A Case Study in Topology Optimization for 3D Printing

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Abstract

Topology optimization is a mathematical method that optimizes material layout within a given design space for a given set of loads, boundary conditions , and constraints with the goal of maximizing the performance of the system. The topology optimization is used to minimize the material in a way such that it doesn't affects the function of the workpiece. This method has widely been used applications in aerospace, mechanical, biochemical and civil engineering. This study aims to see how topology optimization will affect our original design for different targeted mass percentage.

Keywords

Topology, optimization, loads, 3D Printing

Introduction

Additive manufacturing technology is unlike other traditional machining techniques, which makes it possible to produce parts with complex geometries. Additive manufacturing technology has changed the world in different directions because of its noticeable advantages to the industrial sector that has a notable impact as well on the sectors (Ahmed et al. 2019; Ahmed et al. 2018). Moreover, the additive manufacturing technique is used in many fields, such as in prototyping, simulations, and failure mechanism (Aldarmaki et al. 2019; Al-Shamsi et al. 2019),whereas the aerospace field is the most leading sector due to the wide and important applications that could be considered of using 3D printing technology (Alahbabi et al. 2019). However, 3D printing technology started to spread out in schools (Alhamad et al. 2018), for the learning purposes (Alhamad et al. 2019), as well as for university levels (Alhamad et al. 2019). The need for having lightweight objects guided us to use the topology optimization method. However, the final design of the optimized part is quite hard to manufacture; that's why all of the optimized objects are fabricated using 3D Printing. 3D Printing allowed us to print complex shapes and lightweight objects, which will be less expensive and can be manufactured in time significantly less than the traditional manufacturing method.

To start the optimization experiment, we had to gather twenty-five different articles related to topology optimization. These articles are clustered into three main categories, which are topology optimization and 3D printing, 3D printing optimization for material science, and 3D printing optimization for heat treatment.

a) Topology optimization and 3D printing

The solid isotropic material with a penalization (SIMP) technique is used to perform the topology optimization. In this case study, the topology optimization is applied on a supported beam. The Topology optimized designs have complex geometry, and it cannot be produced and fabricated using the traditional manufacturing process. It's clear that the additive manufacturing method is useful in this aspect, with its advantage of making any complex shapes possible (Siva et al. 2019).

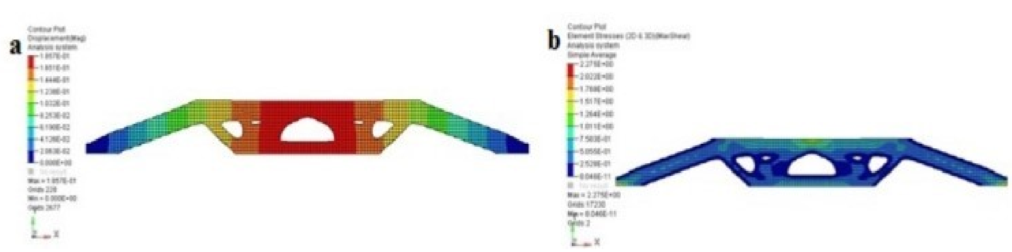


Fig. 1 – Deformation of the optimized beam using FEA.

The study of structural design optimization (SDO) includes several methods like topology optimization (TO), shape optimization, and size optimization to achieve the desired feature and function for a specified set of loads conditions and specified constraints for optimizing specific qualities like the structure weight or uniform stress distribution. Consequently, it is considered as a powerful method to generate weightless implant parts that replicate the biomechanical characteristics of the host bones and diminish stress shielding accompanying complications (Peto et al. 2019).

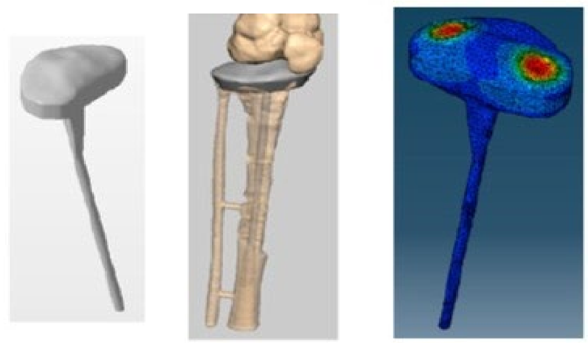


Fig. 2 - Development of customized tibia intramedullary medical implant.

