A Benchmarking Analysis of Commercial Software for Topology Optimization in Industrial Applications

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Abstract. Topological optimization and generative design are methodologies that can reduce the weight of aerospace and automotive components without worsening stiffness, strength, or natural frequency. The obtained shapes are typically based on complex geometries and can hardly be obtained using traditional working processes, such as chip removal machining; additive manufacturing technologies should be used instead. Several commercial tools are available to design lightweight structures, providing different results when optimization is performed to reduce mass while preserving stiffness or strength. In this paper, a case study is shown to support the wide variety of shapes that can be obtained, and an interview among experts in the field has been carried out to understand the motivations underlying the preference for an optimized model over another one. Those comments can be helpful for software developers to match the users' requests better and develop the new generation of CAD systems capable of handling lightweight complex shapes.

Keywords: Lightweight Structures · Additive Manufacturing · FE analysis · Aerospace · Automotive

1 Introduction

1.1 The Need for Lightweight Structures and Their Impact on the Environment

Climate change is pushing modern industry toward a reduction of CO_2 and pollutant emissions. Transportation, particularly commercial aviation and ground transportation, is responsible for significant pollutant emissions [1]. The shift toward electrification is a solution found in ground transportation [2]; however, due to the low energy density of batteries compared to fossil fuels, weight reduction can be helpful to increase the autonomy. At the same time, civil aviation regulations require a longer path towards adopting electric propulsion with energy carried in batteries or hydrogen cartridges. During the 41st International Civil Aviation Organization (ICAO) Assembly, in October

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2022, Member States approved a collective long-term global aspirational goal of net-zero carbon emissions by 2050. Also in aeronautics, one of the ways to reduce emissions is based on the reduction of weights [3]: in this way, the energy stored in batteries can allow longer operations, and in the case of aircraft, a reduction in Maximum Take-Off Weight can be obtained, reducing consumption. On the other hand, structural integrity must be ensured in ground and air transport, especially where strict regulations must be followed to ensure airworthiness. Weight reduction is a key factor that can contribute to reducing emissions because of the low need for batteries, which require rare materials such as lithium, and whose disposal after the end of life is critical. Also, in the case of the adoption of fuel cells, weight reduction is beneficial to the reduction of the size of the power system. Therefore, modern engineering should be focused on the design of lightweight structures to reduce the footprint on the environment. In this framework, Additive Manufacturing (AM) might contribute by allowing the production of geometrically complex structures, where the stress is constant, thus obtaining structures where all the material used contributes to the strength of the component. Moreover, especially in the case of complex parts, AM solves the problem of a massive reduction of scrap materials. For instance, it is pretty standard for aeronautical parts machined with the milling process to have a final mass of the component that is 10% the mass of the slab bought before chip removal.

1.2 Topological Optimization and Generative Design

In recent years, new manufacturing processes based on adding material layer-by-layer instead of chip removal machining or casting have been developed under AM. Using AM, the design has a higher freedom than traditional machining processes [4], and complex lightweight structures imitating nature can be obtained. On the other hand, software tools need to be used to optimize the shapes. Topology Optimization (TO) is a numerical process [5] in which a volume is defined where material is allowed [6], zones with constraints and forces are determined, material properties are set, and Finite Element analyses (FE) are carried out to understand where material can be avoided and where it is necessary. Techniques such as filtering are often used to prevent sparse material [7]. Usually, the compliance is minimized, constraining maximum levels of stresses, stiffness, or natural frequency. SIMP or BESO algorithms [8] are typically implemented in TO codes. Some years ago, unsmoothed parts were obtained, requiring a further re-modelling of the part based on the outcome of the TO process. More modern software provides outputs that can be processed in AM machines. For aeronautical [9] and automotive [10] applications where regulations should be complied with, TO parts are manufactured using metallic powders (*e.g.*, TiAl6V-4, Inconel 718, AISI 304, AlSi10Mg, AlSi12Mg) or plastic materials capable of passing Smoke, Flame, and Toxicity (FST) tests, such as ULTEM 9085 or ULTEM 1010. Regarding AM processes, Direct Metal Laser Sintering (DMLS) can be used with metallic materials, and Filament-Fused Fabrication (FFF) [9] can be used with polymers. On the other hand, under the name Generative Design (GD) are intended optimization processes where not only FE analysis drives the shaping, but also Artificial Intelligence, or preset geometric schemes.

