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Computer-Aided Design AND APPLICATIONS

Case Study of Lightweight Design of a Fixture Using Generative Design Tools

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Abstract. This paper presents the state of the art in the field of lightweight design of industrial components, in particular fixtures for measuring an automotive wheel suspension arm. The application is carried out using the Generative Structural Design method in 3DEXPERIENCE software, where three case studies were subjected to the process. In the first case study, the nylon PA12 material designed for MultiJet technology was used to construct the component. In the second case study, ASA material designed for fused deposition modeling was used to construct the part. In the third case study, the AlSi10Mg aluminum alloy designed for direct metal laser sintering was investigated. All components were subjected to the same process of topological optimization and generative design process in the current innovative software.

Keywords: Generative design, 3DEXPERIENCE, ASA, Nylon, PA 12, Aluminium alloy
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1 INTRODUCTION

Additive manufacturing (AM) processes utilize a computer-aided design (CAD) file, which is subsequently transformed into a stereolithography (STL) file. During this procedure, the CAD software's drawing is approximated using triangles, and the resulting model is sliced into layers, with each layer containing the necessary information for printing. The main parameters evaluated in the design process are production time and costs. The possibilities for designing and manufacturing parts using AM are in the current stage limitless, leading to further development of next-generation software programs that allow designers and engineers to create parts for a wide range of different industries. Increasingly, modelling methods such as topoplogy optimization (TO) can be used to achieve alternative parts that provide advantageous solutions in terms of strength-to-weight ratio.

Design tools for AM have already been integrated with various existing software platforms such as Catia, Solidworks, Inventor and also NX. In addition to these adaptations there is a growing number of standalone software programs specifically developed for TO or internal structure creation. A prime example of such next-generation design software is nTopology [1,2].

Fixtures are employed to align, position, and secure the workpiece while it undergoes machining, inspection, and assembly processes. The primary demands for fixtures include achieving precise alignment, positioning and securing that meet the specifications of the machining operations. For many years, these fixtures have traditionally been fabricated by machining metal components and subsequently welding or assembling them together. The production often requires lightweighting, primarily due to the potential stresses associated with handling and maneuvering. As a result, some metal fixtures are being replaced by plastic alternatives. While AM is already used to some extent in this area, there are only a limited number of applications that combine AM and TO, specifically in the area of fixture manufacturing and development [3,4].

Designing jigs is a challenging task that requires extensive experience as a designer and comprehensive product knowledge. It can often take several days or longer to complete. The expenses associated with traditional fixtures can represent a significant portion, from 10% to 20%, of the total manufacturing cost. These costs include their manufacture, assembly, operation, and design.

The utilization of printing technology can play a vital role in eliminating obstacles and facilitating broader adoption of fixtures in the manufacturing sector. The rapidly expanding professional 3D printing industry offers manufacturers unprecedented opportunities by providing them with a dependable, cost-effective, and versatile solution. This enables manufacturers to explore new avenues and embrace the advantages of additive manufacturing in their processes.

Compared to the conventional CNC machining process, 3D printing offers several advantages. Firstly, it integrates seamlessly with the digital model creation process, reducing time consumption. In addition, it allows for real-time design changes and enables 3D printing production to be resumed within a day. The cost reduction is significant as professional 3D printers require less manpower-assisted supervision compared to CNC machining. In addition, 3D printing is compatible with a wide range of thermoplastics, including a variety of colors. This compatibility, combined with the capabilities of dual-extrusion 3D printers, gives designers the freedom to print fixtures using multiple materials. This feature is especially valuable when color visibility is required or when soft materials are needed to prevent scratching the part [5,6].

It can be assumed that the field of AM will develop at a high speed in the coming years. In industry, fixture printing can also be combined with the aforementioned TO, mainly due to the functional properties of the fixture and the cost-effectiveness in terms of material wastage.

In general, TO and generative design (GD) can be considered as design tools that improve workflows and processes while pushing simulation capabilities to an earlier stage of product development and subsequently providing reliable models of lightweight design. The main fundamental difference between GD and TO is in the process of generating and creating the final shape, whereas in GD a volume is gradually created in space and in TO it is taken from an already existing and predefined volume [7,8,9]. GD sometimes referred to as Generative CAD or Bionic Design and it is an important part of the Design for AM.

