IOP Conference Series: Materials Science and Engineering

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To cite this article: A M Aliyi and H G Lemu 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **659** 012020

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Abstract. Additive Manufacturing (AM), also known as rapid prototyping, rapid manufacturing, layer manufacturing and three-dimensional printing, represents one of the most promising aspects of manufacturing for highly complex geometries. In particular, AM is nowadays seen as provider of possibilities to realize true design optimized manufacturing through topology optimization. Topology optimization is an approach that is considered powerful in design because it contributes to a design that can save energy, materials and time that are not economically achievable using other manufacturing processes. This paper is intended to explore the potentials of topology optimized design approach for AM in developing products that are lightweight and at the same time efficient and have load bearing capacity. A case study has been conducted to demonstrate the steps involved in topology optimization and its benefits in terms of weight reduction.

1. Introduction

Additive manufacturing (AM), also referred to as Rapid prototyping (RP), Additive layer manufacturing (ALM), 3D printing, and many other names is a new manufacturing technique that allows fast fabrication of computer models designed with three-dimension (3D) computer aided design (CAD) software. Nowadays, this technology is seen as a potential gamechanger in a wide variety of industries, from shoes to aircraft manufacturers. It employs a group of technologies capable of performing the layer by layer manufacturing processes almost completely under computer control, with little or no human intervention once the process has begun [1]. The initial concept of AM technology was to assist the design engineering in better visualization and smooth communication through rapid prototyping. In its latter developments, however, the technology transformed itself to a tool of manufacturing functional products as a result of the innovations in different printing machines, materials and printing processes. In deciding whether a process can be classified as a rapid prototyping process or not, five criteria, as specified by Burns [2], are used. These are:

1. Raw material intake is in some shapeless form such as blocks, sheets or a fluid, and the products are solid objects with a definite shape.
2. The manufacturing process takes place without a significant amount of human intervention.
3. The produced shapes have some degree of three dimensional geometrical complexity. This eliminates extrusion and cutting of tubes or rods drilling of holes.

4. The process must not involve manufacturing of part specific new tools. This eliminates all types of molding and casting, electro-discharge machining (EDM) die sinking and copy milling operations.
5. Each produced item must be a single object not an assembly of component parts. This eliminates joining operations such as gluing, welding and riveting.

Employing the above-listed criteria, some of the established fabrication techniques can be classified as illustrated in Figure 1. One of the expected benefits of AM technology is the realization of optimized design through topology optimization. This optimization technique is a mathematical tool used in conceptual design stage to reduce part weight by optimally distributing the material throughout the body. To implement topology optimization technique during the concept design stage, it is necessary to determine the goal function(s) as well as the desired constraints. Material properties, essential geometric features of the part and loading conditions are normally considered as the desired constraints in the optimization process. The optimization tool will then attempt to spread the material within the design boundaries while meeting the design requirements [3]. As a result, there exists no question about the feasibility of the design due to not taking into account the design for manufacturing requirements.

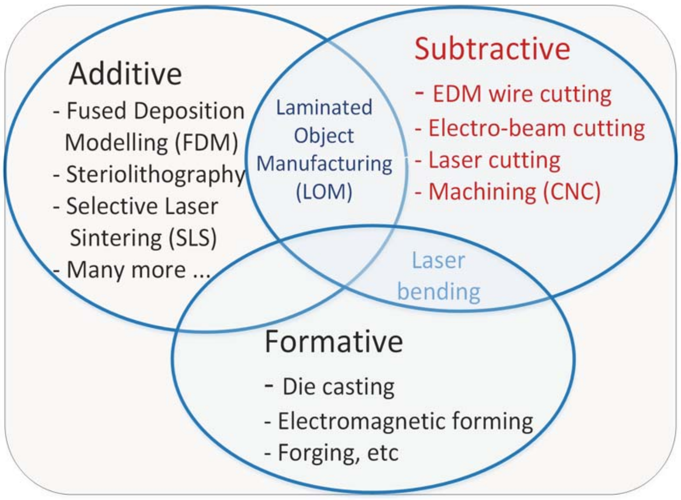

Figure 1. Classification of major component manufacturing methods.

