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The Merger of Topology Optimisation in Additive Manufacturing

Prof. A. K. Madan[1]
Department of Mechanical Engineering
Delhi Technological University,
Delhi 110042

Srashti Saxena[2]
Department of Mechanical Engineering
Delhi Technological University,
Delhi 110042
srashti.saxena99@gmail.com

Abstract: Topology optimization has become a subject of study unto itself in recent years, not only because it provokes the intellectual community's curiosity, but also because it provides significant responses to real-life industrial difficulties. Topology optimization is being used to create a lightweight product while still meeting its functional criteria for a new product or a redesign of an existing product. Additive Manufacturing is defined as the layer-by-layer production of geometrically demanding components, which significantly minimises the complexity restrictions imposed on topology optimization by the old subtractive process. This perspective paper enlists the compassion of these two methods as they work together. The paper compiles the methodology along with the merits and demerits of the optimisation technique. A review has been done on lightweight design and continuum optimisation, which resulted in a reduction of weight by 65% and the use of grid-like ground structures. The goal is to motivate both researchers and engineers to come up with creative solutions to face the modern-day challenge in this field.

Keywords: *Additive Manufacturing, Continuum Optimisation, Lightweight Design, Topological Optimisation.*

1. Introduction

Topology optimization is a comprehensive design technique for making the appropriate structure configuration by allocating materials in a rational way while maintaining given load conditions, performance, and limitations. This method generates an optimal topology by solving a material distribution problem. Using dedicated software, it discards the material that is not subject to stress, therefore making the product effective to produce. The very first breakthroughs in topology optimization relied on subtractive or formative manufacturing techniques. Because of their distinct manufacturing constraints, these traditional manufacturing processes are limited in their ability to produce complicated form of geometries. But with advancements in manufacturing in the form of additive manufacturing, the complexities in the geometries could be included, making it the finest customer. Additive manufacturing does not require any kind of tool motion for the object to be produced, and therefore, layer-by-layer printing can leash the complexities of a geometry. This method relies on layer-by-layer material deposition, which drastically reduces the geometric complexity barrier. From the perspective of geometric complexity [18], manufacturing performance and costs of production are not affected. Topology optimization

[2]Corresponding Author: Srashti Saxena; srashti.saxena99@gmail.com; 7060428334

creates lightweight parts without sacrificing strength. Topology optimization in conjunction with Additive Manufacturing allows for the manufacturing of low-weight and intricate systems. It relocates the material within the design space and does not entail the integration of exterior barriers, resulting in an organically shaped component that bears little similarity to its heritage counterpart and is considerably lighter in weight. STELIA Aerospace has employed topology optimization to create more stable fuselage panels for aeroplanes, combining rapid prototyping and topology optimisation. More than merely making a physical product, additive manufacturing is about putting design and innovation front and centre. One of the key advantages of additive manufacturing is the ability to be creative without worrying about cost or schedule constraints. Additive manufacturing can considerably cut energy consumption when compared to traditional manufacturing by utilising less material and eliminating the unnecessary steps.

With the continuation of the advancements from the last three decades, topology optimisation has still not been able to get the right track and has been criticised for its organic nature due to challenges being faced during the production. It is challenging to ensure that a topologically optimum design is both manufacturable and aesthetically acceptable (contrasts from what a mechanical part would look like in the typical sense).

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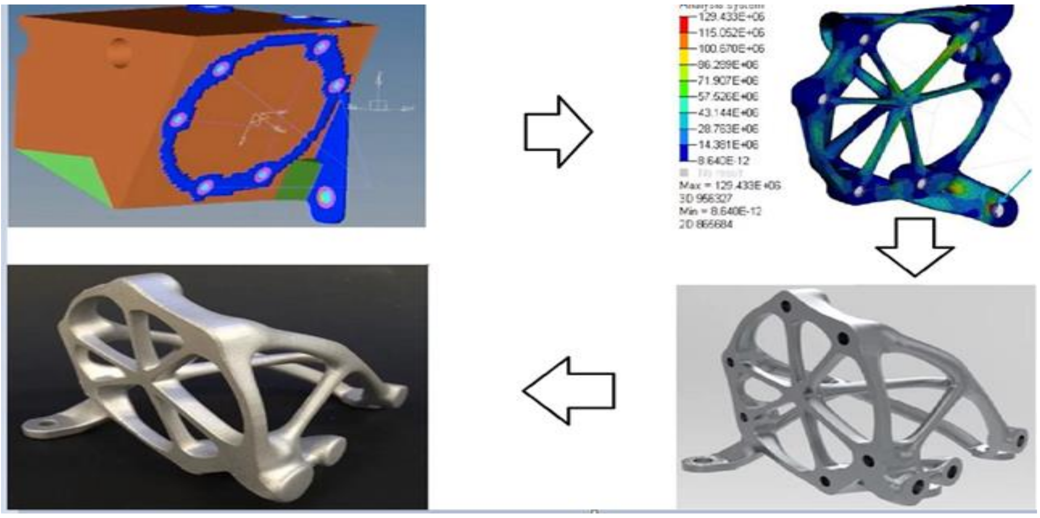

