SIMULATION DRIVEN DESIGN AND ADDITIVE MANUFACTURING. A NEW DESIGN PROCESS TO UNLEASH POTENTIAL OF ADDITIVE MANUFACTURING FREEDOM.

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ABSTRACT

Additive Manufacturing has become sufficiently mature in which is absolutely necessary to make use of the benefits that it provides. In the past, engineering design was limited due to manufacturing constrains and design tools. Now a day, the scenario is completely different. By combining the benefits of design freedom from Additive Manufacturing and optimization driven design, we can open the gates of a whole new structural design method through a process that involves conceptual (topology) optimization, abstraction and application of design principles in geometry creation, detailed (shape) optimization and design validation. Together, this method offers the best practices to design incredibly light, strong and efficient structures, minimizing risks of manufacturing problems and at the same time exploiting the creativity and design freedom in a short period of time using efficient software tools. There are still challenges and questions that come into the application of this method, such as: new design principles taking into account manufacturing constrains from Additive Manufacturing.

1 INTRODUCTION

The process of design by itself is an optimization. Such process is an iterative procedure following the phases of: Conceptual design, testing and optimization based on test result.

Before 1990s, the usage of computational structural optimization was only limited to sizing and shape optimization. Intuition and experience played the central role for a designer when creating an initial concept, defining the initial layout of a design. [1] Designer intuition and experience also relied heavily on available manufacturing methods, such as milling, casting, injection molding, etc. Both, sizing and manufacturability design approach often limit the creation of an optimum designs in terms of performance, cost, and weight.

Bendsøe and Kikuchi pioneered the theoretical foundation of today's modern finite element based topology optimization methodology in 1988 [2]. Altair OptiStruct, first released in 1994 [3], appeared to be the first commercial Software that utilizes this technology with high industrial acceptance, however, the usage of topology optimization has been also limited to available manufacturing processes to create and realize designs.

In order to make use of design complexity from topology optimization, it is often necessary to use unconventional manufacturing methods such as Additive Manufacturing. Specifically, Laser Additive Manufacturing (LAM) [4] systems are gaining high industrial acceptance in the usage of functional parts/assemblies in commercial and industrial applications such as aerospace, automotive, jewelry and tooling, among others.

In this paper, it is intended to introduce a systematical and evolutionary design process which takes advantage of structural computational optimization along with the freedom of additive manufacturing, taking into account the benefits, but also the limitations of the manufacturing process.

Such design process opens the opportunity for the creation of lightweight structures, driven by performance, at the same time mitigating risks during manufacturing process, bringing significant cost reduction through weight savings and time to market reduction in the whole product development cycle.

2 THE MANUFACTURING METHOD

Additive Manufacturing (AM) is the process of making objects from 3D model data by joining materials layer by layer, as opposed to subtractive manufacturing methodologies, such as traditional machining.

The term Additive Manufacturing includes a wide range of technologies, such as: laser sintering, filament deposition, stereo lithography, and many more. These technologies are used in a wide range of industries from the automotive, aerospace, consumer electronics, and consumables sectors as well as being used for medical applications and by individual consumers. For many companies and individuals, as they try to engineer better products, they are turning to AM for the benefits it offers over traditional techniques [5].

Today, metal laser sintering technology, also known as Direct Metal Laser Sintering developed originally by EOS, has matured enough to gain industrial acceptance to make use of it and produce high quality engineered parts to be used in complex assemblies such as jet engines, commercial airplanes, space crafts, automobiles, among others.

