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A review of topology optimization in the design of mechanical components: Benefits of the engineering software

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ABSTRACT

Optimization techniques have appeared as valuable processes in various engineering sectors. Nowadays, topology optimization has been inspired in order to distribute a material within parts regarding to loading conditions. Therefore, the designs have been lighter besides reducing required materials, which savings cost as well as environmental enhancements. After carefully considering of previous reviews, it was noticed that each review covered a specific domain, engineering platform, or material. Accordingly, this review provides a thorough analysis for different mechanical engineering applications in terms of software such as Autodesk, SolidWorks, and ANSYS along with employing the materials in this technique. Furthermore, the historical evolutions, methodologies, and applications have been recognized within various engineering fields. It clarifies the purposes of utilizing this method regarding to processing time, cost, saving energy, and models complexity. This review confirms the benefits of this optimization for mechanical engineers along with employing the tools and method that required to provide the optimum designs.

Keywords: topology optimization; engineering platform; lightweight; materials; mechanical design.

INTRODUCTION

Topology optimization is a high-powerful method that distributes the material into a design model to improve structural properties. This approach modifies material distribution regarding to applied loads, boundary conditions, and constraints to increase strength or reduce weight [1-3]. Over 150 years, it has developed from theory to real applications. In 1870, Clerk Maxwell suggested optimizing the material distribution based on stress fields [4-5]. In 1904, Michell developed this theory by minimizing material besides maintaining strength, numerous notable contributions between 1904 and the 1970s have been occurred to topology optimization, however, many early studies remained classified. After Michell's 1904 research, progress was restricted till the 1950s which researchers like Foulkes, Cox, Hemp, and Shield sophisticated theories for optimizing trusses layout, following in the 1960s to 1970s, Shield, Schmit, Prager, and Rozvany developed optimal criteria. In 1973, Rossow and Taylor initiated finite element related to topology optimization to create modern computational techniques. In 1988, a development happened when Kikuchi and Bendsøe exhibited a homogenization method. Topology optimization has been vital approach in mechanical design due to improve the computational methods along with additive manufacturing. It has progressed using of Maxwell and Michell's theories with Bendsøe and Kikuchi's algorithms to real-world applications. As a result of integration between computational methods and finite element analysis, Topology optimization becomes now related to mainstream engineering, specifically in the automotive and aerospace fields, thereby allowing engineers to develop the structural efficiency [6]. This review presents the challenges and advancements in topology optimization, focusing on automotive, medical, aerospace, and civil engineering, as along with using of composite materials and3D printing. This study demonstrates previous reviews in different applications such as aerospace [7], civil [8], composite [9], automotive [10], biomedical [11], and manufacturing products [12] and distinguishes areas that have not been completely explored. It is noticeable that the generality focuses on particular engineering domains, software, or materials, without any comparative studies. Accordingly, this review purposes studying different mechanical engineering fields as well as making comparative analyses among engineering software.

The material representation has been formulated using of solid isotropic material with penalization (SIMP) approach [13-14]. The design space segments by finite element method in order to analyze load responses [15]. The material has been distributed until convergence by algorithms assessment. Post-processing analyzes manufacturing decisions for optimal designs [16-17]. Figure 1 explores the size, shape, and topology optimization. The size method is efficient for component thicknesses and solid bodies [18]. While the shape method differs in terms of without changing the element connections and needs to remove material through specific holes [19-20]. For frames, size optimization defines the part areas, while shape optimization suits the node position [21]. Topology optimization could provide new designs by removing or inserting elements [7] and one model could allow to create structural designs [22].