Additive manufacturing and topology optimization technologies are both developed for submissive mechanisms design. There are several manufacturing problems, such as lacking self-sufficient capacities and shortage of sacrificial backing material for 3D Printing. A novel approach was developed to regulate the amount of the required support material for additive manufacture of compliant mechanisms, which is called overhang constraint (Garaigordobil et al. 2019).

Along with rising of technologies and advances in various fields for instance additive manufacturing, where new approach of engineering design, optimization, and material applications were achieved. New approaches related to the topology optimization design and cable-nets were discussed. The cable nets were made using elastomeric materials by additive manufacturing. Moreover, additive manufacturing by robotics was elaborated specially for cable-net structure designs (Tish et al. 2019).

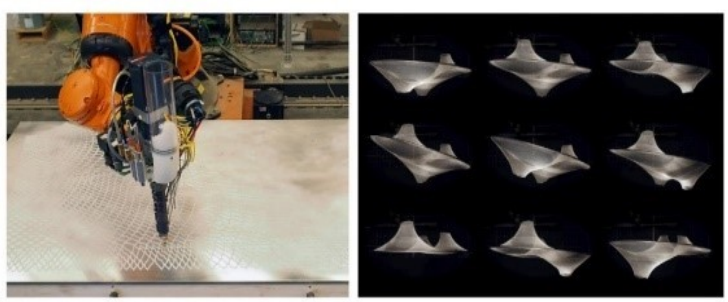


Fig. 3. Work cell using robotic additive manufacturing (L);
Nine distinctive positions of programmed cable net (R).

Additive manufacture is evolving rapidly in recent decades, for instance, the powder bed-based laser AM is selective laser sintering, where the powder may support the overhang construction. A density-based topology optimization approach for designing an effective heat conductive support structure for the development of powder bed laser AM while taking into account the deformation or stress induced by the laser energy (Mezzadri et al. 2018).

Fig. 4. A structure using AM process simulation.

The assembling of the humanoid robot up to these days is manufactured conventionally, but it has another way, which is the topology optimization that takes the special requirement into account from the process of additive manufacturing. Minimizing the number of bolted joints and components is the main aim of this step. Besides, the other objective is to reduce the weight of the assembly part to create the movement easily of the humanoid robot (Junk et al. 2018).

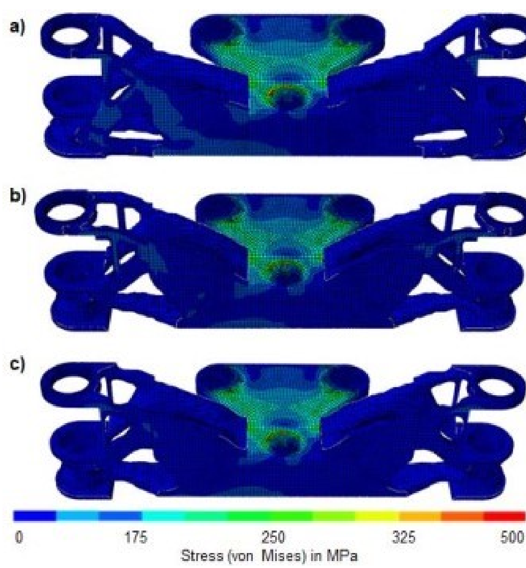


Fig. 5 topology optimization results for AM by using the Titanium alloy (a), Aluminum alloy (b), and tool steel (c)

It is well known that constructional sectors have a considerable impact on the environment that spent mostly in life. For that reason, it's essential that the result of architectural instinct accomplishes sound and fulfills the design necessities. The analysis step denotes the stage of the procedure, where the CAD models are formed to validate the model by CAE package or addictive manufacturing one (Kazakis et al. 2017).