The aim of this paper is to make a closer study of research and development works in application of topology optimization in design of parts for manufacturing using AM technology. In addition to highlighting the recent works in the area in Section 2, the paper explains the key formulation procedures involved in a topology optimization based design in Section 3, whose application has been illustrated using a case study in Section 4. Finally, the withdrawn conclusions are briefly presented in Section 5.

2. Literature review

As stated earlier, topology optimization provides the design freedom because it allows the designer to perform very flexible design optimization problems at early stage of the design process, thus, creating a design concept in terms of a general material distribution as either solid or void. The existing challenge of topology optimization is, however, to initiate design parameterization that leads to physically optimal designs. With the advances in finite element analysis (FEA), however, it has been possible to generate finite element meshes and define the meshed elements in design domain as a design variables. This allows a variation in density (homogenization, Solid Isotropic Material with Penalization (SIMP)) [4 - 7] or void-solid (bidirectional evolutionary structural optimization (BESO)) [8 - 9].

In recent years, in particular, topology optimized design has been an active topic of research from the perspective of using AM technology to manufacture functional parts with complex geometry. A study focusing on topology optimization based design approach for AM with a case study on lightweight design of jet engine bracket was also reported [10]. The angle bracket was redesigned considering four loading conditions and the work was intended to reduce its weight while satisfying all stated design requirements. Altair Hypemesh 14 Optistruct, which is a dedicated topology optimization tool, was used for the optimization purpose. The results of the study showed that topology optimization is a powerful design technique to enable reduction of the weight (65% reduction) of additive manufactured part while maintaining the design requirements.

Gardan and Schneide [11] reported optimization and fabrication of a hip joint implant interior part using AM technique. The implant has an interior pore that makes complex geometry and unachievable with conventional manufacturing techniques. Use of AM enabled manufacturing of the part with its complex geometry and allowed to find porous implants that allow the ingrowth of bone and cells, which could have been impossible if design optimization and AM were not used together in the design process. A topology Optimized Design, Manufacturability, and Performance Evaluation of Ti-6Al-4V Porous Structures Fabricated by Selective Laser Melting (SLM) was also reported by Xu et al. [12]. The porous structures were designed by using topology optimization under the condition of human skeletal stress, obtained a unit cell and constructed a series of porous structures with porosity from 40 to 80 % and unit cell size from 2 to 8 mm. The manufacturability of these parts was investigated for SLM technology. Among others, properties such as compression strength and dynamic elastic modulus were measured. The compressive behavior was explained and three failure models of porous structures were proposed.

Implementation of topology optimization approach for Fused Deposition Modeling (FDM) process is reported by Rezaie et al. [13], who investigated the issues and opportunities for the application of topology optimization methods for additive manufacturing. The topology optimization output files were converted to usable additive manufacturing input data for production and investigation of meso-scale structures for realizing intermediated density regions. Based on the implemented AM technology (i.e. FDM), a case study was redesigned, fabricated and evaluated.

Material usage for the supporting structure in AM is considered one of the major material wastages. Leary [14] introduced the idea of self-supporting designs, where the topology optimized design was altered to include features similar to support structures. Based on existing experience, support structures were introduced as design features. This alters the structural load path because the self-supporting design is introduced after topology optimization. Bracket et al. [15] have also recommended the integration of topology optimization and AM in to minimize the need for support structures. They suggested a penalization scheme on overhanging surfaces, and an edge analysis was carried out on a benchmark 2D example. The overhang constraint was suggested but not demonstrated. Based on the recommendation of Bracket et al. [15], Gaynor and Guest [16] employed a smooth heavy side approximation method to penalize overhanging surfaces within a SIMP based topology optimization. They demonstrated that, for 2D compliance minimization, this scheme changes the topology to be AM friendly. In particular, they demonstrated that it is possible to eliminate support structures by suitably changing the topology optimization process. Though the results seem encouraging, convergence issues when the overhanging penalization was imposed are reported as remaining issues. Another method proposed to reduce the need for support structure in topology optimized design is using the concept of support structure topological sensitivity [17]. This method combines performance sensitivity with the result in a topology optimization framework that maximizes performance, subject to support structure constraints. The robustness and efficiency of the proposed method was demonstrated through numerical experiments, and validated using FDM process.