TOPOLOGY OPTIMIZATION APPLICATIONS IN ENGINEERING FIELDS

Figure 2 shows various domains for removing weight to improve the performance in various engineering field such as civil [24], aerospace [25-28], and automotive [29-34]. The combination

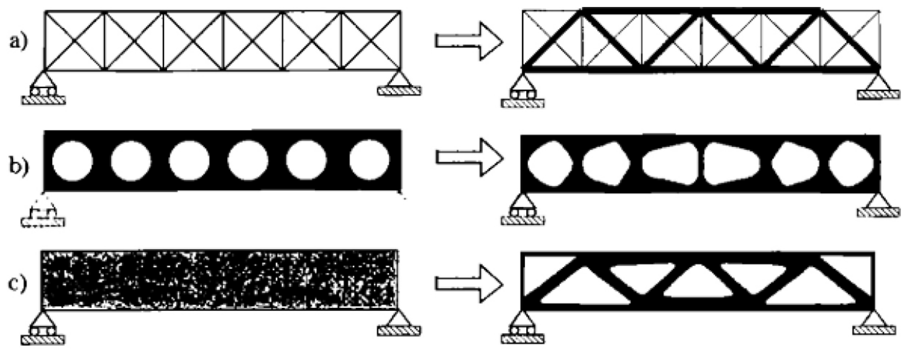


Figure 1. Methods of optimization: a) size, b) shape, c) topology optimization [7, 13, 23]