Figure 1. Stages in Topology Optimisation [16]

2. Approach of topology optimisation

2.1 Topology Optimisation Strategic Methodology

CAD has been used in topology optimization to develop a rough/initial model of the object to be optimised, while Finite Element Analysis is used in seeing how stresses and displacements are distributed throughout the product. The Solid Isotropic Material with Penalization (SIMP) method, the Evolutionary Structural Optimization (ESO)/Bidirectional Evolutionary Structural Optimization (BESO) method, and the level set method have emerged as the three main advances in the fields of topology optimization [21]. It is used to eliminate portions of the component that are not effectively sustaining the applied loads, are not experiencing significant deformation, and therefore do not contribute to the overall function [16]. The optimisation process starts with the designing of the model on the CAD software and optimising it until the desired design is achieved. Based on the objectives and limitations established in the design challenge, the topology optimization tools build a complicated natural shape. Following the shape obtained by the topology optimization procedure, the design is next finished on CAD software to produce a smooth and manufacturable part. Finally, the final optimised design is evaluated using Finite Element Analysis techniques to ensure that the product satisfies its overall performance criteria [16].

2.2 Initial steps of optimization-

1. DESIGN-The process starts as the design has been finalised on the CAD software, which fulfils the initial performance requirements and serves as the basis for the process of optimisation.
2. CONSTRAINTS- The initial conditions of the optimization require boundary conditions; the design space is the area in which the optimization process takes place. This area is the boundary of the existing design. The algorithm eliminates the material within this region only. Part functionality lets the user specify the conditions of the load and the fixed points along with the material of the object to be optimised. As the load and the points vary, part of the functionality process is repeated again.
3. MESHING- The object to be optimised is converted into the mesh. It allows the user to specify different parameters of the elements, the mesh quality as fine or coarse, shape and size of the elements etc. The coarser the mesh is, the less accurate the results are, and the simulation is completed in a short period of time.
4. OPTIMISATION VARIABLE-

    a) Desired Weight- The optimisation process ceases when the desired weight has been achieved. This desired weight is an input variable around which the optimisation process revolves, but fails to work in conditions where a maximum reduction in weight is required.
    b) Number of Runs-The number of runs that can be set up in order to complete the optimization process in a given period of time. Unless the time taken is unpredictable for the optimisation.
    c) Convergence- The convergence criteria allow the optimisation to stop within two to three iterations if the result of the two output weights is less than the value predefined.
    d) Factor of Safety- It specifies the maximum or minimum stress which the desired product can bear.

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5. FINAL PRODUCT- The given steps one to four are run in order to get the optimised parts. Finite Element Analysis is done on the optimised part in order to ensure whether the stresses induced and deflections are within the specified limit or not.

Figure 2. Flow Chart of Product Manufacturing

3. Case Study-

3.1 Continuum Optimisation-

In this study, a review has been done on structural steel design using topology optimisation for its approach up to shape and size only [12]. Topology optimisation is easy to define in shape and size, whereas it has restrictions to variable cross section, the geometry of the product and to some pre-defined restraint variable. A key concern in structural optimization is reliability-based optimization, which considers inconsistencies in geometric dimensions, properties of the material, forces, operating conditions, and so forth that occur in real engineering issues. Until now, numerous reliable ways such as probability methods and interval methods have been proposed [19]. It does, however, make every effort to improve on the existing design. It is significant to mention that Topology Optimisation is not confined to materially homogeneous volumes. It could be used for a heterogeneous material, such as composite or microstructurally created materials. The weight of steel is reduced by 18% to 75%, that has a massive effect on steel structure. Nevertheless, when it concerns to interconnections in structural steel, the reduction is usually 12 % to 25%, which is the majority of the total weight of the steel structure, and its design concept has a significant impact on its weight and effectiveness, making it particularly prone to Topology Optimisation. Over the last several decades, the continuum topology optimization method has been fruitfully developed. It can also be used in grid-like "ground structures" composed of one-dimensional elements. Continuum structures are ground structures with one dimensional element subjecting itself to Discrete Optimisation. With the objective of finding out the optimal number, size, shape, coordinates of the nodes, and structural element connectivity, the optimisation is restricted only to the shape and size. Due to this reason, it is also known as Truss Topology Optimisation or Skeletal Structures Topology Optimisation. The optimisation of nodes is considered one of the major issues [12]. These optimisation techniques are applicable for solids and shells with definite boundaries.

