Additive Manufacturing:
Lattice and minimal surface design using nTopology

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Abstract

Additive Manufacturing is considered to be the chosen method for manufacturing complex and intricate shapes. Its increasing and widespread adoption is a measure of suitability for a wide range of industrial sector uses. As a result, this study looks at the characteristics and capabilities of nTopology, a one-of-a-kind software. This tool is exceptionally fast when it comes to creating and modifying complicated lattice structures and minimal surfaces. Because this software is still relatively new in the field of CAD modeling, this thesis gives an insight into its capabilities and applications in the context of additive manufacturing.

To do so, a jet engine bracket from GE has been topology optimized using nTopology's overhang constraint for additive manufacturing and different cases are compared. Also, a light-weighting operation was conducted on the bottom part of a plummer block that was shelled and the inner hollow area filled with a lattice structure that variates the beam thickness and therefore the amount of material generated through the part based on static analysis.

The results show what current design software is capable of accomplishing. A great weight reduction of 70% in mass and almost 90% of reduced support material needed was discovered while operating the topology optimization with the additional constraint. The results of static analysis on the plummer block were transformed and inserted into the light-weighting operation which created a very fast and accurate material distribution of the material in areas where it is needed only.

The great variety of designing possibilities, options and fast running software that nTopology offered during this study emphasizes the impact design for additive manufacturing tools can have on future designs and companies' long-term competitiveness.

Language: English Key words: Additive Manufacturing, nTopology, DfAM, CAD

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1 Introduction

Additive manufacturing, also known as 3D printing, is a comparably new and very exciting technology in today's world. The first approaches to additive manufacturing were introduced to the industry in 1987 (Gebhardt 2012). Its standardized terminology defined by (ASTM International 2012) is stated as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”. There are many different additive manufacturing methods available now; they vary in the way layers are deposited to manufacture parts, the operating principles, and the materials used (Bikas et al. 2016). As additive manufacturing has developed it revealed changes in the value of creating models, methods, structures, and processes. This technology entails both internal and external transitions for companies, such as time-to-market tactics, product choice, and customer loyalty which as well commits its growth in additive manufacturing’s financial area (Kritzinger et al. 2018). Therefore, it is essential to recognize that, as these tools advance, new technologies, materials, and other strategies for optimizing processes will require the change of the design for additive manufacturing techniques on a regular basis (Diegel et al. 2020). In 2019, the global additive manufacturing market was valued at USD 8.35 billion. This is no longer a pipe dream from 30 years ago. Not with the industry's rapid growth and projections that the global additive manufacturing sector will be worth USD 23.75 billion by 2027, growing at a rate of 14.4% (Research and Markets Ltd. 2021). Additive manufacturing has advanced into the automobile and aerospace industry due to its ability to e.g. manufacture lower-weight structures and has also revolutionized medical applications (Wong and Hernandez 2012). In general, it can be said that this manufacturing approach enables the creation of complicated constructs that would be unrealistic or only very problematic to create if at all, using conventional methods. When diving into additive manufacturing and especially when viewing the design aspect of it, the methodology of topology optimization is an expression that cannot be missed out. As topological optimization is typically the source of these highly revolutionary and complex forms. The results are e.g. significant mass savings or improvements in structure mechanical properties (Brischetto et al. 2017). Due to the fact that there is a need to create an updated set of design standards, this thesis research topic of additive manufacturing focuses on the design for additive manufacturing. The true potential of additive manufacturing’s advantages and production capabilities has only a chance to be realized when its full potential is recognized and used. For this purpose, the author decided to use the software of nTopology, Inc. which was founded in 2015. It is a fairly new design and engineering software but promises much for the future of advanced manufacturing.

2 Aim and Objectives

With the increasing adoption of additive manufacturing, utilizing software to enable this form of manufacturing is required to reach its fullest potential.

This thesis aims to present the capabilities of the nTopology software for the purpose of designing for additive manufacturing.

To meet the thesis' aim, objectives have been established as follows:

- Document the strength and weakness of different CAD modelling methods for 3D models manufactured using additive manufacturing
- Utilize case studies to model optimization capabilities of the nTopology software
- Presenting the features of nTopology with visual aids that best support current and future industrial requirements

2.1 Document Structure

The introduction and the presentation of the aims and objectives of this thesis work created an impression of what this work is about, what the targets are and how they are intended to be achieved. The literature review (section 3) follows as it is divided into different parts. These sub-sections focus on additive manufacturing and facilitating its principles as well as covering its importance to be a valid addition to conventional manufacturing processes. Also, computer-aided design and computer-aided engineering are being presented and their usage within the nTopology software. The theoretical part of this thesis is finalized with the finishing of the literature review including the presentation of the design for additive manufacturing. This, however, views further into topology optimization and light-weighting as these two methods are being focused on later in the case studies. It proceeds with the methodology (section 4). It gives the reader an understanding of how the earlier stated objectives are planned to be achieved. The two conducted case studies follow (section 5) and are supported with a visual aid that gives an insight into the nTopology software and supports a better understanding of the tasks and steps performed. After understanding the theoretical foundation and practical execution of this thesis, the results (section 5) are given for discussion (section 6) before this work is being concluded (section 7).

3 Literature Review

3.1 Additive Manufacturing

This chapter aims to give the reader a brief understanding of what additive manufacturing (AM) is. It will not cover every specific existing technology, but rather give the reader an overall understanding of how each AM technology category works. Before sealing it with AM's advantages and disadvantages, today's broad range of recent achievements and possibilities AM having to offer will be presented.

3.1.1 Introduction AM

Additive manufacturing (AM) is specified by (Diegel et al. 2020) as a method that involves a variety of technologies to create a component layer-upon-layer to the completion of the part, which is based on a virtual 3D model. The major ways that AM machines differ from each other are in the materials that can be used, how the layers are created, and how the layers are bonded to each other (Gibson et al. 2015). With a limited need for post-processing, AM can provide intricate and complex geometries, with near-zero material loss, while being accessible to a range of materials (Bikas et al. 2016). While conventional manufacturing methods require a comprehensive and detailed study of the geometry of the part to decide the order in which various characteristics may be generated, what instruments and processes may be used and what additional fixtures might be needed to complete the part (Gibson et al. 2015), AM offers a great quantity of freedom of design. The future benefits of 3D printing for the development of modern systems and structures in the fields such as aerospace, mechanical, civil and biomedical engineering are indicated by numerical, analytical and experimental knowledge and models (Brischetto et al. 2017). AM methods are usually being classified according to the type of material used, the method of deposition, or the way the material is fused or solidified (Monzón et al. 2015). Processes for additive manufacturing are categorized into seven areas, according to the process mechanism (ISO 17296-2) (Stavropoulos and Foteinopoulos 2018) as presented in the following Table 1.

Table 1: Summary of AM technologies areas (Kutzer and DeVries 2017)

Process	Description	Material(s)
Binder Jetting	A liquid bonding agent is selectively deposited to join powder materials	Polymers, Sand, Glass, Metals
Direct Energy Deposition	Focused thermal energy is used to fuse materials by melting as they are deposited	Metals
Material Extrusion	Material is selectively dispensed through a nozzle or orifice	Polymers
Material Jetting	Droplets of build material are selectively deposited	Polymers, Waxes
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	Metals, Polymers
Sheet Lamination	Sheets of material are bonded to form an object	Paper, Metals
Vat Photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymer	Photopolymers

Those seven AM process types are being summarized in this Table 1 but will find more attention and be presented in slight further detail in the following section 3.1.2 Types of AM processes.

3.1.2 Types of AM processes

In terms of the overall process, all AM applications have a shared foundation. The approach begins with the 3D model, which is converted into file format and software for layer-by-layer slicing of the solid body layer, and a series of motions is sent to the AM system where the component is eventually created (Monzón et al. 2015). Each process has its benefits and disadvantages, and some businesses, therefore, supply the material from which the object is manufactured with an option between powder and polymer. In general, the key reasons for selecting a machine are its speed, the cost of the printed component, the cost and variety of materials, and its color capability (Bikas et al. 2016).

Vat Photopolymerization

Vat photopolymerization processes manufacture parts materials that are hardened by UV light out of liquid resins (Diegel et al. 2020). In contrast with most other AM methods, the VP parts appear to have high dimensional precision and surface finish alongside faster building time. Their key is their use of photopolymers, their strength of impact and toughness, which are inferior to those of thermoplastics molded for injection of good quality (Stavropoulos and Foteinopoulos 2018).

Material Jetting

Thin nozzles are used in material jetting processes to 'spray' either molten material or, more commonly, a binder (adhesive) in a regulated way in order to bind the powder to a solid object. The operating theory of the device is much like all laser-melting processes, except there is no phase change; instead, the binder keeps the powder particles together (Bikas et al. 2016). Material jetting characteristics are high precision, it is possible to print multi-material components, parts can be printed in full color and a small range of materials like photopolymers, waxes, thermoplastic polymers, and composites (Gibson et al. 2015).

Binder Jetting

In order to bind powder content, binder jetting processes deposit liquid in the form of droplets. The binder also has adhesive characteristics and is ink-jetted on the surface of the powder bed. To extract the binder and to densify the constituent powder, the processing of structural materials usually involves some form of post-processing (Bourell et al. 2017).

Nevertheless, its advantages are coming with a high deposition speed at a relatively low cost and make it more appealing with the option to possibly use colors (Gibson et al. 2015).

Material Extrusion

Material extrusion methods are thermal which utilize a heated extrusion nozzle to soften or melt the material supplied in the form of wire, typically plastic (Bikas et al. 2016). By force or pressure, the material then moves through a nozzle or orifice at a controlled plotting of the liquefied material according to a pre-defined path, and the layer-by-layer bonding of the material to itself or secondary building material to form a cohesive solid structure (Gonzalez-Gutierrez et al. 2018). The characteristics of material extrusions are that the material properties of the parts are anisotropic, porous parts can be made, inferior material properties and dimensional precision, as well as a poor surface roughness (Stavropoulos and Foteinopoulos 2018).

Powder Bed Fusion

Powder bed fusion systems operate by distributing a fine layer of building material over the building platform, in powder form, and then using an energy beam (a laser or an electron beam) to scan the part slice and melt the powder anywhere the powder is struck by the laser (Diegel et al. 2020). This approach is extremely complicated as high residual stresses can contribute to the warping of the components, taking into account thermal background and parameters such as the combination of laser intensity, spot size and scan speed, as well as shape, size and distribution of powder. In addition, the dimensional precision, density, shrinkage and curling of the manufactured portion and the recyclability of the unused powder are highly dependent on the laser power and the temperature of the bed (Stavropoulos and Foteinopoulos 2018). As the material properties are similar to many engineering-grade polymers, metals, and ceramics, they are gradually being used for the direct processing of end-use parts (Gibson et al. 2015).

Sheet Lamination

Laminated object manufacturing (LOM) and Ultrasonic additive manufacturing (UAM) are sheet lamination processes. While LOM uses paper or polymer film, which is cut out using a blade into the appropriate shape for each slice of the model, and adhesive to bond them layer upon layer together. The UAM approach uses metal sheets that are bound together by ultrasonic welding (Diegel et al. 2020). The downsides of LOM are the phenomenon of component distortions, and edge roughness is also prevalent. Where UAM's common defects are voids and anisotropic mechanical properties (Stavropoulos and Foteinopoulos 2018).

Directed Energy Deposition

Energy is applied to a small oriented area where, when heated by the power source (mainly the laser beam), the substrate is melted, while at the same time there is the deposition of material which is also melted as a result (Stavropoulos and Foteinopoulos 2018). In comparison to devices capable of selectively melting a powder bed, with the use of direct energy deposition technology, high build rates and greater component volumes can be achieved (Mazzucato et al. 2017).

3.1.3 Advantages and Disadvantages of AM

The additive manufacturing approach allows so-called evolutionary forms to be constructed: Objects of complex nature that are impossible or difficult to create by conventional milling or machining. Typically, evolutionary forms are the products of topological optimization. Using AM, substantial mass savings or improvements in structural mechanical properties are achieved for these purposes (Bourell et al. 2017). AM also provides remarkable possibilities for in-process control, which allows the possibility to track the creation of the final product when layer by layer or particle by particle is formed (Greeff 2019). As prototyping, for both function and form, is one of the main uses in additive manufacturing, it is accomplished at a much faster rate and only a fraction of the costs of other processes (Camburn et al. 2017). On the downside, AM still must mature further as numerous drawbacks challenge its employment. Most analysts believe that the barrier to extensive adoption of AM is the absence of AM standards (Monzón et al. 2015). Further analyses, exploration and advanced technological development must be conducted (Abdulhameed et al. 2019) to solve the issues of low efficiency, inferior quality, and uncertainty regarding the mechanical properties of the final component (Bikas et al. 2016) as well as facing high cost, the building of overhang surfaces, small building volume and the issues regarding converting AM into mass production (Chen et al. 2017).

3.1.4 Recent achievements in AM

Additive manufacturing is compared to conventional manufacturing technologies seen as modern and keeps growing rapidly. In 2011, the additive manufacturing economy was worth $1.7 billion, and it is projected that by 2025 it would be worth $10+ billion (Muthu and Savalani 2016). Following, companies and their state of art technologies are being mentioned to present the application range AM has.

DMG Mori is a company that provides hybrid machines that combine additive manufacturing like laser metal deposition welding with five-axis milling operation in one machine. This gives manufacturing new possibilities in regard to product design and material (dmgmori.com 2021).

Optisys supplies high-performance aerospace and defense applications with metal 3D printed antenna devices (on the ground, maritime and airplanes). They realize to minimize product weight, scale and the part count of their products (Optisys.net 2021).

Relativity Space is a modern and pioneering company that interferes with conventional aerospace manufacturing. Relativity consists of automated robots, software and data-driven 3D printing, which results in time improvements, reduced costs and product designs that were not possible before, while conventional rocket development requires rigid factories, fixed tools, complicated manufacturing chains and extensive manual labor costs. The conventionally produced rocket consists of 100,000+ components, whereas Relativity provides rockets of less than 1000 components due to the use of advanced manufacturing methods such as 3D printing (relativityspace.com 2021).