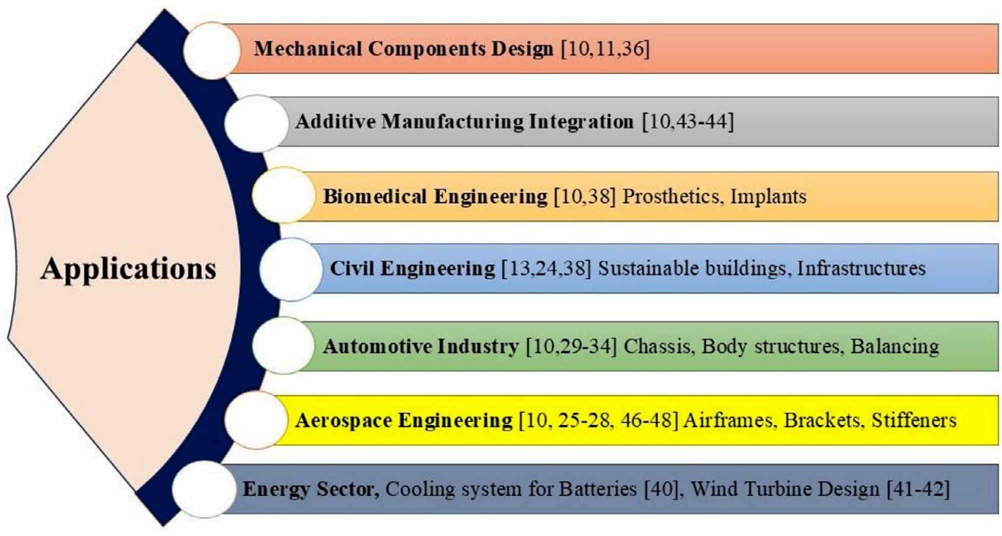
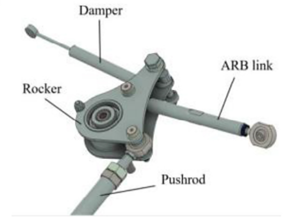
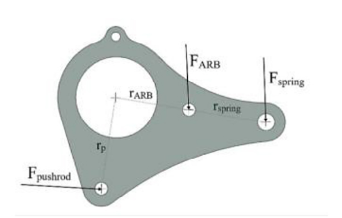
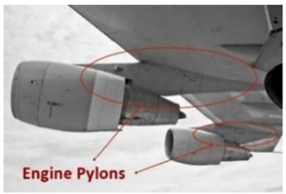
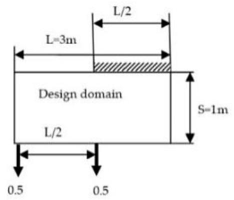
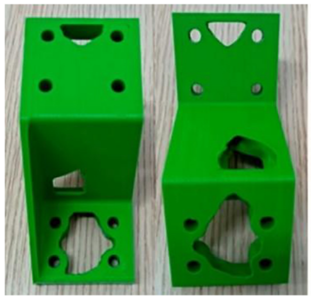
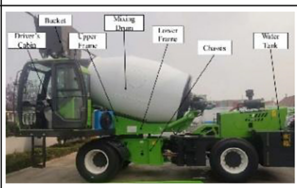
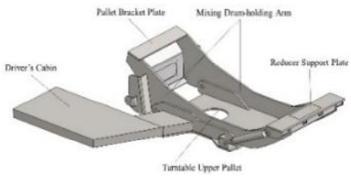
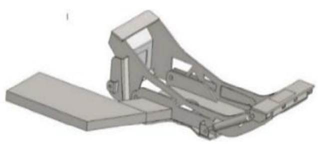
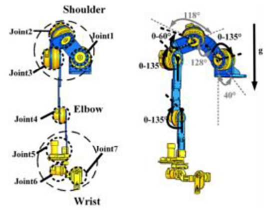
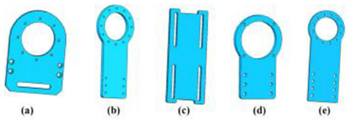
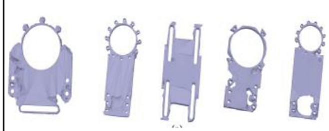
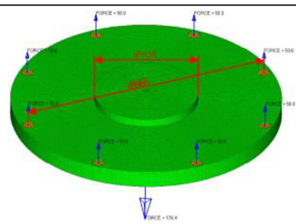
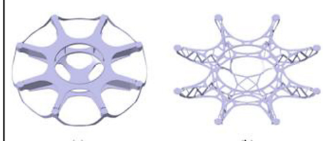
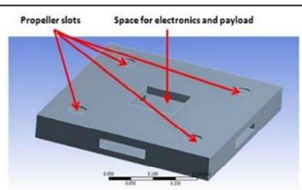
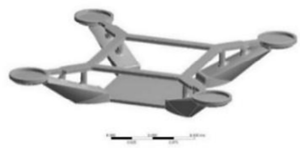
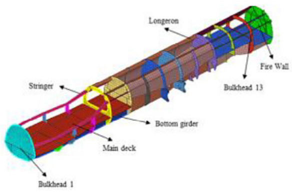
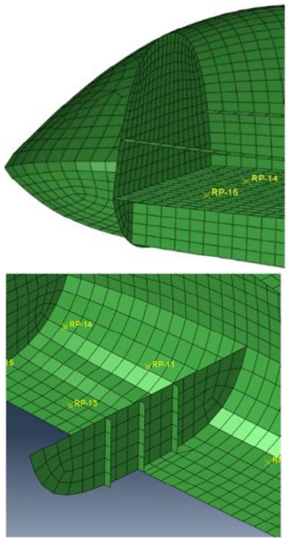
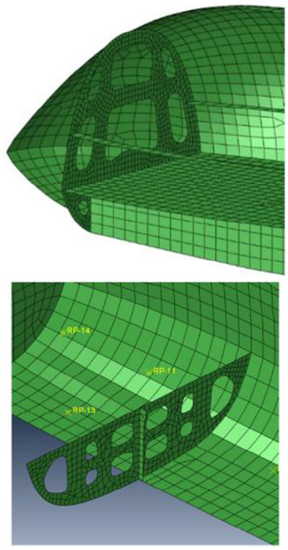
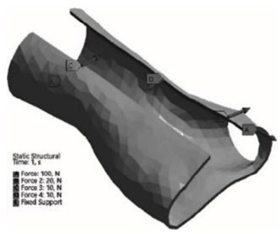
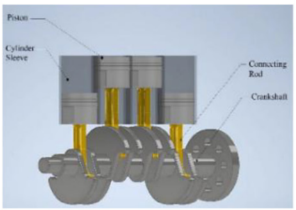
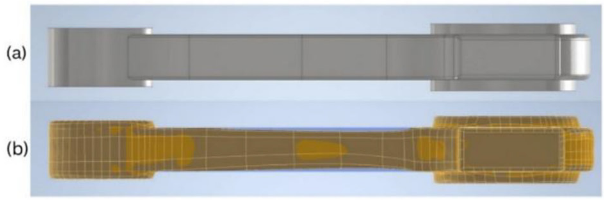
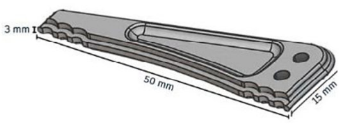
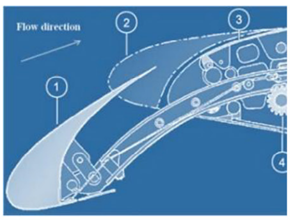
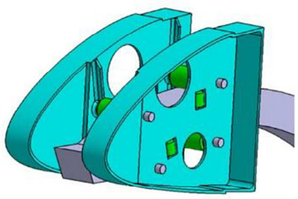
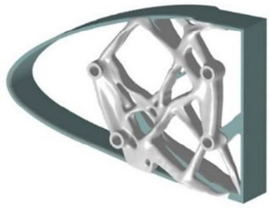