2 Evaluation of the Software

On the market, several software packages allow additive manufacturing design using TO or GD algorithms. SolidWorks shows a TO module, CREO from PTC implements Generative Design, Altair offers Inspire, and Solid Edge embeds a GD module for TO. Where not present, TO codes can be added to CAD, such as for FreeCAD, where at the University of Bologna, a routine in Python based on the BESO approach and Calculix has been developed.

However, all the software provides different solutions, as the following case study will show. An actual lever, which can be found on the main rotor of an EASA CS27-certified helicopter, has been considered. A simulation was conducted to evaluate optimization scenarios using three commercial software packages whose names were not given to avoid commercialism. The material is a 6000-series aluminum alloy, while the default automatic mesh density settings suggested by the software have been set without any intervention.

The loads and constraints are depicted in Fig. 1: a) a concentrated force (F1) of 5000 N is applied to the lug-pin connection, b) while an equilibrating load (F2) of 5728 N is applied to the housing of the opposite pin, finally, c) a fixed constraint is imposed to the central pin housing.

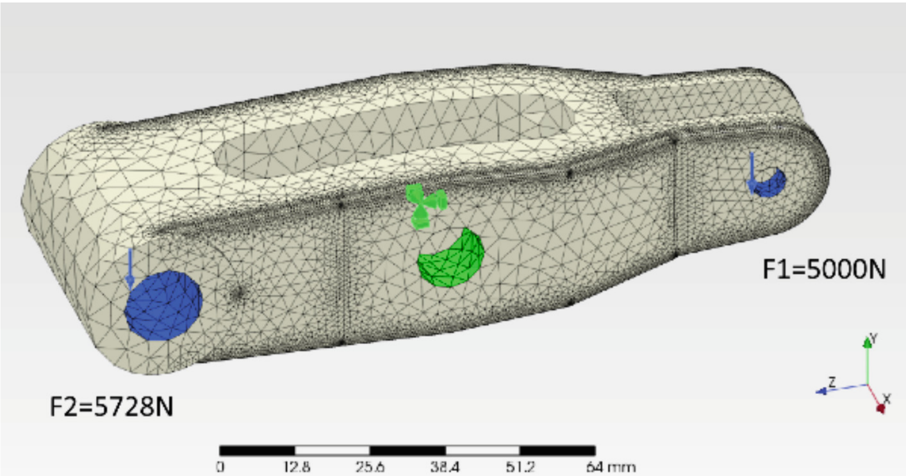

Fig. 1. Load scheme for an aeronautical component

At first, a static FE analysis has been carried out using different software to evaluate the most critical zones and the stress state in the part. Figure 2 shows the displacement field and the deformed shape, while Fig. 3 shows the equivalent von Mises stress contour plot.

Values of the maximum displacement of 0.2097, 0.2269, and 0.2021 mm have been evaluated in the three FE software. Moving to the von Mises stresses, the maximum values are noticed in the same *locus* (*i.e.,* at the pin-lug connection) and they equal 137.6, 144.9, and 130.0 MPa, respectively.

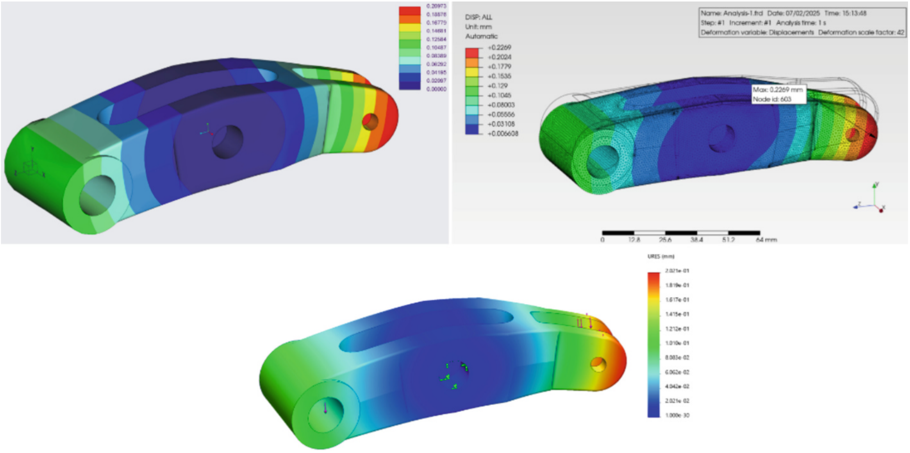

Fig. 2. Displacement field collected from the three FE solvers.