Voxel8 is a start-up company that developed and released a 3D desktop electronic printer in 2015, capable of both plastic printing and conductive ink deposition. Since selling this technology, they have concentrated on material dispensing technologies to 3D print plastic on fabrics, along with an inkjet head that offers a wide spectrum of colors (voxel8.com 2021).

3.2 Computer Aided Design

Also, computer aided design (CAD) is a fundamental property not only for this thesis but also for engineering. After presenting the importance and benefits that CAD has in today's world of engineer designing, this chapter continues with the different possibilities on how geometries within CAD software are displayed. As a matter of this thesis, the different approaches nTopology's software utilizes CAD as a tool and how additive manufacturing takes a significant role in the approach of nTopology will be discussed.

3.2.1 Introduction CAD

Computer-aided design is defined by (Groover and Zimmers 1983) as the use of computer systems to assist in the creation, modification, analysis, or operation of a design. Traditionally, CAD is able to show a complete 3D representation of a component that can be rotated, viewed from a number of angles, cut to expose detailed cross-sections, submitted to computer-aided engineering (CAE) packages for analysis, and used to create data sets for computer-aided manufacturing (CAM) (Liker et al. 1992). An infinite number of 2D pictures can be generated quickly and easily from this 3D data set. Overall CAD can be seen as a method that improves the effectiveness and performance of all facets of production and manufacturing activities (Groover and Zimmers 1983). As a 2020 physics article reports, the introduction of CAD allows for a shorter product development period of 1.5-2 times (from design to manufacturing), a reduction of the product's resource consumption by 20-25 percent, a reduction of production costs by 15-20 percent, as well as a boost in product efficiency and an enterprise's competitive edge (Gilmanova 2020). The global Computer Aided Design industry, valued at US$8.3 billion in 2020, is expected to hit a revised size of US$12.4 billion by 2027 in light of the COVID-19 crisis (reportlinker.com 2020). The most common mechanical computer aided design software for the development of parts and assemblies are SolidWorks, AutoDesk Inventor and CATIA (Gilmanova 2020) as well as Siemens NX and AutoCAD.

Solid Modelling Methods

Solid modelling (SM) is a method of CAD with a software toolset for forming, shaping, shifting, and manipulating bodies, curves, edges, lines, and other geometric forms in a spatial context based on computer graphics. To create a graphical representation of a desired object or component (either stand-alone or for assembly purposes) with comparisons to sizes, proportions, material types, and mathematical formulas, while being able to add remarks or directions about the part and animation, for improved contextual interpretation and input when demonstrating (Kollataj 2017).

Constructive Solid Geometry

Constructive Solid Geometry (CSG) is a way of defining solids. The parameterized CSG solids are constructed from a few primitives forms such as cones, cubes, cylinders, prisms and spheres (Rossignac 2001). The primitives can be replicated many times, possibly with different parameter values, positions, and orientations. The transformed forms can be combined as union, intersection, and difference through regularized Boolean (Tsuzuki et al. 2007). As a direct result of applying these Boolean operations to a set of instantiated and transformed primitives, a solid is defined.

Boundary Representation

Boundary representations (B-Reps) are used by the great majority of current CAD systems (Siemens NX, Catia, Creo, SolidWorks, and others) to express the shapes of solid objects. A boundary representation, as the name suggests, is a set of faces that make up the object's boundary (or outer skin) (Cerrolaza et al. 2018). As seen in Figure 1, "topology” details join the faces together by describing connectivity (Stroud 2006), such as which edges lie on each face, which faces intersecting at each vertex, and so on.

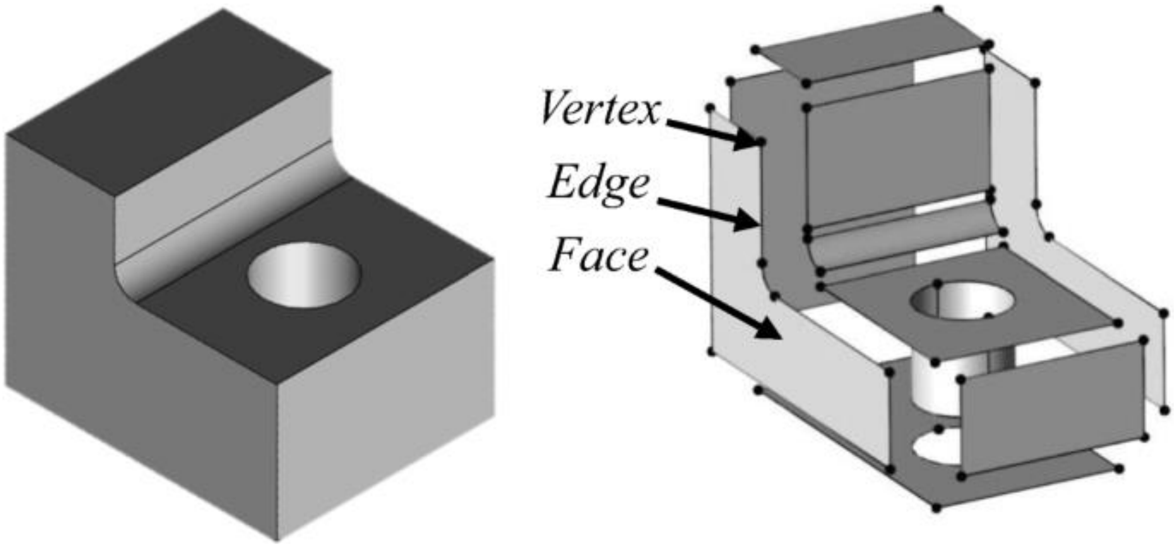


Figure 1: Solid Model (left) and B-rep Model (right) (Kwon et al. 2020)

The topology uses vertices, edges and faces, while the geometry contains points, curves and surfaces. An edge, for example, is a bounded curve region and a face is a bounded surface region (Langnau 2020). Boundary representation is more versatile and provides a much richer range of operations compared to CSG representation, which uses only primitive objects and Boolean operations to integrate them. B-Rep has extrusion, blending, shelling, drafting and other operations that make use of them, in addition to the Boolean operations (Mäntylä 1988). With the accurate mathematical formulas of B-Rep, organic/natural objects are difficult to replicate. That is because B-Rep uses too much computing power when an object has to be visualized, rendered, or animated (Spatial Corp. 2019). The file sizes and reconstruction times increase exponentially when models have large numbers of features because the calculation of the topology on the computer is also exponentially more demanding (Langnau 2020).

Implicit modelling

Implicit modelling is a method for describing, modifying, and representing three-dimensional geometry. Unlike meshes and B-Reps, geometry is described by equations rather than a network of vertices, edges, and faces (Reitz 2019). A mathematical implicit function returns negative function values of any point in the 3D space if that point lays within the boundary of the solid, positive values are outside and any point with the function value of zero is on the boundary (Figure 2) (Langnau 2020).

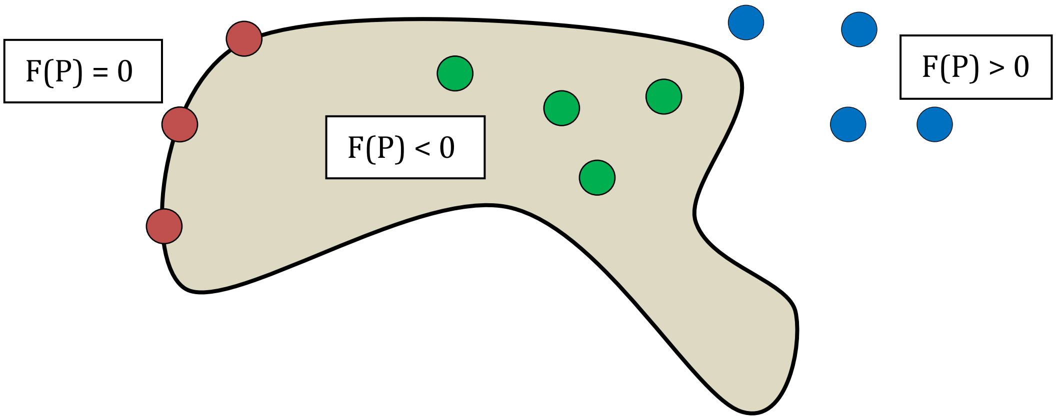


Figure 2: Simplified visualization of the mathematical implicit function terms (created by the author)

Consequently, deciding whether a point is inside or outside is very straightforward. In addition to this positive/negative property, the function value often provides additional detail, such as a measurement of the distance between point P and the boundary of the solid. So, the magnitude of the function can tell how far outside (or within) the point is located, and the sign of function tells whether points are inside or outside the object (Allen 2021). Since implicit models are not discretized like meshes and B-Reps, which do not always catch continuity exactly, they are much easier to compute and preserve their pure shape (Reitz 2019). Mesh geometry, for example, is a faceted reflection of the real shape, independent of its resolution as can be seen in the following Figure 3 (Allen 2021).

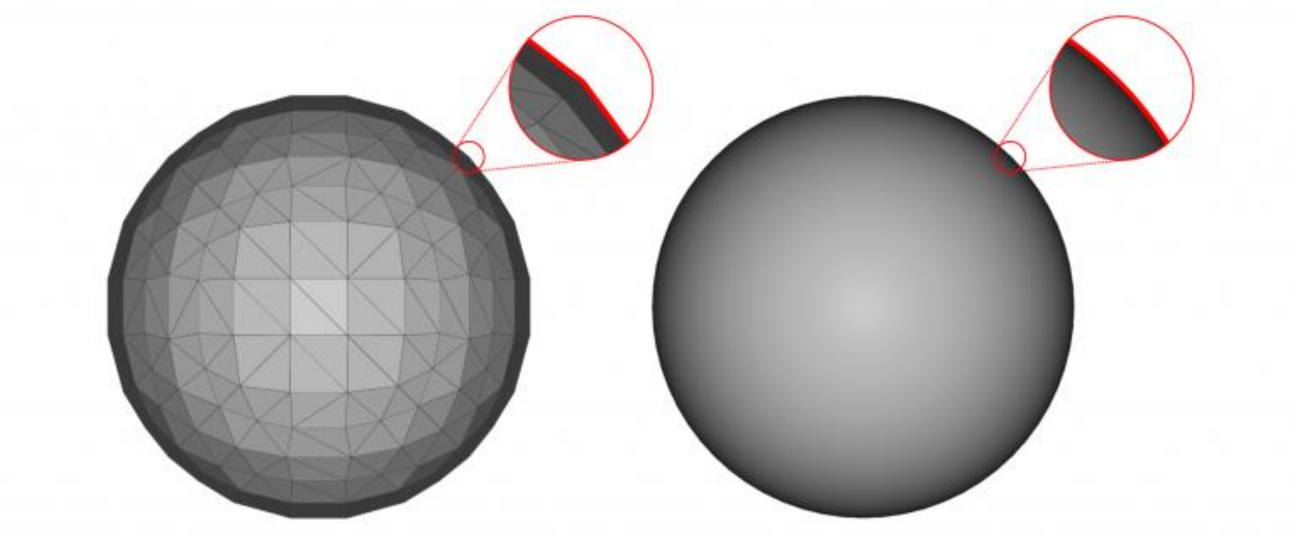


Figure 3: A mesh representation compared to an implicit representation of a sphere (Reitz 2019).

The sphere's mesh face count is deliberately low in this example to highlight the discretization. The file size would increase especially with the mesh face count dramatically expanded to reflect the sphere more correctly. Implicit geometry, in addition to being much quicker to compute, often results in very lightweight files since only a small amount of data is needed.

3.2.2 nTopology as a CAD tool

It is useful to look at the explicit modelling of conventional CAD tools and the emergence of additive manufacturing and its 3D ramifications of modelling, separately to appreciate the significance, capabilities, and technology of nTopology. The importance of nTopology is linked to the convergence of the two.

One difficulty is that, as previously discussed, 3D modelling CAD implementations in general track geometry to directly describe solid boundaries. They specifically grab where the surfaces are for that in space, in XYZ coordinates (Deng and To 2020). A solid, for example, is described as a sealed volume. Explicit 3D modelling is advantageous because it is fast, precise, and could be recreated and regenerated using all its features and parameters when working with simple geometries. On the other hand, it has the drawback of capturing any single piece of geometry in space as geometries become more complex (Langnau 2020). Which means that it contains a lot of data by default. As a result, models grow to be very large very quickly, causing performance issues (Spatial Corp. 2019).

The other concern is that the industry has acknowledged the importance of using additive manufacturing to liberate engineers from manufacturing constraints. As current CAD systems presume that the object's interior is homogeneous (B-Rep), in which case the object's boundary alone provides sufficient detail to completely characterize the object (Allen 2021). This assumption is not valid anymore when it comes to AM. As it is possible to produce a component with holes inside that would be impossible to make using conventional manufacturing methods such as machining. It is, however, achievable with 3D printing. The use of lattices is a new frontier in AM (Reitz 2019). Over the course of the volume, the lattice's parametric traits and characteristics may be modified. Changing the density, for example, changing structures and allowing the spacing to get wider. The structural stiffness of a component can be managed to satisfy very explicit and very precise engineering criteria by having that difference vary over distance. Since material properties can be varied, it has a lot of tools to solve engineering problems. Another example is increasing the porosity of a solid piece of material from bottom to top (Guo et al. 2019).

The difficulty is that since there is much geometry in a small space, capturing lattice structure in explicit modelling becomes a heavyweight model. This is visualized in the following Figure 4 which represents the difference between explicit modelling (B-Rep) and nTopology's implicit modelling approach on a standard strut lattice structure.