Figure 2. Topology optimization applications. Various engineering disciplines, including mechanical engineering, have employed this optimization for improving performance by removing weight while keeping strength in acceptable limits

Table 1. The original and optimized models for mechanical applications

Ref.	Year	Engineering software	Applications	Original Model	Optimized Model
[21]	2020	Autodesk Fusion 360			
[25]	2024	Ansys			
[26]	2023	Ansys	Aerospace bracket		
[30]	2024	Ansys			
[45]	2022	Ansys		 a) joint 1, b) joint 3-4 (1), c) joint 3-4 (2), d) joint 3-4 (3), e) joint 4-5	
[46]	2021	Ansys	Rotary-wing UAV frame		 (a) (b) a) first result, b) second result
[47]	2022	Ansys	Quadcopter structure		

Cont. Table 1.

[48]	2023	solidWorks			
[49]	2020	Ansys			
[50]	2025	Ansys		 a) Original rod; b) 6% reduce weight	
[51]	2025	SolidWorks	Wrist design		
[52]	2024	Autodesk Fusion 360, nTopology			
[53]	2025	ABAQUS			

between lightweight and strength is essential for fuel conception in automotive and aerospace engineering along with creating complex shapes [35-36]. The safety of automotive structures could be prioritized by designers for crash performance [33] besides focusing on cost reduction by companies using advanced technologies [37-38]. While, in biomedical applications, it is important to improve the balance between weight and functionality [39]. Now, complex designs, such as wind turbine blades and battery brackets, along with minimizing waste can be produced efficiently [40-44].

Table 1 lists the original and optimized designs for the mechanical applications using topology optimization to enhance the components with various engineering platform. The weight reduction could be clearly discernible.

UTILIZING ENGINEERING SOFTWARE IN TOPOLOGY OPTIMIZATION

To implement this optimization, it has been used various engineering programs. They ultimately achieve the same outcomes; however, each program follows an individual process and serves a distinct target. Some of these platforms could be followed [54]:

- SolidWorks: It is strongly approved for utilizing in aerospace, automotive, and architectural applications.
- Autodesk Fusion 360: It is highly recommended for enhancing engineer's design strategies in industries, and aiding production.
- Creo: It can be utilized for design under various constraints due to its features, particularly in thermal and structural applications.
- Altair OptiStruct: This tool was specifically designed to analyze structural models that need enhancements in their lightweight features.
- nTopology: The simplest optimized designs along with automation methods have been achieved by this platform as a result of using this tool for complex engine geometries. In addition, the optimized designs convert without complex mesh.
- Tosca Structure: This platform has been used for realistic models in shape optimization, especially when designers require to facilitate quick modifications along with maintaining the existing structure.
- Ansys Discovery: It is strongly employed for advanced simulation procedures besides topology optimization.

