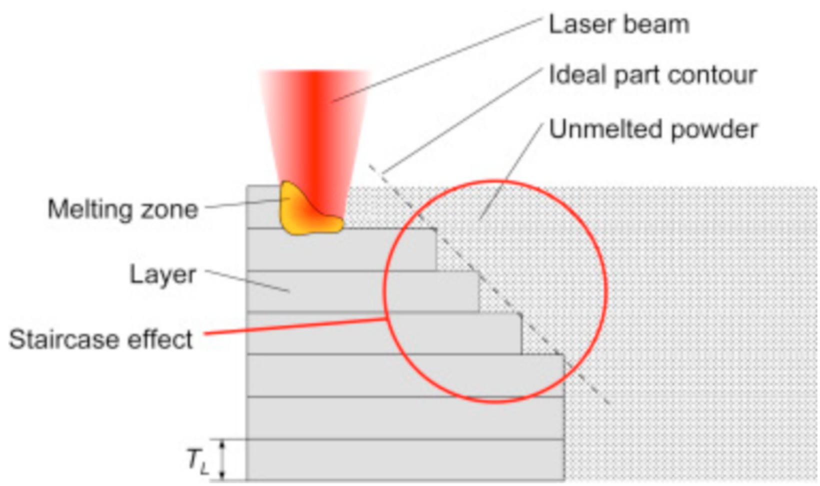



Figure 3.9: Staircase effect during 3D printing

## 3.5 Post processing

Indipendently from the AM technology used to create the part, the minimum required processing is the removal of build part from build plate, generally done with vibrations, compressed air and pressurized water, and the removal of support structures from the build part, with the employing of milling, bandsaws, cut off blades, wire-EDM and other metal cutting techniques. If high quality of the component is required, in terms of dimensional accuracy, roughness, or fatigue life, it is necessary to operate a mechanical machining, using, for example, electropolishing, abrasive flow and laser polishing.
In addition to these types of machining, a thermal annealing process can be used to prevent part warpage, reducing significantly the thermal stress in the part; in particular, this is obtained through Hot Isostatic Pressing, or HIP, which puts the component under extreme conditions of pressure (above 100 MPa) and temperature (over 50% of the melting point of the material), and makes the final bulk density reach more than 95% of the true density of the material.

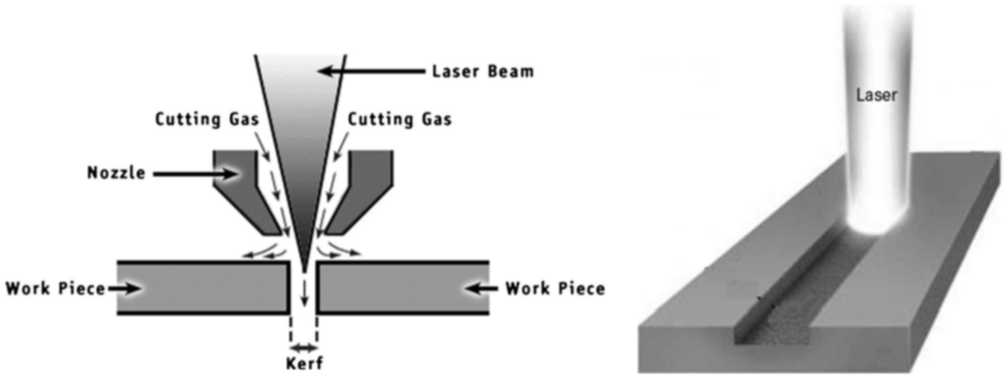



Figure 3.10: Example of machining techniques used during AM process

# Chapter 4

# Structural Optimization

Thanks to the continous increasing of computational power and the advent of finite elements methods, the optimization process has become an effective tool that can be used by the designer to define innovative components to be fully integrated in the production cycle.
In fact, until 60's optimization problems required an analytical approach, forcing mathematician and engineers to solve complex differential equation systems to find a solution, which was not obtainable in a closed form. This issue was overcome with the advent of computers, which allowed to use an iterative process based on the finite element discretization of the object domain and on the transformation of the differential equations system into an algebraic equations system.
Due to the fact that there are a lot of optimization methods developed for specific applications, in this work we will refer only to structural optimization, which can be defined as the subject of making an assemblage of materials sustain loads in the best way [2].
The mathematical model of this type of optimization does not differ from the one aforementioned, and will be subsequently described; neverthless, the problem is formulated by picking up one of the structural performance, like weight, stiffness, critical load, stress, displacement and geometry, as an objective function that should be maximized or minimized, and using others as constraints.
Based on what geometrical feature is parametrized, the structural optimization problem can be classified into [15]:

- Topology optimization: the design variable $x$ represents the connectivity of the domain;

- Size optimization: the design variable $x$ represents a structural thickness, such as a distributed thickness or a cross-sectional area of a truss model that can be varied;

- Shape optimization: the design variable $x$ represents the boundary of the state equation.

## 4.1 Optimization problem definition

A general structural optimization problem can take the form:

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

where:

- $f$ is the *Objective function*: it represents an objective to minimize or maximize, such as the field of displacements and the natural vibration frequencies.

- $x$ is the *Design variable*: it is the parameter that control the geometry of the optimized structure, and can take either continuous or discrete variables. The first include all the values within a defined range, and the latter, on the other hand, include only part of these values.

- $y$ is the *State variable*: it is a function or a vector that represents the response of the structure; it can be displacement, stress, strain or force.

Generally, the optimization problem is formulated including a single objective function, but it is possible to convert the problem into a multi-objective optimization, characterized, for example, by a weighted combination of multiple objective functions. A concept often used in these optimizations is Pareto optimality, which states that a solution is Pareto optimal if there exists no other feasible solutions that would decrease any of the objective functions without causing an increase in any of the other objective functions.
An effective method to find Pareto solutions is scalarization, which transforms the multiple objective functions into a scalar function of the design variables [11].

The weighted sum method is an example of scalarization method:

$$\min_{x} \sum_{k=1}^{p} w_k f_k(x) \tag{4.1}$$

where $f_1, ..., f_k$ are the objective functions.
The feasible solution of a nonlinear problem can be graphically represented:

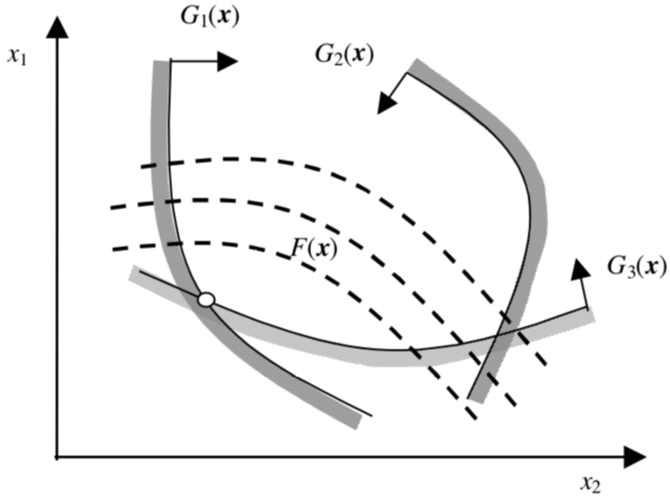



Figure 4.1: Space of feasible design solutions

It is also fundamental to underline that, according to the characteristics of the analysis which has to be done, the designer can choose to perform the optimization using two different types of algorithms:

- Local algorithms: they are always gradient-based and, as the name suggests, they take advantage of gradient information to find the optimal solution. Due to their intrinsic complexity, which make their efficient implementation difficulty, they are used only to solve optimization problems with a large number of design variables, when gradients are readily available and local minima is not an issue.
  These algorithms typically make use of a two-step process to reach the optimum that can be summarized mathematically as:

$$x^q = x^{q-1} + \alpha^* S^q \tag{4.2}$$

  - A search direction $S$ which to move in is found using grandient information;

– The optimum step size $\alpha^*$ is provided through a one-dimensional search.

Newton's method, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method and the Sequential Unconstrained Minimization Techniques (SUMT) can be mentioned as gradient-based methods.

- Global algorithms: on the contrary, these algorithms provide a much better chance to find global solutions, but they can be implemented only in computationally unexpensive problems with few design variables and a severe numerical noise.

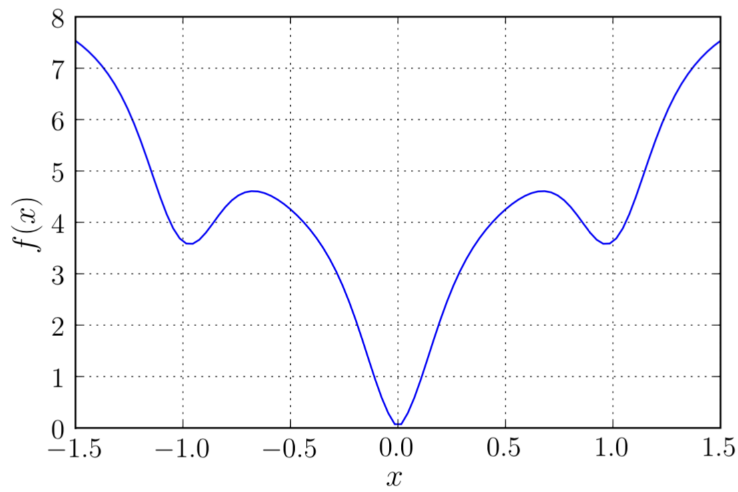



Figure 4.2: Local minima and global minimum of a single objective optimization

## 4.2 Optimization software

Referring to topology optimization method, which has been implemented in the analyses of this work, numerous software are available, as the Table 4.1 shows.
The tools that fall into the the commercial group offer relatively standard capabilities, and can solve numerous types of problems with various manufacturing constraints, and features like symmetry planes, minimum member size, pattern repetition, and draw direction are common [5]. They also utilize the density-based topology optimization, based on the concept of Solid Isotropic Material with Penalization (SIMP), which will be discussed later.
On the other hand, the software which are not in the commercial group are affected by several problems while performing also simple analyses with few load cases, and, for this reason, they

| Commercial software | Educational Tools |
|---|---|
| • Altair OptiStruct<br>• Vanderplaats Genesis<br>• Simulia Tosca<br>• Abaqus ATOM<br>• MSC Nastran<br>• SolidThinking Inspire<br>• Within Enhance<br>• PERMAS-TOPO<br>• FEMtools Optimization<br>• OPTISHAPE-TS | • TopOpt<br>• BESO3D<br>• ParetoWorks<br>• CATOPTO<br>• Topostruct<br>• ProTOp<br>• SmartDO<br>• META4ABQ<br>• ToPy<br>• TRINITAS |

Table 4.1

are not viable for use in an industrial setting.
The program used in this thesis work to perform finite element analyses and optimizations is the solver Optistruct 10.0 from Altair Engineering, which supports other types of optimization, in addition to the aforementioned topology optimization:

- Free-size optimization;
- Shape optimization;
- Free-shape optimization;
- Topography optimization;
- Size optimization.