The research on reduction of the need for support structure is part of the measures to reduce the material cost in AM process. Among recent efforts, the work of Wang et al. [18], who proposed a novel strategy to reduce the material cost by first extracting the frame structure of the design, can be mentioned. In this proposed design frame, solution of a multi-objective optimization problem (MOOP) was used to minimize the number of struts while accounting for stability and printability. The combined topology optimization and shape optimization is also considered [19] as a means of providing more self-supporting printing process by generating a volumetric tetrahedral mesh and mapping the overhang tetrahedra onto a Gauss sphere that is minimally rotated to a self-supported state. This method is also reported to be an effective method in finding optimal build direction.

3. Formulation of topology optimized design

3.1. Design optimization – backgrounds

Topology optimization for mechanical design is a mathematical approach implemented in a finite element mesh (the design space) and finds the tradeoffs in both minimizing material usage and maximizing part strength for a given design. The approach functions as a solver as well as a high-end analysis tool because it requires a pre-processor solver for meshing. The earlier optimization works extensively focused on size and shape optimization that are employed to manipulate design variables to improve performance of structures and/or mechanical systems. For a truss design, for instance, the design variable during a size optimization uses the cross sectional area of its members. The structure is optimized by finding the cross sectional areas that maximize its stiffness for a particular weight [5]. Shape optimization is also employed in performance enhancement of energy converters such as gas turbine blades [20] and hydropower converters [21]. The basics of shape optimization is often demonstrated when it is applied to alter the shape of holes to reduce the stress concentrations, resulting in a more structurally efficient part. The design variables in such cases are the parameters that control the shape of the holes in the original design.

Topology optimization is far more comprehensive than both size and shape optimization techniques. It is widely applied using the SIMP approach that involves modification of the stiffness matrix of the model so that it depends continuously on a function that is interpreted as a density of material. The optimal distribution of material is then obtained through making the material density as a design variable. This leads not only the optimum shapes of the model, but also the material distribution.

3.2. Topology optimized design process

Topology optimization in design may be applied to two different types of structures; namely, continuum and discrete. While the former refers to optimized design of single objects like an engine block or a turbine blade, the latter is optimization of truss-like constructions composed of many members. The topology optimization algorithms solve design problems by applying boundary conditions, design responses and constraints to a design domain. The design domain involves all possible configurations of the design. Using finite element meshes, the optimization algorithms find the optimal distribution of material and voids in the given design space, depending on the loading and boundary conditions such that the resulting structure meets the prescribed performance targets.

Figure 2 shows processes involved in a design process based on topology optimization. The process starts with the development of the original design using a 3D CAD modeling software and then the design and non-design spaces are identified (Figure 3), where the former represents the part of the model that is subjected to topology optimization. In other words, the topology optimization algorithm is “allowed” to remove materials from areas defined as the optimization design space. The non-design space, on the other hand, remains untouched by the optimizer, and all boundary conditions including loads and constraints are applied to this space. The next step involves meshing and conducting finite element analysis (FEA), which provides stress and strain distributions. The topology optimizer utilizes the stress and strain distributions for the optimization procedure. Based on the distribution of stress and strain/displacement, the topology optimizer removes materials from areas that have insignificant contribution in carrying the loads.

The material removal usually leaves an irregular geometry that needs smoothing using proper algorithms or remodeling using approximate surface of the exterior boundaries of the optimized shape. As illustrated in the figure (Figure 2), the topology optimization based design involves iterative procedures of changing the geometry of the model within a specified design domain constrained by the given boundary conditions. Provided that the design optimization is verified, i.e. it satisfies the design requirements, a physical verification model such as physical prototypes can be developed. If not, the part is remodeled until it is verified. The final design model is then developed for manufacturing using AM technology.

The key steps given in Figure 2 [10] were used to conduct a case study on a jet engine angle bracket, which was intended to demonstrate the potentials of topology optimization. With reduction of the weight of the angle bracket as an objective, the bracket was subjected to different loading conditions (horizontal, vertical and torsional loads). As reported earlier in Section 2, the topology optimization resulted in a 65% weight reduction, which is very significant for aircraft components. The step-by-step application of the procedure is illustrated in Figure 3.

