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A Comparative Study about Topology Optimization and Generative Design in Additive Manufacturing

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Abstract: Manufacturing industries and investors in the aerospace area have been searching for improving techniques to achieve lower cost, weight, energy consumption, and expanded capability of them. Conventional and advanced methods in manufacturing are used with some optimization techniques in the aerospace industry to produce lightweight parts with cost-performance efficiency. Also, the usage of plastic parts is increasing in aerospace applications. So, conventional metal parts have been gradually replaced by optimized plastic/metal parts in the aerospace industry with the help of additive manufacturing (AM) technologies and advanced optimization techniques such as topology optimization (TO) and generative design (GD). In this area, AM is the most effective manufacturing technology because of its excellent capability to generate complex geometries with less material waste and less leading time than conventional methods. This study aims to define the capability of TO and GD methods to decrease aerospace parts' weight. The workpiece was designed as a simple bearing model of armrest for the passenger seat. TO and GD methods were used to generate new, lightweight models, and these models were built-up by Fused Deposition Modelling (FDM) desktop type 3D printer. ABS and PLA materials were used for generating 3D geometries. After comparing the results, it is recorded that GD presents more realistic results, and it saves weight 31,3 % for ABS, 40,4% for PLA material.

Keywords: additive manufacturing; generative design; topology optimization; FDM.

1. Introduction

Lightweight parts and materials are getting popular in the aerospace industry for decreasing the aircraft's overall weight, meeting increasingly stringent emission regulations, and becoming more sustainable and more fuel-efficient. Thousands of metal-based structural components exist in the aerospace industry, which traditionally adds significant weight and cost to the aircraft's final design. The lightweight parts reduce fuel consumption and CO_2 emissions [1]. Previously, magnesium or aluminum alloys were generally used in the aerospace industry to obtain lighter components and better performance than other commercial metallic materials. However, some designs currently use aluminum alloys; magnesium alloys are not used on aircraft anymore [2-4]. By having high corrosion and impact resistance, chemical stability, and being lightweight and economical, thermoplastic polymers have been increasingly used to take the place of metal brackets and other components in the aerospace industry.

One of the aircraft parts manufactured with thermoplastic material is the passenger seat's armrest, which supports the passenger's arms. The main function of an armrest is to provide resistance surface or a firm gripping for passengers to support in the protection of the passenger from damage and to push against during repositioning themselves [5]. To achieve the functional requirements, different designs and manufacturing methods can be used for the armrests. By searching existent commercial products, it can be seen that armrests generally have a metal frame connected to the seat with a metal bracket that owns a lock mechanism on it and mounted to the armrest frame, generally by a bearing that made of plastic [6-9]. Although conventional manufacturing methods such as die-casting for metal parts and injection molding for polymer parts have been used to produce the armrests, novel manufacturing methods and new materials are being developed to manufacture lightweight, functional and economical parts.

Additive manufacturing (AM) is a rapidly growing technology used in a wide range of areas, including the aerospace industry. It can be described as a computer-controlled manufacturing method with deposition of material layer by layer to obtain the desired geometry. AM technologies are divided into seven main categories by The American Society for Testing and Materials (ASTM) according to their printing method and material as stereolithography (SLA), fused deposition modeling (FDM), selective laser melting (SLM), electron beam melting (EBM), direct energy deposition (DED) and binder jet printing (BJP), powder jet fusion [PJF] [4]. AM methods can obtain complex parts with the same mechanical properties and less weight that are impossible to produce with conventional methods. Also, each process decreases the cost and production time. [4,10,11].

Topology optimization (TO) and generative design (GD) are increasingly used with AM technologies to reduce weights with less material waste. As a mathematical method, TO optimizes material layout in a given design space for given boundary conditions, then sets constraints and loads to maximize the system's performance [2]. GD is a design strategy for AM, which is commercially important. GD gives a high occasion to get optimal results despite minimal engineering effort due to the compatibility of AM methods. The designers or the engineers determine the design's objectives and constraints, and GD automatically implements algorithmic methods to satisfy these requirements [12]. Optimized models generally have complex geometries that are impossible to produce with conventional manufacturing methods due to their limitations. On the other hand, conventional methods often require post-processes (hole processing, surface finishing) to obtain the desired geometry for many designs. However, AM methods can obtain high-complexity near net-shaped functional structures without subtracting post-process [13].