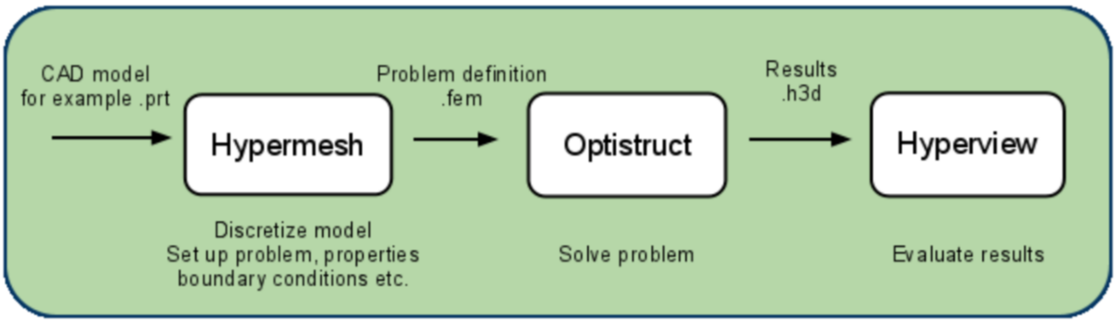



Figure 4.3: Overview of the workflow in Hyperworks

## 4.3 Topology optimization

The topology optimization is the most general structural optimization technique and it tries to find the optimal domain of the governing equations contained within some design field. After the definition of the objective function and of the constraints, a design variable is determined; it is connected to each finite element and it determines if they represent structural material or a hole.
The number of different combinations is 2N , where N is the number of elements. As a normal FE model easily results in hundreds of thousands of elements, this problem is out of reach to solve for any practical problem [11].
The optimization problem solution is often reached through two different strategies, the density method and the homogenization method, although other methods that use genetic algorithms or an heuristic approach are currently being developed.

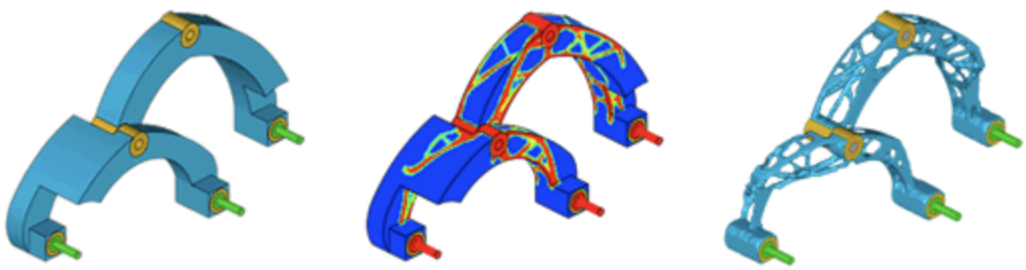


Figure 4.4: Topology optimization of a structural component

### 4.3.1 Density method

According to this method, the design variable of the optimization problem is the density, which is a function varying over the design domain. The density is associated to each element, and it can take any value between zero and one. To get a result which is possible to manufacture, it is desired that the solution only consists of solid or empty elements [11], and for this reason the intermediate elements are always penalized. The application of a penalization factor characterizes the SIMP (Solid Isotropic Microstructures with Penalization) method, that expresses the material stiffness as a function of the material density:

$$E = \rho^p E_0 \ , \quad p > 1 \ , \quad 0 \leq \rho \leq 1 \tag{4.3}$$

$$Mass = \int_{\Omega} \rho \; d\Omega \tag{4.4}$$

Where $p$ is the penalization factor, whose typical values are 2 - 5.

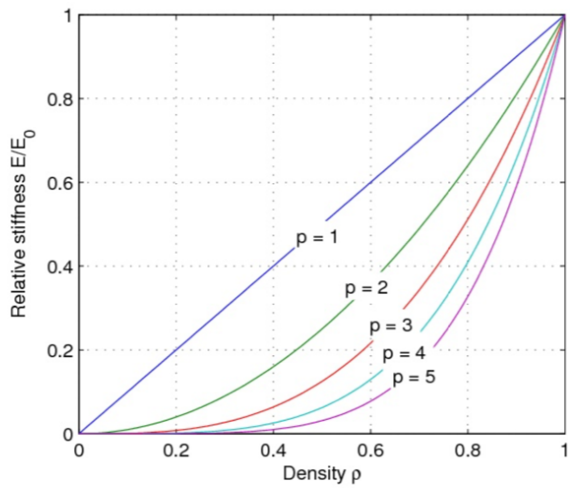



Figure 4.5: Effect of the penalization factor on the relation between relative stiffness and density

### 4.3.2 Homogenization method

The main idea of the homogenization method is that a material density is introduced by representing the material as a microstructure, which provides some penalization on intermediate densities and is characterized by an infinite number of infinitely small voids.

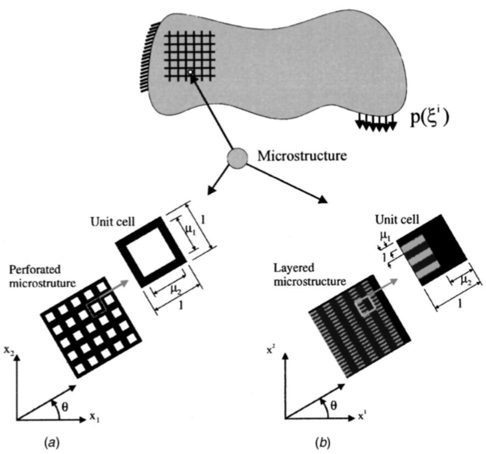



Figure 4.6: Example of different microstructures used by the homogenization method

For most types of microstructures the elasticity needs to be calculated numerically by using the finite element method for different sizes and then interpolating between these values [11]. Although its higher precision, the homogenization method requires more design variables per element than when using the density method.

## 4.4 Topography optimization

Topography optimization is an advanced form of shape optimization method. Differently from the topology optimization, which operates by varying the density of the elements from 0 to 1, topography optimization allows to modify the design space of the model by changing the offset of the surface elements and generating beads or swages. This approach is ideal for maximizing the stiffness of components without adding mass or for maximizing the frequency of the model [12].

Typically, beads are very regular and are often simply aligned to major geometry features. Although they are well understood by manufacturers and do increase the stiffness of structures, topography optimization will usually result in a bead pattern that outperforms standard bead layouts.

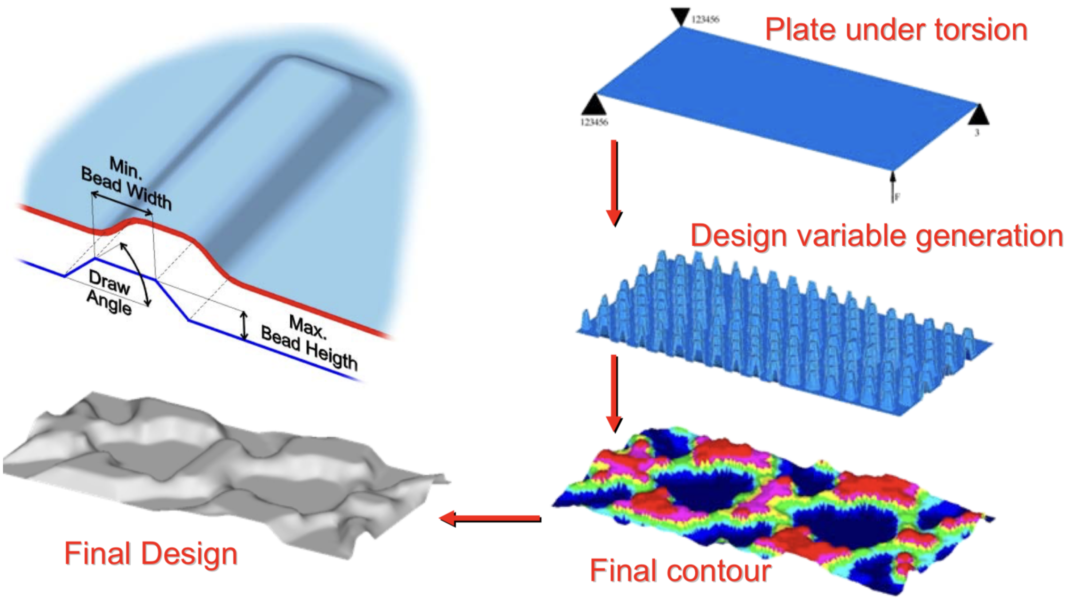



Figure 4.7: Parameters and results of topography optimization performed on a loaded plate

Before performing this type of analysis, some bead parameters, such as bead width, bead height (maximum depth), and draw angle can be modified. It is important to note that decreasing the bead width will increase the time it takes to run the optimization, as it will generate a more detailed optimization result [12]. Due to the fact that a minimum bead width is necessary, instead of a required bead width, the results of topography optimization with no manufacturing or symmetry constraints often show large areas of varying bead widths.