These systems rely on the melting of a very fine layer of metallic powder such as Aluminum alloy (AlSi10Mg), Titanium (TiAl16V4), Nickel alloy (In718), etc. through a high power laser beam, which solidifies the metallic powder and creates incrementally layer by layer a three dimensional metallic solid object as shown in Figure 1:

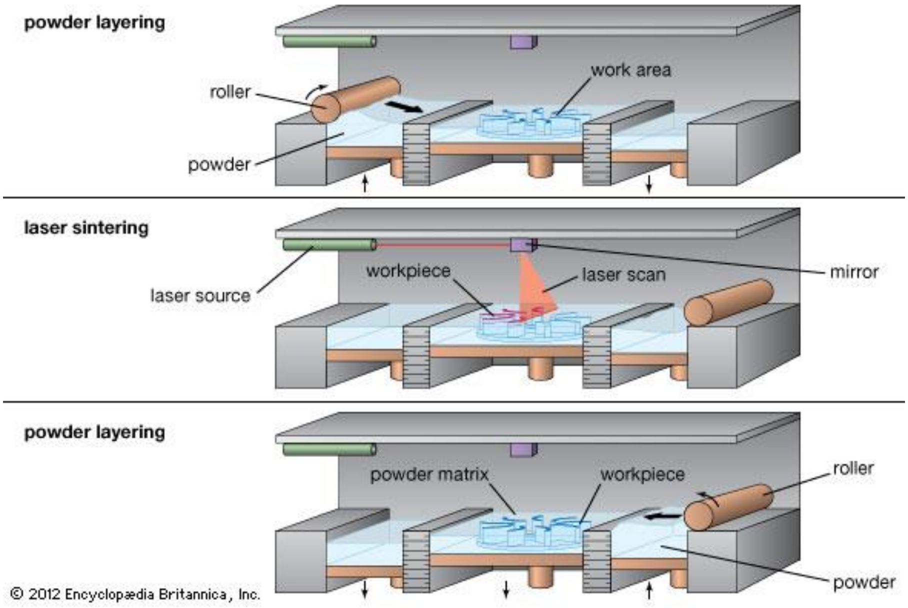

Figure 1: Direct Metal Laser Sintering (DMLS) process (photo courtesy of Encyclopedia Britannica)

The chance of manufacturing an object layer by layer could seem to bring infinite possibilities with respect to design freedom, however there are certain limitations from the manufacturing process which should be carefully taken into account during different design stages.

3 THE DESIGN PROCESS

These days, design is mostly driven by virtual tools, often known as Computer Aided Design (CAD) and testing is mostly driven by virtual simulation tools, also known as Computer Aided Engineering (CAE). Due to the level of complexity of such tools, usually, both disciplines are separate entities inside a company, making the design process time consuming and expensive.

As stated before, concept design, if created from scratch, is usually driven by intuition and experience. A designer must take into account a set of requirements and design targets in order to make the process as efficient as possible and reduce the amount of iterations with CAE department.

Here is where computational structural optimization helps a designer to create efficient designs with few iterations, from a new concept, to detailed definition covering the phases as shown in Figure 2.

Figure 2: Design approach using computational structural optimization.

3.1 Model Preparation

Before proceeding in any design activity through topology optimization, it is required first to understand four aspects of the part/assembly to be designed:

1) Geometrical constrains (design space): Geometrical envelope in which the part/assembly will be designed. Such space should not have interference with nearby parts/assemblies.
2) Design requirements (constrains): Boundary conditions in which the part/assembly should perform.
3) Design targets (objective): Desirable outcome or objective of the design, e.g. weight reduction, stiffness increase, stress reduction, etc.
4) If the design task is targeted to a re-design activity of a previously designed part/assembly, then a baseline Finite Element Analysis (FEM) of the previously part/assembly should be performed in order to get a good understanding of boundary conditions and structural behavior of the old part/assembly.

Once these aspects are understood, the task is to build and formulate a FEM with the correct representation of the physics to be analyzed. This would require to model correctly not only the geometrical design space with a good discretization scheme (element size and element formulation), but also to make proper assumptions of loads and boundary conditions. A proper modeling and representation of the physics through the FEM is key to success for good topology optimization results.

3.2 Conceptual Optimization

Conceptual optimization, also known as topology optimization, refers to the task of extracting the load paths of a structure from a given design space. The goal of this task is to obtain an overall load distribution of the structure and understand the global structural architecture of a design.