Design consideration and optimization are the subjects that have been studied very hard recently. Froes F. [4] presented a study with additive manufacturing and conventional casting compound. The researcher demonstrated that the parts manufactured by additive manufacturing methods had reduced weight with the same mechanical properties due to their reduced density. However, their complex geometries are impossible to produce with conventional methods. Tomlin M., Meyer J. [14] investigated a study about TO in AM for aerospace. The researchers applied TO on the A320 nacelle hinge bracket, and they obtained a less-weight model with the same mechanical properties after optimization. Reis L., Seabra M., Araujo A., Azevedo J., Pinto E. [15] presented a study about SLM and TO for lighter aerospace components. The researchers obtained a less weight model by TO. Also, the model is tested by Instron 3669 machine, and it is found that the optimized model has the same mechanical strength as the original model. Gokce H., Sahin I. [16] investigated TO in AM for an application on the handbrake mechanism. The researchers found the ideal design for the handbrake mechanism to manufacture with the SLS method. The new design has less weight with less waste material, even with the same mechanical strength. Shi G., Guan C., Quan D., Wu D., Tang L., Gao T. [17] presented a study about an aerospace bracket that is designed with thermo-elastic TO and manufactured with the SLM method. The researchers optimized a heavy-loaded aerospace bracket using both size and topology optimization to reduce mass. Then the bracket is manufactured with AM. Duan S., Xi L., Wen W., Fang D. [18] presented a study about the mechanical performance of the 3D lattice materials that topology-optimized and manufactured with SLS. The researchers obtained results that stiffness and the strength of lattices become higher after optimization. Their work demonstrated that light-weighted lattices designed with TO demonstrate better mechanical performance.

Although research has been done about TO, there is a restricted number of studies comparing the effectiveness of TO and GD. The present study aimed to demonstrate the ability to obtain lightweight parts by TO and GD approaches in the AM process for ABS (acrylonitrile butadiene styrene) and PLA (poly-lactic acid) materials. The results were compared in terms of the part weights manufactured by the FDM process.

2. Materials and Methods

FDM printing technology is used in this study as an AM method because of the ease of printing process for PLA and ABS materials. FDM is a 3D printing technology, where a thermoplastic filament is partially heated to the melting point and extruded through a heated nozzle and deposited on a build platform layer by layer to obtain the desired geometry [4,11]. Plastic filaments in FDM printing are fabricated by manufacturers according to ISO 527, ISO 178, ISO 179 standards [19].

Based on ISO 6440 Wheelchairs - Nomenclature, Terms, and Definitions, the armrest's function is to support the passenger's arm [20,21]. Also, their size should be suited to 95% of the passenger population for the arm length's dimension. According to the standards, the length must be almost 305 mm (12 inches), and the frame width must be between 50 and 53 mm. The materials in the manufacturing of the armrest should be long-lived, waterproof, stain-resistant, non-slip, cleanable, and fire retardant. Also, the armrest should be able to base 110 Kg (the weight of the 99th percentile male) [20,21]. Based on the existing designs [6-9], the armrest's generic parts are; the bracket that carries the load on it and mounts the armrest to the seat; the frame is mounted to a bearing and covered by coating layers with other components. And the lock mechanism holds the armrest either stable or free. Some designs have a full-metallic bracket; some have a metal sheet with a plastic bearing [6-9]. In this study, the existed designs were considered for optimization, and a sample plastic bearing model in simple form was modeled. The model is shown in Figure 1. This model does not belong to any commercial design. According to ISO 6440 standard [20,21], the model dimensions were considered and the existing designs [6-9].