## 4.5 Shape optimization

Shape optimization is a method used to improve the design of a component whose topology has already been defined.

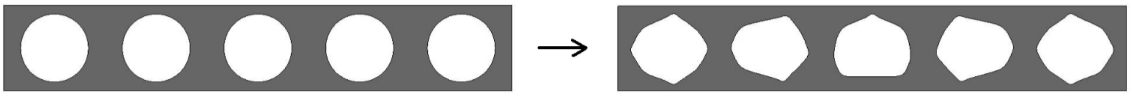


Figure 4.8: Effect of shape optimization on a holed beam

The design variables can be, for example, thickness distribution along structural members, diameter of holes, radii of fillets or any other measure. One way of introducing shape changes to the discretized finite element model is with the perturbation vector approach. First one or more shapes are defined as perturbations added to the vector of nodal coordinates [11]:

$$x = x_0 + \Delta x \tag{4.5}$$

where:

- $x$ is the vector of nodal coordinates;
- $x_0$ is the initial vector of nodal coordinates;
- $\Delta x$ is the perturbation vector.

The design variables for the optimization can then be defined as the weights of the perturbation vectors through a linear combination of the perturbations:

$$x = x_0 + \sum_{i=1}^{n} \alpha_i p_i \tag{4.6}$$

where:

- $n$ is the number of shapes/design variables;
- $\alpha_i$ is the magnitude of perturbations.

The optimization problem is then to find the optimum set of shape weights.

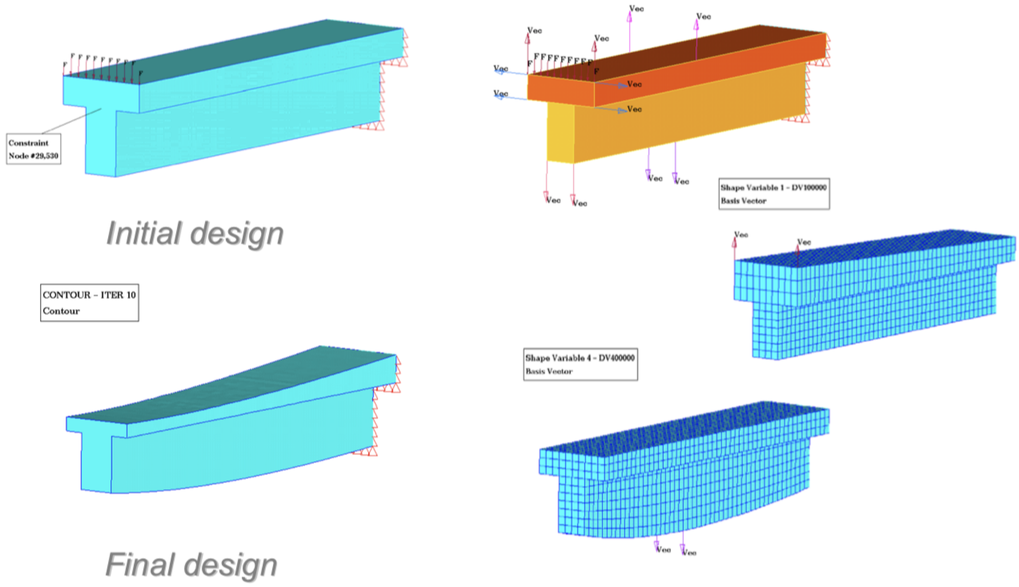



Figure 4.9: Cantilever beam optimized through shape optimization

## 4.6 Free-shape optimization

The essential idea of free-shape optimization, and where it differs from other shape optimization techniques, is that the allowable movement of the outer boundary is automatically determined, thus relieving users of the burden of defining shape perturbations.
Free-shape optimization uses a proprietary optimization technique developed by Altair Engineering, Inc., wherein the outer boundary of a structure is altered to meet pre-defined objectives and constraints.

This approach is intended to use a particular type of design regions, defined on the outer boundary of the structure by grids that can move:

- Normal to the surface edge in the tangential plane, in case of shell structures;
- Normal to the surface, in case of solid structures.

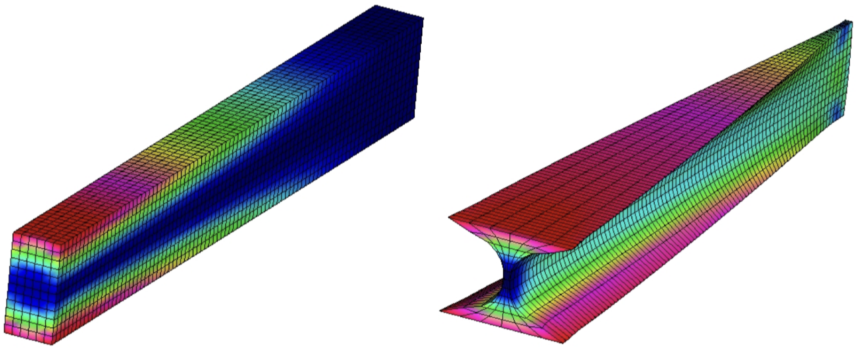


Figure 4.10: Example of a cantilever beam before and after free-shape optimization

Moreover, it is fundamental to define appropriately this design regions; they shoud contain locations of the structure where it is desired for the shape to change indipendently, and, generally, they include feature lines of solid structures and sharp corners of shell structures.
Parameters like direction type, move factor, number of layers for mesh smoothing, maximum shrinkage and maximum growth also affect the deformation of the design regions [12].

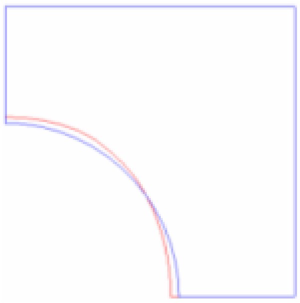
## 4.7 Size optimization

Size optimization is the simplest form of structural optimization, and it deals with optimizing properties such as shell thickness, mass, moment of inertia and stifness of the structure such that the optimum design results in a structure with uniform stress distribution eliminating the stress concentration. It needs to be underlined that these properties are a function of design variables [12].
This type of optimization is based on a mathematical method called "Gauge optimization", which establishes that:

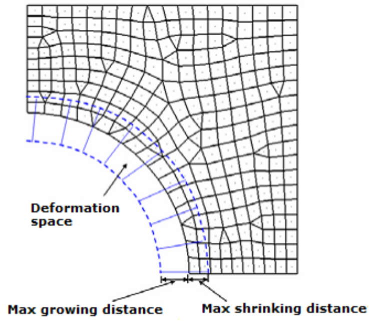
$$p = C_0 + \sum DV_i \cdot C_i \tag{4.7}$$

where:

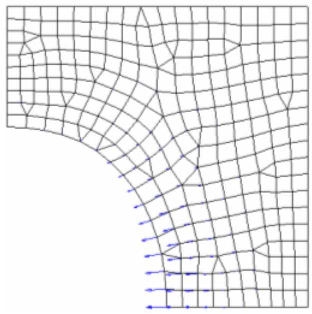
- $p$ is the element property;
- $DV_i$ is the design variable;
- $C_i$ is a constant.



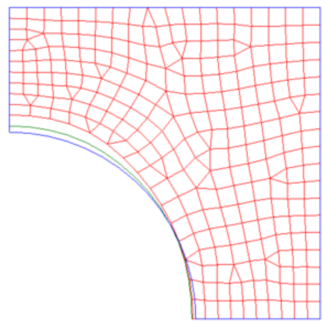
(a) Direction type influence with unconstrained grids




(b) Max shrinkage and growth limit the total amount of deformation



(c) Number of layers moved to avoid distortion



(d) Move factor: max movement of the grids in one iteration

Figure 4.11: Parameters used to set up free-shape optimization

The setup of these parameters can be easily made before performing the optimization, which, in its simplest form, allows to define the following relation:

$$T = DV_i \tag{4.8}$$

where $T$ is the thickness of the structure.

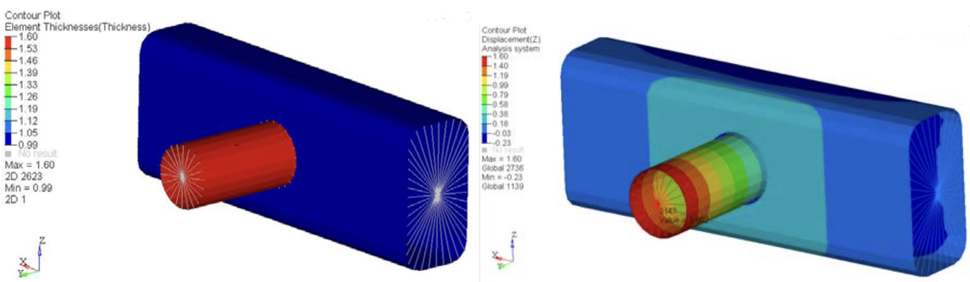
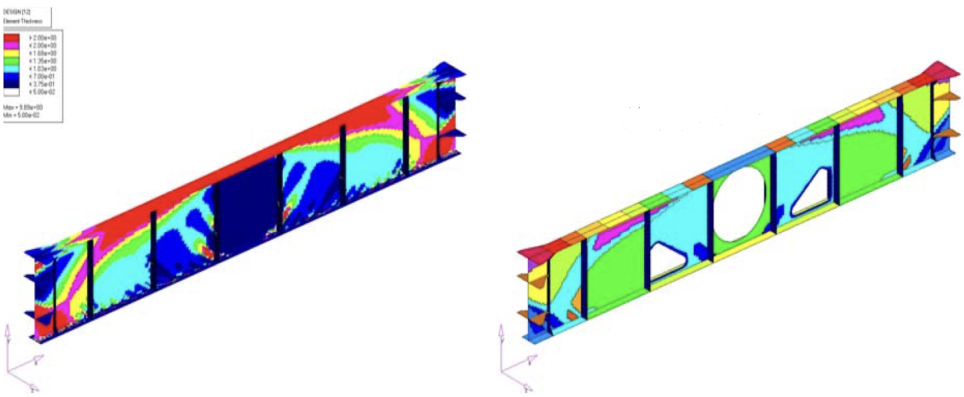



Figure 4.12: Size optimization of a rail joint

## 4.8 Free-size optimization

This method is based on a mathematical technique that produces an optimized thickness distribution per element for a 2D structure. Furthermore, it is important to point out that while free-size often creates variable thickness shells without extensive cavity, it does not prevent cavity if the optimizer demands it.
Free-size optimization can be set up including different features, such as minimum member size control, symmetry, pattern grouping and pattern repetition, and stress constraints applied to von Mises stress of the entire structure.
Although free-size approach offers more design freedom and better results than topology optimization in terms of compliance and stress reduction, it creates geometries difficult to produce, due to the variable thickness which is typically far more expensive to manifacture.
Another critical factor that needs to be considered is that free-size optimization is meant to create a spread thin shell instead of concentrated full thick members, which are stronger against out of plane buckling [12].