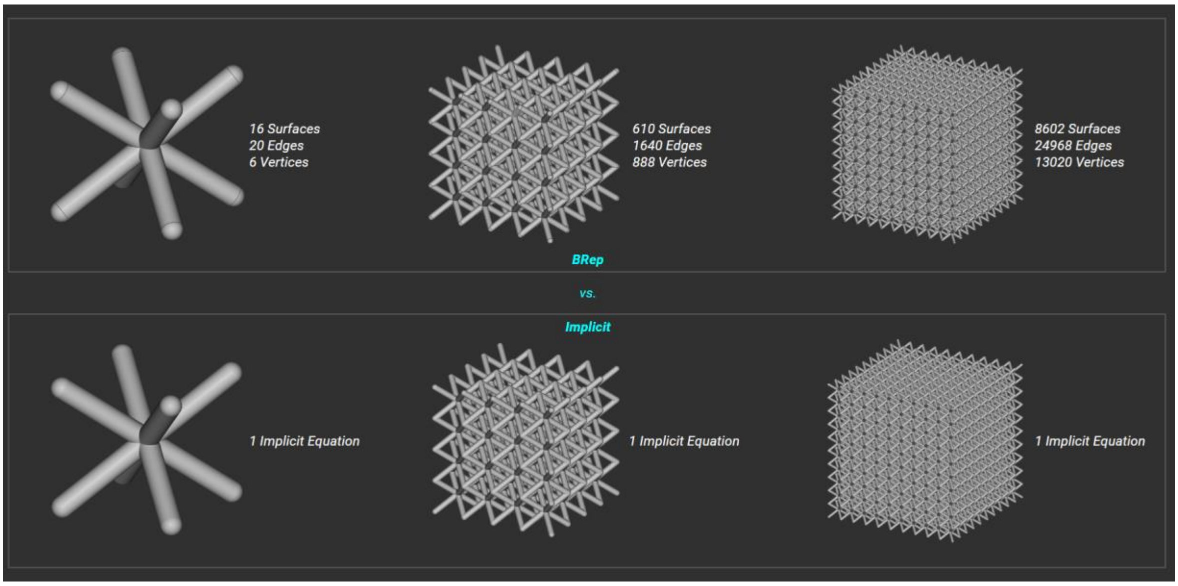


Figure 4: Illustration of the difference between traditional BRep and nTopology's implicit modelling (McGuire 2021)

The geometry of nTopology's Implicit representation is determined by a single volumetric equation that specifies where the object is and is not, whereas the framework in the traditional approach must handle the presence and placement of all geometric subcomponents such as surfaces, edges, and vertices in standard boundary representations (McGuire 2021). It is not inherently complicated geometrically, but it is simpler to describe them using equations, which is essentially what implicit modelling is. However, with explicit modelling and its intersection with AM, as well as the way engineers are working with lattice systems, differing porosity, and varying material properties, explicit modelling easily becomes overloaded (Courter 2019b). As a result, explicit modelling can no longer accurately reflect where AM is headed. That is why implicit modelling collects the mathematical equations that describe certain spatial positions rather than the spatial position of a piece of geometry anywhere in the model. The models are smaller and lighter than the originals, but they still catch every detail (Allen 2021). Implicit modelling, in general, is advantageous when working with AM as a next-generation manufacturing process. That is just what nTopology provides. nTopology has a lot of features, including the ability to import models from explicit modelers of standard CAD applications. It also involves a number of simulations, as well as the ability to describe lattice structures and material porosity. Different inputs, such as simulation outcomes, may be used to drive these lattice and porosity concepts in a component.

3.3 Computer Aided Engineering

Computer-aided engineering (CAE) has equally high importance and is just as fundamental to modern engineering and its users just as the CAD of the previous chapter is. With CAD aiming to support and realize the visualization of a product idea, CAE uses that designed visualization to run different analyses. This chapter presents the underlying idea of CAE and discusses the for this thesis significant approach nTopology has by implementing CAE in their software.

3.3.1 Introduction CAE

CAE stands for Computer-Aided Engineering, and it refers to the whole product engineering process, from modelling to simulated testing of advanced computational algorithms to manufacturing preparation (Raphael and Smith 2003). Any company that uses design tools to produce products has computer-aided engineering as a standard. CAE is a tool that supports engineers in constructing a device and helping the manufacturing process. It can provide physical property tests and models without building a prototype in the first place (Ledermann et al. 2005). Finite Element Analysis (FEA) is possibly the most widely used simulation analysis type in CAE. FEA is also known as Finite Element Method (FEM) which are both the same according to the Altair Universities book: *Practical Aspects of Finite Element Simulations*, as the expression "FEA" is more commonly used in industry, whereas "FEM" is more commonly used at universities (Altair University 2014). The industry is often driven by the popular saying “time is money”. Conventionally, it takes up to several days, if not weeks, to create a physical prototype while running simulations with CAE methods requires only a fraction of that time. CAE addresses not only the time-saving aspect but also creates an improved product. With a great variety of applications and vast designs possible, the CAE software can be used in many different areas as (SimScale 2021) describes on their website e.g. the following:

- fluid flow
- mass and thermal distribution
- fluid-solid interaction
- static or dynamic analysis
- stress analysis on parts and assemblies

- conjugate heat transfer
- conduction
- convection

The total development period can be significantly shortened by using the benefits of these engineering simulations (Chang 2016). Typically, the CAE workflow starts with a CAD geometry which is simulated after materials, forces and constraints have been added. With the results of this simulation, the engineers and designers can adjust specifications or the geometry of the model to improve the tested part in case the requirements were not met. In case of change, the simulation runs again and the process is repeated until all the product's specifications have been achieved.

Finite Element Analysis

Finite element analysis (FEA) is a computer-based simulation and analysis technique for engineering products and structures. FEA is a powerful and complex engineering modelling approach. Its simulations are of continuous field systems subject to external forces, in which a variable, or a set of dependent variables, is represented by a set of detailed mathematical equations (Thilmany 2002). Engineers often use FEM to determine if a product's structure will survive the loading and atmosphere to which it is exposed. Furthermore, the approach can be used in both, structures where the overall behavior is analyzed along with stresses and displacement, and in complex optimization problems, where the aim is to find the best design for the given premises (Eriksson 2003). It, therefore, offers many benefits, if used correctly (Szabo and Babuška 1991). Below are some of the most common benefits:

• increased product efficiency and cost

• reduced development time

• removal or reduction of testing

• first-time achievement of needed quality

• improved security

• compliance with construction codes

• improved knowledge for engineering decision making

• greater comprehension of components enabling more reasonable design

It is important to note, however, that all FEA models and their solutions are approximate. Understanding the behavior of the device, the principles, and the constraints input of the model by the consumer in the first place are all critical to their accuracy and validity (Sharma 2017).

FEA can be divided into the three main phases of pre-processing, solution and post-processing (Figure 6). The first and very important phase is the pre-processing phase because it is often the most work-intensive part of the FEA.

Pre-processing

The discretization of the solid model is the first step in this phase. The 1D, 2D, or 3-dimensional body is subdivided into a set of small pieces known as elements. A mesh is a set of all the elements (Logan 2012). Different element types are used in different use cases and the most basic ones are being illustrated in Figure 5.

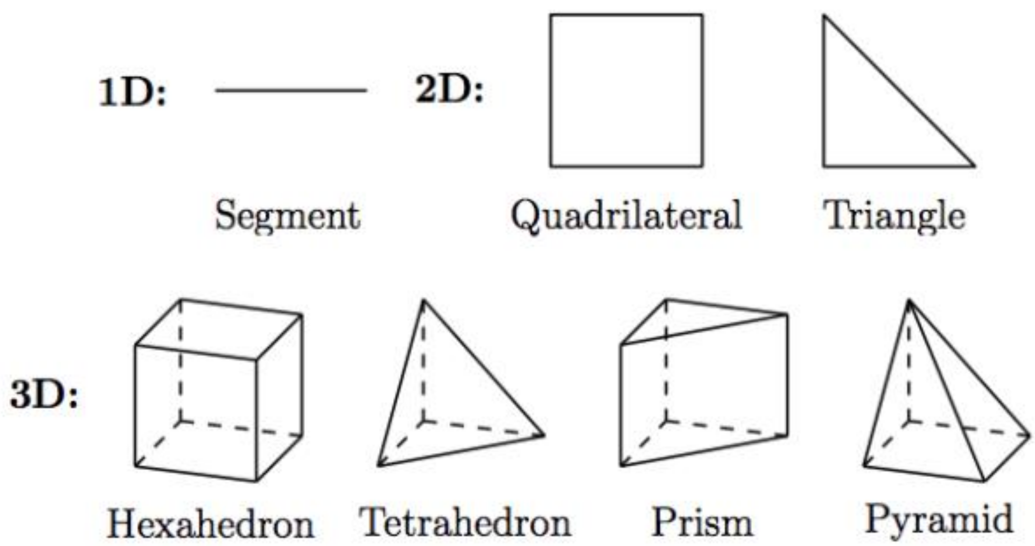


Figure 5: Illustration of basic 1D, 2D and 3D elements (Fuentes et al. 2015) - edited by author

The amount and type of elements must be chosen adequately because if the mesh's geometry and size immediately affect the computing time, computer storage requirements, and the accuracy of the numerical results (Reddy 2019).

Once the meshing is completed the materials design must be defined, since the capability to endure external force depends strongly on the used material. This step is being followed by the last preprocessing step, which is the application of boundary conditions. A constrain is needed in order to prevent the component from moving around as well as further boundary conditions that determine the component's external forces, as deflection does not occur without them (Gokhale 2008).

Solver

After the pre-processing, and with that the completion of the component preparation, is done the FEA runs its solver. This program will run and solve the system of equations. This will usually either happen directly or iterative, depending on the type of problem (Benzley et al. 1995).

Post-processing

Once the scheme of equations has been solved, the desired parameters can be computed and the results visually presented in the form of curves, deformed geometry, maps, or color images. From this point on the data must be interpreted as displacements provide knowledge about the component's geometric deflections, whereas the mechanical durability of the component is determined by the stress (Gokhale 2008). It often happens that the presented results are not satisfactory on the first try. That means that the analysis is often run multiple times and the design, or the parameters being adjusted each time until the part is able to withstand the stresses (Logan 2012).

The whole process from pre- to post-processing of FEA is visualized in Figure 6 to summarize and support the understanding of the FEA process and its phases.

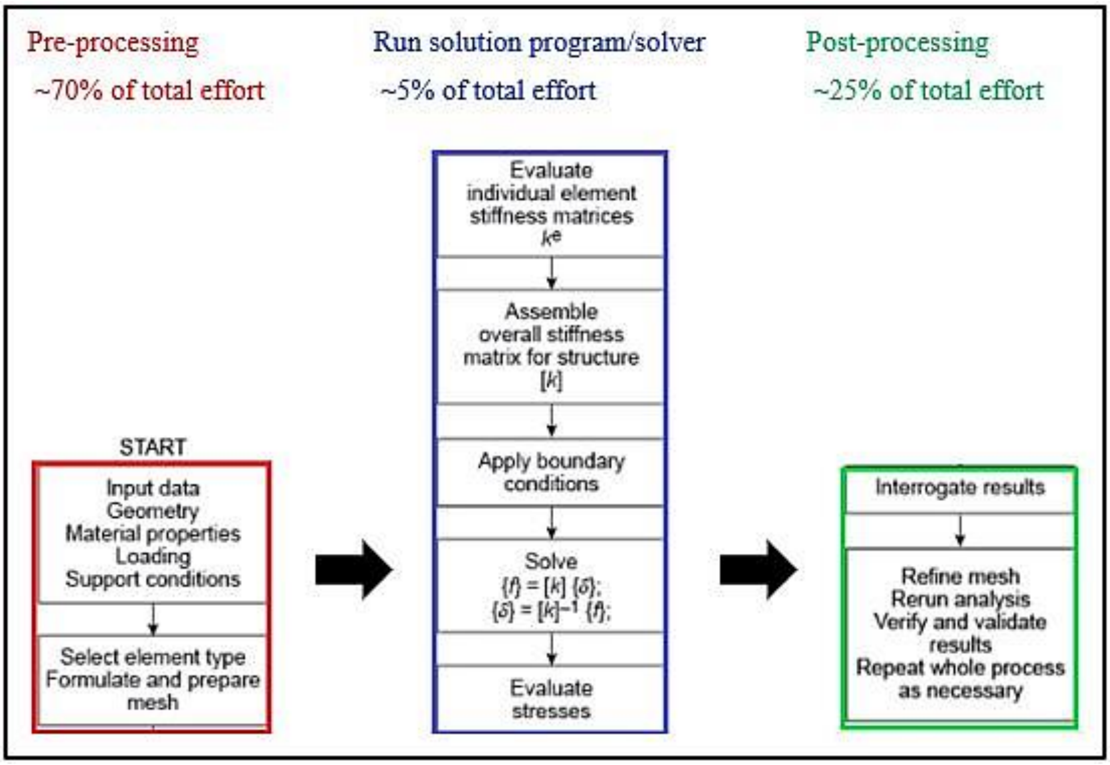


Figure 6: FEA process overview for structural simulation (The Open University 2020) – edited by author

The given percentages in Figure 6 of total effort put into the FEA represent the approximate effort that is put into an FEA and is an estimation by (The Open University 2020).

3.3.2 nTopology as a CAE tool

When diving into and discovering the nTopology software and its possibilities, there are some principles that need to be looked at to understand what nTopology does. It approaches generative design and engineering differently which separates them from other software.

In general, generative design can be described as a method for rapidly developing products with extremely high-performance specifications that are too difficult for the conventional design process (Shea et al. 2005). Designers or engineers enter design expectations, as well as criteria like performance or spatial specifications, materials, manufacturing processes, and cost limits into generative design software (Autodesk Inc. 2020). The software autonomously generates optimal model alternatives by exploring all possible scenarios of a solution by the series of given criteria (PTC 2021).

nTopology (nTopology 2021) defines three main pillars that differentiate their software and approach from others, these are:

Unbreakable geometry

As nTopology uses an implicit modelling approach, as explained previously in section 3.2, it uses mathematical equations instead of a surface-based representation to create volumes. That allows unlimited complexity and never-failing designs, as topology issues often lead to representational design failure or error with explicit modelling software.