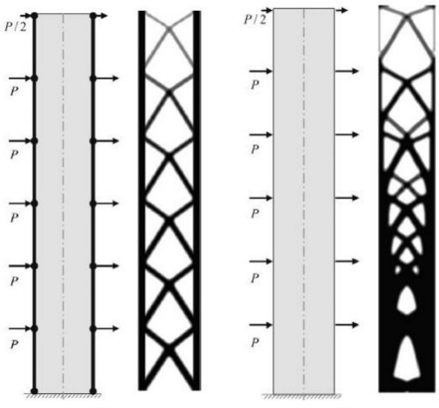

Figure 3. (a) Discrete optimisation (b) Continua Optimisation [12]

3.2 Lightweight Design-

In this study, a review has been done on a jet engine bracket to depict its weight reduction merits and the adoption of additive manufacturing techniques for production purposes [16, 25]. Finite element analysis has been done to investigate the distribution of the stress and the Von Misses distribution contour has been plotted. The software shows an area in blue, which indicates the material which needs to be removed has an insignificant effect on the performance of the parts. The bracket is subjected to four load conditions and the objective of the optimisation technique is to reduce its weight up to a satisfactory level. The characteristics of the material used for the bracket are-

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1) The material used is Ti-6Al-4V with a strength of 904MPa at a 23 degree C temperature.
2) The diameter of the pin is 1:19 mm.
3) The pin's stiffness is infinite.
4) The maximum diameter of the nut face is 10.287 mm (inner diameter) and 14.173 mm (minimum outer diameter).

The optimisation is subject to minimising the weight of the bracket. Subject to

1. 30% mass fraction
2. Minimum feature size: > 1.13 mm.