The initial implementation of topology optimization in OptiStruct followed the original theory of [2]. The topology optimization problem is stated as:

$$\text{Minimize} \quad W(\rho)$$

$$\text{Subject to} \quad V = \sum \rho_i v_i \le \overline{V}, \quad \eta \le \rho_i \le 1, \quad i = 1, \dots, n \tag{1}$$

Here, the quantity $W(\rho)$ represents the objective function. The quantities ρ_i and v_i are element densities and volumes, respectively, $\overline{V}$ is the target volume, n is the total number of elements, and η is a small number that prevents the stiffness matrix being singular.

To enforce the design to be close to a black-and-white-solution, a penalty is introduced to reduce the efficiency of elements with intermediate density. This is achieved by a power law formulation.

$$\widehat{K}_i(\rho_i) = {\rho_i}^p K_i \tag{2}$$

The matrices $\widehat{K}_i$ and K_i represent the penalized and the real stiffness matrix of the ith element, respectively. The power p is the penalization factor that is larger than one. This method is frequently referred to as Density Method or Single Isotropic Material with Penalty (SIMP) Method [1].

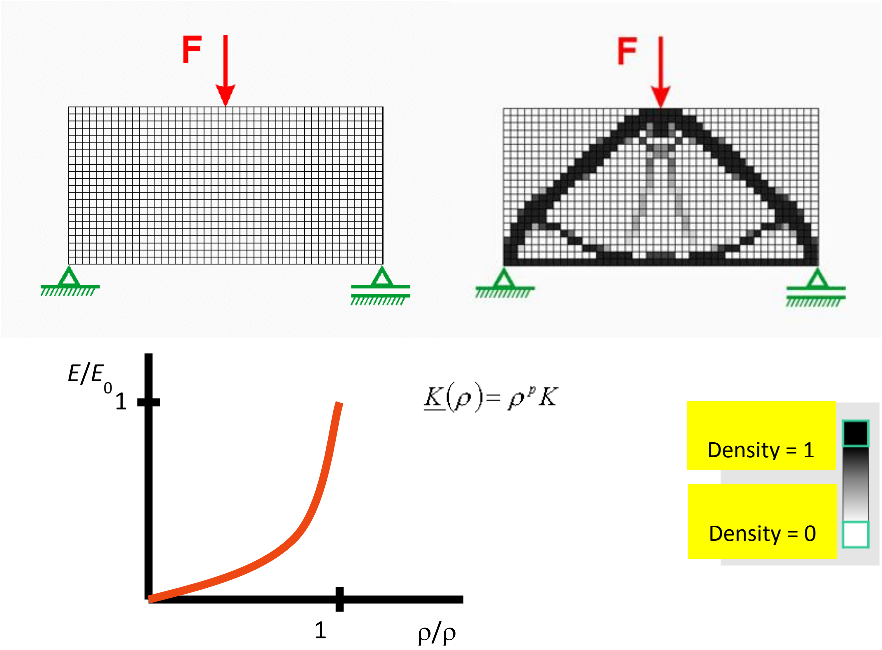

Figure 3: SIMP method. Upper left, initial design space. Upper right, Topology optimization.

During this stage, it is assumed that a proper FEM has been built such that is suitable to perform a topology optimization.

Since conceptual optimization has the goal to have an overall understanding of the global architecture of the load distribution in a given design space, it is required to perform not only one single topology optimization but rather a full study varying several optimization parameters and strategies.

A typical study strategy would consist on the combination of the following criteria:

1) Optimization objective function:
    a) Minimize Compliance (maximize stiffness) OR
    b) Minimize Mass
2) Optimization constrains:
    a) Volume/Mass fraction: typical values are 40%, 30%, 25%, 20%, 15%, 10%, etc.
    b) Stress constrain activation/deactivation (available in Optistruct).
    c) Displacement constrains in specific grid(s) (if objective is Minimize Mass).
    d) Compliance (stiffness) value for a given load case (if objective is Minimize Mass).
    e) Etc.

3.3 Conceptual Interpretation

After the execution of a conceptual optimization study, it is required to understand the output of such study in order to determine the quality of obtained results and to eliminate concepts that would not potentially bring any value in terms of design and manufacturing requirements. Such process is usually done through a comparison matrix monitoring several design requirements and optimization parameters. This comparison matrix will help to choose the most significant designs that could be candidates for further development.