2 APPLICATION OF STRUCTURAL GENERATIVE DESIGN

Structural Generative Design is module in the 3DEXPERIENCE software which offers a wide range of applications. In this module, topological optimization can follow three different strategies:

1. maximize stiffness with respect to a specified component weight
2. minimize the weight while respecting the constraints
3. maximize the value of the lowest natural frequency for a given component weight

For strategies 1 and 3, the desired weight of the generated optimized component has to be defined before the actual optimization.

The model used in the following application for TO is a fixture designed like support to measure the suspension arm of a car wheel. The original construction of the fixture was a 20 mm thick aluminum plate. The plate further contained 5 aluminum standing elements which had to be mounted on the plate. The beds at the end of these standing elements are designed in steel as they are harder and more durable compared to aluminum. The arm model is attached to the fixture using 4 attachments. The design of the beds and the clamping force of the grips prevent unwanted movement of the model during the measuring process. The fixture also included holes for handles and easier handling. The original construction of the fixture is shown in Fig. 1(a).

The process in the software to achieve the optimum shape of the part while maintaining sufficient rigidity at minimum or reduced weight would be the same for all three materials. The process begins by defining the basic shape of the automotive wheel suspension arm, which has been influenced by the following limiting factors:

- Dimensions of the suspension arm of a car wheel
- Functional areas fixing the arm
- Minimum height of the fixture
- The range of the measurement device

3 TOPOLOGY OPTIMIZATION IN 3DEXPERIENCE SOFTWARE

The first step in this process is to define the volume that represents the boundary space (exploration envelope) of the fixture placement. The result is an object in the space of the form of a cube-shaped object with recesses that allow gripping handles and contact measurement of the functional areas of the component using the measuring arms. The functional surfaces on which the part will be placed are subsequently cut. These areas must remain untouched from the TO point of view and must be designed with maximum precision. Pre-prepared functional areas are set like „Region to preserve" in the Structural Generative Design in the 3DEXPERIENCE software shown in the Fig. 1(a) and Fig. 1(b). The result of this part is a configured model, the so-called semi-finished model with radius, which represented the largest design space required for the part shown in the Fig. 1(c).

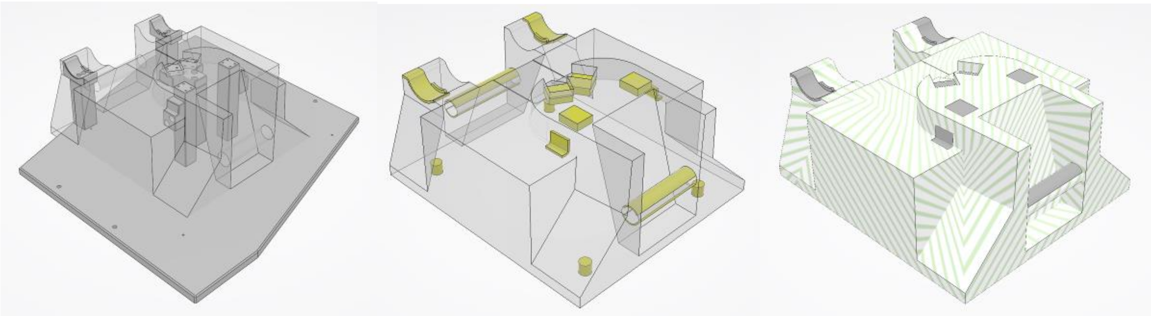

Figure 1: (a) Regions to preserve, (b) Preserved regions with functional areas (yellow color) (c) Semi-finished model.

The second step is to apply loads and constraints as shown in the Fig. 2. The software allows us to specify different boundary conditions, which are further combined in different load cases as required. When applying loads, functional areas must be omitted, and loads can only be applied using static quantities. Dynamic loads are only used to a limited extent in the AM process due to the fact that this area is not sufficiently researched. Dynamic loads and gravity present a limitation with respect to a system solution, the results of which could converge to incorrect values.