Field driven design

This approach uses data points in space to influence the designs. Whether it is a distance from one point to another or simulation data representing the pressure acting on a surface area or computational fluid dynamic, also known as CFD, analysis showing the fluid flow for aero- or hydrodynamics. nTopology introduces simulation to its platform as well as manufacturing knowledge to the initial design process. That means that it is not only used as a verification tool.

Reusable/repeatable workflows/processes

Processes are created and not only single designs when using nTopology. The designer has absolute full definition control throughout the workflow in its creation. A workflow is customized in a way that it can be reused and applied on any file, which allows a high level of efficiency.

In other words, the way nTopology operates is performance-driven. As results are determined by real physics, due to the fact that it is capable of processing and perceiving more data than just geometry. It drives the geometry to generate, inspect, and verify the object for manufacturing processes, whether it is by material, thermal simulation, or analytical results. As simulations play a key role in designing for engineering, nTopology inputs external simulation results to drive the geometry, uses internal tools or export its data for other solvers. For example, when using the lattice modeling options of ordered, stochastic, and TPMS unit cells in order to change the lattice properties of imported simulation results or test data (Figure 7).

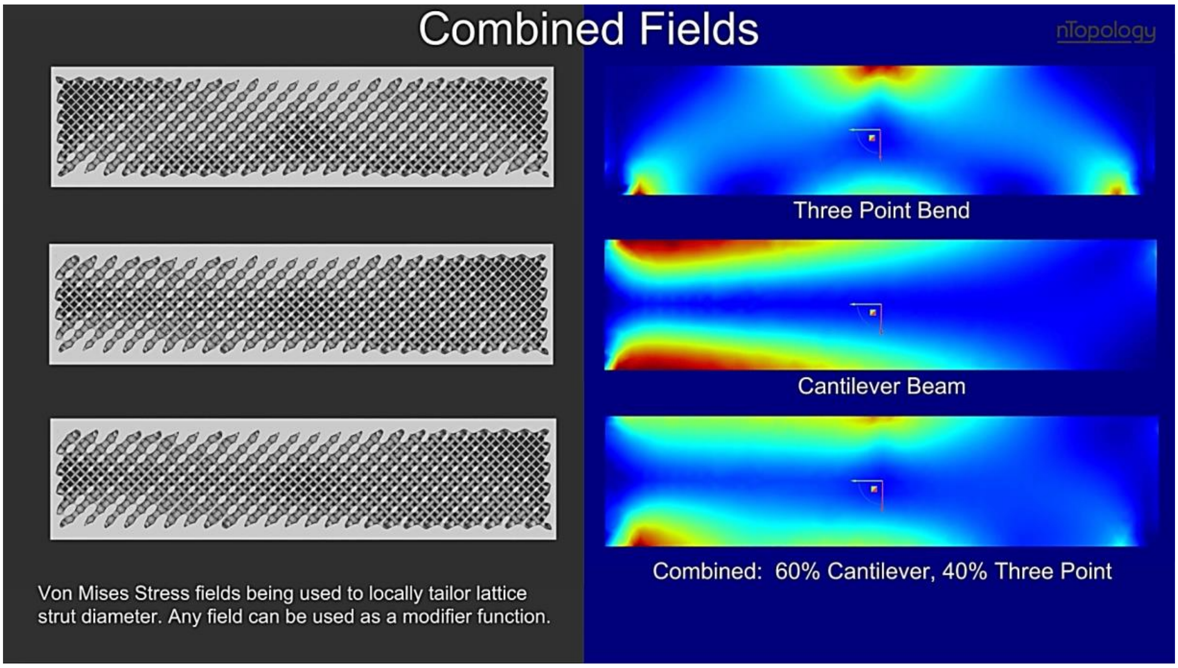


Figure 7: Illustration of possible stress map usage in nTopology (Courter 2019a)

Multiple simulation results can be imported and converted into stress maps. These can then be applied on the part in a function to generate material only in locations where it is needed. The simulation tools within nTopology offer great additional variety. As it is possible to run static, modal, and buckling structural analyses, as well as steady-state, transient, and non-linear thermal simulations, and lattice unit cell homogenization. Nevertheless, data can also be exported for further FEA or CFD simulations in case other solvers are preferred. Another point that makes nTopology so special, especially when looking at topology optimization as the main generative design tool, is its automated geometry reconstruction, smoothening tools, the range of post-optimization options as well as the overhang constraint for additive manufacturing their software offers.

3.4 Design for Additive Manufacturing

In this thesis, a case study will be conducted by performing the methods of topology optimization and light-weighting on a jet engine bracket from GE and the bottom part of a plummer block by using nTopology's Design for Additive Manufacturing (DfAM) features. This chapter will present these two methods in brief detail as well as DfAM itself. The complexities of DfAM are much greater than what will be discussed, however, that is beyond the scope of this thesis.

3.4.1 Introduction DfAM

Design for Additive Manufacturing is the secret to success and realizing the benefits of additive manufacturing. DfAM necessitates some design considerations when modelling for AM to expand the use of AM's resources in a cost-effective and practical manner. Since the final part is constructed with a layer-by-layer material deposition, it distinguishes AM from traditional manufacturing methods such as Subtractive and Formative. Consequently, there is a significant knowledge difference between a designer for traditional manufacturing and a designer for additive manufacturing (Tharanath 2020). Nevertheless, DfAM refers to a group of methodologies and tools that assist designers in taking into account the unique characteristics of additive manufacturing (technological, geometrical, pre/post-processing, etc.) during the design process (Laverne et al. 2014). It produces topologically optimized structures, improved strength-to-weight ratios, lattice structures that save material and weight, and conformal cooling channels (Kianian 2019).

In AM when printing structures with overhangs above 45 degrees, support structures are needed (Figure 8). To eliminate the need for external supports during the 3D printing process, self-supporting structures are used to reduce the number of support structures that must be removed during the print's post-processing (Jiang et al. 2018).

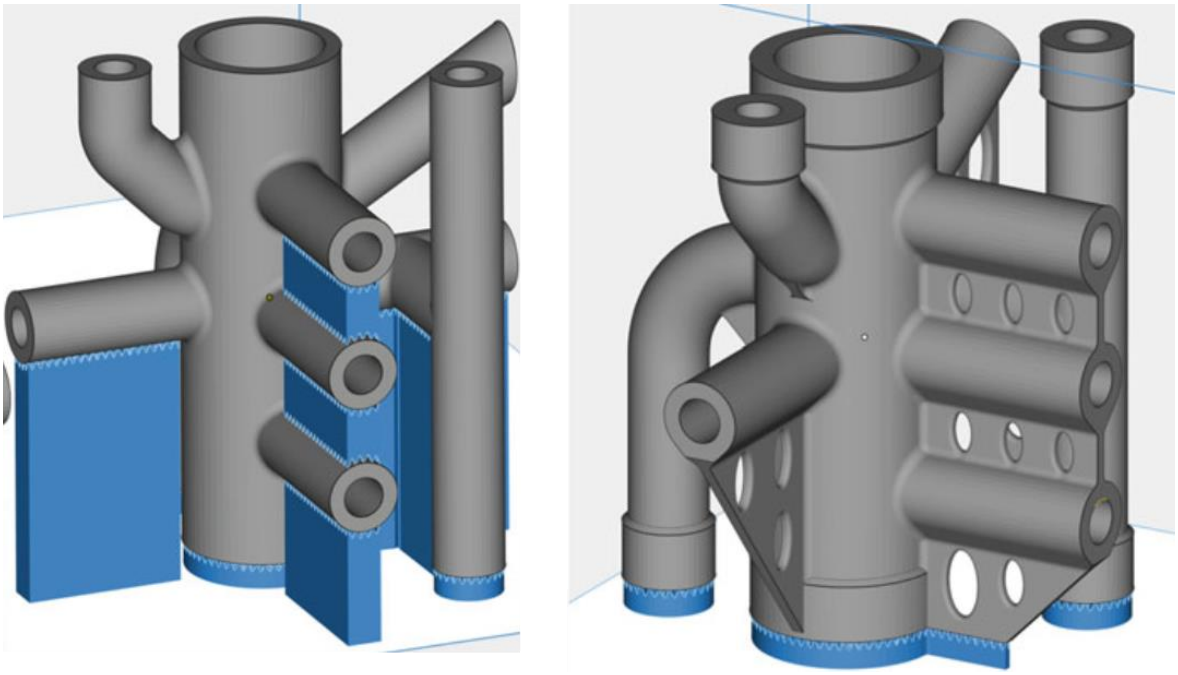


Figure 8: Support material required (left) and optimized (right) (Diegel et al. 2020) – edited by author

This structural self-support occurs when the print item is placed perpendicular to the printing direction and is less than 45 degrees inclined (Langelaar 2016). When support material is used less, time spent post-processing will be reduced as well. Support structures can help enhance print quality, but the approach must ensure that they are only employed where they are needed. In the case of the powder bed fusion metal printing process, the support material can be required to support dissipation of heat, part balance or printability in general (Jiang et al. 2018).

3.4.2 Topology Optimization

One of the most significant benefits of additive manufacturing is that it allows for the innovation of intricate and complex geometries (Bikas et al. 2016). Topology optimization uses mathematics to addresses a basic engineering question: Where should material be placed within a design space and where should material be excluded that is not serving a useful purpose to achieve the best structural performance? (Sigmund and Maute 2013) and (Bendsøe and Sigmund 2013). Most topology optimizations follow a general workflow of six steps as (Diegel et al. 2020) present in their book:

1. **Simplify the model** - Ideally, a comparatively large 'block' of material from which the software can optimize. The more 'design space' for topology optimization applications that can be provided, the better.

2. **Apply an appropriate material to the model** - The amount of material used is reduced dramatically as topology optimization is used, allowing for the use of a more costly and/or stronger material than the original.

3. **Divide the model** – The goal is to divide the model between areas that the software can impact and areas that the software should not affect. The greatest possible design space is the aim.

4. **Setup the scenarios** – All the forces that apply to the model must be set up for optimization.

5. **Perform the topology optimization** – once everything is set up, the software runs the optimization on the model.

6. **Convert to results smooth the model** – the topology optimization results must now be converted into a smooth and printable model.

Topology optimization can be used for any kind of manufacturing process. However, to utilize its full potential AM is the go-to technology as traditional manufacturing processes become extremely expensive or cannot possibly manufacture the optimized parts as the optimized designs become very complex (Tharanath 2020).

3.4.3 Light weighting

The topic of lightweight design is one of the most prominent innovation drivers and technology developments, especially in the automotive industry (Kaspar and Vielhaber 2017) and for aerospace applications as the reduction of energy consumption is the targeted goal. Lighter designs caught the attention of many other industries as well for the fact that they save on raw material volumes and/or use replacement materials, are more cost-effective, preserve or increase target strength, and can improve internal cooling behavior (Waterman 2015). The tradeoff between stiffness and strength to weight ratio is extremely appealing and implemented on lightweight structures (Vannutelli 2017). Complex lightweight part designs include applications such as open cellular foams, strut lattice structures, honeycomb structures and many more. The vast majority of them are initially inspired by nature and due to their geometrical complexity not able to be manufactured with conventional manufacturing technologies (Schaedler and Carter 2016). This supports the fundamental AM design concept and encourages a designer to maximize design for functionality based on technical specifications rather than manufacturing capability constraints (Milewski 2017).

Cellular structures

An interconnected solid scaffold composition characterizes cellular structures (Carneiro et al. 2021). “The design and manufacturing of cellular structures are striving by the desire to save the expensive functional materials, build time, consumed energy, and offer high performance, high stiffness/weight ratio, excellent energy absorption features, low heat conductivity, significant acoustic and thermal insulation properties to aerospace structures, and automotive parts and medical products”, as (Nazir et al. 2019) states in their study. There are various different designs of cellular structures but only a few will be mentioned in this thesis as that can be a research topic for itself.

An open-cell structure is one that only has solid edges (Figure 9) and (Figure 12), while a closed-cell structure has both solid edges and faces (Figure 10).

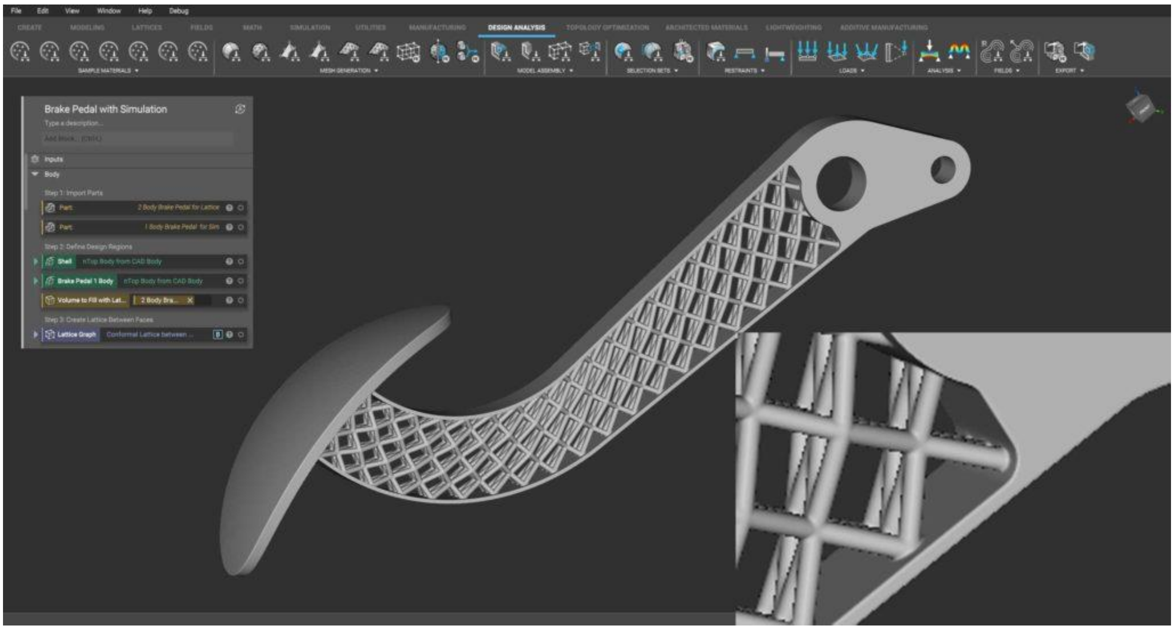


Figure 9: Strut based lattice structure applied on a breaking paddle in nTopology (Engineersrule.com 2019)

Lattice structures are efficient and relatively easy to implement and analyze. Further being possibly optimized for each specific part to achieve the engineering goal (Wenjin Tao and Ming C. Leu 2016).