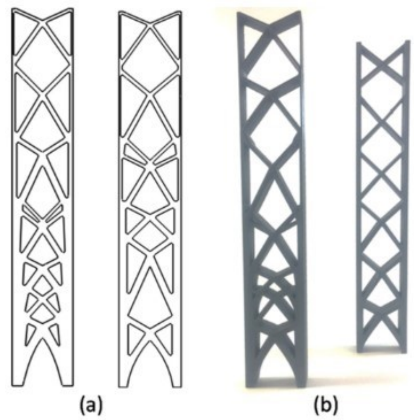


Fig. 6. MRF test instance: Illustration of a 3D printed items at 30% CAD model geometry.
fraction (a) Representative case and (b)structure case.

Study of topology optimization with comprehensive restriction in the manufacture of additives. It represents the program to scout the distribution of local density, and completion of the structural boundary. The material volume fraction of the elements contains two combined bonds that violate the overhang angle, which helps in reducing the cost (Zhang et al. 2019).

Additive manufacturing has a problem in preventing wide-ranging metal applications from building failure due to residual stress accumulation during the manufacturing process. The goal is to explore the possibility of using topology optimization to build a support structure to mitigate the residual stress-induced construction failure. The latticular structure is used as the support material for the support system and the graded topology lattice structure optimization framework is suggested to minimize the structure of the sacrificial support under maximum residual stress constraint (Cheng et al. 2019).

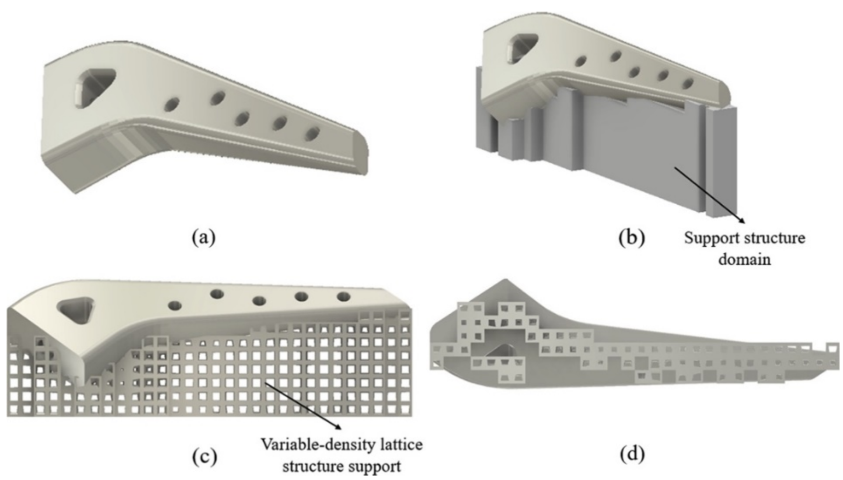


Fig. 7. Support structure design by LSTO method: (a) element, (b) bulk support (c) optimized support for the variable density lattice structure, (d) bottom view of the component's optimized support structure.

b) 3D printing optimization for material science

The core motivation is the intention to develop an algorithm for large-scale, 3D printed parts for a structure-based infill patterning method. In fact, a simple modular, elastic system is available which reflects the structural logic of printable parts by voxelized 3D virtual models into a FE demonstration which used to feed a typical model (Nadal et al. 2017)

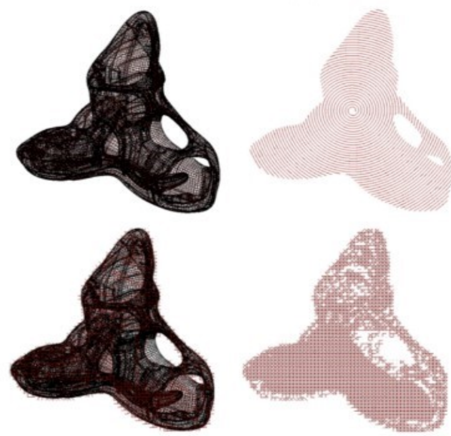


Fig. 8. Plan view of complex part design result using optimization

Along with the improvement in the additive manufacturing that have enable the production and manufacture of cell materials whose mechanical properties are indicated because of their chemical composition, micro-scale topological, and optimizes the physical properties of the individual cells to ensure material interaction and the change in physical properties (Garner et al. 2019).

