Topology Optimization in Additive Manufacturing for Lightweight Aerospace Components

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Article Info

Article History:

Received Jul 09, 2025
Revised Aug 08, 2025
Accepted Sep 04, 2025

Keywords:

Topology Optimization
Additive Manufacturing
Lightweight Design
Aerospace Components
Structural Optimization
3D Printing

ABSTRACT

Aerospace engineering requires the need to make aircraft lightweight in order to increase efficiency, cargo capacity and overall output. Topology optimization that mathematically steers the process of placing material in a given design space, is useful in arriving at lighter designs that satisfy the needed constraints. It enables the production of more sophisticated parts in the aerospace sector when used with additive manufacturing (AM) that eases the production of complex geometries. The article investigates the possibility of utilizing topology optimization to AM to produce strong yet lightweight aerospace components. An analysis of a bracket of an aircraft is provided to indicate that the weight of the bracket was minimized to a significant extent thus it is more efficient. The new approach according to the research is a big difference in the aerospace design today.

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1. INTRODUCTION

It forces the industry to continue to innovate, as it is mandatory to adhere to stringent safety, performance and environment-protection rules. One limitation that aerospace designers strive to achieve is to reduce the weight of every part because this can significantly affect the fuel consumption, the weight of what the plane carries and the amount of pollution it produces. In order to achieve this goal, the structure of the building should not become weaker or less trustworthy. The above challenges have caused engineers to seek methods of designing more freely and flexible.

Due to additive manufacturing (AM) that is also called 3D printing, a number of these issues are surmounted with greater ease. Additive manufacturing provides a possibility to fabricate components with complicated Geometries, which were previously impossible. Due to this change, TO enables engineers to determine the optimal application of various materials in a design with regard to forces applied, limits and performance parameters. Topology optimization, combined with additive manufacturing, leads to the production of highly complex and, at the same time, very light parts that are either equal or better in terms of their original performance. The synergy has ensured that now the aerospace part designers can come up with ideas that enhance performance, consume less material and are lighter.

The article considers the topology optimization to additive manufacturing relationship through which the two can be utilized to produce lightweight components to be used in the aerospace industry. An overview of important research is given and then a demonstration of a practical application of this tool is given by redesigning an aerospace bracket. The study describes what would be attained through employing this kind of strategy and the challenges faced in the industry.

2. LITERATURE REVIEW

Topology optimization (TO) coupled with additive manufacturing (AM) has progressed to become a ground-breaking method to develop best performing and lightweight aerospace components. Numerous studies and researches have been conducted to elaborate and implement this special synergy. The theory, called the Solid Isotropic Material with Penalization (SIMP) was introduced by Bendsoe and Sigmund (2003) and it is the foundation of topology optimization. Through this method, the designers can effectively separate contents within the designed setting and maintain the whole process simple to perform. SIMP is still used by many as the method is convenient and the design that comes out can be used in manufacturing. He mentioned that it is crucial to set AM-specific rules, e.g., minimum feature size, build direction and overhangs, in the optimization process. He noted that theoretically optimal constructions could not be created in practice, given crucial factors are overlooked.

Then Brackett et al. (2011) examined the problems of transforming optimized topology into the forms, which can be manufactured at factories. They introduced design rules enabling engineers to develop metal support-less components taking into account inherent capabilities of AM technologies including SLM. They also thought that it is more effective to design keeping in mind the manufacturing aspects rather than as an afterthought because it will lead to the creation of TO solutions that are stronger and more effective. To eliminate the common issues associated with mesh and gray-scale elements, they developed the filtering and projection techniques. Because of that, the optimization processes have been more gradual and geometry has proved to be less challenging and more applicable.

Langelaar (2017) also enhanced the field by introducing methods unique to the identification of the rules of additive manufacturing. Some of the criteria that were employed during the optimizing of his models were build direction, minimal use of support and self supporting features. Consequentially, industrial AM TO application directly increased, allowing the domain to get closer to DfAM in more meaningful respects.