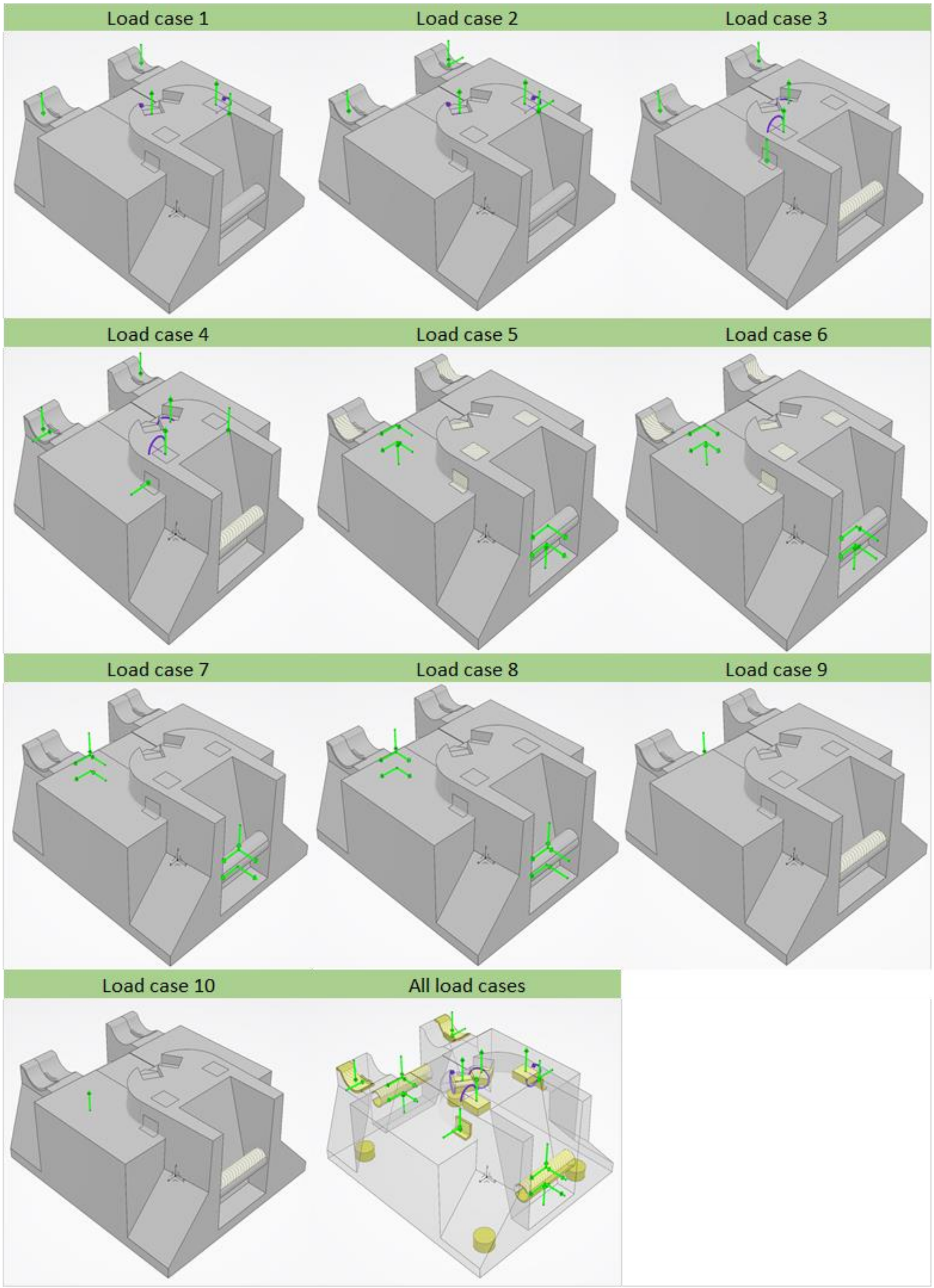

Figure 2: Representation of all load cases considered.

The main essence of TO in the 3DEXPERIENCE software are load cases, which allow several FEA analyses to be combined. The following Tab. 1. lists the forces and torques in all axes of the coordinate system determined for the different load cases. The main advantage of using this process is that it is possible to test several load situations simultaneously and thus evaluate the optimum shape of the component. The parameters determined were conditioned on actual observed values when either measurement or handling of the fixture was involved. The force parameters were derived from the weight of the component and the necessary fixing forces of the clamping element. Loads and forces were applied according to whether it was an Absolute Axis System (AAS) or Local Axis System (LAS) as shown in the Fig. 3.