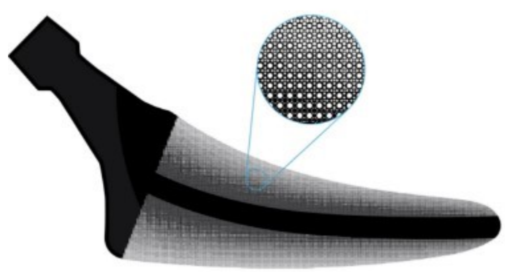


Fig. 9. An orthopedic implant optimized by the proposed method with functionally graded microstructures.

Effective cooling or heat exchange in various industrial products is a general engineering issue. Additive manufacturing enables revolutionary 3D layer-by-layer assembly by optimizing the distribution lattice density using the approximation of the lattice structure and the gradient method. Nevertheless, the steady-state cooling performance was evaluated in this study under a uniform heat flux, and other characteristics like stiffness and strength (Takezawa et al. 2019).

The studies in this time are obtained from the fundamental gap between the tools of numerical design and the manufacturing processes. The heat exchanger designs are using as a medium in the microchannel to achieve an effective and quick optimization method. The aim of the optimization is to reduce the pressure drop between the inlet and outlet channels. Additionally, making the most of the heat flow on the top and bottom walls and taking full advantage of the heat transfer to the pressure drop ratio (Kirsch et al. 2018).

c) 3D printing optimization for heat treatment

Using topology and size optimization for mass reduction, a heavily loaded aerospace bracket is optimized and then manufactured using additive manufacturing techniques, taking into account both mechanical forces and temperature loads. The method of SLM can create complex shapes that include indoor holes. This work shows that topology optimization and additive manufacturing technologies are combined with being a powerful tool for engineering designers (Shi et al. 2019).

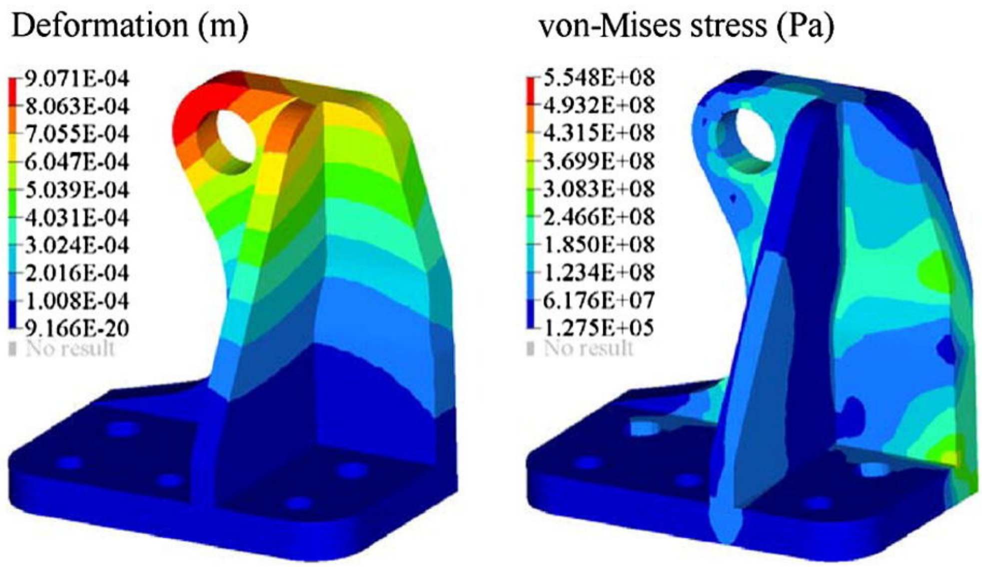


Fig. 10 - Numerical analysis of the original design.