ABS and PLA filaments with 1.75 mm diameter were used as sample materials. ABS is a thermoplastic polymer made of acrylonitrile and polymerized styrene with polybutadiene. The best advantage of ABS on printing is the combination of the strength and rigidity of styrene polymers and the acrylonitrile with the polybutadiene rubber's toughness. 3D printing of ABS is harder than PLA because of its thermal requirements and material properties [11,22,23]. PLA is an aliphatic polyester thermoplastic that is derived from renewable resources. Being easily available, environmentally friendly, and requiring low energy and temperature for processing, PLA is the most widely used 3D printing polymer filament. PLA processing is safer and easier to use and provides a shinier and smoother appearance. Otherwise, PLA is more brittle but provides greater details than ABS. Otherwise, ABS is more flexible and suitable for engineering components [10,24].

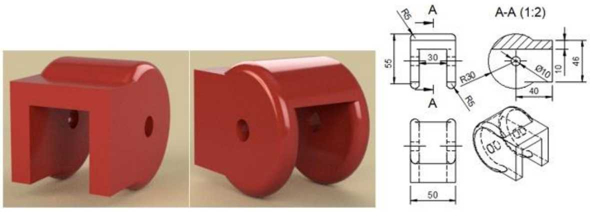

Figure 1. View of the model.

Fusion 360 software was used for the optimization process in this study. First, fixed sections and pin connections on the model should be defined for TO. Then, constraints and forces were identified. All the parameters were defined on Fusion 360 according to ISO/DIS 7176/11 "Wheelchairs - Part II: Test Dummies" [20,21]. Based on the standard, the upward force with the magnitude of 1600N was applied outward to both sides on the right and left, at 10 degrees to the vertical. The downward force with the magnitude of 1470N was applied at the front of the horizontal surface, at 45 degrees. There was also a moment with the magnitude of 329,12 N.m at pin connection because of the passenger's weight that 110 Kg [20]. The definition of the loads that were applied is shown in Figure 2.

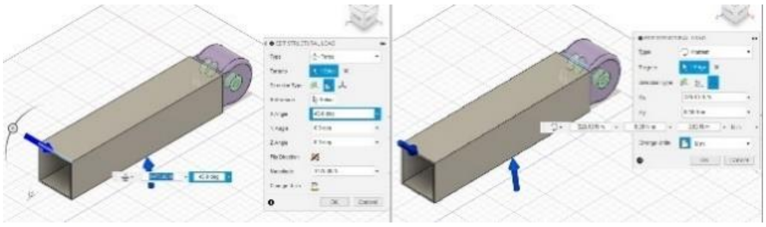

Figure 2. Definition of the test parameters for TO.

In GD, first preserve and obstacle geometries were determined based on the function of the bearing model on work. Then the simulation scene was designed for the bearing model due to the definition of the fixed sections of the part and the forces with the moments according to ISO 7176/11 for the generative design setup on Fusion 360 software. The setup can be seen in Figure 3. The manufacturing method was selected as AM, and the materials were determined. The objective was defined to minimize mass. Then AM parameters were defined. The safety factor was set to 1.5, which was used to design the parts for the aerospace industry [25,26]. The production quantity was almost 200 pcs (average armrest quantity of an economy class airplane) [27].

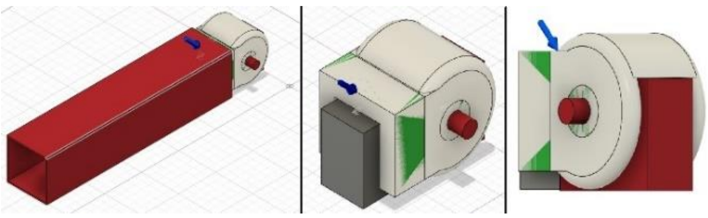

Figure 3. The optimization setup for GD.

The optimized models were sliced on the slicer software ULTIMAKER CURA 4.4, and G-codes were created for each material. The sliced views for TO and GD approaches are shown in Figure 4 and Figure 5, respectively. The models were printed with the printing parameters that are given in Table 1. Also, the estimated material weight that would be used and the estimated printing times were given in Table 2. The thermal and mechanical properties of the materials are given in Table 3 [11,28].