Loads	Axis system	Axis of action	Values	Load cases									
				LC 1	LC 2	LC 3	LC 4	LC 5	LC 6	LC 7	LC 8	LC 9	LC 10
Force 1 [N]	AAS	z	-220	x	x		x						
Force 2 [N]	AAS	x	110		x								
Force 3 [N]	AAS	z	100	x	x								
Force 4 [N]	AAS	z	100	x	x								
Torque 1 [Nm]	LAS 1	x	1.86	x	x								
Torque 2 [Nm]	LAS 3	x	3.59	x	x								
Force 5 [N]	AAS	z	-220			x							
Force 6 [N]	AAS	x	-110				x						
Force 7 [N]	AAS	z	100			x	x						
Force 8 [N]	AAS	z	100			x	x						
Torque 3 [Nm]	LAS 4	x	1.86			x	x						
Torque 4 [Nm]	LAS 2	x	3.59			x	x						
Force 9 [N]	AAS	z	150					x	x				
Force 10 [N]	AAS	z	150					x	x				
Force 11 [N]	AAS	z	-150							x	x		
Force 12 [N]	AAS	z	-150							x	x		
Force 13 [N]	AAS	y	50					x		x			
Force 14 [N]	AAS	y	-50					x		x			
Force 15 [N]	AAS	y	-50						x		x		
Force 16 [N]	AAS	y	50						x		x		
Force 17 [N]	AAS	x	50					x	x	x	x		
Force 18 [N]	AAS	x	50					x	x	x	x		
Force 19 [N]	AAS	z	-50									x	
Force 20 [N]	AAS	z	50										x

Table 1: Forces shown for the absolute axis system and the local axis system, also displaying possible load cases used in the TO.

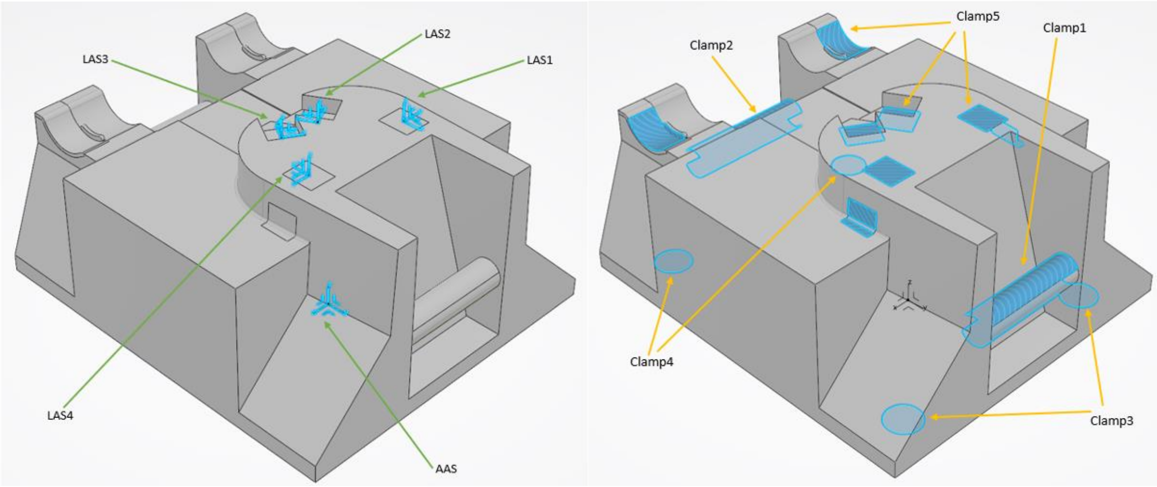

Figure 3: (a) Display of all load cases considered on the selected fixture, (b) Display of fixing forces of the clamping element.

The third is the user settings, which depend mainly on the desired result and the shape of the optimized part. This part of the procedure involves the creation of a network that divides the component into smaller units. The size of the mesh elements for all the above materials was increased to 9 mm so that the total number of mesh elements was optimal, and the simulation time was only a few hours, as shown in Fig. 4(a) and Tab. 2. The model further takes into account the weight of the fixture itself as well as the weight of the component intended for the fixture while maintaining the fixture dimensions of 330x330x150mm. The coefficient of friction varies depending on the material. This step also involves evaluating and determining the possible situations to which the fixture will be subjected, such as 90 to 180-degree rotation, tilting, and similar manipulating positions. In the following sections, the design of the fixture shown in Fig. 4(b), will depend on the material chosen for manufacture, which significantly affects the weight and final shape.