Analyzing the quality of the surface and optimizing parameters of the process for further improvement of the quality of the AlSi10Mgparts that are made by SLM method. Using the selective laser melting (SLM) method will lead the laser to melts the metallic powder particles together and forming a 3D component. SLM is known for its manufacturing freedom constraints, which allow complex geometries and high material efficiency. The effect of the parameters of the process, like scanning velocity, overlap rate, hatch distance, and laser power of The SLM system during the manufacture of AlSi10Mg alloy components, is used to investigate surface quality. At the end of the analysis, the result shows that the surface roughness differences were observed, which is the reason behind the manufacturing system's seated random errors and surface roughness that increased when the level of laser power is increased(Arfan et al. 2019).

An optimization method was established (i.e., lattice distribution) to handle the heat-exchanger device with coolant flow in the lattice considering many aspects which are fluid flow, linear elastic problems, thermal conduction and thermal convection heat transfer. Besides, two optimization cases were considered, which are fluid cooling performance maximization that is subjected to strain energy constraint, and the normal direction of the heating and loading surfaces minimization (Takezawa et al. 2019).

After collecting all of these articles and summarizing them, we used Autodesk Fusion 360 software to see how the optimization work for different targeted masses (8%, 15%, 30%, and 75%) and three different cases for each target mass. The three examples are for fixing the two holes only, the second one by setting the two holes and unlocking the Uy constraint, and the third one is by setting the side edge.

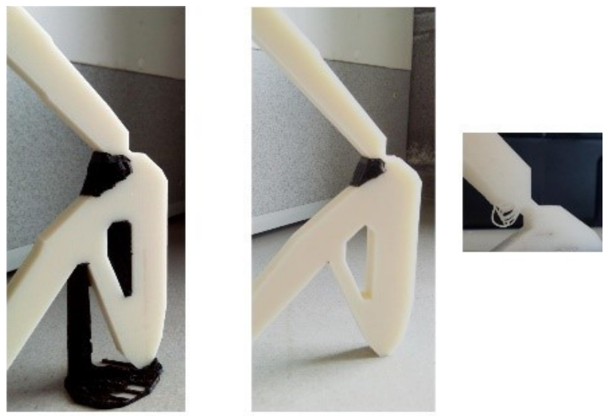


Fig.11 - Optimized 3D printed part with different targeted masses.

D) Topology optimization software

Additive manufacturing is a machining technique that allows producing more complex geometric parts with an optimized total weight using a numerical method, which is topology optimization. Topology optimization can be considered as one of the powerful tools for design methods or concepts in recent decades. These powerful methods can be achieved by maximizing or minimizing one or various properties of the structure, subjected to constraints, critical loading, and boundary conditions. Also, it allows the engineer to establish the design of essential paths of load and stress by optimizing the material within a specified region. Topology optimization is used in many fields. For instance, automobile and aircraft industry that reduce both the direct and indirect cost by saving tons of material and consume less fuel.

Moreover, Topology optimization software is established be redesign a real aerospace mounting plate that focuses on manufacturing considerations that are significant for additive manufacturing (AM). For the industrial use of topology optimization, the software must be able to simulate and optimize various mechanical responses.

E) Advantages and disadvantages of topology optimization

Some evident benefits of having topology optimization are the increase in sustainability, weight reduction, and aesthetics increase. The mathematical approach that can optimize ze material layout is named topology optimization. This process can be implemented on a structure by generating holes or removal of the inefficient material region without changing the structural performance concerning the applied loads and support conditions. The significance in design that it reduces deign iterations, which reduce time as well, also experience is not necessary as the computational system will develop the optimized structure. In contrast, some topology optimization disadvantages are difficulty in manufacturing an intricate part that required more cost.

Case study

This study where the part is redesigned using a topology optimization approach while taken into consideration in the percentage of optimizing and three boundary conditions, which means the Ux, Uy, and Uz at the upper, lower bolts holes as well as the left edge wall.