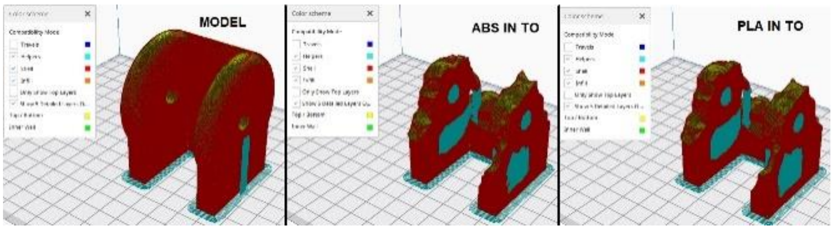

Figure 4. Sliced views of the mesh models of TO.

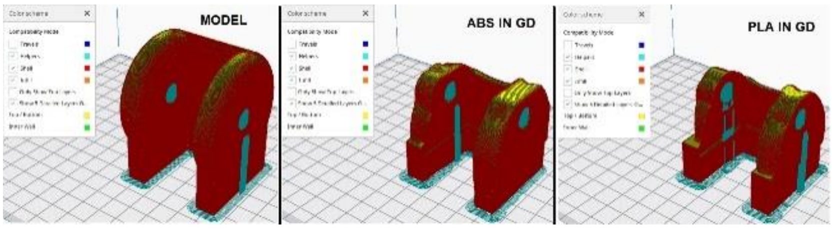

Figure 5. Sliced views of the mesh models of GD.

Table 1. Printing parameters for each material.

Parameter	ABS	PLA
Layer Height (Resolution)	0.1 mm	0.1 mm
Nozzle Temperature	240 °C	190 °C
Build Plate Temperature	115 °C	50 °C
Printing Speed	35 mm/s	50 mm/s
Infill	60%	60%
Support Structure	Yes (10 %)	Yes (10 %)

Table 2. The estimated printing times and filament weights.

Estimated Values	**Without Opt.**		**With TO**		**With GD**	
	ABS	**PLA**	**ABS**	**PLA**	**ABS**	**PLA**
Printing Time	4h 54min	3h 34min	2h 45min	2h 03min	2h 32min	2h 00min
Filament Weight	115g	108g	58g	52g	80g	70g

Table 3. Mechanical and thermal properties of the materials.

Mechanical Properties	**ABS**	**PLA**
Density (g/cm^3)	1.04	1.24
Tensile Strength (MPa)	27	37
Yield Strength (MPa)	40.96	62.63
Thermal Properties	**ABS**	**PLA**
Coefficient of Thermal Expansion (µm/m-°C)	90	68
Melting Point (°C)	220-260	190-220

The custom-made, cartesian FDM 3D printer with 200x200x195 mm of build size was used to manufacture the samples. The printer has a Bowden-type extruder, 0.4 mm nozzle diameter, 1.75 mm filament diameter, and an aluminum frame. The printing process is shown in Figure 6.

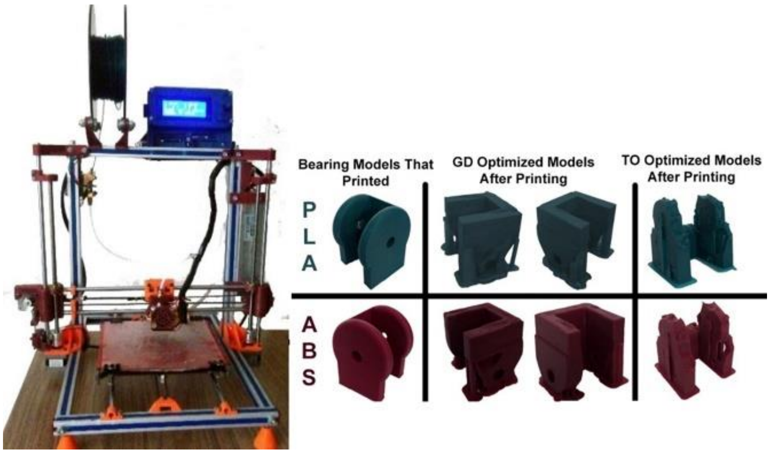

Figure 6. The custom FDM printer and the models after printing.

3. Results and Discussion

The TO results can be seen in Figure 7 for ABS and Figure 8 for PLA with the optimized mesh models. The GD results are shown in Figure 9 for ABS and Figure 10 for PLA. The volume, mass, and area values for each model were given for ABS in Table 4, for PLA in Table 5.