Formular driven lattices are different from the standard (strut-based) ones. One of the most popular designs is the Schoen Gyroid (Figure 10), which is one of the so-called triply periodic minimal surface (TPMS) structures. Topologies developed by mathematical implicit methods are contained in these TPMS structures (Tharanath 2020).

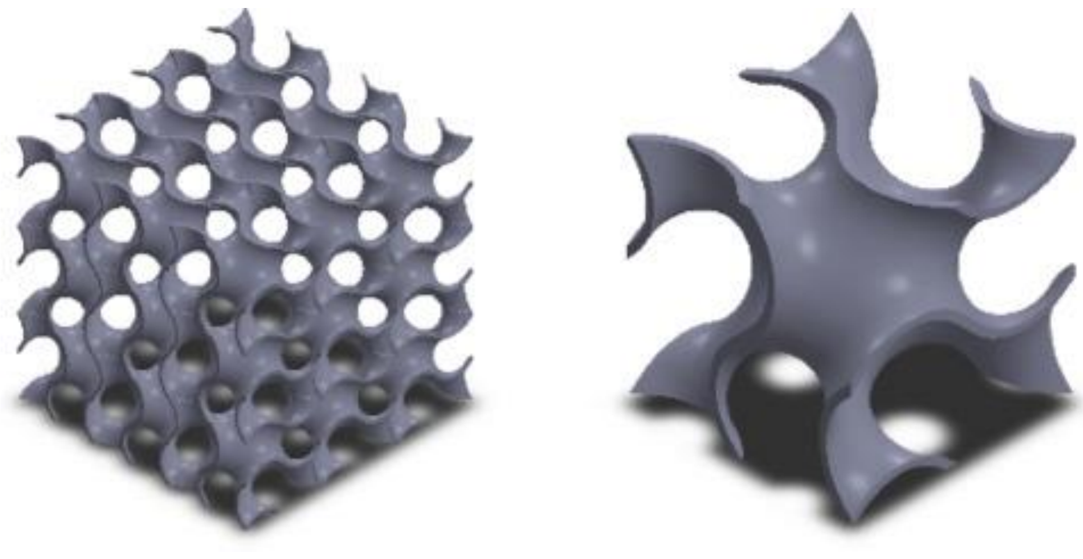


Figure 10: Illustration of a Schoen Gyroid structure and single Schoen Gyroid unit cell (Abueidda et al. 2019)

These formula-driven lattices are structures with minimal surfaced unit cells that are essential in additive manufacturing not only because of their design but also because they are naturally self-supporting (Yang et al. 2018). That means that when they are printed, they do not need additional support structures to support the build process. That reduces material cost as well as reducing or even eliminating the need for post-processing on the printed part to remove those support materials. Also, the density of these complex formula-driven lattices can be varied. A small assortment of different lattice structures is presented in the following Figure 11.

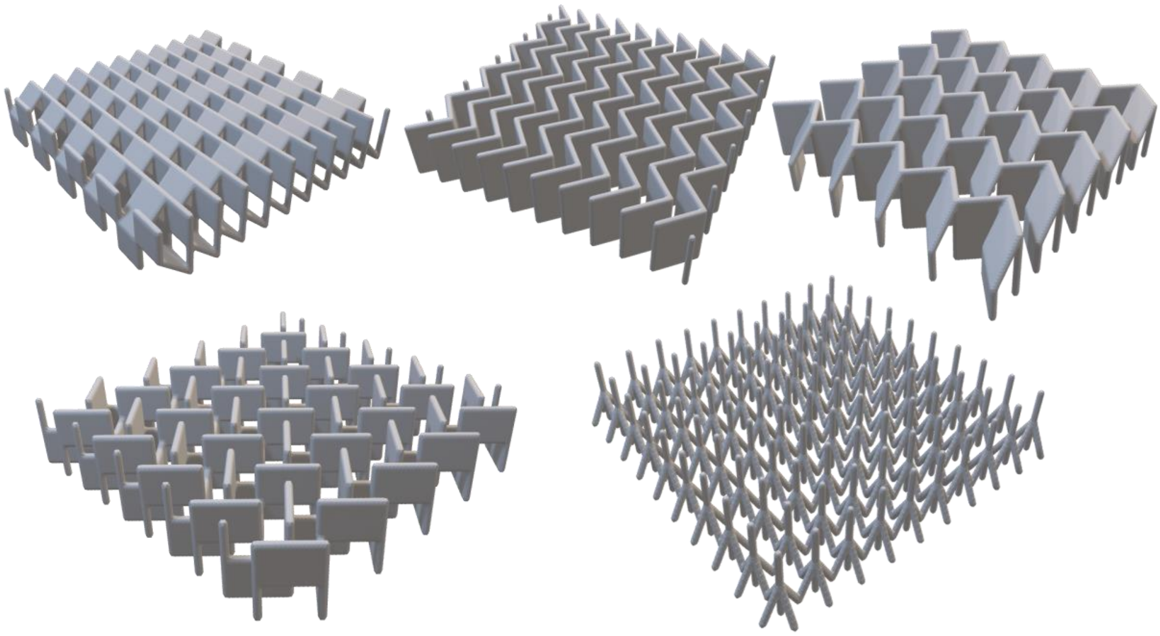


Figure 11: Different lattice structures (Tharanath 2020)

A stochastic structure or foam (Carneiro et al. 2021) is in this case a beam-based structure, that conforms to or follows the shape of the model (Figure 12). Allowing a frame to be built on top of the shape of a foam structure to be built within the shape. The density, complexity, and number of lattices that can be constructed are the most important aspects of them. In the medical field, for example, they are widely used (Chen and Li 2005) and have found a major use case of these stochastic structures in the medical industry.

Figure 12: A two-element hip replacement with bio-compatible stochastic structure (genysis.cloud 2019).

In the medical industry for example, the aim is to create an implant that can be grafted onto the bone or used for noise reduction scenarios. Hundreds of thousands of extremely detailed struts can thus be regenerated, visualized, and their mass properties measured, among other things (Aimar et al. 2019). In the past years, research has been conducted into the cellular structural geometry that is needed to attain specific equivalent properties for critical applications such as prosthesis creation, where high specific strength must be obtained with low stiffness modulus to allow alignment between the implant assembly and the hard tissue surrounding it, such as bone (Erica Liverani et al. 2017).

4 Methodology

As this work is meant to focus on the possibilities nTopology offers to design additive manufacturing, several stages have been conducted to meet the thesis' aimed objectives.

- Literature Review

Firstly, a literature review has been carried out with the purpose of collecting background information and gain knowledge about the connected areas considering this thesis' work. The conducted review focused on becoming familiar with additive manufacturing, its technologies and its designing process as well as generating a basic understanding of computer-aided engineering and computer-aided designing with an additional view on the nTopology software as it has been mentioned before in the introduction.

- Choosing suitable geometry and load cases

Two case studies were conducted for the use of the nTopology software. One focusing on topology optimization, the other focusing on a light-weighting operation. Both times a CAD model was inserted into the nTopology software, which was extracted from grabcad.com. GrabCAD is an online platform that provides the download and upload of CAD files of its library (GrabCAD 2021). In the case of topology optimization, the jet engine bracket design from GE was used. Due to an official designing challenge from 2013, GE and GrabCAD cooperated and provided the data file and a spread sheet of the load cases free for the public (https://grabcad.com/challenges/ge-jet-engine-bracket-challenge). In the case of the light-weighting operation, the bottom half of a plummer block has been used (https://grabcad.com/library/plumber-block-29). The load cases were used from the SNL plummer block housing spread sheet from the company SKF (SKF 2010).

- FEM simulation and Topology Optimization

The GE bracket has undergone a static analysis prior to the topology optimizations. The optimizations contained different values for the nTopology overhang constraint for additive manufacturing. The final topology optimized GE brackets then were re-checked and compared using another statical analysis on the optimized parts and the properties of the part.

- Light weighting based on FEM results

The light-weighting was realized using an operation that shells the part and filled the hollow volume with, in this case, a lattice and a gyroid structure. The thickness of the shell and the volume structures were defined by the results of the prior executed static analysis.

5 Results

5.1 Introduction

As the manufacturing industry develops, computer-aided designing and engineering programs often fail to realize possible designs of the advanced manufacturing possibilities. With nTopology there is for a few years now a continuously updating, evolutionary software on the market to give designers and engineers the tool and the freedom to explore capabilities of designing that have not been possible before. It can produce any geometry, no matter how complex, to satisfy the technical demands of high-performance devices. To explore the potential of the nTopology software, two case studies have been conducted considering current industrial standards. The first case study looked at, in the AM community the very popular and important, topology optimization and its special feature of adding additive manufacturing constraints. In the second case study, a light-weighting operation was executed with the addition of using FEA results to match possible technical requirements.

5.2 Study 1: Topology Optimization

It is only fair to mention that topology optimization, in general, can be seen as a light-weighting process as well but is especially with the overhang constraint for additive manufacturing, that nTopology uses, interesting enough to be mentioned on its own. Another important note to be made is that the six different cases of this first study were not optimized nor was it the goal to find the best possible optimization. This thesis focuses only on the use of the software and not on the best possible numerical result for a specific part. The different angles of each case were chosen rather randomly and were not chosen to present the best part possible concerning its use case.

1. Workflow, Set up and load cases

As the very first step, the GE jet engine bracket file from GrabCAD was imported into the nTopology software. The projected body was then converted into an implicit body which made working on the design possible. In the next step the surface areas with special constraints and boundary conditions in this case three, were defined. Before running a finite element analysis or topology optimization, the body had to be meshed (Appendix 1).

The meshing process started with the meshing of the part's surface before this mesh was converted into a volume mesh. The volume mesh was converted into the so-called FE Volume Mesh, which is used as the base for the static analysis. Also, the different surface areas were converted into FE Boundaries (Appendix 1 & 3).

The topology optimization was then conducted once the boundary conditions (load cases) and constraints were added as well as the material.

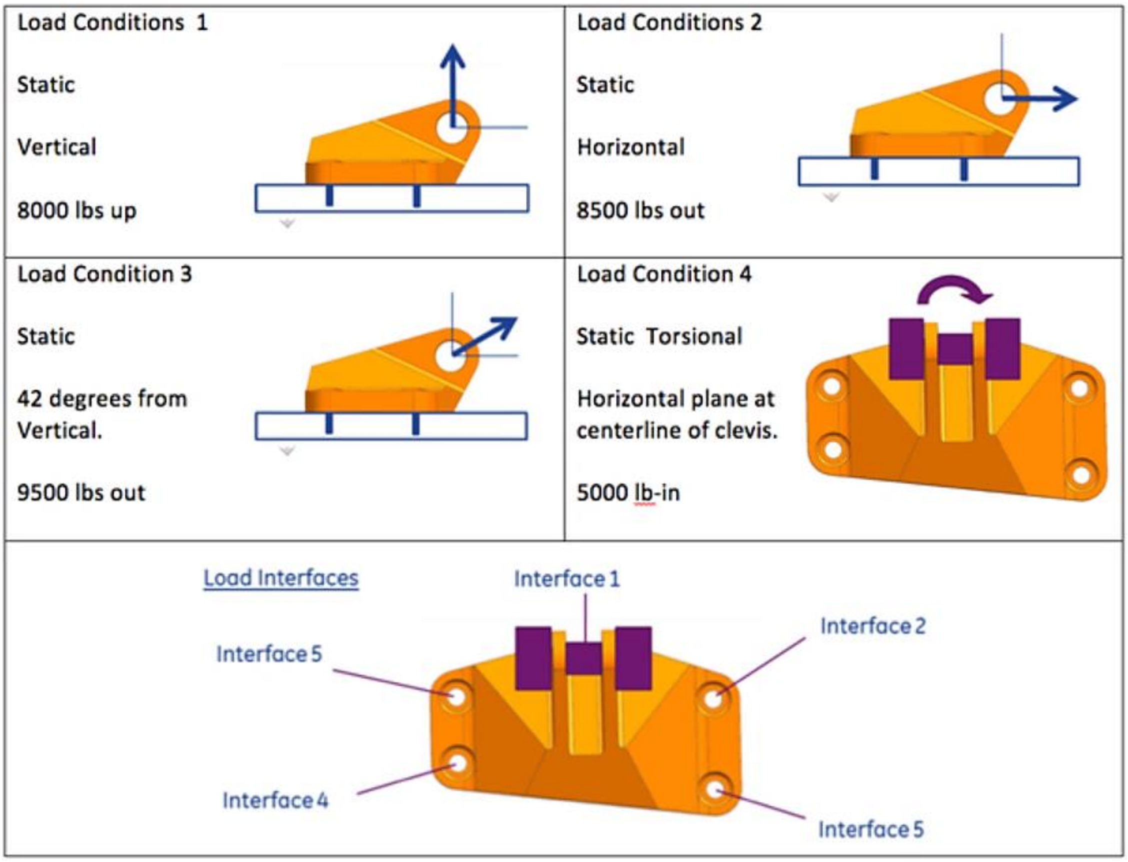


Figure 13: GE jet engine bracket and load conditions (GrabCAD challenge 2021)

On the GE bracket, six different cases were analyzed. As the load cases and material stayed the same, constraints were changed for every topology optimization and analysis.