(a) Free-size result (b) Interpreted zones of constant thickness

Figure 4.13: Free-size optimization of a supporting beam of an airplane door structure

## 4.9 Lattice optimization

The recent implementation in Altair Optistruct software of lattice structures in addition to the topology optimization methodology represents a considerable innovation related to Additive Manufacturing. In fact, it is possible to generate the optimal hybrid or blended solid-lattice design based on desired functionality of the part identifying both regions where material is not

necessary and others where lattice structure is required.
Lattice structures can be considered as porous structures and, with their introduction, it is possible not to penalize semi-dense elements, retaining more "porosity" in the design space. The lattice regions of the model, which are identified using a density range, are interpreted as a network of beam elements describing a particular cell type.
Lattice optimization is achieved through two optimization phases:

1. In the first phase, a topology optimization of the design domains is performed excluding the intermediate density elements, which are represented by user-defined lattice micro-structures, whose properties can be associated to stiffness of the intermediate densities.

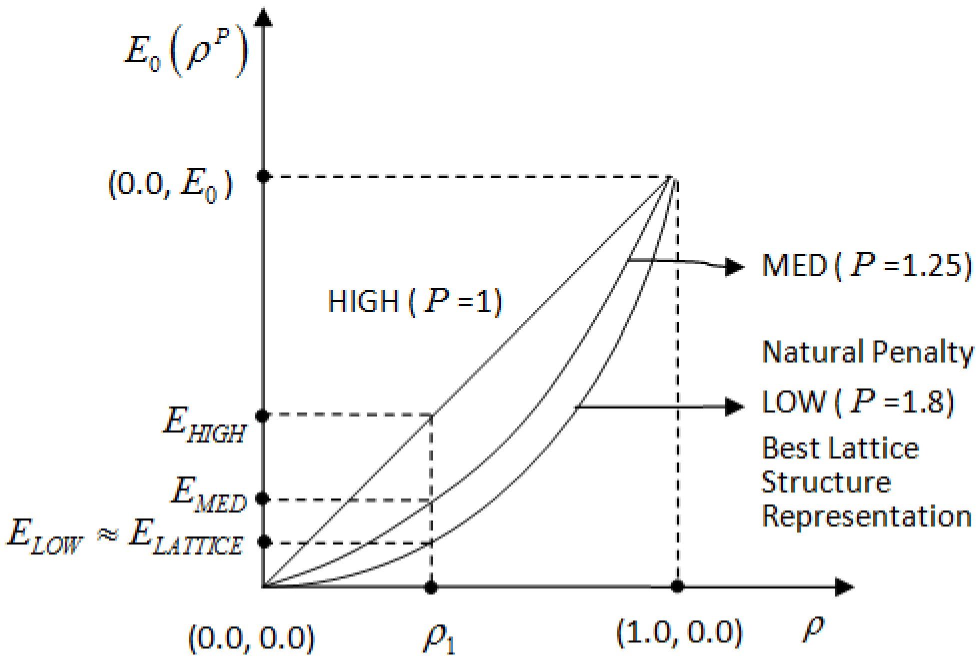



Figure 4.14: Penalization factor effects on lattice optimization

This phase is influenced by the following two factors:

- Porosity control: a penalization factor is applied to modify the intermediate densities; for example, if the penalty is reduced, the percentage of lattice structures increases and, consequently, higher porosity is obtained;
- Stiffness penalization: it is possible to correlate the density of a topology element to

its stiffness using the following equation:

$$E = E_0 \rho^p \tag{4.9}$$

where:

- $E$ is the optimum stiffness of the topology element for the density $\rho$;
- $E_0$ is the stiffness of the initial design space material;
- $\rho$ is the density of a topology element;
- $p$ is the penalty applied to the density, and it aims to control the generation of intermediate density elements.

According to extensive testing and observations, the optimal penalty value that ensures an optimized topology design cell should be set to 1.8.

2. In order to make the structure more efficient and to optimize the end diameters of each lattice cell member, in the second phase a size optimization is performed. This allows for further weight reduction while meeting design requirements, such as buckling, stress, and displacement.

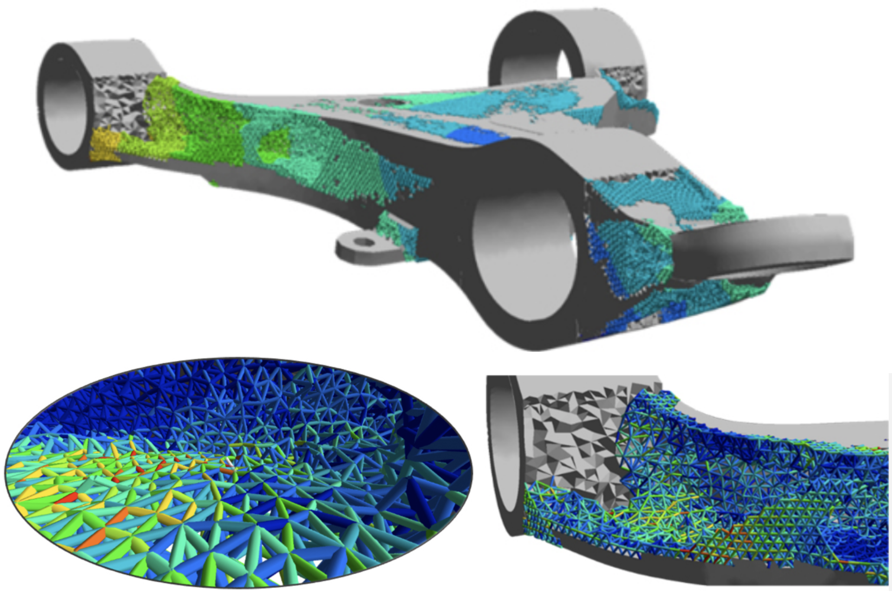


Figure 4.15: Displacement and stress results post processed on the lattice design

# Chapter 5

# Exercise of Topology Optimization of an Aeronautical Turbine Blade

The capability of Additive Manufacturing technologies to manifacture lighter and, at the same time, stronger component is the reason why aerospace industry, which is always looking for new components with low weight and more efficient geometries, make efforts to develop new AM metodologies and to improve their efficiency. Consequently to this benefits, the companies operating in this sector can take advantage of the reduction of cost production and of fuel consumption.

In particular, the pressure on costs related to the manufacturing of more and more complex LPT airfoils, whose production with casting technologies is generally complicated, pushes companies like Avio Aero to implement AM as cost technology for turbine components, using Direct Metal Laser Melting (DMLM) as enabler for non castable geometries.

In this chapter the methodology used to leverage a topology optimization of aeronautical turbine blade will be described. In accordance with the steps mentioned in Chapter 2, after having simplified the geometry of a blade currently under develpoment and meshed it, the optimization has been performed. As last step, the results obtained have been validated through another analysis.

## 5.1 Problem definition

The study case is a low-pressure turbine rotor blade mounted on an aeronautical turbofan engine, whose main components are represented in the figure below:

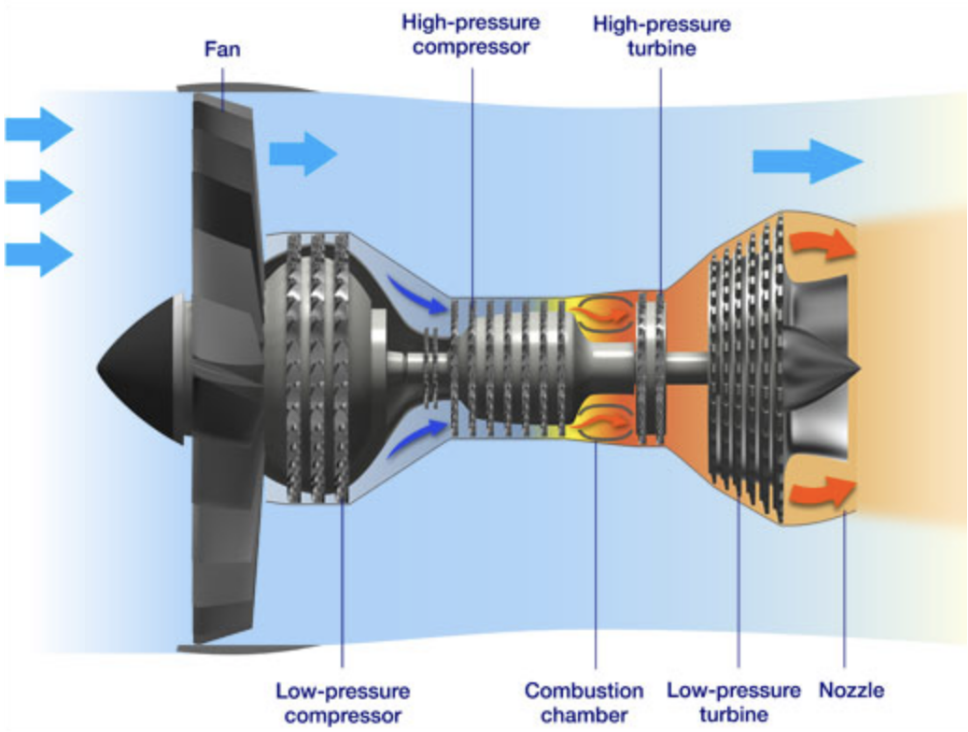



Figure 5.1: Basic structure of a turbofan engine

- Fan: it uses the mechanical energy from the gas turbine to accelerate rearwards a secondary airflow, which can be eventually mixed with the gas flow coming from the nozzle. This configuration ensures a considerable reduction of specific fuel consumption.
- Low/high-pressure compressor: the primary airflow is compressed gradually thanks to two compressors, whose section is variable depending on the compression ratio of the single stage. They are generally mounted on two shafts which rotate at different speed;
- Combustion chamber: in this chamber the compressed air is mixed with fuel and subsequently burnt, increasing the pressure and the temperature, which can reach about 1400 °C;
- High/low-pressure turbine: the two turbines expand and accelerate the gas flow, in order

to extract energy from it and to convert it into work useful to allow the rotation of the two shafts.