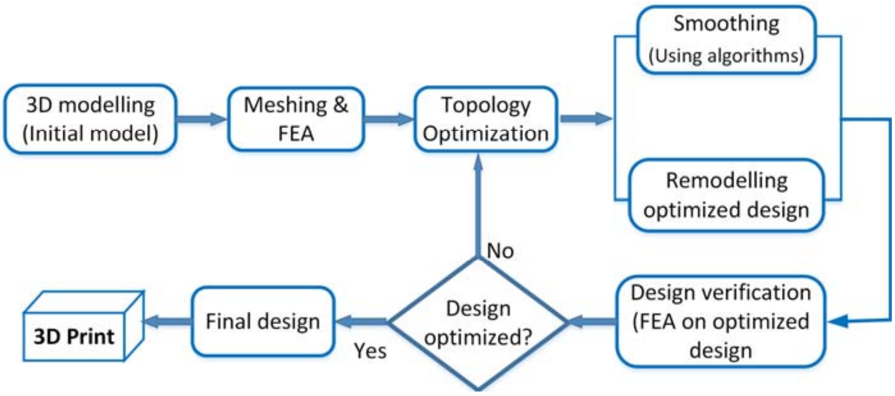

Figure 2. Topology optimization based design process.

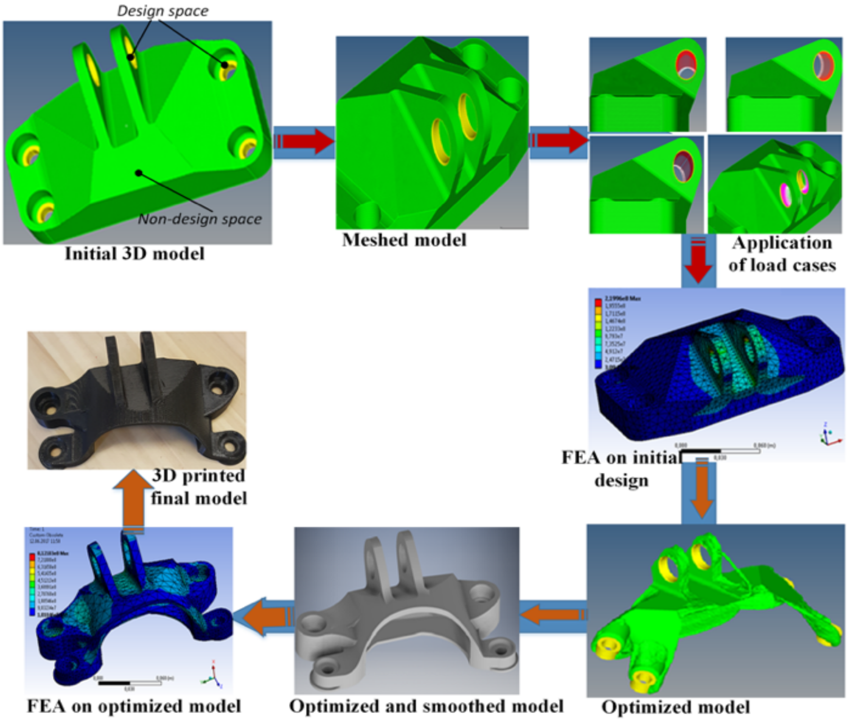

Figure 3. Sequential demonstration of topology optimization design process (Adapted from [10]).

3.3. General topology optimization problem statement

Topological optimization is sometimes referred to as layout optimization [22]. As stated earlier, its goal is to find the best use of material for a load carrying object such that an objective criterion (i.e., global stiffness, natural frequency and the like) is achieved subject to given constraints such as weight or volume reduction. In topology optimization, the material distribution function serves as optimization parameter.

To formulate a topology optimization based design optimization, five steps are commonly employed [23].

1. Developing the optimization problem statement: This involves definition of the design goals, the objective of the optimization and defined group of criteria.
2. Collecting data and information: This step involves collection of all the necessary information.
3. Identifying and defining design variables: At this step, the design variables describing the system are identified and defined.
4. Identifying the optimization criterion: This involves identification of the objective function and the stop criteria of the optimization process.
5. Identifying constraints: These represent the restrictions on the problem and can be extracted from the resources and stated performance requirements.