In addition to the comparison matrix, in order to identify concepts that could potentially be further developed, it is recommended to understand two aspects while interpreting a chosen concept: Structural concept interpretation and manufacturing concept interpretation.

3.3.1 Structural Conceptual Interpretation

The concrete goals to make a structural interpretation include:

1) Understand the tendency of the optimization: Visualize and understand the evolution of a topology optimization.
2) Identification of primary and secondary load paths: How the structure will distribute the loads.
3) Understanding of internal load distribution in structural members: Compression, tension, shearing, bending and torsion.
4) Identification of structural similarities and common structural principles among several designs.
5) Identify numerical noise which could drive erroneously the tendency of the optimization. Such numerical noises could come from mathematical assumption and simplifications on the FEM.

3.3.2 Manufacturing Conceptual Interpretation

Despite the high geometrical freedom that AM provides compared to traditional manufacturing processes in terms of design possibilities, it is often a misconception that the process can bring endless options to manufacture every design no matter the complexity of it. The process of AM has specific restrictions that, if they are not taken into account as early as possible during the design process, they can significantly bring additional time, costs and delays, making the design activity and manufacturing process expensive and not suitable for industrial adoption and usage.

It is recommended that specific AM restrictions are taken into account after topology optimization during the concept definition stage.

Because of the nature of the upward incremental building process of AM, there is the existence of an overhanging phenomena due to the own weight of the sintered material deposited layer by layer. Usually this critical angle is known as overhang angle β (Fig 4). Typical values for metallic alloys is β > 40°.

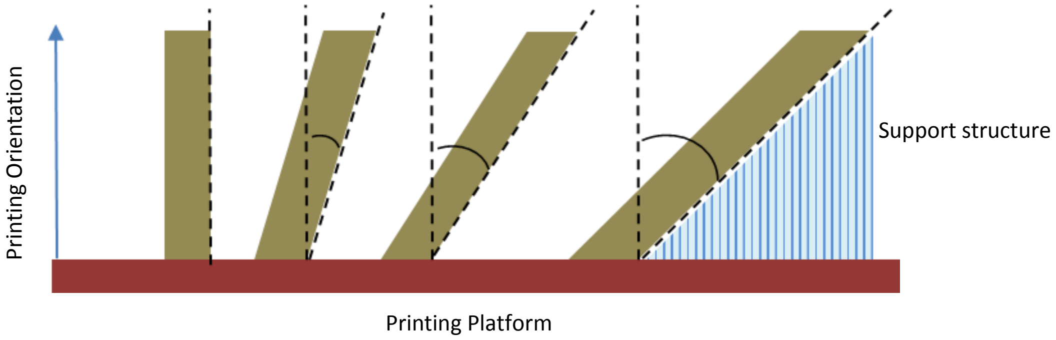

Figure 4: Overhang angle β and the need of support structure.

Excessive or erroneous usage of support structure could have a tremendous impact on the final costs, performance and dimensional tolerances of the part. It is important to choose properly such concept design that is able to fit and minimize the manufacturing limitations of AM like:

1) Printing orientation to minimize support structure volume.
2) Counter act recoater device induced force through printing orientation or extended support structure design to fix properly the part to printing bed.
3) Heat and stress concentration which could cause part distortion and thermal residual stresses due to laser sintering.
4) Post processing activities like support structure removal, surface finishing and machining.

This activity can be performed through the usage of a slicing software such as Materialise Magics [6]. A slicing software will determine the position of support structures according to a given orientation. It will also provide additional feedback like part placement in the build chamber and critical areas of the concept design which need special care when creating a CAD geometry model in the following step.

3.4 Conceptual Design

Concept design refers to the step of realizing all the information recovered during Conceptual Interpretation stage and realizing it into a proper CAD model.

There are several commercial CAD tools to create geometry through different methods. The main methods available in the market can be divided in:

1) Parametric solid modeling
2) Explicit modelers

Parametric solid modeling refers to the traditional mechanical CAD packages which relies mostly on solid Boolean subtraction and addition to create a solid 3D geometry. Through this technique, the solid objects can be created and modified through a history construction tree, accessing the parameters and spatial position of the features that define a solid geometry model.