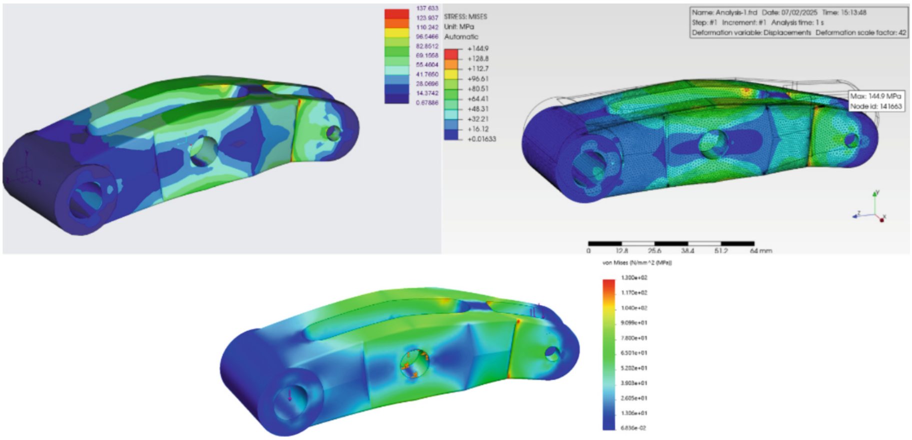

Fig. 3. Equivalent von Mises stress contour plot evaluated from the three FE solvers.

In the following, two TO approaches were carried out using three commercial software programs and adopting the reference geometry previously analysed. The first method aims at reducing the mass of the part by 40% while maintaining compliance as high as possible (from 215.6 g to 0.129.4 g); the results obtained are listed in Fig. 4.

The second topology optimization was set up by reducing the component mass since the maximum stress value was below 130 MPa. Under this assumption, the final mass of the part becomes 102.8, 108.0, and 113.0 g for the three solvers (Fig. 5).

Table 1 details some data about the simulations carried out. Preset settings suggested by default were adopted, provided convergence was reached and the time necessary for the simulation was lower than an hour. Six simulations were run, namely best stiffness with a reduction of mass, and mass reduction up to reach a threshold stress, using software