In general, a topology optimization problem can be formulated as:

$$\begin{gathered} \text{Minimize: } F = \int_{\Omega} f(u(x),x)dV \\ \text{Subject to: } G_0 = \int_{\Omega} x dV - V_0 \leq 0 \\ G_j(u(x),x) \leq 0 \text{ with } j = 1, 2, \dots m \end{gathered} \tag{1}$$

Where $f(u(x), x)$ is the objective function, which represents the quantity that is being minimized for the required best performance. In structural optimization, for example, compliance function, which maximizes the stiffness of a structure, is often used as the objective function. $u(x)$ is the material distribution variable described by the density of the material at each location of the given volume dV. Using this variable, the optimization is defined by either 1 (presence of material) or 0 (absence of material). Ω is design space and it indicates the allowable volume within which the design value exist or valid. $G_j(u(x), x)$ define the m constraints that the solution must satisfy. Examples include maximum amount of material, which is volume constraint or the maximum stress values.

4. Case Study on a Triangular Bracket

In this section, a case study conducted on a triangular bracket or angle bracket with three holes is presented. The bracket (shown in Figure 4(a)) has arbitrarily selected dimensions of $D_1 = 2\ mm$, $H_1 = 13.9\ mm$, $H_2 = 18.4\ mm$, $L = 25.7\ mm$, $V_1 = 20.8\ mm$ and $V_2 = 25.3\ mm$. The stress distribution (von Mises) from FEA on the original design with contour plots is shown in Figure 4(b). As the contour plots indicate, the portion of the part shown in blue color represent the inefficient use of material. This indicates the probability that materials can be removed from this areas of the model because they have insignificant effect on the mechanical performance of the part in carrying loads.

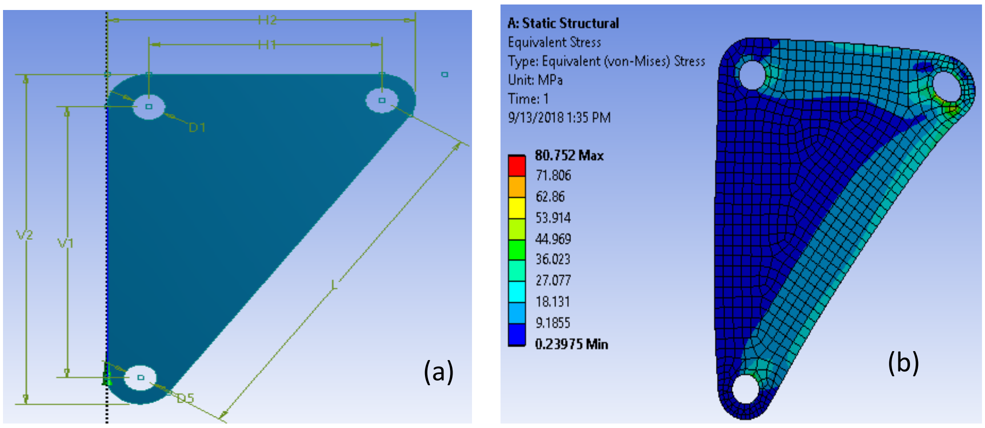

Figure 4. Original triangular bracket with three holes, (a) Dimensions and (b) FEA of the model.

In this study, the triangular bracket is redesigned using topology optimization based design approach using the three holes as the non-design spaces, where the two left side holes are fixed support and a bearing load is applied to the right hand side hole. The objective of this study is to reduce the weight of the bracket while satisfying all the design requirements related with its performance including:

- The optimized geometry must fit within the original part envelope.
- The material is structural steel with tensile yield and ultimate strength of 250 MPa and 460 MPa respectively at room temperature (20 ºC).
- The wall thickness is 2.0 mm.

Figure 5(a) shows the model processed by the topology optimizer in ANSYS Workbench, where the portion that contributes to the load carrying (gray) and non-load carrying (red) are demarcated after the computation of the stress and displacement distribution on the part for load bearing. As optimized (Figure 5(b)), the geometry looks rough and very natural showing the layout of the optimized material within the design space.

To smooth the irregular surface of the optimized model to not only make it aesthetically good looking, but also to represent the geometry by solid modelling functions, i.e. curves and surfaces, for further FEA for verification, it is important to create a new model that roughly circumscribes the optimized shape. Then the new model is remeshed and followed by computation of the stress and displacement distribution under the same loading conditions as the first analysis. If required, the final part is prepared for the second round of topology optimization process as shown in Figure 6.