This technique is very efficient and powerful for classical mechanical designs where it is required to have a closed relationship with the possibility to manufacture it through traditional manufacturing procedures such as milling, casting, etc. Also, the ability to further modify and update parametrically a solid geometry model, makes these tools a very flexible solution for design updates and modifications.

Explicit modelers refers to CAD packages that rely on the creation and edition of geometry without the existence of a history tree. Therefore, such tools do not have a parametric capability to further edit and update a solid geometry model. These tools rely on features and tools that interact on-the-fly to create and modify relatively quickly a geometry. Some of the advantages are their flexibility and ease of use, as well as the ability to produce very organic geometry models without major effort.

With the use of design freedom provided by AM, a designer could be able to create very organic, yet efficient, lightweight and performant designs by incorporating the use of structural optimization. However, creating an organic design through a parametric solid modeling tool has shown that it can be a highly time consuming activity since such tools were not conceived to create these types of designs. Therefore the effectiveness of explicit modelers can aid to relief the time spent to create an organic design suitable for AM. However, there are two major disadvantages when using explicit modelers:

1) Absence of history tree for further parametric update and modification.
2) Underlying technology relies mostly on a mesh. No NURBS [7] representation of the geometry.

It has been shown that solidThinking Evolve [8] can overcome these disadvantages by providing a hybrid modeling framework that combines both parametric and organic surface modeling capabilities, all of which relies on NURBS technology [7]. As well, solidThinking Evolve [8] incorporates the traditional explicit approach to create geometry models through the cutting edge technology of PolyNURBS [8]. Such technology combines the freedom and capability of on-the-fly interaction to create solid geometry, through the underlying technology of NURBS surfaces.

It is proven that, through the usage of solidThinking Evolve [8], creating geometric solid models taking the output from a structural topology optimization and the information from the conceptual interpretation, it is possible to reduce the time dedicated for this task, making it fast, robust, easy, reliable and editable at any point in the design process. As mentioned early, these requirements in a CAD tool are of great help to adopt this design process for industrial usage.

3.5 Detailed Optimization

Once a concept design has been conceived into a proper CAD model, where the information and ideas from conceptual optimization and interpretation are used to create such CAD, it is required to further fine tune the performance and manufacturability of the concept design. This is achieved in the step of detailed optimization, also known as size/shape optimization.

3.5.1 Detailed Structural Optimization

In order to perform a size/shape optimization, it is required first to perform once again an FE simulation to corroborate the structural behavior of the concept design that has been created in the previous stage. Such FEA should include all the boundary conditions, assumptions and a proper discretization scheme (mesh) to represent accurately the physics of the part/assembly. Using this FEM, it is possible to formulate a correct strategy to perform a detailed shape/size optimization to further increase the performance.

Depending on the assumptions and idealization of the FEM, it will be performed either size and/or shape optimization. Typically, an organic 3D solid model is more suitable for performing purely a shape optimization. However, this will be strongly dependent on the FEM assumption and modeling techniques.

Typically, it is intended to increase the performance in terms of stiffness, stability (buckling), stress levels and weight. There can be certain areas in the model which will present stress levels that have higher values than the design requirements, as well as some areas which might have lower stress levels, in which it is possible to further reduce the amount of material needed, thus, weight. Also, cross section geometries in certain structural members could be optimized to achieve stability requirements and further reduce weight.

OptiStruct has the capability of performing shape optimization. In shape optimization, the outer boundary of the structure is modified to solve the optimization problem. Using finite element models, the shape is defined by the grid point locations. Hence, shape modifications change those locations as shown in Figure 5.

Shape variables are defined in OptiStruct in a way very similar to that of other shape optimization codes. Through HyperMorph technology, available in HyperMesh, it is possible to define shape variables.

The optimization problem, objective and constraint functions, is defined in the same manner as the other types of structural optimization. OptiStruct then goes through an iteration process to solve the optimization problem. The figures below show the optimization result of the cantilever beam [3].