- Nozzle: a turbofan designed for civil use has always a convergent nozzle, whose function is to further accelerate the gas flow and, subsequently, to generate the required thrust.

In particular, both compressor and turbine are characterized by a certain number of stages, each of which includes a stator and a rotor. The stator blades are fixed and their geometry ensures an increasing of flow velocity and a decreasing of pressure; on the other hand, the rotor convert part of the gas flow kinetic energy into work that allows the shaft rotation.
The rotor blades are particularly stressed due to the inertial load generated by the centrifugal force, in addition to the pressure load and the temperature load, which is much higher than the compressor one; for this reason, creep resistant materials such as superalloys have been developed specially for high-pressure turbine blades.

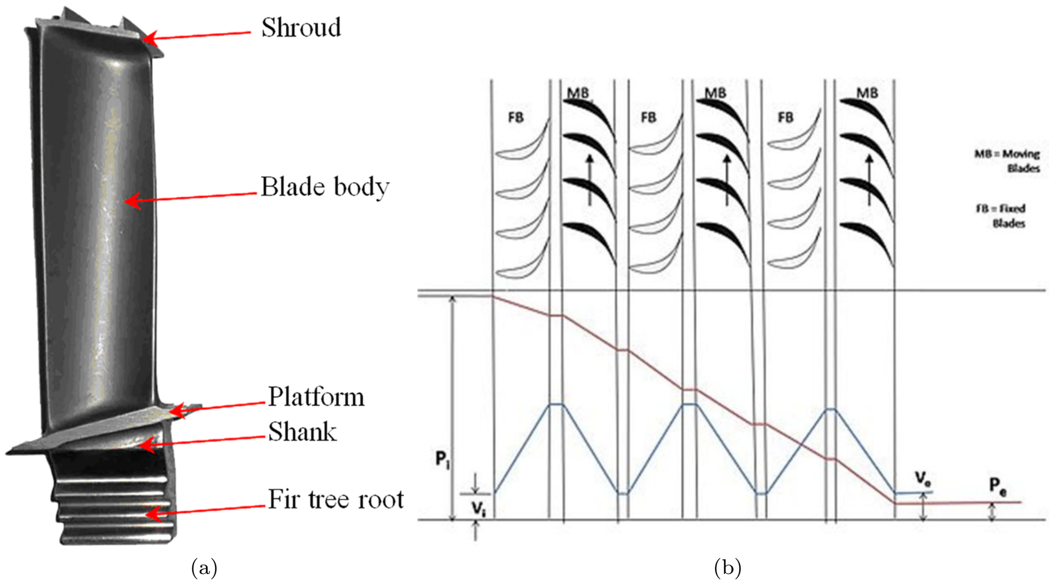



Figure 5.2: Rotor blade representation (a); pressure and velocity distribution of a turbine (b)

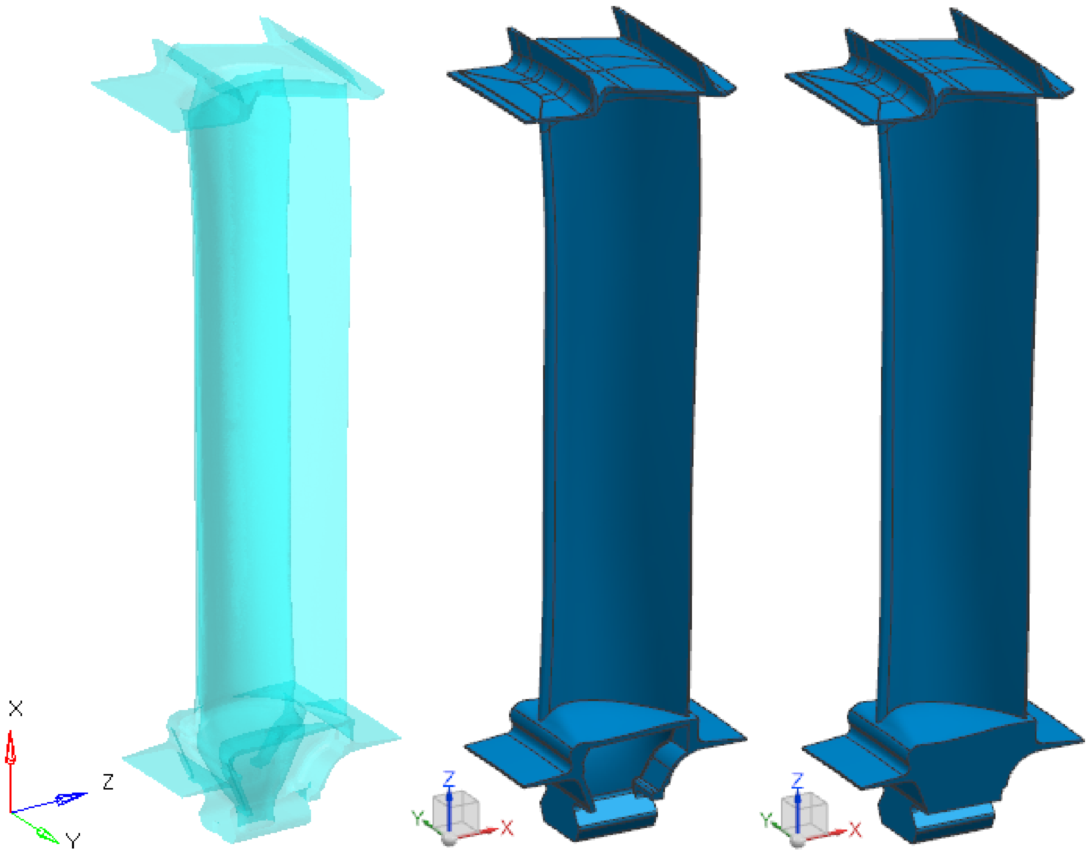
A typical rotor blade consists of different features:

- Shroud: it contributes to limitate the tip leakage flow losses, whose influence to the performance of the turbine stage is not negligible;

- Blade body: the blade body, which is nothing more than an airofil, is fundamental to properly modify the flow properties, like pressure and velocity, compressing or expanding the flow. Depending on the operating conditions, every stage can be characterized by blades with different curvature angles.

- Shank: thanks to the presence of angel wings and to the cyclic symmetry, a correct design of the shank ensures the absence of leakage of the flow path to the bottom;
- Dovetail (Fir tree root): it is a critical zone of the entire component, because here the interlocking between the disk, which is mounted on the shaft, and the blade takes place; therefore it is necessary to eliminate the relative motion between the two parts, in order to ensure a correct force transmission from the blade to the shaft.

## 5.2 Baseline validation




(a) Baseline model (b) Model 1 (c) Model 2

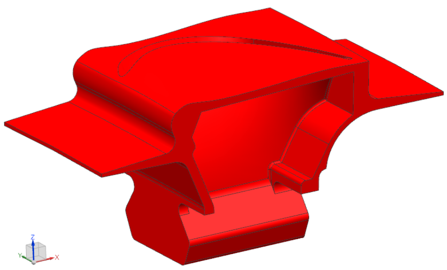
Figure 5.3: Baseline model and baseline derived simplified models

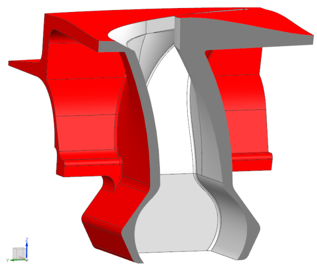
In order to leverage a correct topology optimization it is necessary to follow a certain number of steps which has to be validated; starting from a baseline model, its validation is characterized by:

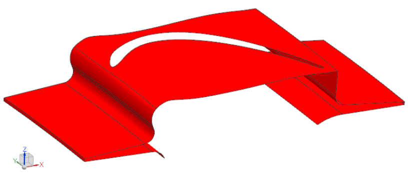
- Analysis of static loads and constraints applied on the baseline model;
- Simplification of the overall geometry;
- Definition of Design space and Non-Design space;
- Application of mesh, loads and constraints on the new model;
- Static analysis of simplified models and comparison with baseline results.

### 5.2.1 Design space and Non-Design space definition

Starting from a model of a low pressure turbine hollow blade, a similar model has been created through Siemens NX; in this first phase, the geometry of the shank has been simplified through the elimination of some edge blends and other features, and successively the empty volume has been filled in order to have complete freedom while defining design space and non-design space.