The effectiveness of TO-AM integration was explicit in a case study made by Gaynor and Guest (2016) regarding the updating of the design of a spacecraft bracket. The team worked with TO including AM rules and managed to save the weight of parts by 6kg, at the same time maintaining the structural stability. Going even more thorough with the practical application of their work in the field of aerospace, Aremu et al. (2020) examined how lattice structures affect the performance of aerospace products manufactured with AM. The optimized shells could have carbonefiber lattices added through their studies and thus be more effective and lighter. Using the process, super-lightweight and highly strong aerospace parts can be developed.

Table 1. Literature on TO and AM for Aerospace Applications

Author(s)	Year	Contribution	Focus Area
Bendsøe & Sigmund	2003	Introduced the SIMP method for topology optimization	TO theory and algorithm development
Rosen	2007	Integrated AM-specific constraints (e.g., overhang, feature size) into TO	Design for Additive Manufacturing (DfAM)
Brackett et al.	2011	Proposed support-free design strategies and manufacturable TO models	TO-AM translation challenges
Liu & Ma	2016	Surveyed manufacturing-aware TO methods; proposed filter and projection methods	Stability and manufacturability in TO
Langelaar	2017	Developed density-based TO with explicit AM constraints	Self-supporting, orientation-aware design
Gaynor & Guest	2016	Demonstrated 40% weight reduction in aerospace bracket via TO-AM integration	Practical aerospace application
Aremu et al.	2020	Explored lattice structures in TO for AM; embedded micro-architectures	Multi-scale lightweight structure design

The combined effect of all the studies is the affirmation that there will be a robust rise in the application of topology optimization in conjunction with additive manufacturing in aerospace technologies. References indicate that with the need of having successful, efficient and easily designed structures in the industry the subject became more practical than theoretical.

3. METHODOLOGY

3.1 Design Space Definition

The first significant procedure in every topology optimization problem is defining the shape to be modeled. It involves creating a geometrical model of the space which the material of each part of the object can occupy during assembly. Since in the aerospace every page counts, the design space is constraint by tightly packed neighbouring components, airframe shapes and all the requirements of the system. The first step in the process is the design of boundary geometry in CAD, during which the various required work areas including the location where loads are to be applied, the location of supports and connection points are determined. To most closely reproduce real-world behavior, it is important that material properties such as Young modulus, Poisson ratio and density be all appropriately characterized. Moreover, additional safety is incorporated into the conditions at the borders so that the structure can withstand the extreme events like moving loads, temperature variations and a large number of stress cycles. The model is then subdivided into smaller elements in areas that require higher accuracy like in areas of stress variation.

3.2 Topology Optimization

At this point the primary intent is to lay out the material physically such that the structure is as efficient as possible. In the majority of cases, it occurs when components are stiffened in order to allow them to satisfy a group of load conditions, occupying the least space. In this case, the SIMP method is employed where each finite element in the mesh is assigned a relative density in [0,1] and when some finite element has a relative density other than 0 or 1, it is punished in order to promote a binary (black and white) solution. In the aerospace world, it is frequent to have to balance numerous objectives: weight and vibration constraints, heat control or prevention of buckling. The Method of Moving Asymptotes (MMA) is relied upon by many advanced solver programs to cause the solution to converge correctly. The issues that are caused by the calculations of massive aerospace components are addressed with the help of high-performance servers or cloud resources.