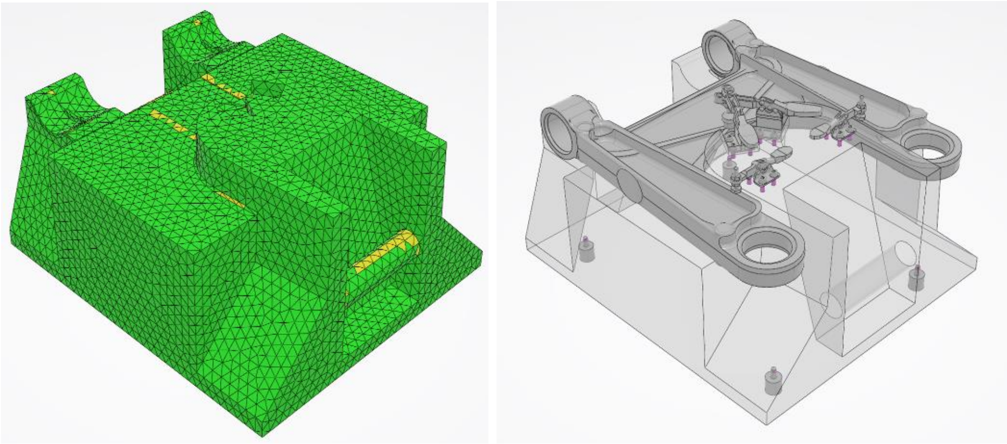

Figure 4: Application of wheel suspension arm.

Meshing information								
								Quality
Criterion	Good		Poor		Bad		Worst	Average
Aspect ratio	107096	99.93%	72	0.07%	6	0.01%	14.706	1.444
Maximal angle	107164	99.99%	10	0.01%	0	0.00%	164.232 Deg	93.773 Deg
Minimal angle	107138	99.97%	36	0.03%	0	0.00%	5.361 Deg	52.317 Deg
Skewness	107125	99.95%	49	0.05%	0	0.00%	0.002	0.801
Stretch	106809	99.66%	364	0.34%	1	0.00%	0.1	0.771
Global (107174)	106780	99.63%	387	0.36%	7	0.01%		

Connectivity	
Number of analyzed meshes	1
Total number of nodes	153662
Total number of elements	107174

Failed criteria	
Criterion	Failed elements
Aspect ratio	6
Stretch	1
Total	7

Table 2: Meshing information.

The fourth step is to start the TO process after defining all the necessary parameters. The result of the TO is a raw fiber model that will be used in the following steps. The model is then modified not only to reduce weight and simplify the shape but also to make the resulting design attractive to the customer.

Since the result of the optimization is a raw component shape with the number of unnecessary material, it is necessary to modify the model in the last step. The basis of the modification is to create surfaces with circular diameters that are an approximation of the fibers of the raw model. For clarity and simplification of the process, the raw model is divided into several parts. The method of generating individual fibers is based on drawing lines of the approximate diameter of the support circle on the fibers of the raw model to form an irregular cylinder surface. The individual surfaces can be modified by sliding portions of the support surface mesh. In order to achieve a smooth connection of the fibers with the functional surfaces of the model in the final modeling steps, approximate surfaces representing the functional areas for an automotive wheel suspension arm placement were created.

To implement and use the fixture, the functional fixing surfaces would need to be adjusted to the exact dimensions for all materials. In real production it is possible to use e.g., a milling cutter suitable for the selected material for this process. In order to achieve the best material properties, it is necessary to remove the material gradually and with a small layer height in the machining process of the part to avoid damaging the 3D printed part. The smaller the layer that is removed, the lower the forces generated during machining and the less likely the part is to be damaged. The tool must have suitable parameters for machining the material to avoid damaging it.

3.1 Nylon PA12

Nylon Pa 12 is often used in the AM due to its pliability and ease of melting in the manufacturing process. In addition to being environmentally friendly, it also has advantageous mechanical properties such as good durability, flexibility and surface smoothness, while maintaining good precision and excellent abrasion resistance. The disadvantage of the material is that it is hygroscopic and has material anisotropy, which severely limits its use for more complex applications. The combination of Nylon Pa 12 with a multi-jet fusion printer brings advantages in terms of speed and accuracy [11]. In optimizing this material, the weight of the component was changed from a raw blank weighing 10.4 kg to 2.5 kg. The advantage is the strength of the parts printed with this technology, but also the flexibility that the material is able to retain. The post-processing time of the fixture shown in Fig. 5 can be adjusted to 4 hours to achieve optimum. Fig. 5(a). shows the TO process as a raw component without any modification. Fig. 5(b). and Fig. 5(c) show the result of TO after adjustments using the 3DEXPERIENCE software.