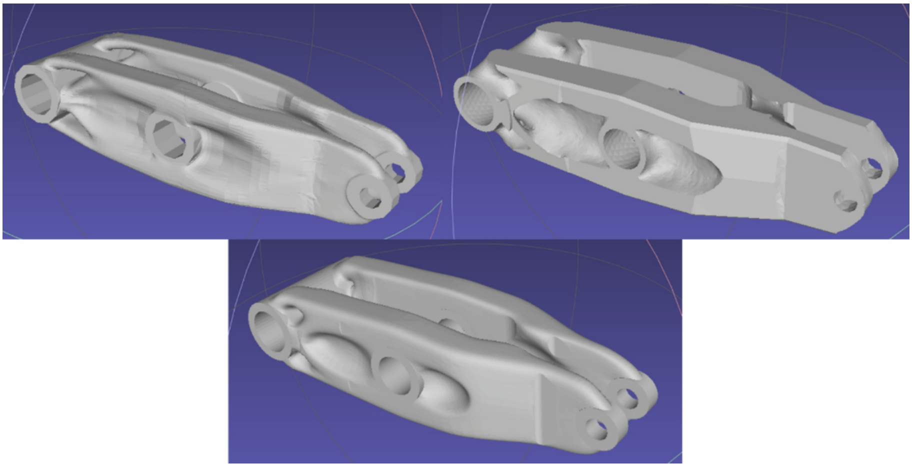

Fig. 4. Shapes after a reduction of 40% in mass, and maximum stiffness

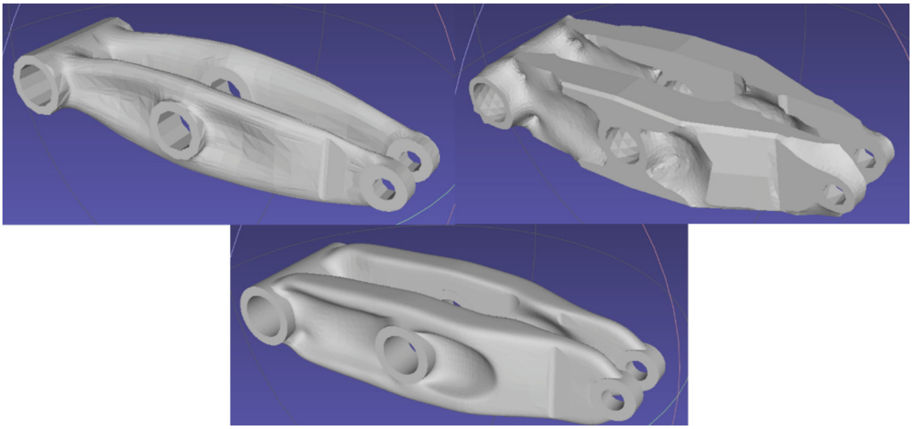

Fig. 5. Shapes after a reduction of mass up to a maximum stress equal to 130 MPa

#1, #2, and #3. The workstation used in the simulations was equipped with 32 GB of RAM and an i9 processor.

Table 1. Data for simulations carried out.

Software and type of Test	Element Type, count	Computational time [s]
#1, −40% mass	Tetrahedral, 109087	79
#2, −40% mass	Tetrahedral, 95435	181
#3, −40% mass	Tetrahedral, 74000	63
#1, max stress ≤130 MPa	Tetrahedral, 42460	502

(*continued*)

Table 1. (*continued*)

Software and type of Test	Element Type, count	Computational time [s]
#2, max stress $\leq$130 MPa	Tetrahedral, 32362	1440
#3, max stress $\leq$130 MPa	Tetrahedral, 247000	92

3 Interviews Among Engineers

As the case study described in the previous section shows, the TO output differs from a geometrical point of view, even if the target requirements are reached in all cases. Consequently, the user should evaluate which is the best shape to consider for further analysis and manufacturing. To understand the driving considerations, an interview was conducted among practitioners in the field of AM.

Table 2. Score distribution for the evaluation of driving factors towards the choice of the best optimized part to be produced in AM

Driving factor	1^{st} choice	2^{nd} choice	3^{rd} choice
1) Constant diameter legs	1	2	
2) No zones critical for fatigue	2		
3) Low request for support material	1	2	2
4) Preservation of flat surfaces		2	
5) Aesthetically appealing (symmetry)		2	1
6) Best value in the highest stiffness or lower mass with the specified stress	2		2
7) No sparse material			3
8) Reduced overall dimension	2		

Eight engineers in the aerospace and automotive sectors have been interviewed, asking which of the three driving factors is, and asking to rank them. Table 2 lists the factors and the times they are set as the 1^{st}, 2^{nd}, or 3^{rd} driving factors (n_{1st}, n_{2nd}, n_{3rd}). Finally, an equivalent score for each single Driving factor is obtained, using this formula:

$$\text{Driving Factor Score} = 3 * n_{1st} + 2 * n_{2nd} + 1 * n_{3rd} \tag{1}$$

Figure 6 depicts the outcome of the statistics, dividing answers by choice (1^{st}, 2^{nd}, and 3^{rd}), while Fig. 7 shows the final ranking obtained using Formula (1) for equivalent score.