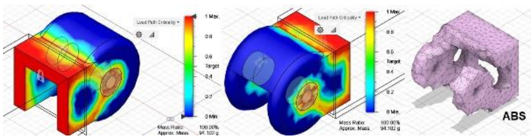

Figure 7. TO result for ABS material.

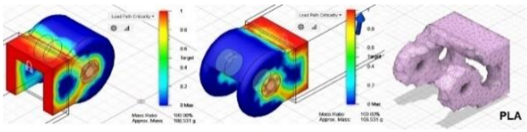

Figure 8. TO result for PLA material.

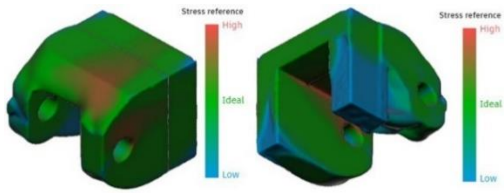

Figure 9. GD result for ABS material.

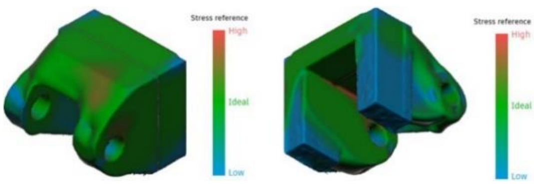

Figure 10. GD result for PLA material.

Table 4. Mass, Volume, Area values for ABS material in each process.

Value	Without Optimization	With TO	With GD
Mass	98.600 g	46.314 g	67.757 g
Area	205.603 cm^2	151.617 cm^2	154.975 cm^2
Volume	89.637 cm^3	42.103 cm^3	61.600 cm^3
Saved Weight Per Part		**52.286 g**	**30.843 g**

Table 5. Mass, Volume, Area values for PLA material in each process.

Value	Without Optimization	With TO	With GD
Mass	107.564 g	45.520 g	64.064 g
Area	205.603 cm^2	143.09 cm^2	142.165 cm^2
Volume	89.637 cm^3	37.933 cm^3	53.390 cm^3
Saved Weight Per Part		**52.286 g**	**30.843 g**

It is clear from the results that GD gives more realistic results because the setup of the optimization process is better suited to real conditions. The determination of the constraints and load forces was more detailed than TO. The optimized models built up by 3D printing can be seen in Figure 11, and the actual printing times and filament weights were recorded as in Table 6.

Figure 11. The printed models.

Table 6. The actual printing times and filament weights.

Actual Values	Without Opt.		With TO		With GD	
	ABS	PLA	ABS	PLA	ABS	PLA
Printing Time	5h 02min	3h 48min	2h 54min	2h 12min	2h 46min	2h 04min
Filament Weight	114g	109 g	58 g	52 g	81g	70 g

As shown in Table 6, GD optimized models were printed faster than TO optimized ones; however, TO optimized models weights were less. This was because of the complexity of the TO optimized parts that requires more support structure, which caused to delay in print time. It was recorded that the actual and estimated printing times and weights were different because the slicing software did not consider the calculation of the time for heating build plate and hot-end; also, the slicing software calculated weight with its constant density for materials.

It is clear from the results that TO and GD are promising approaches for decreasing part weight, which provides a reduction in fuel consumption, a decrease in CO2 emission per flight, and so more economical and environmentally friendly applications in the aerospace industry.

4. Conclusions

In this study, the application of the TO and GD approaches was determined and compared on FDM printed PLA and ABS armrests in terms of a decrease in print time and weight. It can be concluded that GO provided more realistic models with a significant decrease in print time and weight. Both approaches are promising for decreasing additive manufacturing time and final product weight, vitally important for the aerospace industry.

In further studies, it would be better to apply these TO, and GD approaches in different AM technologies for developing AM technologies, both for metal and polymer parts with different designs. So, it will be possible to optimize the AM processes, decrease manufacturing time, and support the technology to become suitable for mass production.

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Conflicts of Interest

The authors declare no conflict of interest.

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