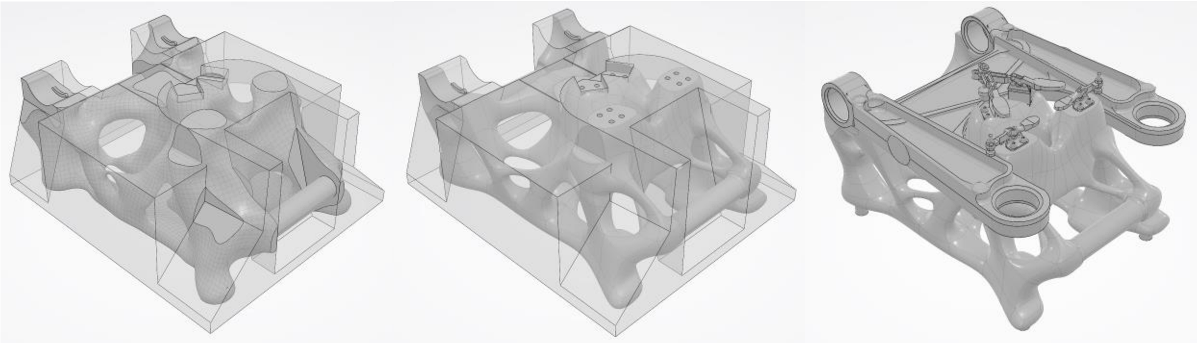

Figure 5: (a) Raw component after TO (b) Component after TO and modifications (c) Application of the fixture.

3.2 ASA

The material, referred to as ASA, stands for acrylonitrile-styrene-acrylate, which is a substitute for ABS material for use in 3D printed parts, with its main advantage being better resistance to temperatures at which the material does not degrade during cooling [10]. The material is used in combination with fused deposition modeling (FDM) technology, in which the filament is essentially heated to a temperature just above the melting point of the material. When the filament reaches the molten state, the material is extruded through the nozzle of the 3D printer [12]. In optimizing this material, the weight of the component changed from a raw blank weighing 11.1 kg to 2.97 kg. The fixture was, after optimization, subjected to modifications, as shown in Fig. 6.

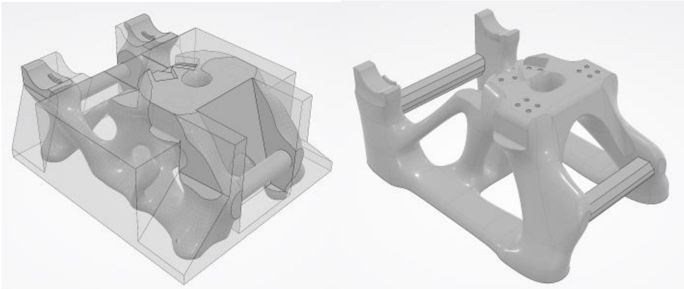

Figure 6: (a) Raw component after TO for ASA material (b) Component after modification for ASA material.

3.3 Aluminium Alloy

3D printing of aluminum is achieved using direct metal laser sintering (DMLS) technology, combining good thermal properties, while the weight of the printed parts is lower compared to steel. The aluminum parts are created by sintering the powder using a powerful laser beam, which ensures excellent bonding of the layers, but the disadvantage is the explosiveness of the aluminum powder in the 3D printing process. In optimizing this material, the weight of the component changed from a raw blank weighing 27.3 kg to 3.4 kg, so the greatest weight reduction can be observed with this material. The reduction of the material and the modification of the raw component is shown in Fig. 7.

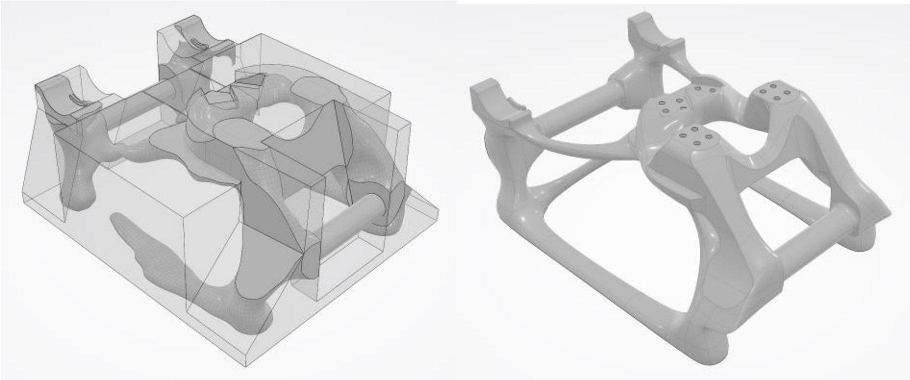

Figure 7: (a) Raw component after TO for Aluminum Alloy (b) Component after modification for Aluminum Alloy.