From the analysis of the above software, it is noticeable that Autodesk Fusion 360 and Solidworks provide robust optimization characteristics for enhancing innovative design solutions as others. Curkovic focused on optimizing three robotic arms, as shown in Figure 3. Five different engineering software tools have been used to improve the performance and highlight the variations between the arms [55].

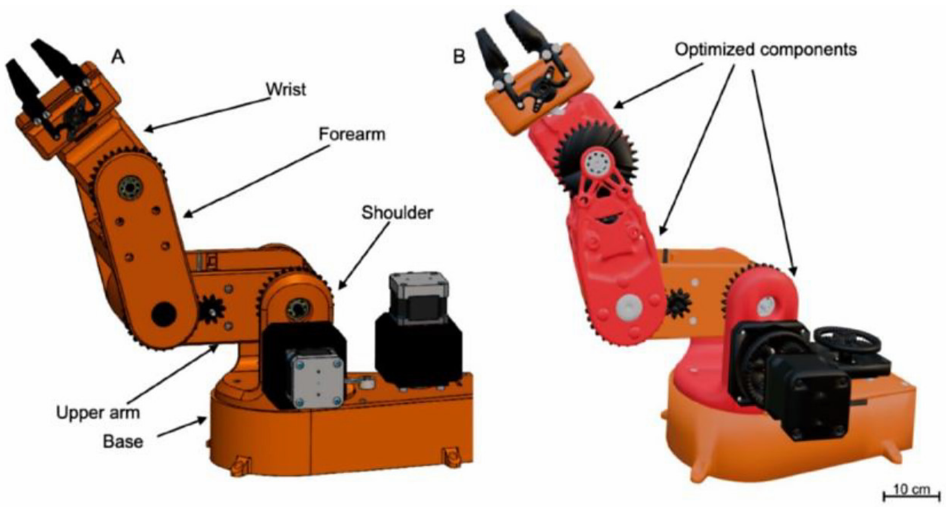


Figure 3. Robotic arms with six degrees of freedom: A) original shoulder, forearm, and wrist; B) optimized arms. The arms have been assessed regarding to criteria including completion time, weight reduction, forearm safety factor, and post-optimization printing time. Remarkably, the most complex optimized design could have achieved using Altair Inspire, while Creo yielded a more traditional design [55]

The optimized shapes, as shown in Figure 4, differ significantly, with the Creo Parametric manifesting minimal shape modification and failed to optimize the wrist. These were investigated regarding to the completion time, weight reduction, safety factor of the forearm, and printing time, as listed in Table 2. The most intricate design has been achieved by Altair Inspire, while Creo developed a traditional design.

Table 2 lists the studied parametric of the five platforms under identical loading conditions. Fusion 360 provided the highest weight removing but the lowest safety factor, while the other platforms provided higher safety factors with less reduction. The longest processing time was in Fusion 360, followed by SolidWorks, Altair Inspire, Creo Parametric, and ANSYS Discovery. After optimization, the shortest printing time has been achieved by Fusion 360 as compared to other software.

Altair Inspire provides innovative designs that are recommended for applications requiring design flexibility, although their shapes increase post-processing and printing time. SolidWorks utilizes when it needs to provide user-friendly workflows with effective CAD tools; however, its optimized shape is computationally intensive and needs surface smoothing. Fusion 360 excels in cloud integration and generative model yet lacks mass control and exceeds removing targets. Creo Parametric supplies conservative designs suited for multimaterial optimization and engineering modifications, even if limited topology modifies. Ansys Discovery allows fast simulations with thorough load options, however academic licensing restricts STL form. Struz et al. studied the topology optimization of a bracket using ANSYS Workbench, SolidWorks, Altair Inspire, and Autodesk Inventor [56]. Table 3 shows the original and optimized brackets. The optimized model weighed 8.616 kg with Altair Inspire, 8.808 kg with Ansys, 8.72 kg with Autodesk Inventor, and 8.863 kg with SolidWorks. Altair Inspire and SolidWorks finished the optimization fastest, whereas ANSYS required five times longer, followed by Autodesk Inventor.