This final design has to be verified with the given design criteria so that the von Mises stress values for the load cases should not exceed the yield strength. For this triangular bracket, the final design satisfied the yielding condition with safety factor that varied from 1.067 to 50. The optimized design weighed only 1.188e-003 kg, compared to 4.378e-003 kg in the original design, which is a significant weight reduction of 72.86%. Though this case study is conducted on a simple geometry to demonstrate topology optimization steps and benefits with practical examples, the real benefit is the parallel use of AM technology to produce the resulting complex shape with no manufacturing constraints.

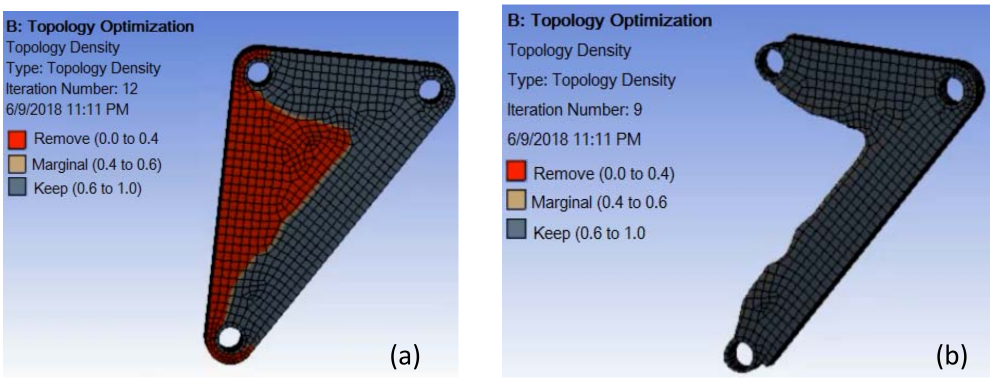

Figure 5. Optimization phase (a) Optimization region generation and (b) Design topology optimized geometry of the triangular bracket.

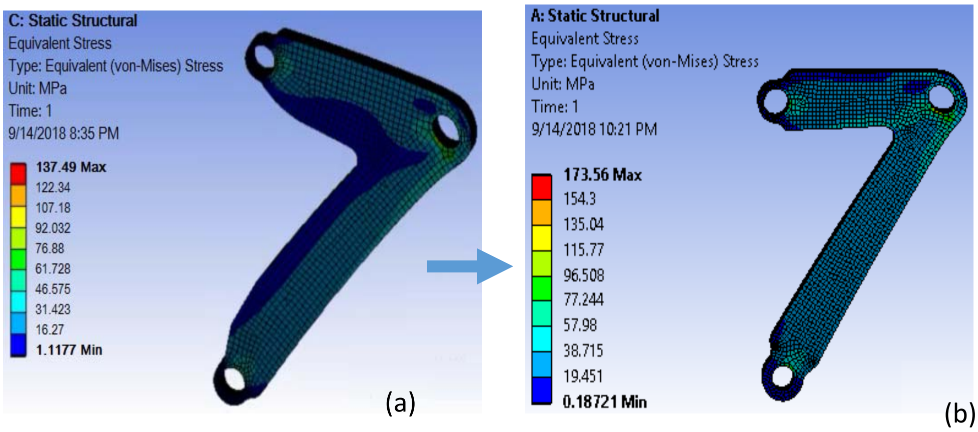

Figure 6. Topology optimized design geometry (a) Remodeled and computed (FEA) and (b) Design stress verification after second optimization.

5. Conclusions

Topology optimization based design may provide more freedom to change design than conventional design for structural products. In this era of additive manufacturing, in particular, the designers design freedom can better be realized through topology optimization that results in possibilities of fabricating parts at low cost and lightweight. However, there still exist remaining challenges in the topology optimization process to make it effective and user friendly. Among these, the existing optimization algorithms are not yet fully capable to smooth the geometry that remains after optimization, which appears natural than a model defined by modelling functions. Though the considered case for topology optimization is simple and intended only to apply the optimization procedures on a practical example, the case study reported in this paper has demonstrated that topology optimization is a powerful design concept that can reduce the weight of structural products. Among others, reduction of weight can save large amount of material, processing energy and hence cost of the product.

As demonstrated by the case study, the weight reduction of approx. 73% implies a significant achievement in terms of products that require lightweight design such as in aircraft component design. Because the finally optimized geometry can be of irregular and complex shape, it is possible to conclude that real optimized design can be realized only through application of AM technology.

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