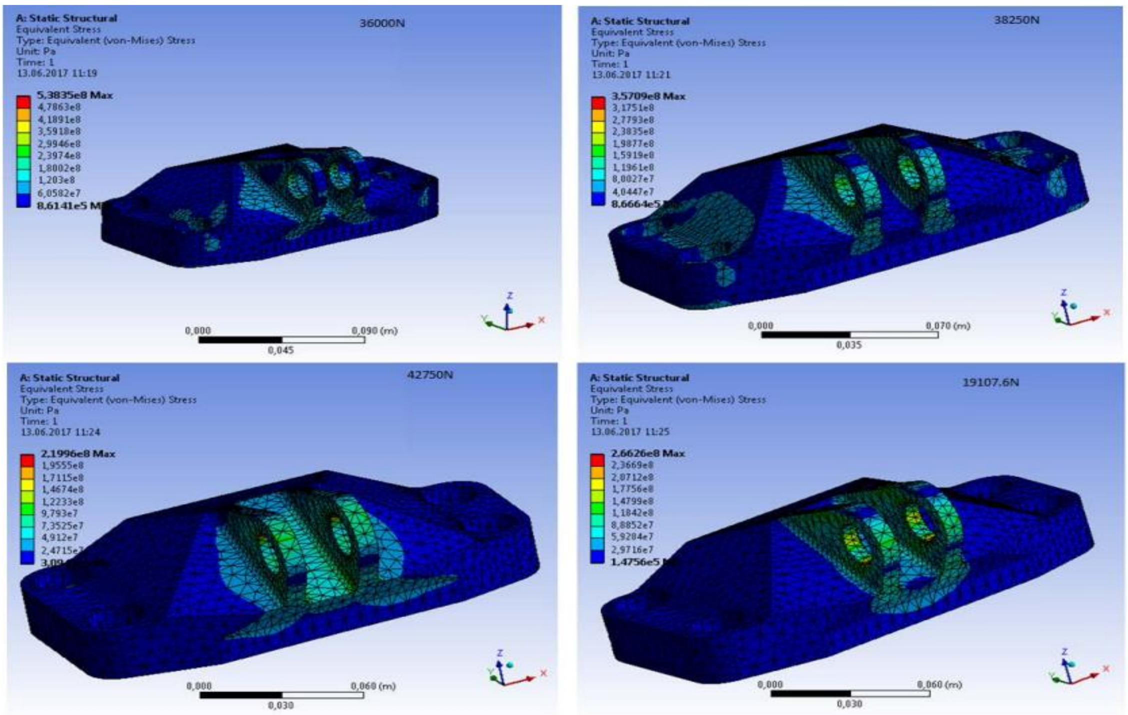

Figure 4. Von Mises distribution contour plot marked by blue [16]

The optimisation starts by dividing the design into two parts, the first one being the design space and the second one being the non-design space where the topology optimisation tools work. These spaces are then meshed using the tool present in the Altair Hypemesh 14 Optistruct software for commercial uses and a fine mesh is used of element size 0.25 mm. The non-design spaces are then subjected to loading conditions and constraints, and instead of torque, two equal couple forces are applied in different directions. The topology optimisation tool evaluates the distribution of stresses applied and the displacement for all the loads distinctly. Depending on this stress and displacement distribution, the regions where insignificant loads are acting are eliminated by the software. A rough geometry is formed that is then remodelled to give a pleasant and an aesthetic look. Figure 10 [16] shows the design which has been finalised and is created in Autodesk Inventor Professional. This final design bears the mechanical load as per the prerequisite condition. This structural verification is performed on the software ANSYS R17 Academia Educational Tool where the von Mises stress value is checked and compared with the yield strength of the material used. The design, when fully examined for stress, is then manufactured by a rapid prototyping method using the technique of fused deposition modelling (FDM). Figure 12 [16] shows the final product, and it can be concluded that the final product of the jet engine bracket resulted in a 65% reduction in weight. The mass is reduced from 2.067 kg to 0.72 kg.

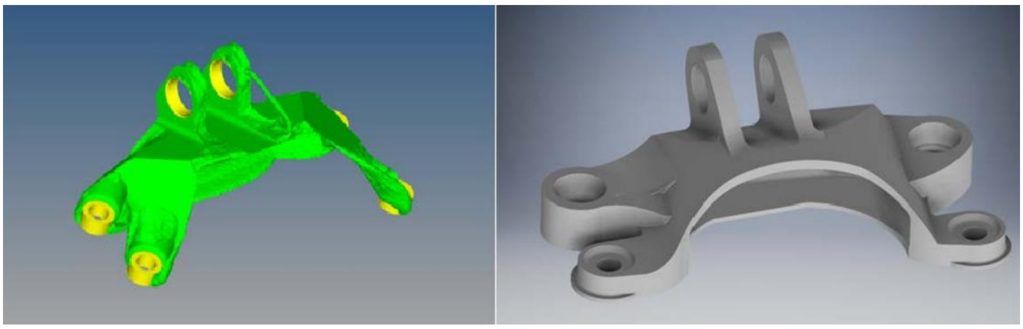

Figure 5. Optimal Geometry and Remodeled design [25]

Figure 6. Engine Bracket after Fused Deposition Modelling (Additive Manufacturing) [16]

4. Conclusion

Here a detailed account of Topology Optimisation methodology was explored, as well as its conjunction with the additive manufacturing. The optimising technique's strategic planning has been reviewed in detail so that it may be simply comprehended. This paper has examined its benefits and drawbacks. The case study shows that the continuous optimization is restricted to changing cross section and dimension, however various efforts have been done to improve the current product. It can now be applied to both homogeneous and heterogeneous materials. The second case study explains how the product's redundant stress-free portion can be discarded hence the weight minimized. The weight of the jet engine bracket has been lowered by 65%, from 2.067 kg to 0.72 kg. Overall, it is reasonable to state that topology optimization, in association with additive manufacturing, is important in the design and manufacture of lightweight goods for usage in a variety of industries.

5. Future Scope

The anticipated use of Additive Manufacturing is the most significant driving force for implementing Topology Optimisation in design practice. This technique should be used in the majority sector of manufacturing for waste management. It can find its role in Space Science for the manufacturing of satellites and rockets. Also, for more complexity, the software tools should be able to complete the optimisation technique within a given span of time.

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