The purpose of the case study is to observe the change in the weight of the part while satisfying all the design requirements. The simulation was developed using shape optimization technology by using Fusion 360 Autodesk software, which allows simulating an improved model based on a given applied load which is 100N on the curvature surface and shows the locations of the constraints using preserved region tool.

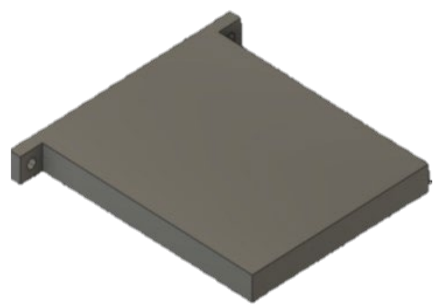


Fig.12- Original Part shape designed using Fusion 360 software.

The boundary conditions

Boundary conditions BC mean that Ux, Uy, and the Uz at the bolted joints and any connection point, in our case: holes at upper and lower as well as the left sidewall.

- The upper and lower bolt holes surfaces for all Ux=0, Uy=0, and Uz=0 are locked. (Case1)

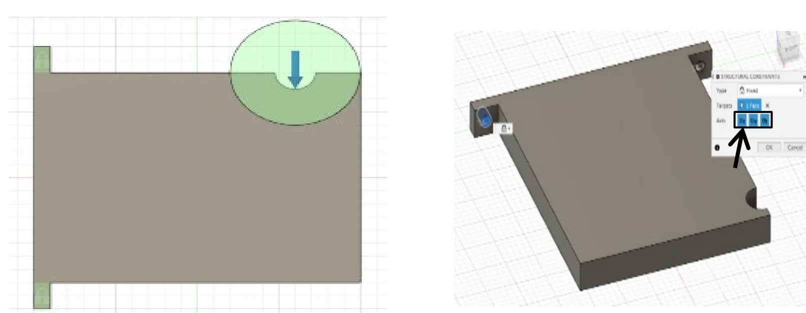


Fig .13 BC in both bolts holes surfaces.

- The upper and lower bolt holes surface for Ux=0, Uz=0 are locked and unlocked in the y-axis only. (Case2)

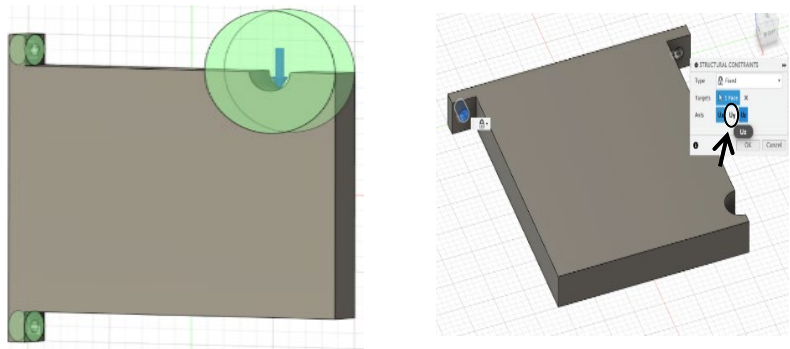


Fig .14 BC in both bolts holes surfaces except the y-axis in the lower hole surface.

- The left side edge, the upper and lower bolt holes surfaces for all Ux=0, Uy=0, and Uz=0 are locked. (Case 3)

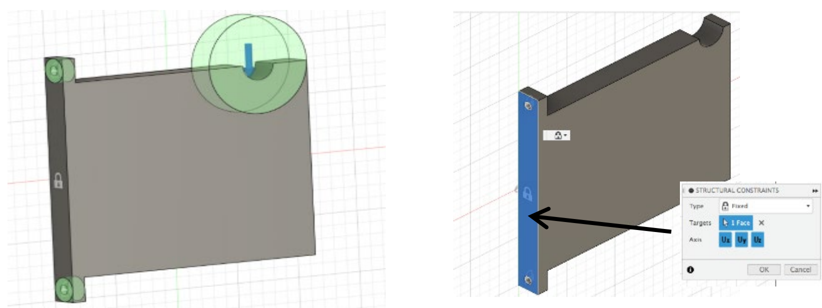


Fig. 15 BC in the left edge and both bolts holes surfaces.