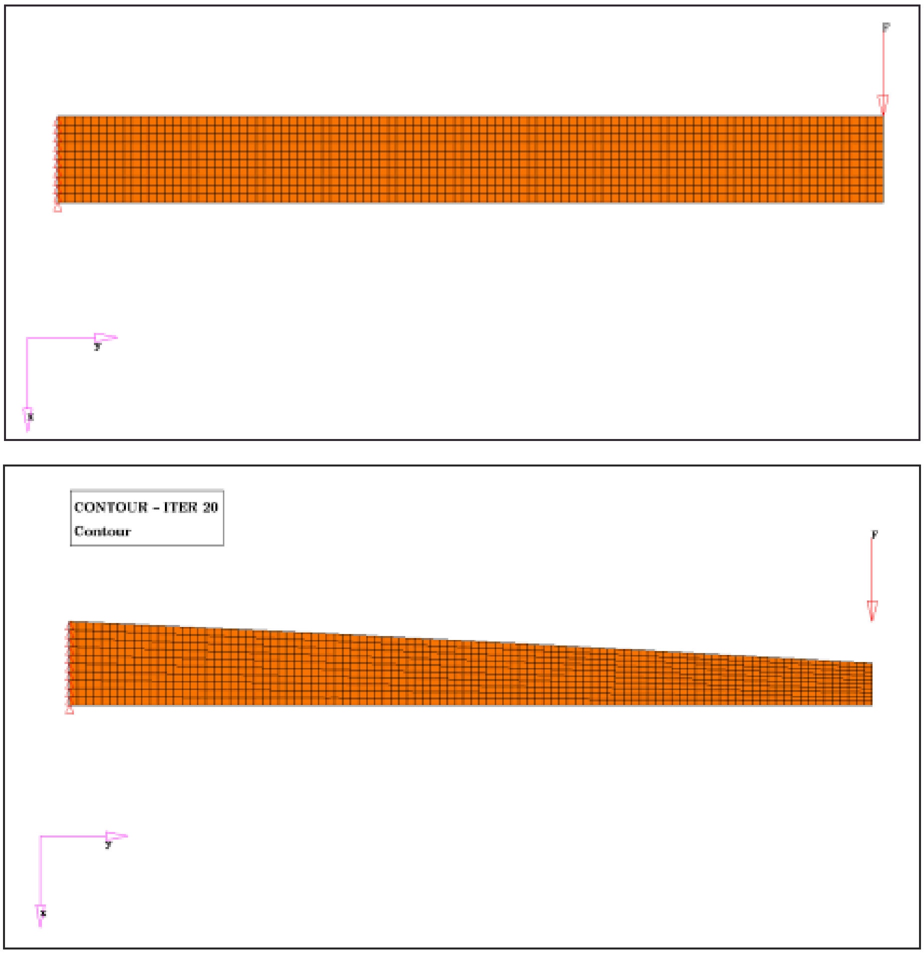

Figure 5: A cantilever beam shape is sought that minimizes the structural mass and allows a limited vertical deflection at the lower right corner. Upper image is the initial iteration, lower image shows the last iteration [3].

3.5.2 Detailed Manufacturing Optimization

During detailed optimization stage, it is also important to consider manufacturing restrictions of AM. A second loop in a slicing software like Materialise Magics [6] should be performed in order to corroborate manufacturability of part/assembly and mitigate further risks downstream the process. It is also intended to optimize usage of support structure, for example:

1) Modifying fillet radius such that they overcome the overhang angle problem.
2) Increase thin wall thickness.
3) Optimize cross sections to avoid sharp corners which are not optimal for AM due to thermal distortion.

3.6 Stress Verification

After performing a detailed optimization, such that the result fulfills all the design criteria and requirements while achieving the optimum performance, it is required to update the CAD model. Here the importance of using a flexible and parametric CAD tool in order to do fast and smooth design updates.

Once design updates have been made in the CAD model based on the result of the detailed optimization and manufacturability feedback, it is required to validate and confirm that all the design requirements and criteria are successfully met. Usually this final verification is done through an FE model with high level of detail. A good practice is to use second order FE to have high accuracy in results.