(a) Shank and dovetail-Model 1


(b) Section of shank and dovetail-Model 1


(c) Shank-Model 2

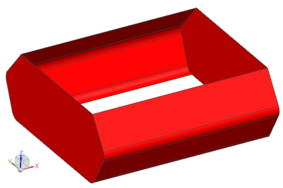
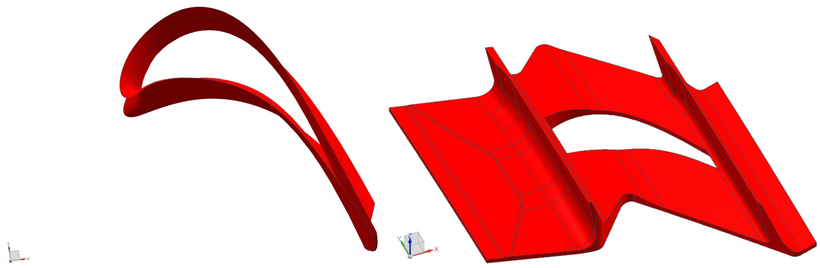

(d) Dovetail-Model 2

Figure 5.4: Non-design spaces of Model 1 and Model 2

The design space is represented by an internal volume of the entire component, and its size is

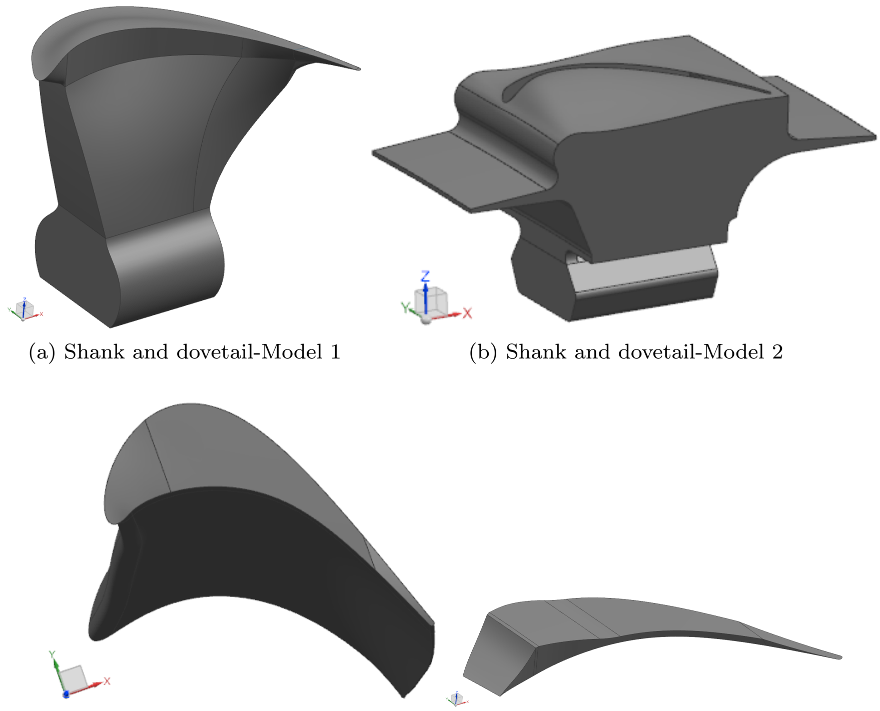
larger than the empty volume aforamentioned; this characteristic ensures a much better optimization, because the solver can modify almost all of the geometry.
The validation is therefore performed making a comparison between the baseline model and the non-design space of the modifed model, which can be considered as a sort of "husk" with an airfoil thickness equal to the spot of the laser used during the Additive Manufacturing process.



(a) Blade (b) Shroud

Figure 5.5: Non-design spaces of both Model 1 and Model 2

Then the new geometry file has been imported into Hypermesh in order to mesh the different parts. The best results in terms of mesh quality have been obtained applying, initially, a 2D mesh and, after having checked the results of the mesh quality control, the 3D mesh has been generated, trying to obtain a trade-off between high mesh density, useful to guarantee results precision, and optimization speed.
Moreover, this method guarantees a certain coeherence of the results obtained, above all for the blade body section; in fact, a critical factor of the desired optimization is the preservation of the airfoil geometry, which cannot be absolutely modified because it ensures the correct changing of the gasflow direction. For this reason, a shell with a given thickness has been used for the airfoil meshing instead of a 3D mesh, hard to create with very thin thickness; this shell is then used as part of the non-design space.
The design space, beacuse it is totally contained within the non-design space, has been meshed first; subsequently, this 2D mesh has been duplicated and used as a starting point for the generation of the 2D mesh of the non-design space. After having performed a node equivalence between the two mesh, which guarantees the perfect cohesion of the different volumes, the solid mesh, characterized by tetra elements, has been finally created.
In addition to this first geometry, a second design space has been created through a different approach in order to investigate multiple optimized geometries. In fact, this new design space



(a) Shank and dovetail-Model 1 (b) Shank and dovetail-Model 2

(c) Blade (d) Shroud

Figure 5.6: Design spaces of Model 1 and Model 2

has been created adding material instead of using the baseline geometry, with the aim of guaranteeing as much freedom as possible during optimization using only a shell as non-design space.

### 5.2.2 Static analysis

Using the Altair Optistruct solver it has been possible to perform different static analyses related to the different models and to the different load cases. Through a particular procedure developed by Avio, the meshed model characterized only by non-design space has been imported in Patran, which allows to apply correctly pressure and thermal distribution, in addition to an inertial load.

Once completed this step, a re-exportation into Hypermesh has been done in order to add the temperature dependent properties of the material, here referred to as Material 1, to the component.

Before starting the analyses, a fourth load case, which simulates the combined effect of the three

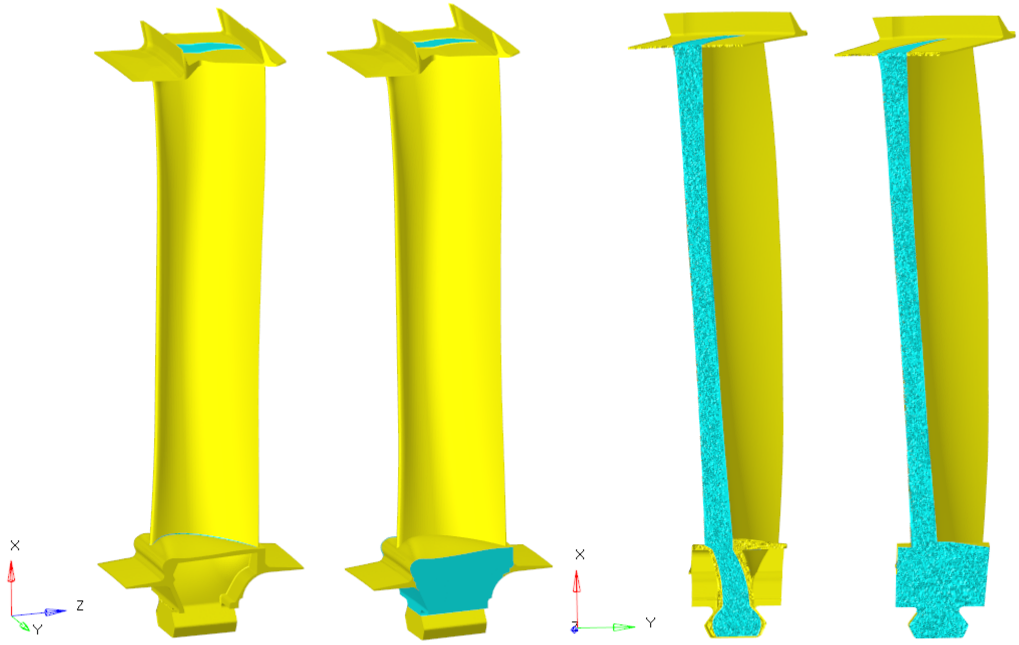



Figure 5.7: 3D mesh of Model 1 and Model 2

single load cases, has been added, in addition to SPCs (Single-Point Constraints) applied on the dovetail to simulate an interlocking condition with the disk. This last step has been repeated also for the baseline model, characterized initially by MPCs (Multiple-Point Constraints) because of the effective presence of the disk.

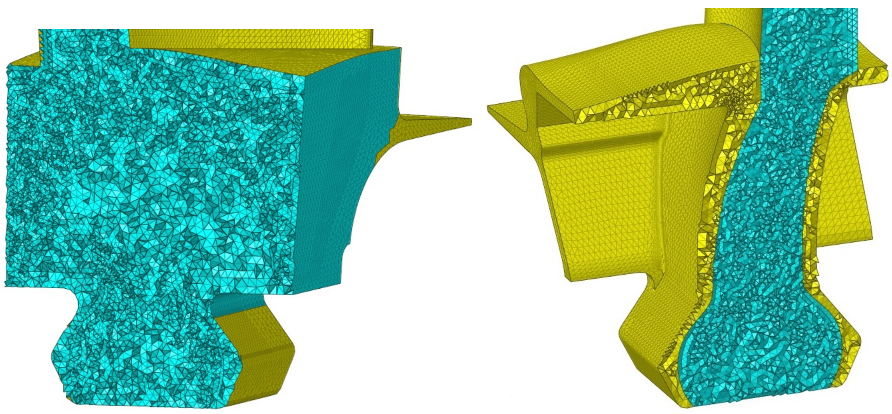


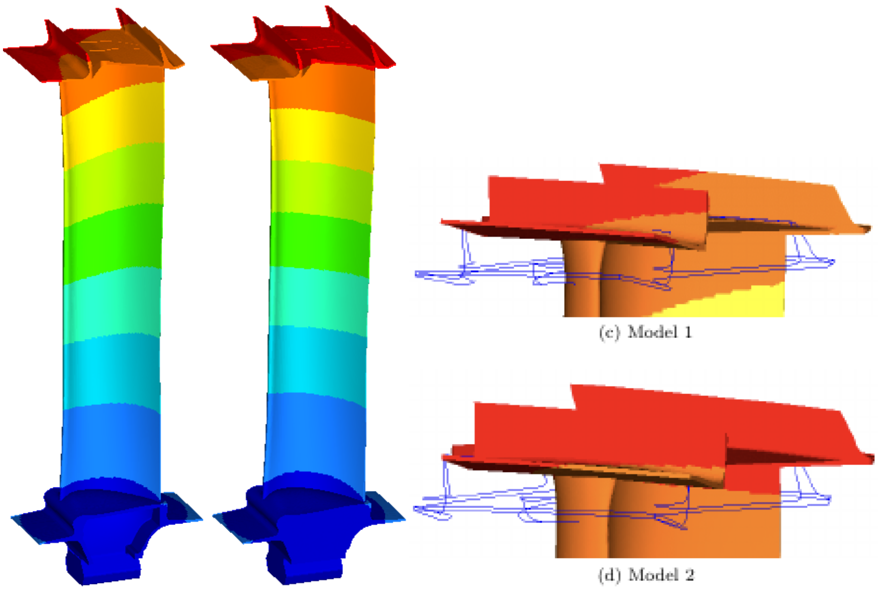
Figure 5.8: Detail of 3D mesh

### 5.2.3 Post-processing

The comparison between the static analyses of the baseline hollow model and the modified hollow model shows that:

| Percentage deviation from baseline (Max Displacement) |
|---|
| +10% |

The percentage deviation from baseline can be justified considering some changes that have been applied during the loads application in Patran, which have slightly modified in particular the pressure distribution; in addition to this, a mesh with a density higher than the baseline has been used. Taking into account also that some features of the baseline geometry have been modified or eliminated, it can be possible to validate static analysis and, in general, the method used.