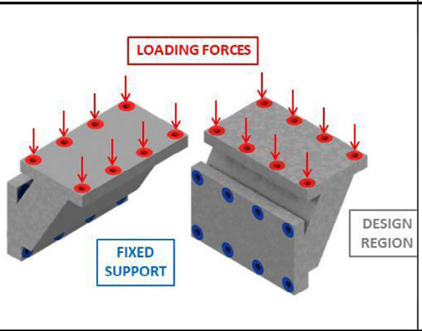
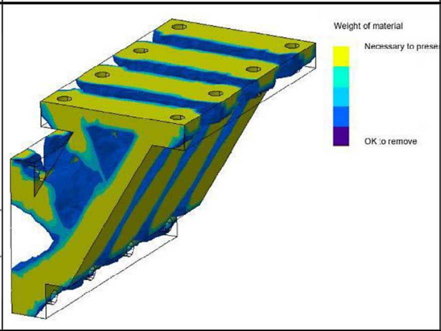
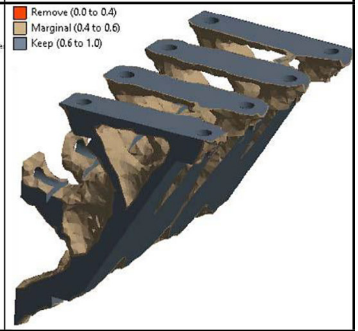
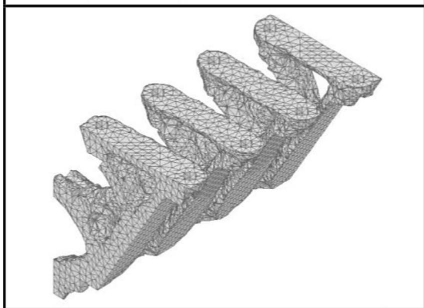
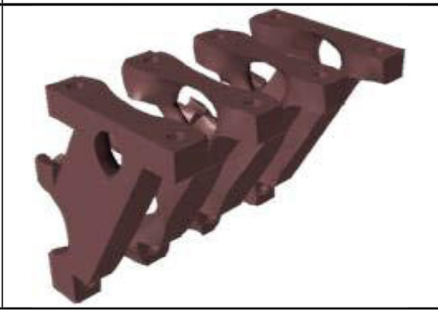
The bionic structures could be enhanced by Altair Inspire in terms of rapid computation with minimal mass. Ansys Workbench provides longer computation times with "Level set based" optimization. SolidWorks provides swift processing

Figure 4. Three optimized arms after optimization. Five engineering software tools have been employed by the authors to optimize the arms based on specified criteria. The results propose that these platforms can effectively balance simplicity and complexity [55]

Table 2. The studied parameters under five engineering software for forearm [55]

Parameter	Altair Inspire	SolidWorks	Fusion 360	Creo Parametric	Ansys Discovery
Weight reduction	16.12%	17.85%	32.31%	14.21%	16.93%
Time to finish the process	10 min	49 min	60 min	2 min	1 min
Time to print after optimization	14 h 25 min	13 h 51 min	12 h 11 min	14 h 58 min	–
Safety factor	54	48	35	49	51

Table 3. Measuring device bracket before and after optimization [56]

Original Model	Optimized by SolidWorks	Optimized by Ansys Workbench
		
Optimized by Autodesk Inventor	Optimized by Altair Inspire	
		

for CAD workflows and moderate weight removing. The Autodesk Inventor needs a finer mesh, divides brackets, and yields intermediate results, thus affecting structural safety. This investigation supposes homogeneous steel properties, excluding multimaterial behaviors, and limiting composite applications. The node reductions were in Altair Inspire (91%) and SolidWorks (85%), and lack of standardized loading conditions, especially in ANSYS, which affect reproducibility [55]. Tyflopoulos et al. utilized ANSYS Mechanical, SolidWorks, and ABAQUS to optimize a pillow bracket, bell crank, and a small bridge. Table 4 shows the platform effects. ABAQUS provides maximum material removal for the pillow bracket and bell crank, whereas SolidWorks allows the lightest bridge and needs less optimization time. ABAQUS produces the strongest results, however SolidWorks remains the most user friendly [57].