Further on, the generation of proper documentation will be required of the whole design activity and as well as the presentation of results. In some companies, it will also be required the upload of the geometry file to a proper PDM (Product data management) system.

3.7 Additive Manufacturing

With an updated, verified and documented CAD model, the task is then to generate a physical part through AM. Such part will be submitted to a specific test campaign in order to corroborate physically that the part/assembly meets the design requirements and is suitable to be used. Testing campaign details are out of scope of this technical paper.

The geometry file to be converted into a physical part needs to have the proper requirements for machining and post processing. Some of this requirements are:

1) Additional material in holes. Diameter should be smaller to allow material removal through drilling or milling.
2) Functional surfaces which require flatness tolerance should include additional material to be removed through machining.
3) Proper adherence to printing bed. Allow extra material to be removed from bed and then machined.

Once the geometry is prepared for AM a schematic process for converting a CAD model into a physical part is shown in Figure 6.

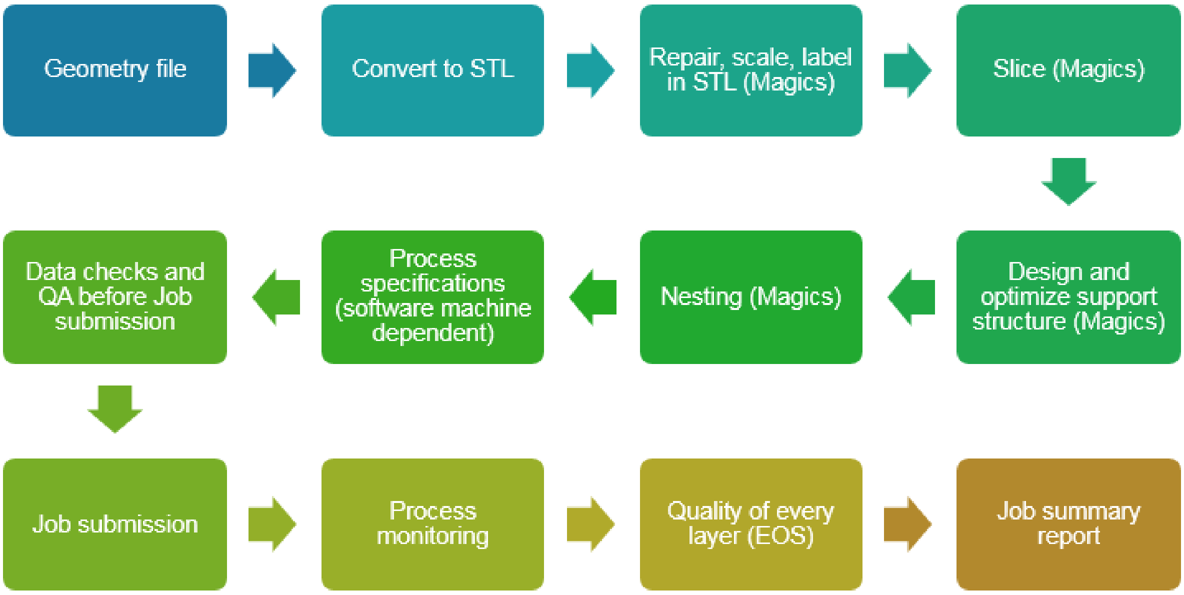

Figure 6: Process to produce through AM a CAD model.

4 CONCLUSIONS

Through a systematic design approach combining both innovative, yet mature, disciplines of computational structural optimization and additive manufacturing, along with flexible, reliable and fast design tools, it is possible to achieve the creation of lightweight, performant structures in a relative short period of time.

Cost savings in terms of efficient use of design tools to reduce development times, weight reduction and lean manufacturing with AM are imminent by the adoption of AM and the design process presented in this paper.