In the first case, nothing has been changed. Only the load cases and material were applied to provide stress distribution without any topology optimization conducted. That offers a better view and understanding of the changes conducted later (Appendix 3).

In the second case, standard topology optimization was conducted without the addition of the overhang constraint for additive manufacturing. This enabled a base for the later comparison of all cases (Appendix 2).

In the third up to the sixth case, topology optimization was executed with the addition of the AM constraint. These constraints were defined with an angle of 30°, 35°, 40° and 45°. These angles are being measured relative to the building direction and describe the overhang. Additionally, another FE face was created to define the future building surface on which the printer start building the layers up from and to give the software the relation to the given angles (Appendix 4 & 5).

After finishing the pre-processing and running the solver for cases two to six, the topology optimized body was then put into an automatic smoothening operation. After the smoothening process, static analysis was conducted to analyze the changes and results of the topology optimized parts. Also, the part's properties were viewed to see the reduction of the mass savings in regular material and the support material that needs to be added in additive manufacturing in case the printing process demands it in areas that are not self-supporting.

2. Outcome

The comparison of the results of the six different cases of the first study is represented in Table 3. These are different views of the part and its simulation results presented as well as the properties of the parts with part mass, support material mass needed, and the analysis results in the static analysis maximal displacement and maximal stress.

The following Table 2 represents the percentual difference within the six cases, monitoring the mass savings of the body and the savings on mass for the support material.

Table 2: Comparison of part and support material mass for the six cases

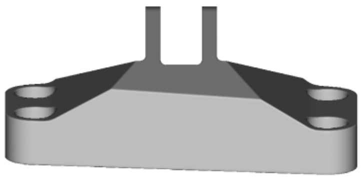
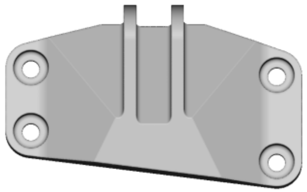
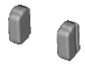
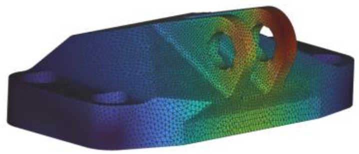
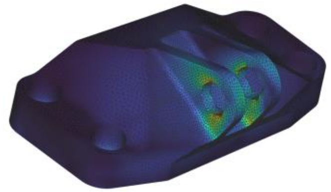
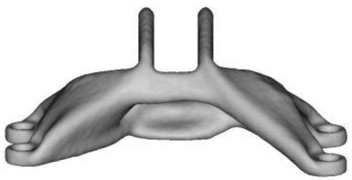
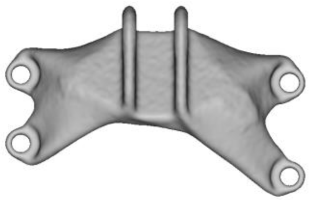
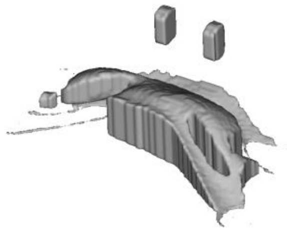
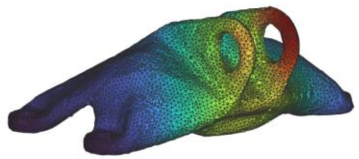
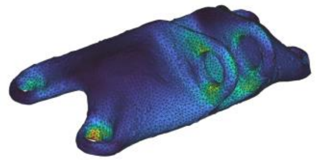
Topology optimized part	Part mass saving compared to the original	Support material mass saving compared to constraint without overhang
Without overhang constraint	69,1% (- 1418.93g)	/ /
With overhang constraint 45°	70.3% (- 1443.57g)	78.9% (- 277.71g)
With overhang constraint 40°	70.4% (- 1445.27g)	84.1% (- 296.02g)
With overhang constraint 35°	70.4% (- 1445.68g)	87.9% (- 309.23g)
With overhang constraint 30°	70.7% (- 1451.03g)	89.6% (- 315,39g)

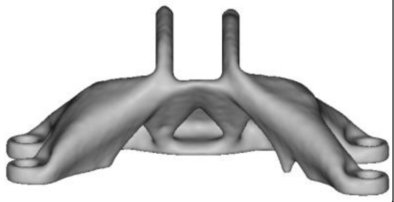
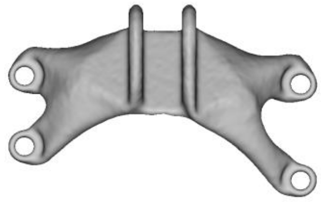
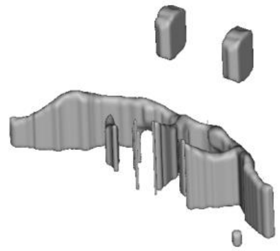
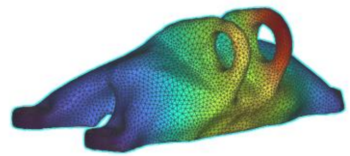
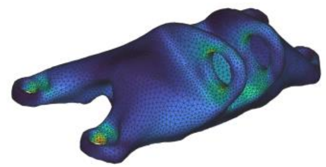
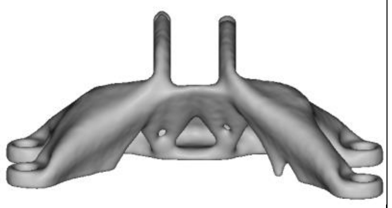
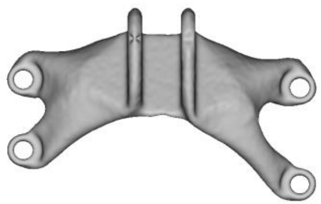
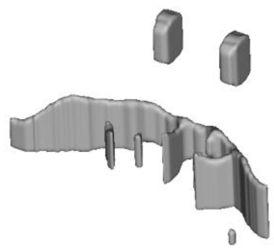
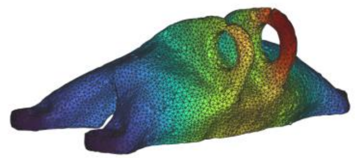
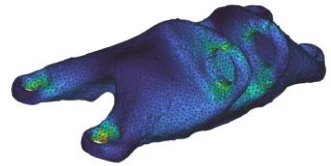
There are major changes to be recognized from the original GE bracket to the optimized GE bracket. The mass of the part itself was reduced in all cases by roughly 70% as a result of the topology optimization. That turned the 2052.38g, rather bulky, original part into an, in the case of the topology optimization with the overhang constrained of 30°, optimized part of 601.35g. With the use of the overhang constraint for additive manufacturing the support material necessary to print the optimized part shrunk from 351.86g needed without the constraint to 36.47 grams of support material with a constraint definition of 30°. That records a saving of almost 90% of support material. That leads to a major reduction of costs and time needed to clear the part from its support material in the post-processing after the printing is done.

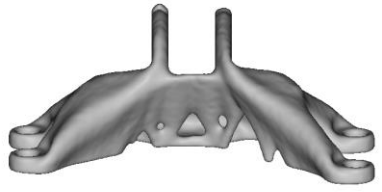
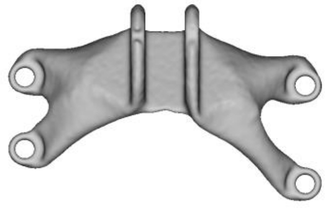
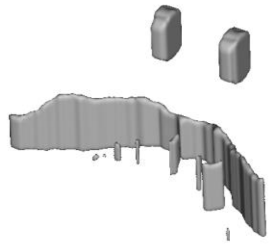
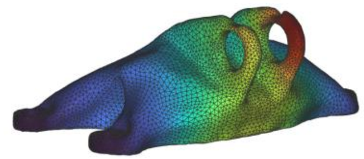
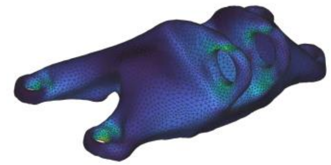
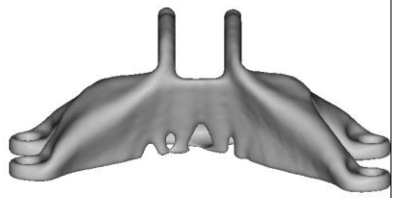
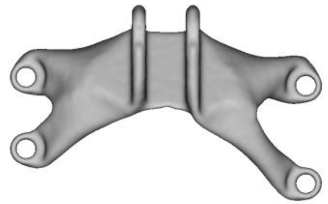
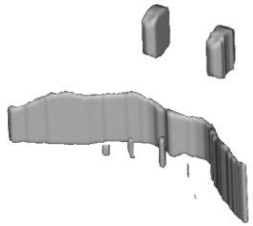
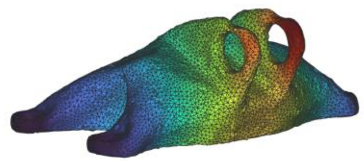
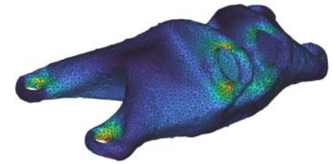
Running a static analysis on the parts of each case allowed the view on the maximum stress and maximum displacement occurring on the part. As the maximum displacement from the original part compared to the optimized parts show, all optimized parts presented a raise in displacement whit the worst-case presenting a gain of almost twice as much displacement from the optimized part to the original. Also, when viewing the maximum stress of the cases, all optimized parts had higher values of maximum stress in their worst areas from 37% – 92% more than the original part.

These recognitions, as the evaluations of these simulations and analysis, were conducted, determine the further processes for the product. As there is no complaint about saving about 70% of the material of the part and up to 90% of supporting material, there must be a closer look taken at the FEA results. It must be decided if the values are within an area where there will occur no issue when the analyzed loads are applied or if there is an issue. The optimization constraints and boundary conditions as well as the part design including the material must be reviewed and changes must be made to create a part that withstands the loads applied in case of an issue or part failure.

Table 3: Overview of the original and topology optimized GE bracket values

Part	**Back View**	**Top View**	**Support Material**	**Static Analysis Displacement**	**Static Analysis Stress**
Original					
	Mass: 2052.38g		Mass: 12.75g	Max. Displacement: 0.380mm	Max. Stress: 0.97MPa
Topology Optimization without AM Constraint					
	Mass: 633.45g		Mass: 351.86g	Max. Displacement: 0.714mm	Max. Stress: 1.33MPa

Topology Optimization with AM Constrain 45°					
	Mass: 608.81g		Mass: 74.15g	Max. Displacement: 0.697mm	Max. Stress: 1.39MPa
Topology Optimization with AM Constraint 40°					
	Mass: 607.11g		Mass: 55.84g	Max. Displacement: 0.706mm	Max. Stress: 1.49MPa

Topology Optimization with AM Constraint 35°					
	Mass: 606.70g		Mass: 42.63g	Max. Displacement: 0.735mm	Max. Stress: 1.86MPa
Topology Optimization with AM Constraint 30°					
	Mass: 601.35g		Mass: 36.47g	Max. Displacement: 0.702mm	Max. Stress: 1.43MPa

5.3 Study 2: Light-weighting

The bottom half of a very basic plummer block (Figure 14) was utilized for light-weighting operations.

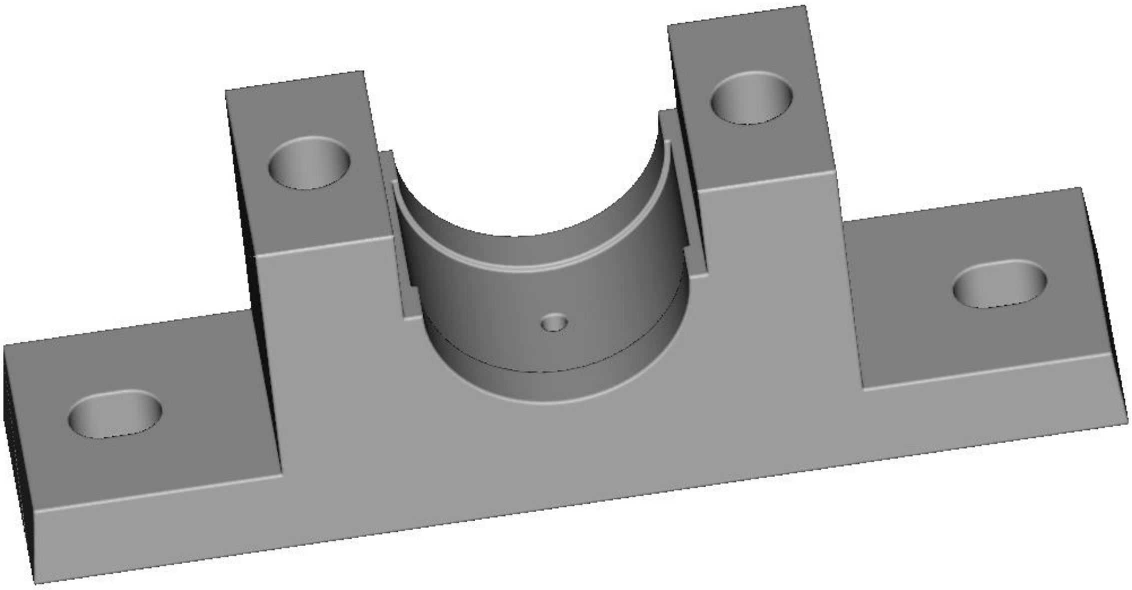


Figure 14: GrabCAD model of the plummer block

After the CAD file from GrabCAD of the plummer block was imported into the nTopology platform, a very efficient light-weighting process was executed.

1. Workflow, Set up and load cases

The GrabCAD file of the bottom part of a plummer block was imported first. This imported part was then transformed into an implicit body to work with it inside nTopology. The important surface area, where the loads will apply later, and the surfaces that are fixed were defined. Before the block was light-weighted it underwent an FEA. To run the static analysis, the plummer block had to be meshed. First, a surface mesh was generated and with that mesh as the base, a volume mesh was then created. To run the analysis the volume mesh was transformed into a FE volume mesh for the static analysis. With the body set up, the constraints and boundary conditions (load cases) were applied to the part for the static analysis with the support of the predefined surfaces.