(a) Model 1 (b) Model 2

Figure 5.9: Static analyses results

Following all of the steps aforamentioned other static analyses have been performed on the two blades, now characterized also by the design space. The results obtained in terms of maximum displacement are consistent with the others obtained previously, and the percentage deviation from baseline is higher because of the weight increasing, which leads necessarily to a greater intertial load.

| | **Percentage deviation from baseline (Max Displacement)** |
|---|---|
| Model 1 | +27.32% |
| Model 2 | +27.74% |

## 5.3 Optimization

The optimization method used is a topology optimization, chosen because it allows to obtain a certain reduction in terms of weight and compliance without affecting too much the overall mechanical properties of the component. It is also generally followed by several optimizations like, for example, size optimization, thanks to which it is possible to reduce significantly residual stress.

The topology optimization has been leveraged for both the components previously described by setting an objective function, different optimization responses and a certain number of optimization parameters, which improve the quality of the results and the convergence velocity of the optimization.

In particular, the objective function of this topology optimization is the minimization of the static compliance, which is the ratio of the strain energy of the structure, and can be calculated using the following equation:

$$C = \frac{1}{2}\int \epsilon^T \sigma dV = \frac{1}{2}u^T F = \frac{1}{2}u^T K u \tag{5.1}$$

where:

- $C$ is the static compliance;
- $\epsilon^T$ is the strain vector transpose;
- $\sigma$ is the stress vector;
- $u$ is the displacement vector;
- $K$ is the stiffness;
- $F$ is the force.

Equation 5.1 is valid when a single load case or load step is applied on the structure. A different formulation of compliance can be written in the case of multiple load cases:

$$C = \sum_i W_i C_i = \frac{1}{2} \sum_i W_i u_i^T F_i \tag{5.2}$$

The static compliance is now expressed as the weighted sum of the compliance of each individual subcase, which is characterized by a weight factor $W$.
A minimization of the complicance leads to a maximization of the component stiffnness and to lower displacements, when a force $F$ is applied. However, these improvements can result into an increasing of the mass of the component; for this reason, and due to the need for an optimized component as heavy as the baseline, a mass constraint is defined as optimization response.
In addition to this constraint, a displacement constraint has been added in order to reduce the maximum displacement with respect to the baseline. In particular, referring to Model 1, this displacement constraint has been applied on all of the nodes of the component and, after several attempts, it has been set to a value of maximum displacement inferior of 11%. On the other hand, the topology optimization of Model 2 is characterized by two displacement constraints: the first is applied on the nodes of the shroud and the blade body, and consists of a reduction of 12.5% of maximum displacement; the second is applied on the nodes of the shank and the dovetail, and, using a value which corresponds to the displacement of this parts obtained through the static analysis, it has been possible to create a continous structure between the dovetail and the shank.
As said before, several optimizations has been performed to find optimal constraints and parameters and to ensure the convergence of the analysis and a feasible design.

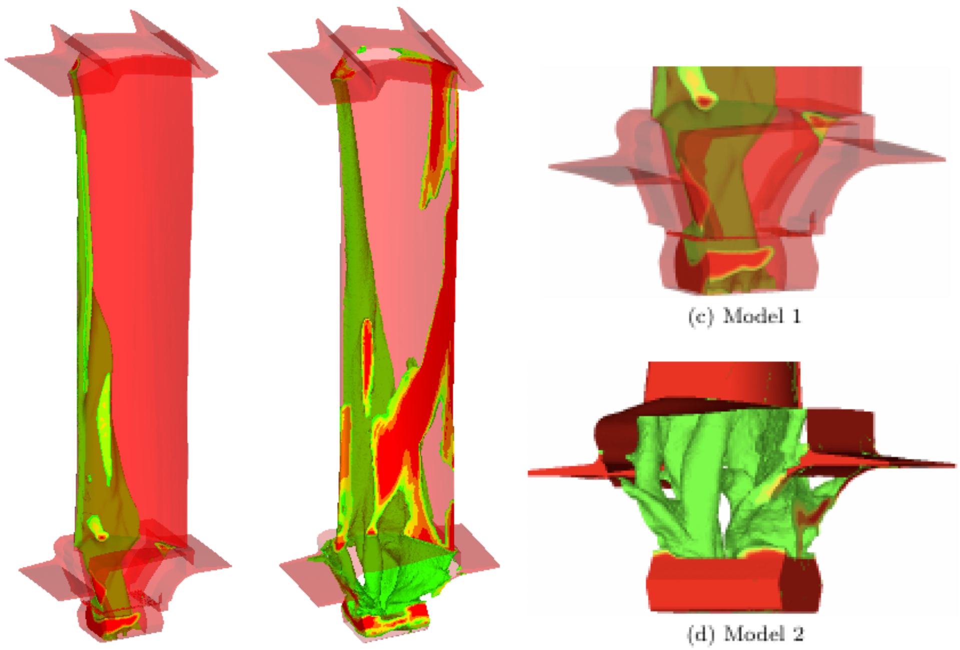
| | **Model 1** | **Model 2** |
|---|---|---|
| **Objective Function** | • Minimize Compliance | • Minimize Compliance |
| **Material** | • Material 1 | • Material 1 |
| **Optimization constraints** | • Mass +6.3% wrt. Baseline<br>• Max Displ -11% wrt. Baseline | • Mass +9.35% wrt. Baseline<br>• Max Displ -12.5% wrt. Baseline |
| **Optimization parameters** | • DISCRETE<br>• MINDIM<br>• MATINIT | • DISCRETE<br>• MINDIM<br>• MATINIT |

Table 5.1: Topology optimization parameters

The three optimization parameters affects to varying degrees the quality of the results:

- DISCRETE: Discreteness parameter. Influences the tendency for elements in a topology optimization to converge to a material density of 0 to 1. Higher values decrease the number of elements that remain between 0 and 1. Recommended value is 3.0 for solids. In Optistruct, the DISCRETE parameter corresponds to (p-1) for the SIMP method formula (4.3);
- MINDIM: Specifies the minimum diameter of members formed in a topology optimization. This command is used to eliminate small members. It is recommended to use MINDIM value equal to a multiple of the size of the elements used for the discretization of the Design Space.
- MATINIT: Defines the initial material fraction. For Topology and Free-Size runs with mass as the objective, default is 0.9. This parameter helps to avoid the problem of mesh dependency.

The results of the topology optimization are showed below:



(a) Model 1 (b) Model 2 (c) Model 1 (d) Model 2

Figure 5.10: Topology optimization results

| | Model 1 | Model 2 |
|---|---|---|
| **Compliance** | -27.9% | -43.75% |
| **Max Displacement** | -11.04% | -12.56% |
| **Iterations** | 50 | 110 |
| **Overhang Constraint** | Yes | No |

Table 5.2: Topology optimization results with overhang constraint

Thanks to a simpler design space, Model 1 has been optimized including also the overhang constraint, which is fundamental to ensure the creation of a geometry without overhanging surfaces. Generally the use of this constraint, which increases significantly the computational cost and, consequently, the running time of the analysis, is avoided thanks to the support structures; however, the design space of this component is completely inside the non-design space, making the creation of support structures impossible. For this reason, the overhang constraint is necessary, but Model 2, due to a more complex design space, needs to be further modified to allow a convergent topology optimization.
A first attempt has been made in this sense, and its results are showed below:

| | Model 2 |
|---|---|
| **Compliance** | -54% |
| **Max Displacement** | -3.35% |
| **Iterations** | 87 |
| **Mass** | +0.25% |
| **Overhang Constraint** | Yes |

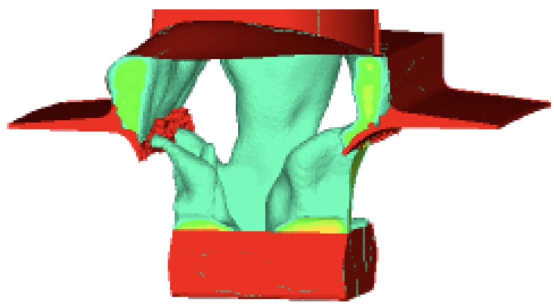


Figure 5.11: Topology optimization results of Model 2 with overhang constraint

## 5.4 Results validation

The final step that characterizes this work aims to validate the methodology used by reapplying the same loads and costraints of the baseline model to the optimized geometries, in order to perform a static analysis whose results have to match with the others obtained after the topology optimization.
Given the more complex geometry of Model 2, this process has been applied to this geometry, which, first of all, has been smoothed using FEA reanalysis Altair Optistruct option; the new mesh has been imported again into Patran and then exported into Hypermesh.