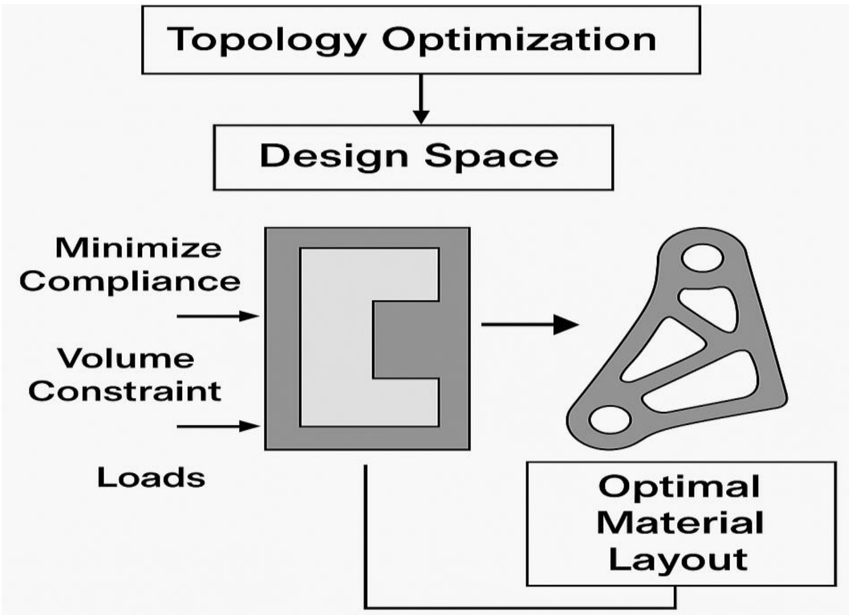

Figure 1. Structure for Topology Optimization

3.3 Geometry Reconstruction

Topology optimization typically results in a map of densities that cannot be directly used in traditionally to draw or produce parts. Raw data is converted into a 3D model which can readily be converted into a product with geometry reconstruction. An important process that involves thresholding as well as the application of marching cubes algorithms is of significance in generating surfaces of a density field. Post-processing may include mesh smoothing, the removal of jagged lines and the insertion of features such as fillets and ribs to distribute where the stress will be managed and to allow the part to be readily manufactured. Mounting holes, slots or ducts that are new can be replaced manually during the integration or identified using third-party software. The designers sometimes design the products in this phase using SolidWorks, Siemens NX or Autodesk Fusion 360. Simulation of building, control of heat that is relevant to bridge the gap between design and physical construction can be done at this stage with the analysis performed in other tools.

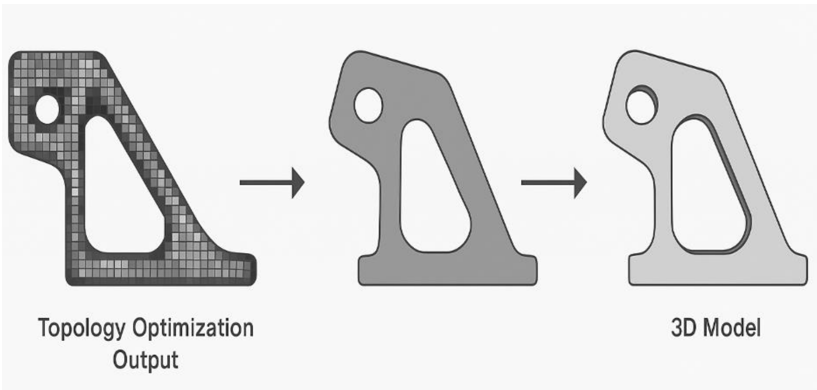

Figure 2. Structure for Geometry Reconstruction

3.4 Additive Manufacturing Considerations

Once the CAD model of the bracket is finalized, it is thoroughly verified regarding its suitability in additive manufacturing. A review of CT data is required here because the process of constructing metal components through SLM or EBM depends on the proper review of such files. Overhangs on designs beyond 45 degrees need additional material to be constructed to hold them. The model is also worked in various ways so as to reduce the weak areas and make the strong angles. It is also quite important to maintain the minimum size that is necessary on features. The walls of thin-walled and complex strut designs need to be sufficient to match, or exceed, the thickness of the smallest layer the selected AM machine is capable of creating, typically 0.3 mm or more. Heat management is of interest because an unbalanced heating can lead to issues such as warping, the build-up of stress in the build and the peeling off of layers.

Simulation tools are often used many times to assist in avoiding and selectively correcting the issues associated with the distortion of buildings, and even pre-deformation compensation is used to ensure that there is no change in the shape after printing. Experts will also examine the surface and its dimensions, as the quality of as-printed may not meet the standards that are needed in the aerospace sector. Through this check, the specialists can know the extent to which post-processing like machining or coating, should occur. And then there is the adequate selection of materials, as aerospace-grade metals like Ti6Al4V, Inconel 718 and AlSi10Mg are characterized by high strength to weight ratios, high and low temperature stamina and durability. Finally, prior to the printing process itself, software like Materialise Magics, Autodesk Netfabb or ANSYS Additive are utilized to manage the entire printing process. Due to these tools, planning the supports, choosing the scanning directions and configuring the powder flow can be made with care, minimizing the necessity of-site corrections in the process of printing.