The plummer block was shelled, and the hollow inner part of the block was filled with a structure. With the results of the static analysis, a stress map was generated. This resulting stress map was inserted into the light-weighting application and caused the generated structure to have variable thickness depending upon high and low-stress areas. This structure was in one case a lattice structure and, in another trial, a gyroid structure.

After the plummer block was light-weighted the mass properties were looked at to compare the original and optimized part and its weight savings. A view of the workflow interface of the light-weighted plummer bracket can be viewed in Appendix 6.

Light weighting of the GE bracket was done as another example.

2. Outcome

The outcome of this study presented a very fast generated solution with a generative approach of using material where it is needed. The results of the static analysis can be seen in the following Figure 15. The darker the color is the less stress is applied in that area. The brighter the color gets the more stress is occurring. It goes from dark blue (least stress) area over to light blue, green, yellow and then red (highest stress) area. Depending on the setup of the result viewer the colors are more or less intense.

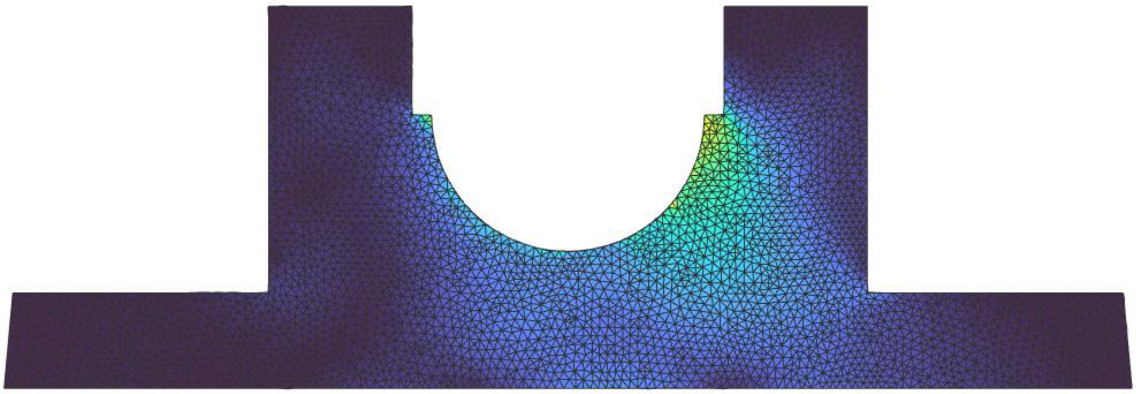


Figure 15: Static analysis results of the plummer block presented as a color map

Figure 15 presents clearly in what areas the stress is high (yellow) and where it is very low (dark blue almost black). Also, the prior generated mesh is visible and can be identified as very small triangles across the part. The numerical values of the FEA result were then transformed into a stress map. This stress map was then inserted into the light-weighting operation as a condition. For visual aid, the following Figures 16 & 17 represent the structural results of this light-weighting process.

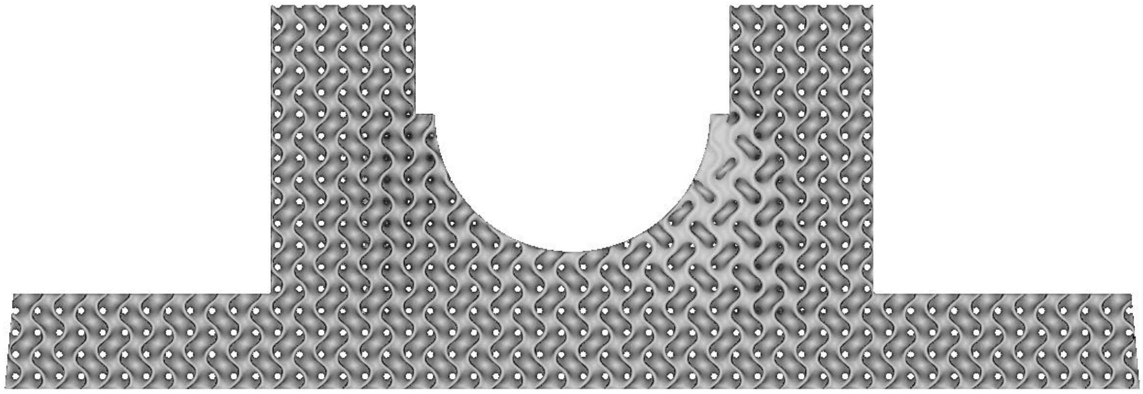


Figure 16: Gyroid structure generated using the stress map of the FEA

In this Figure 16, a gyroid structure was chosen and it is clear to see that in the areas of high stress, which were identified before through the FEA and seen in Figure 15. The outer parts of almost no stress are equally in material, whether the inner area is much denser and the gyroids are even entirely filled with material. How much material or how fine the structure is supposed to be can be defined within the light-weighting operation to create the optimal part for given conditions. Another example but with a lattice structure is presented in Figure 17.

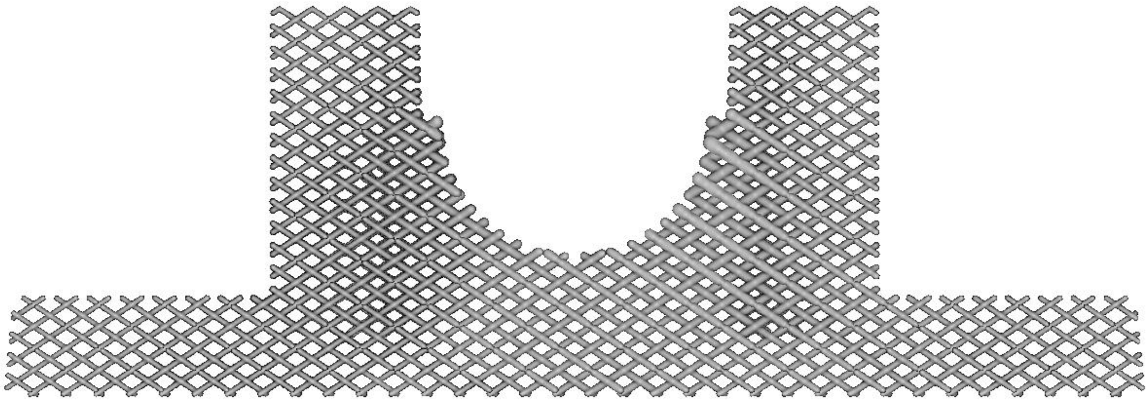


Figure 17: Lattice structure generated using the stress map of the FEA

In this case, a lattice structure was used. The change from the gyroid to the lattice structured part was done in no time inside nTopology with a single adjustment. As everything remains the same, only the structural configuration was changed with a single click of a button by choosing the preferred structure over the other. The results are almost the same. As more material is generated in the areas of higher stress only the structural design has changed.

The final part is presented in Figure 18 and shows the inside of the plummer block with a lattice structure as well as an added shell.

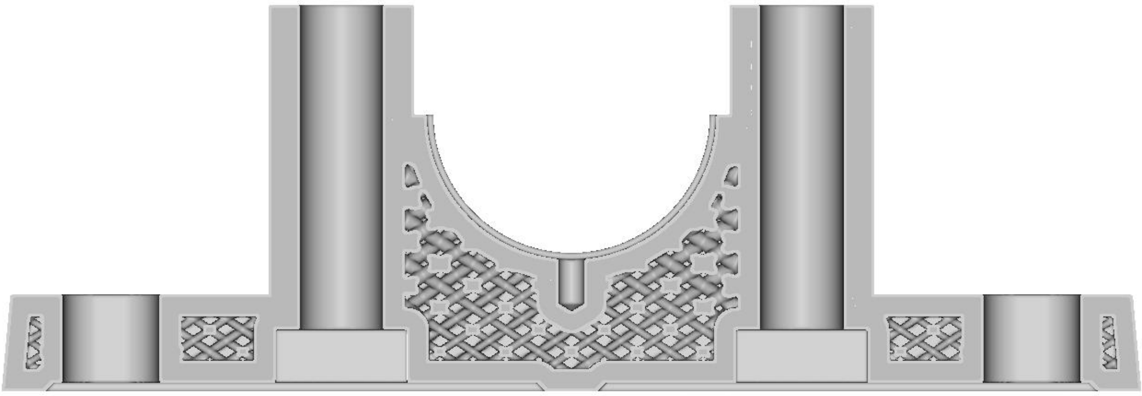


Figure 18: A possible result of the final part after the light-weighting process

As the shell was added the lattice is generated inside the remaining hollow area with a greater amount of material in the high-stress area as before. The thickness of the shell, the change in structure or the thickness of the lattice beams, everything can be accessed and changed individually inside the chosen light-weighting operation of nTopology.

For that case, another FEA could be executed at the end on the light-weighted part for further optimization purposes to check how the change has affected the plummer block.

Another light-weighting example (Figure 19) using the GE Bracket from the topology optimization example has been conducted. The body was also shelled and a gyroid structure was added.

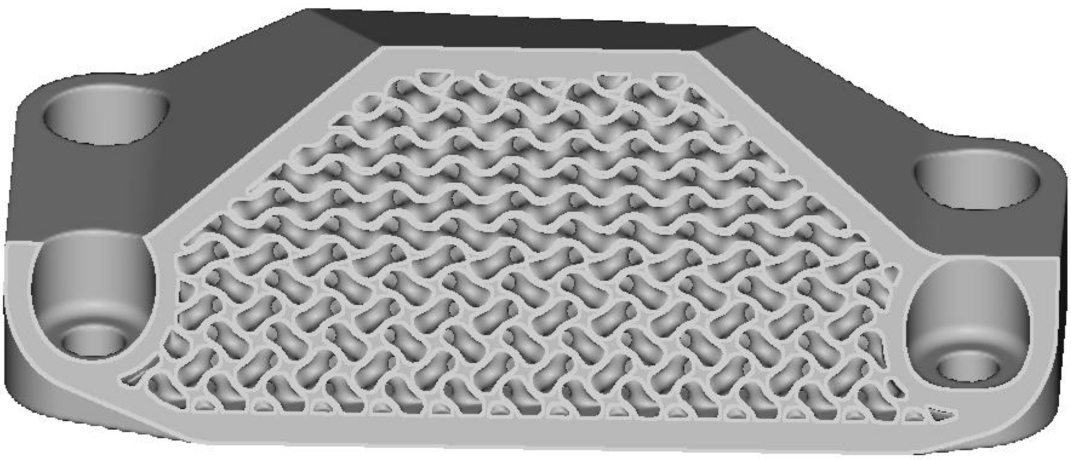


Figure 19: Shelling and gyroid structural light-weighting operation on the GE Bracket

This presents a great variety of possibilities for lightweight parts and components of any kind.

6 Discussion

This section of the thesis work focuses on the discussion and evaluation of the proposed aims and objectives and their obtained results. Also, limitations that occurred along the way of conducting this work will be mentioned.

Aims and Objectives

With respect to the initial aims and set objectives, the main goals have been achieved sufficiently, though not to their fullest potential. Nevertheless, the results provided what was aimed to be accomplished.

Regarding the first objective, this work created a fundamental insight for additive manufacturing and its modelling methods. Designing for additive manufacturing, different additive manufacturing techniques, as well as computer-aided software functions and differences, have been researched and the knowledge of their strengths and weaknesses were presented.

Before conducting the case studies with the software of nTopology, it had to be introduced. This software seemed very complex at first sight and it remained that way at the beginning. Nevertheless, it became natural to use with time spent. Sometime in and even before conducting the two case studies of topology optimization and light-weighting it became very clear that the operations that are used will only scratch the surface of this software's potential.

For the second objective, two case studies were conducted to model with nTopology's optimization tools and capabilities. With the knowledge that was gained when meeting the first objective through the literature review, structures were created and a simple analysis was run to explore the features of the software considering AM, focusing on topology optimization and light-weighting.

The results of these case studies were presented and provided numerical as well as visual aids to meet the third objective. As the industry keeps aiming to get faster, lighter and stronger, the features used in nTopology show the potential possibility of how to achieve this continuous thriving of the industrial requirements.

Further, the results of the first case study indicate that when using nTopology with its for additive manufacturing constructed software weight savings of 70% in part mass and up 90% of support material can be saved. These numbers equal enormous financial benefits in many ways. Lighter components that keep the same durability mean fewer material used for manufacturing the part and support structures. That also leads to immediate benefits when those optimized components are used in e.g., aerospace applications which automatically leads to fuel and CO2 savings.

Similar benefits can possibly be created when using stress analysis results as a baseline for the light-weighting process as it has been done in the second case study. These analysis results determined where the material was added (high-stress areas) and where the lightweight structure could withstand the applied forces with less material. That ultimately gives the designer the opportunity to create a part that has no more weight and material as really necessary for its use case.

Nevertheless, even with the findings of these significant optimizations during this thesis work, it was never the goal to create the perfect part possible with one of those methods. Therefore, these numbers are not the norm for any component optimized and even the ones used might possibly be even greater optimized.

Limitations

This thesis work process has been followed and faced numerous limitations along the way. As the work was conducted during the Covid-19 pandemic the starting date of the practical part with using the nTopology software was postponed several times. As the computer laboratory, where the software was running on a specific computer was at times accessible as the university did not allow access into their facilities. As a consequence, the time frame turned out to be tight as the due date did not change. With nTopology being a newer software not much information or tutorials on how to use this platform as an entirely new user being found. That did not support the already tight timetable. As a result, the designs and operations used are very simple and do not represent the full capabilities of what is possible when using the nTopology platform.

7 Conclusion

The fundamentals and knowledge gained about what designing for additive manufacturing means to advanced manufacturing and what role nTopology can play as a tool to support this generative design approach have been demonstrated in this study. The adaption of AM in the industry as an additional manufacturing method is inevitable as well as the way designing has changed and must be further developed for the future to unlock the full potential of AM.