As a proof of success of the application of this systematic design approach, a redesign activity took place for the S-Band antenna support bracket used in the ESA (European Space Agency) Sentinel 1-B Satellite. The activity emanated into a design suitable for AM, fulfilling not only virtual testing through FE simulation, but achieving successfully all the physical test campaign. The time invested for this design activity was 4 weeks with a weight saving of 40% as shown in Figure 6 and Figure 7.

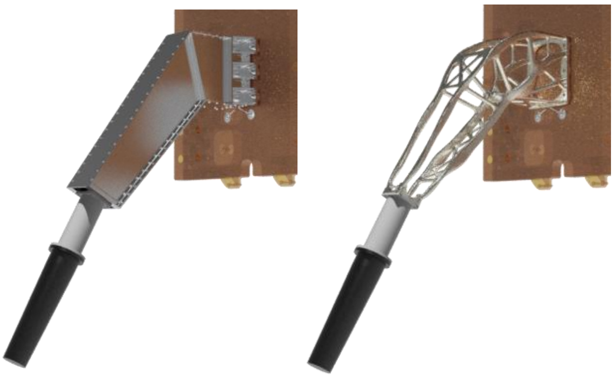

Figure 6: Left, baseline design 1.626 Kg. Right, AM optimized design 0.936 Kg.

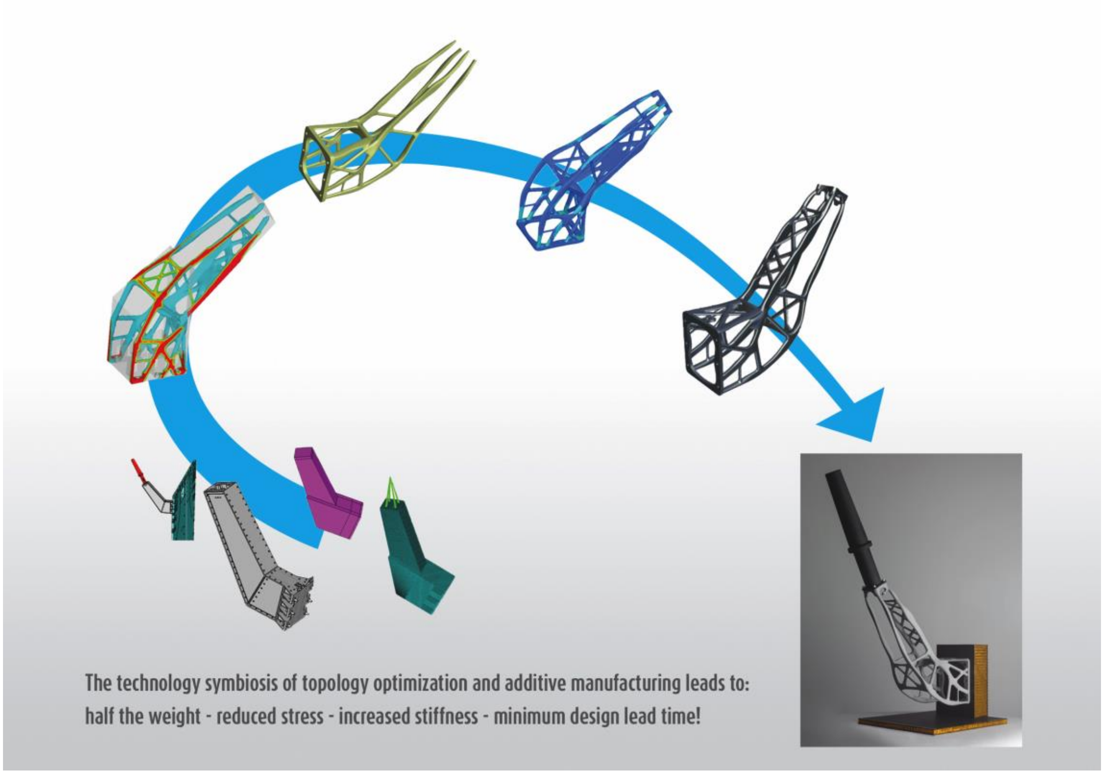

Figure 7: Design cycle driven by structural optimization on the Sentinel 1-B Antenna Bracket.

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