Shape optimization was developed using a finite meshing where the ideal size was 3 mm that's results more accurate evaluation of the design objective and constraints.

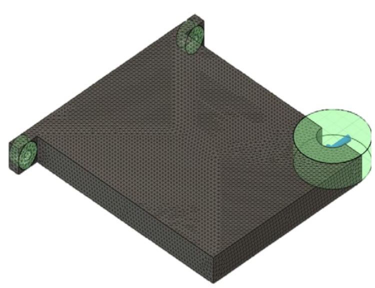


Fig .16 Generating a finite Mesh.

Topology Optimization results with weight ratio reduction

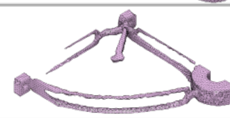
Software Topology Optimization %	Case	Boundary conditions	Results	%Weight Reduction
8%	1	Upper and lower bolt-holes are locked in all axis.		**92.1**
	2	Upper and lower bolt-holes are locked except y axis.		**77.0**
	3	Left side edge, all Ux, Uy, Uz=0.		**92.2**
15%	1	Upper and lower bolt-holes are locked in all axis.		**92.1**
	2	Upper and lower bolt-holes are locked except y axis.		**84.3**
	3	Left side edge, all Ux, Uy, Uz=0.		**84.3**
30%	1	Upper and lower bolt-holes are locked in all axis.		**70.0**
	2	Upper and lower bolt-holes are locked except y axis.		**69.8**
	3	Left side edge, all Ux, Uy, Uz=0.		**70.0**
75%	1	Upper and lower bolt-holes are locked in all axis.		**25.0**
	2	Upper and lower bolt-holes are locked except y axis.		**24.6**
	3	Left side edge, all Ux, Uy, Uz=0.		**25.0**

Table 1

Results & Discussion

Additive manufacturing is considered a machining technique that allows producing a sophisticated geometric design with an optimized total weight using a computational method called topology optimization. So, this method aims to reduce the design weight and material by changing the boundary conditions and constraints. Whereas a result, the optimized designs would eventually lead to an efficient reduction of material, saving time and money that results a fast production process of sustainable manufacturing. In our case study, as the percentage of optimization increases, it needs more material to avoid or overcome any reduction in strength at these critical and significant points, which the upper and lower holes for all cases where we implemented three boundary conditions. So, there are various sizes of concentration considered, for instance, the point where (surface curvature); load applied. This is critical also because it subjected to a high compressive load and bearing stress. Besides, it has been concluded through studied cases that not necessarily the weight reduction of the optimized parts are the same as the optimization percentage. In fact, it depends on the boundary conditions that have been selected during the analysis, which rely on the experience of the user.

Moreover, it has been shown that the optimized parts for low optimization percentage mostly not suitable for 3D printing fabrication due to shape and the slenderness ratio of the optimized parts. That leads to a conclusion that the user should do further to decide whether to proceed or not with the net stage of the optimization. It is recommended that the achieved optimized parts to be analyzed using FEA to inspect the safety factor levels for all members of the optimized parts.

Consequently, for practical design considerations, to avoid stress concentrations at sharp corners. Moreover, flexibility concerning locations and holes of sizes that could be fixed into the optimized problem.

Conclusion

From the previous case study, it can be concluded that topology optimization is an influential method that can be used to manipulate material and weight distribution to satisfy all the part circumstances. The weight reduction saves a considerable quantity of the material and processing energy, thus saves a remarkable amount of money. Moreover, it shows that the topology optimization capability can be utilized completely using the shape optimization technology using open source resources (Ahmed et al., 2020). From the case study result, as the optimization percentage increase, the material and weight increase as well. Consequently, this can be adopted to develop innovative optimized designs (Ahmed, 2019, Alnajjar et al. 2019, Aljassmi et al.).

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