The findings for this report suggest that the usage of software like nTopology can be of high value as great design improvements can be realized. As it has been presented that weight savings of 70% and cutting down the volume of needed support structures to manufacture the part by 90% are no exceptions when using this type of software. It allows designers and engineers to maintain competitive designs in the future. It is not only about the design itself, that it is more lightweight, almost no material surplus remains and that the whole process from the idea until the manufacturing of the optimized design is shortened significantly but also the possibility to free the engineer and designer from designing restrictions.

It must be mentioned that this study in its execution within nTopology might be biased in case of how nTopology was used and may not present the real potential of the software due to the lack of experience in operating this software or ever conducting similar operations like topology optimization and light-weighting before. During this study work, clear evidence has appeared that only the tip of the iceberg has been investigated when working with the nTopology software.

Therefore, future studies could more extensively investigate other features of nTopology and how these contribute to DfAM. Also, comparing this software with others that use similar approaches could be researched as designing develops at a great pace. As only two operations and their capabilities were monetarized it is also a possibility to create a more detailed study that represents a step-by-step workflow guide to monetarize the usage of the software.

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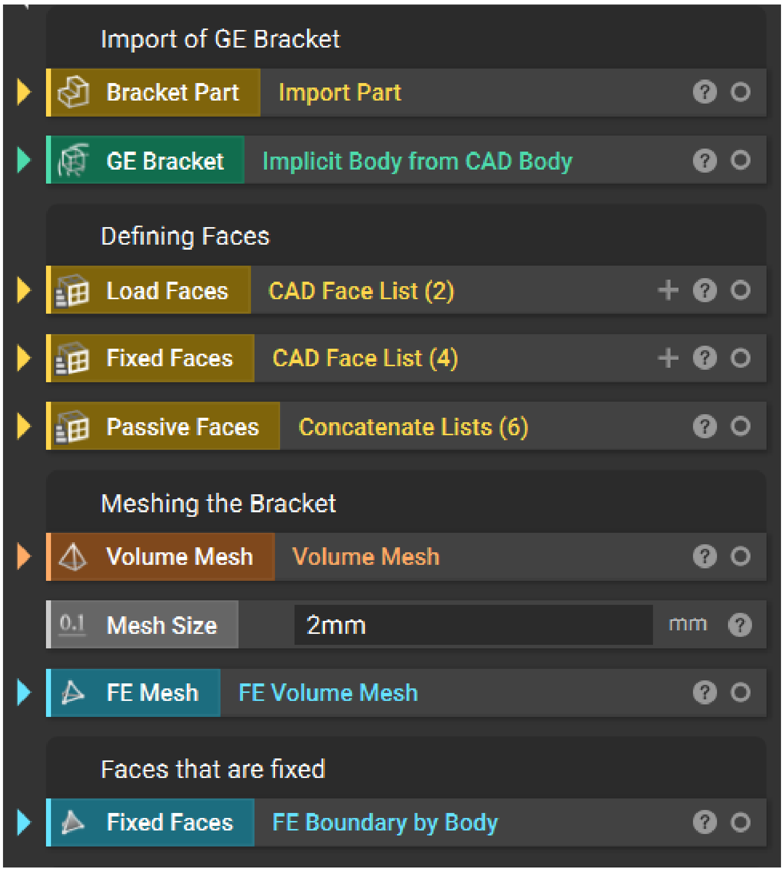
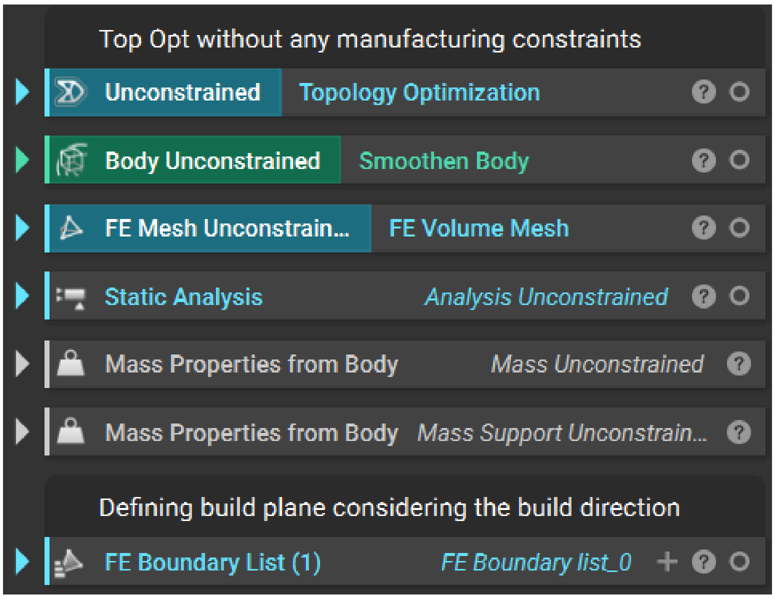
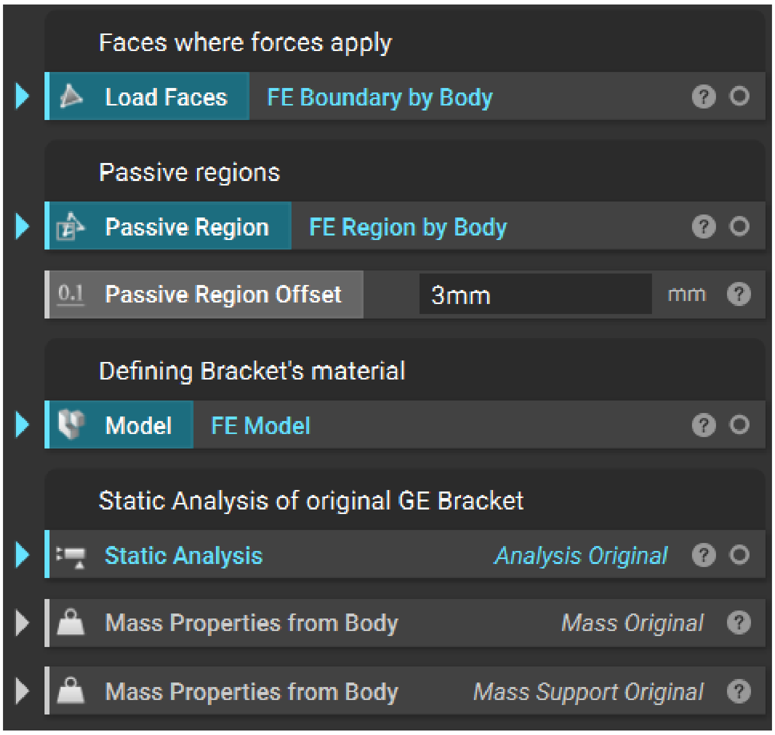
9 Appendices



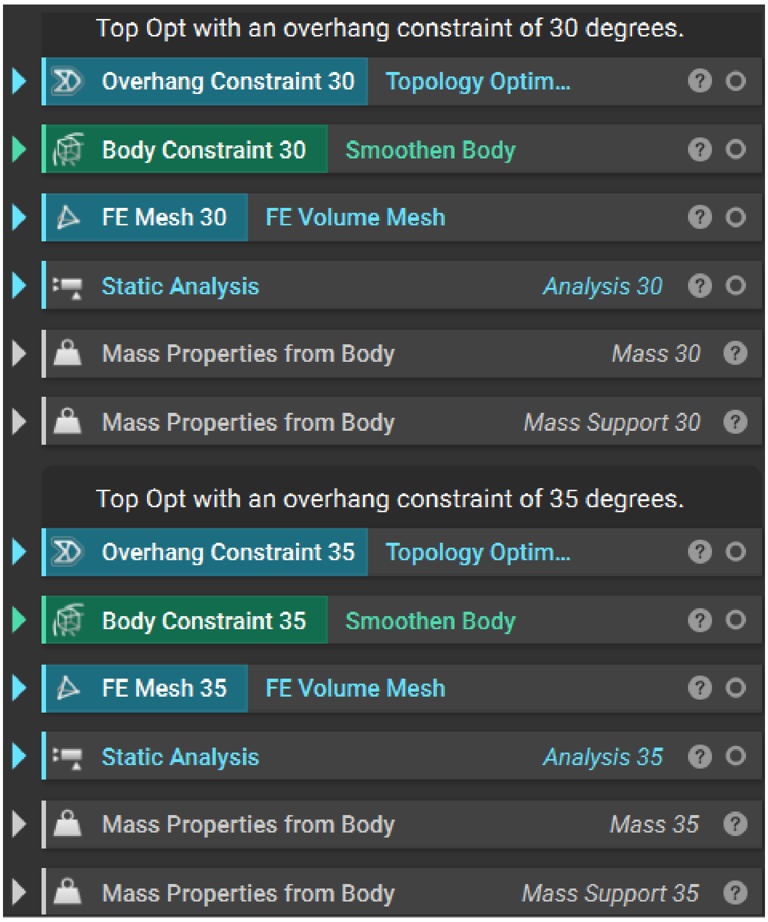
Appendix 1: Workflow topology optimization in nTopology 1/5



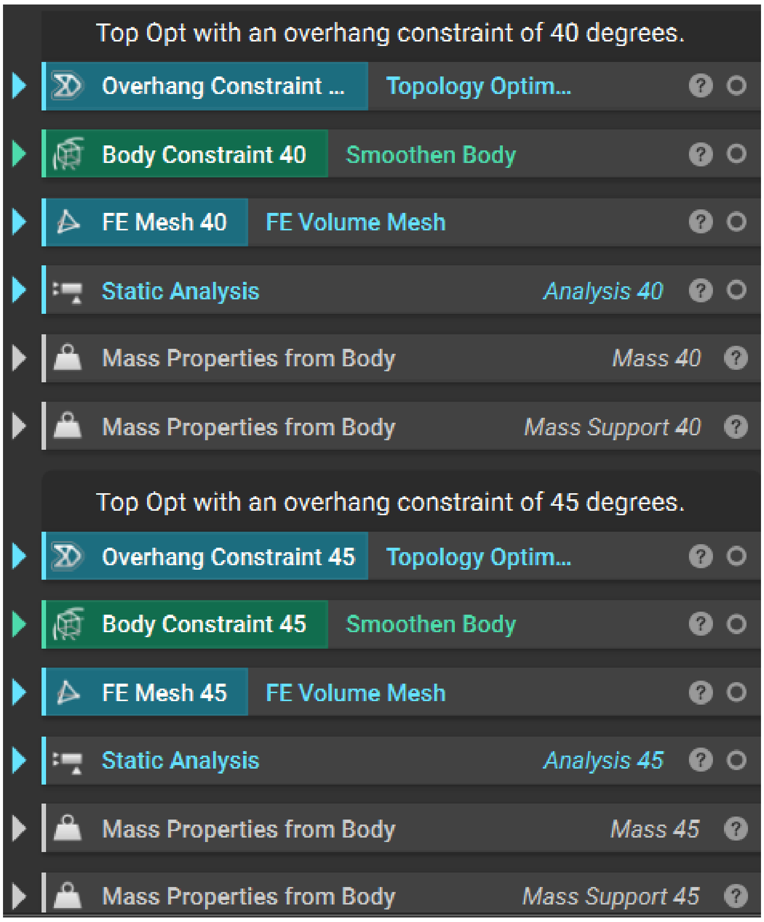
Appendix 2: Workflow topology optimization in nTopology 2/5



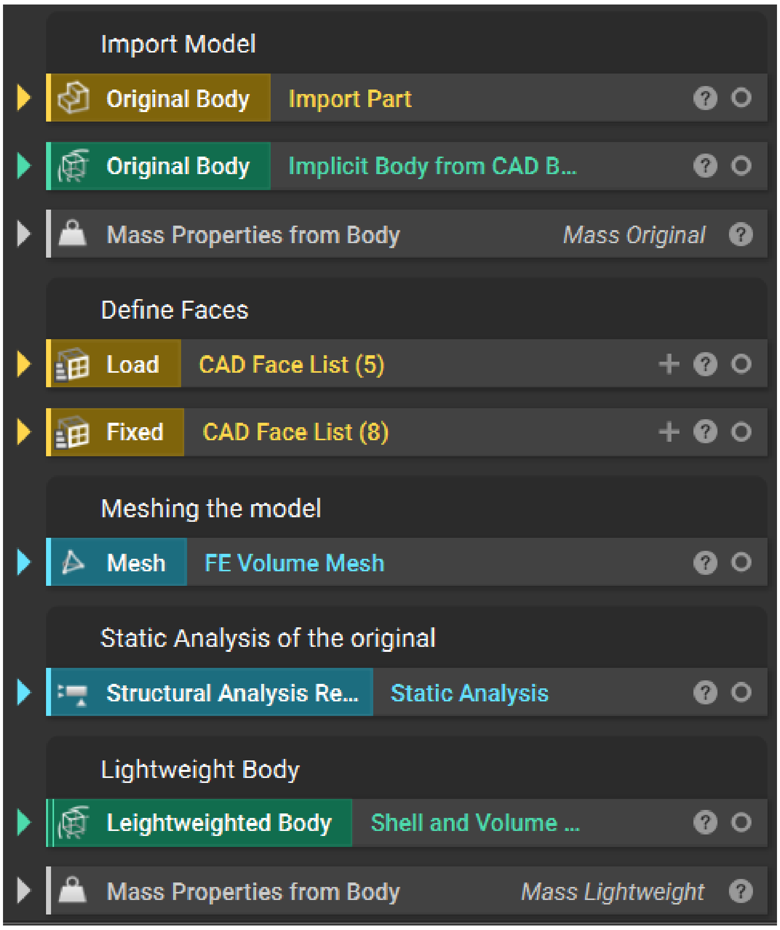
Appendix 3: Workflow topology optimization in nTopology 3/5



Appendix 4: Workflow topology optimization in nTopology 4/5



Appendix 5: Workflow topology optimization in nTopology 5/5



Appendix 6: Workflow light weighting in nTopology (plummer block)