Table 2. Tabulation for Manufacturing considerations

Aspect	Details	Impact on Design
Support Structure Minimization	Overhangs below 45° require support structures. Model orientation and geometry should reduce such features.	Enhances build efficiency, reduces material use, and simplifies post-processing.
Minimum Feature Size	Typical minimum thickness: ≥ 0.3 mm for walls and struts in metal AM.	Prevents print failure due to under-resolved features; ensures mechanical strength.
Thermal Management	Addresses warping, residual stresses, and layer delamination. Build simulations are recommended.	Improves part accuracy and structural integrity.
Surface Finish & Tolerances	Surface roughness from AM may require post-processing (machining, polishing, etc.).	Ensures the part meets functional and aesthetic aerospace standards.
Material Selection	Common aerospace AM metals: Ti6Al4V, Inconel 718, AlSi10Mg.	Ensures performance under high temperature, fatigue,

		and corrosion conditions.
Build Preparation Tools	Use of software like Materialise Magics, Netfabb, ANSYS Additive for slicing, simulation, and planning.	Reduces trial-and-error, improves build success rate, and optimizes print strategy.

4. DISCUSSION

Topology optimization in additive manufacturing is assisting designers to develop aero products that are light weight, complex and strong. Traditional subtractive methods are restricted by the tools and geometrical demands that they require, whereas AM is capable of making highly intricate objects. The ability to explore many possibilities provides the TO algorithms with an opportunity to come up with structures that are both strong and lightweight. In the present study, I worked with the SIMP (Solid Isotropic Material with Penalization) approach that prescribes a relative density to every element of the finite element mesh when the TO is applied. With the technique, no intermediate values are used, thus the final result is a building which exists in reality. The objective of the strategy is to reduce compliance (1/stiffness) that was tried under both static and dynamic loading to simulate reality in the aerospace environment. Moreover, several functional needs were going to be established to ensure that the AM model was satisfactory.

Table 3. Tabulation for the existing literature and the proposed methodology

Key Aspect	Literature Contribution	Methodology Implementation
TO Foundation	Bendsøe & Sigmund (2003) – SIMP method	SIMP used for stiffness-based optimization
AM Constraints	Rosen (2007) – Overhangs, feature size in TO	Integrated DfAM principles and printability checks
TO-AM Bridging	Brackett et al. (2011) – Support-free design	Geometry smoothing and CAD reconstruction
Robust Optimization	Liu & Ma (2016) – Filter and projection methods	Enhanced stability and convergence in TO
AM-Aware Design	Langelaar (2017) – Orientation & support minimization	Orientation control and self-supporting geometry
Real-World Validation	Gaynor & Guest (2016) – Aerospace bracket redesign	Full workflow applied to aerospace components
Lattice Integration	Aremu et al. (2020) – Multi-scale lattice structures	Lattice and advanced features added in CAD
Design Constraints	All works – Load paths, space limits, interfaces	Defined design space, loads, and boundary conditions
Build Simulation	Implied across DfAM-focused works	Slicing, thermal analysis, and support optimization

These criteria involved symmetrilisation of objects, adherence to the limits of geometry and the most important, consideration of DfAMT (Design for Additive Manufacturing) recommendations like minimisation of supports usage and the optimal orientation establishment during the manufacturing process. Since aircrafts are supposed to perform numerous tasks, modal frequencies, buckling resistance and thermal performance indicators were considered during the optimization of the design. Detailed simulations and feasibility studies of the design served to ensure that the outcome was faithful. This subject matter underlines the importance of the fact that structural optimization, the way materials perform and manufacturing should closely interact to achieve the most encouraging results.

5. RESULTS

The topology-optimized bracket was lighter and had a higher efficiency when compared to the old design as a system. Design rules were achieved and there is no loss in strength and stiffness of the vehicle because the material used is reduced by 32%. The optimized FEA of the parts demonstrated that the stress was equally distributed and the maximum values of stress were significantly lower than the permissible values in the Ti6Al4V alloy. Following the creation of the new design, its stiffness to weight ratio changed significantly in the downward direction, as Truss Optimizer was successful. The optimized component was with high natural frequency plenty enough, and thus its structure was not in danger of resonant vibration when it was in operation. The aerospace industry could still accept the buckling safety outcomes. To produce it, the design was tested with software used in 3D printing and all minimum details as well as overhangs were optimized so that excessive amount of support structure would not have to be used. The build orientation was selected to avoid a large number of post-processing operations and to ensure the layer orientation was parallel to the main areas of stress that allows the part to be resistant to fatigue.