4 RESULTS

The aim of the study was to illustrate the impact of advanced tools and programs in TO on real applications. The achieved results clearly show the possibility of accelerating the development of fixtures at their current reduced weight. FDM printing remains the cheapest technology to produce a wheel suspension arm, but the disadvantage of this technology is clearly the high height of the deposited layer. The largest difference in weight between the raw blank and the final optimized component can be observed especially in the case of aluminum materials and DMLS technology. Tab. 3 shows a comparison of prices for different technologies in terms of the whole production process.

Type of manufacturing and material	Quotation					
	Design			Manufacturing [€]	Post-processing [€]	Total [€]
	Duration [h]	Costs [€/h]	Overall design costs[€]			
Milling-AlSi10Mg	40	35	1400	1100	0	2500
DMLS-AlSi10Mg	10	50	500	12500	200	13200
FDM-ASA	13	50	650	550	150	1350
MJF-PA12	12	50	600	1650	150	2400

Table 3: Production process.

Problematic from the process point of view is the limitation of the software to work with only four cores, which considerably lengthens the simulation process and the length of the computation. This problem can be solved by purchasing a license to work with more cores but this affects the resulting price for the use of the software. Another problem in terms of software setup concerns linear network elements. The software also offers the option of using a linear mesh, but this does not accurately display curved edges and surfaces. Therefore, for better convergence of the results, it is preferable to use a quadratic mesh, which is relatively less sensitive to deformation of the elements and gives better results. However, the disadvantage is that it is also computationally demanding.

The last limiting factor in terms of settings is the restriction of the optimization to low maximum voltages, which is shown in Tab. 4. Although aluminum can have a relatively high yield strength, the optimization option is only set to 5 MPa. This is influenced by the large difference between the stress induced by the applied load and the actual stress that the material would be able to withstand. In order to load a given material to larger stress values that approach the inter-material yield stress, we would also need larger emergent forces acting on the fixture in service. Tab. 4. illustrates the weight of the components with and without considering the region to preserve as shown in the row mass to optimize.

Topology optimization	
Model configuration	1 parts to optimize
Regions to preserve	16 of 17
Loads	24
Restrains	5
Load cases	10
DMLS (Direct metal laser sintering) - AlSi10Mg	
Mass to optimize	26.995 kg of 27.273 kg
Stress constraints	max 5 MPa
Shape control	YZ plane
FDM (Fused deposition modeling) - ASA	
Mass to optimize	11.036 kg of 11.115 kg
Stress constraints	max 10 MPa
Shape control	YZ plane
Manufacturing control	max overhang angle 45°
MJF (Multi jet fusion) - PA12	
Mass to optimize	10.321 kg of 10.395 kg
Stress constraints	max 15 MPa
Shape control	YZ plane

Table 4: Comparison in terms of mass and stress constraints.

5 CONCLUSION

In conclusion, to summarize the topic, it was necessary during the process describe the basics of TO and the principle of GD in the lightweight design case study. The current state of the art in the design and manufacture of fixtures was provided. In the next part of the study, the software that was used to lightweight the fixture using TO was described. Three different types of materials and technologies were used and compared in the results. The results highlighted the challenges but also the advantages of each technology. Lightweighting the fixture with TO in this respect offers advantages particularly in terms of reducing part complexity and eliminating assembly processes. A comparison of several materials in terms of weight and cost options was presented in the paper. Another advantage is the possible substitution of the aluminium fixture by a plastic one, thus improving the factor affecting recycling, which is currently more difficult for aluminium components compared to plastic ones. The reality in this area of fixture design is that there is no need to deal with tolerance chains, as the model is produced as a single piece on which the fasteners are retrofitted. However, in the future, it is necessary to select the appropriate type of fixture for the above application. Particularly suitable are fixtures intended for measuring of production inaccuracies.

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