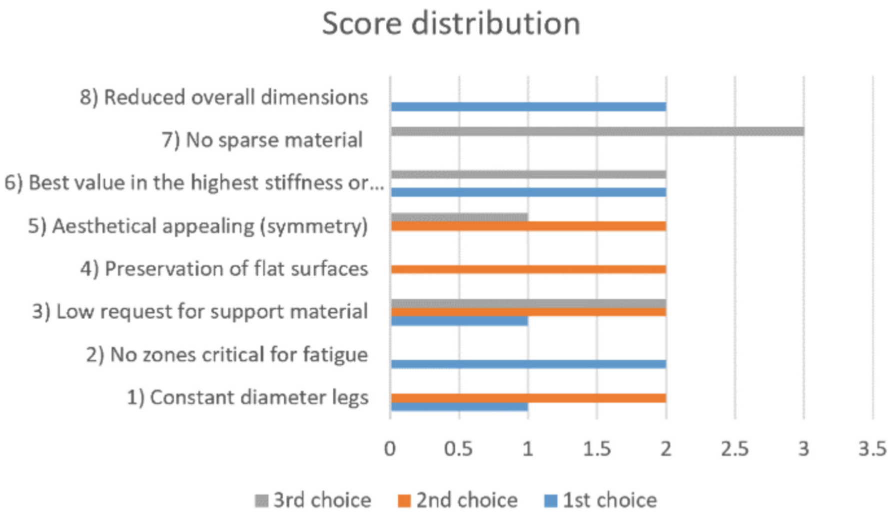

Fig. 6. Score distribution (1st, 2nd, 3rd choice) for factors driving engineers towards preferring an optimized shape for AM instead of another one.

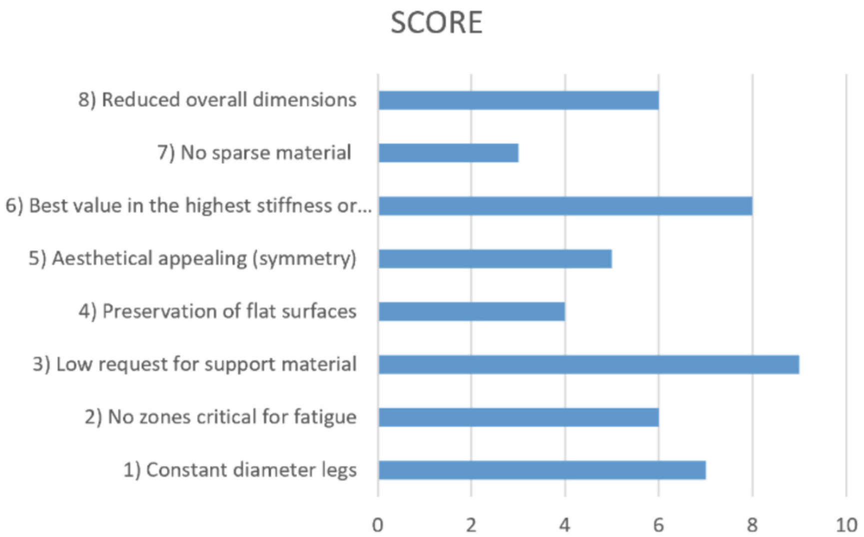

Fig. 7. Ranking of the selection choices for topologically optimized models for AM

As a general comment on the interviews carried out, aerospace engineers are keener on ranking the problem of fatigue as the most important. In contrast, automotive engineers consider reaching the best in maximizing the stiffness or reducing the mass, with the specified stress being more critical in selecting the best choice. Engineers who take care of the manufacturing also consider essential problems related to supports or the presence of a flat surface in a body to allow easy orientation in the building base of the AM machines. The requirement related to geometrical shapes, where connecting legs (ligaments between bulky zones) are of constant diameter, reached a good score: this is mainly because constant diameters tend to avoid too thin elements that may be hard to manufacture and become a weak area of the part.

4 Conclusion

Lightweight structures can alleviate the problem of high emissions in aeronautics, while in the case of automotive applications, they can increase the autonomy of electric vehicles. Structural optimization aims to reduce components' mass while preserving the maximum stress, stiffness, and natural frequencies. The case study suggested that software packages on the market fulfill similar target values when the optimizations are carried out. The users (typically engineers) select the best optimized shapes based on criteria not included in the optimization settings, mainly based on personal impressions and experience. The capability of reaching an optimized mass to preserve maximum stress in the part is secondary to factors such as the need for support. The new generation of commercial structural optimizers should also consider factors such as fatigue resistance, presence of support materials, and thin elements, which engineers regard as of straightforward importance. Further scientific research is required to translate those essential requirements into the optimization loop. This paper suggests that software houses implement further settings to control fatigue and manufacturability during the optimizations, and confirms that commercial software packages can inspire efficient lightweight geometries for structures.

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