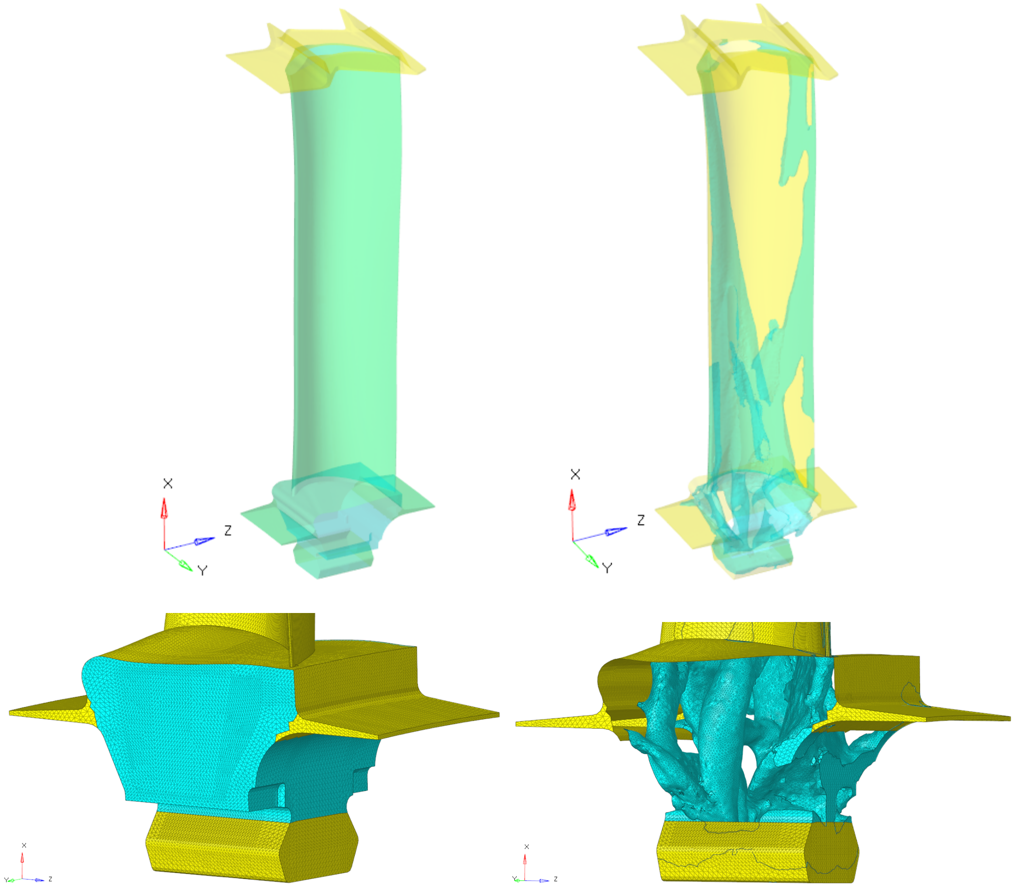



Figure 5.12: Smoothing of Model 2 without overhang constraint

The static analysis results match perfectly with the results coming from the topology optimization; the methodology developed is therefore validated.

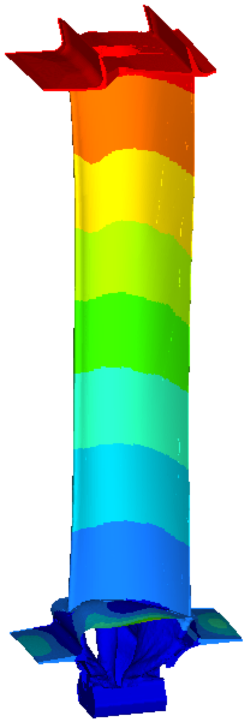
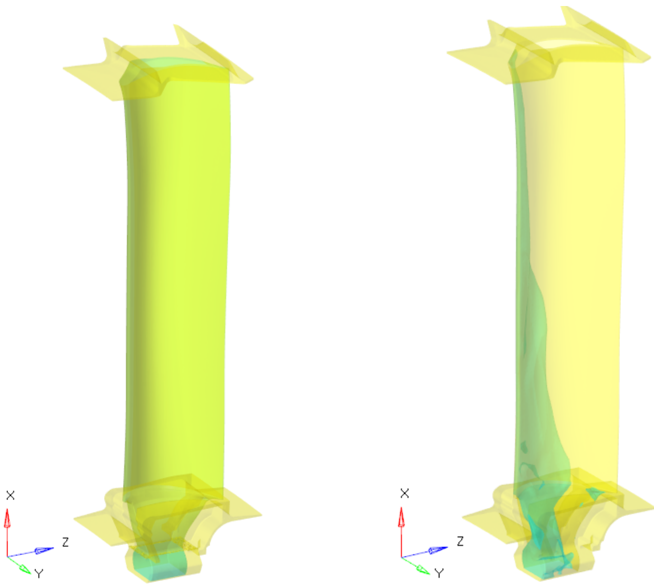


Figure 5.13: Static analysis results of smoothed Model 2 without overhang constraint

For completeness, the smoothing related to Model 1 and Model 2 with overhang constraint is showed below:



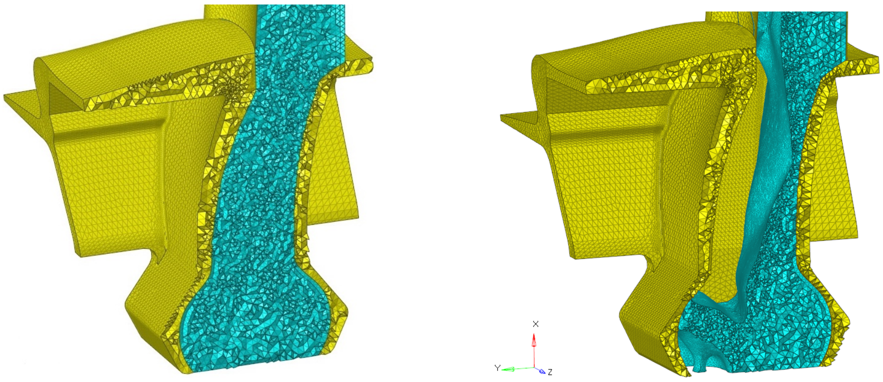


Figure 5.14: Smoothing of Model 1

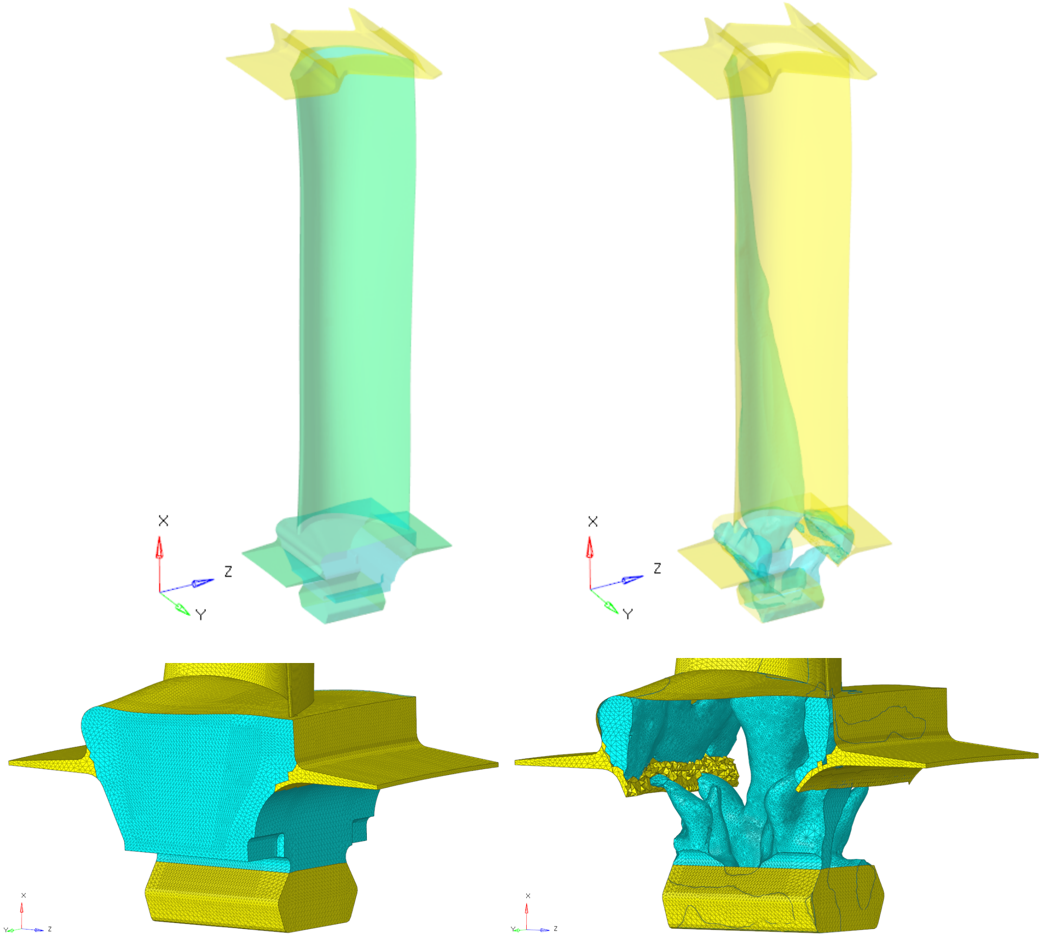



Figure 5.15: Smoothing of Model 2 with overhang constraint

# Chapter 6

# Conclusions

In this thesis the guidelines for structural topology optimization has been presented, also taking into account the benefits derived from Additive Manufacturing technologies. In particular, it has been developed an effective methodology which allows to apply multiple load cases on such a component using Altair Optistruct software, thanks to which it has been succesfully leveraged the first topology optimization on aeronautical turbine blade, whose results demonstrates that this is the right way to improve significantly mechanical properties and overall performance.
Moreover, one of the aim of this work was to evaluate the effectiveness of the overhang constraint, which has given interesting results especially for the geometry of Model 1, while several improvements has to be done to obtain a feasible design of Model 2.
On the other hand, further steps are necessary to develop an effective business case feasibility study, first of all a preliminary CAD rebuilding needs to be done in order to validate the final design, also with LCF and HCF analyses; in case of high residual stress or other undesired effects, the designer should perform other structural optimizations and, as final step, a complete process simulation.

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