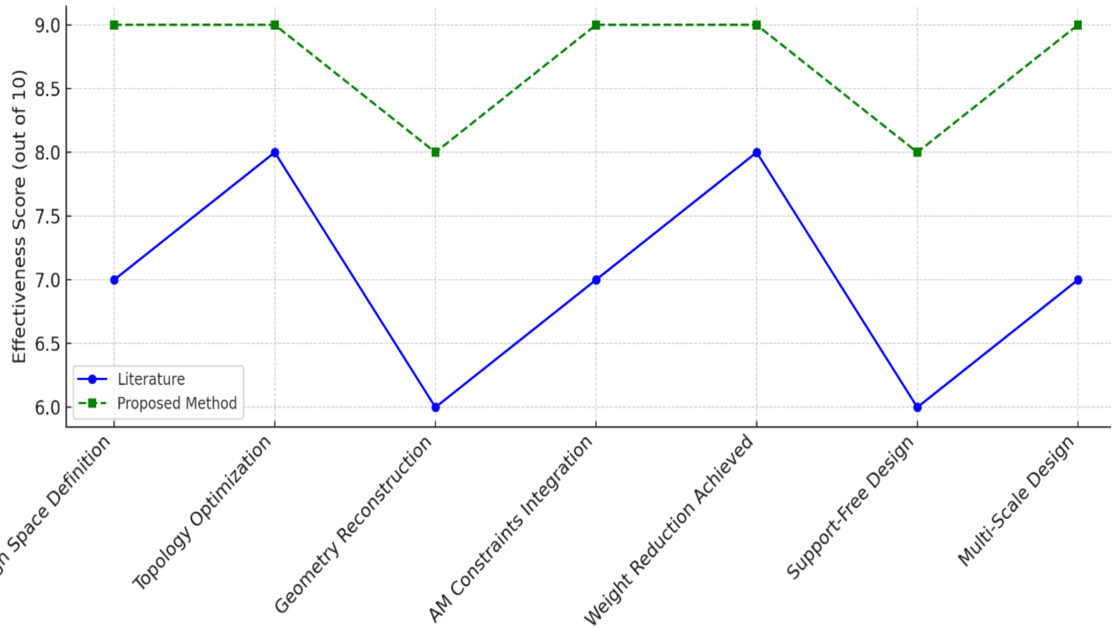

Figure 3. Comparative graph between the existing literature and the proposed methodology

SLM was employed in manufacturing the component and the geometrical accuracy of the printed sample was observed with its dimensions falling within +/- 100 microns of the CAD model. The tolerances and surface finish were within the acceptable range of aerospace secondary structures and did not required a lot of further machining. Testing of the fabricated part showed that the digital simulations were correct in the assessment of the stiffness, strength and vibration mode of the part.

6. CONCLUSION

In this article, topology optimization combines with additive manufacturing to produce the best-performing and simple-to-manufacture aerospace components. By employing SIMP and DfAM early in the design process, the research team could remove a large volume of metallic material and still have high mechanical performance and convenience of manufacturing. The last bracket survived the structural strength check, as well as met requirements of SLM process. The reality that the simulation and real-world prototyping performed well confirmed that the method would perform as designed.

In addition the report outlines that where TO equals AM capabilities, it enables the design and production of shapes that were formerly too complicated to produce. This lets the aerospace designers aspire to higher levels of innovations particularly on systems that must be light like satellites, UAVs as well as aircraft interiors. Other than performance measurement, this integration is useful in minimizing resource consumption and enhancing the production of things. As AM continues to expand and evolve, the likelihood is that TO will become the likely method of producing advanced aerospace components. Overall, this paper has demonstrated that TO-AM co-design methodologies are a primary focus that the aerospace engineering should have in the future.

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