In a further analysis, software has been selected relies on design priorities. SolidWorks has been preferable in terms of optimization time speed, particularly for considerable size structures such as bridges, making it best possible for time-critical projects. ANSYS Mechanical gives supports SIMP and level-set methods and strong post-processing capabilities, which are suitable for both conventional and additive manufacturing. ABAQUS successfully handles multi-objective problems with complex designs, but it is computationally intensive without integrated post-processing tools. A popular limitation across software is their dependence on the SIMP method, which supposes isotropic material properties, and may struggle with composite materials or anisotropic [57].

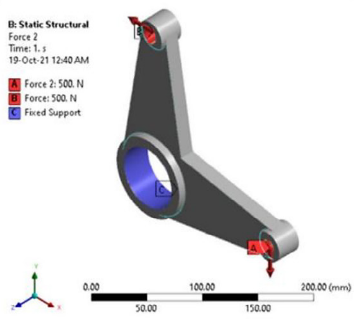
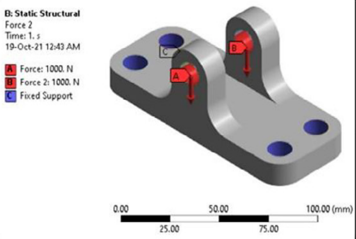
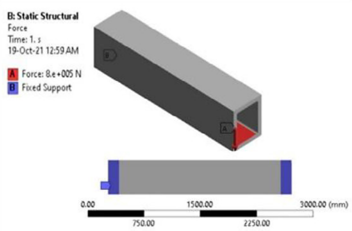
TOPOLOGY OPTIMIZATION PURPOSES

Topology optimization considers a significant role in designing geometries under practical conditions, including loads such as force, pressure, torque, and moment, and setting constraints for material distribution and support. The industrial production lines have been improved as a result of using topology optimization and its benefits which can be listed as following.

Performance of structures

The lightweight can be achieved by distribution of material into design area using topology optimization in order to enhance the mechanical properties. Therefore, the performance could be improved with the optimized model as compared with its original. Thus, it is strongly essential for designs that require controlling between strength and weight. Lightweighting of 3D printed designs

Table 4. The results of bell crank, pillow bracket, and small bridge after optimization [57]

Original Models	Models after optimization by:		
	SolidWorks	Ansys Mechanical	ABAQUS
	50% 		
	50% 		
	50% 		

can improve stiffness, stress distribution, lattice structures, and mechanical performance, besides minimize production cost, providing potential enhancements in structural design [58].

Development of innovative designs

In the engineering fields, topological optimization creates novel designs in which conventional processes are complex. This method creates bone-like structures that are strong and light, with novel functionalities. This approach enables gyroids with diverse solid-to-porous patterns and multifunctional models with cooling channels, without requiring any extra support in 3D printing process [59-61]. Another approach transforms optimization outputs into editable CAD forms using Visual Basic macros and Python algorithms in SolidWorks, allowing CAD editing with 75% shape accuracy [62].

Decreasing time and cost

Production lines have been continuously enhanced by Industrial companies to lower their product costs. Therefore, topology optimization has employed as an effective approach for decreasing costs by removing material required to create engineering designs. By employing FEA, 3D printing, and optimization algorithms, a design process was improved that significantly minimized waste, accelerated development, and allowed the creation of a robust frame more cost-essential and efficiently than conventional methods [59].

UTILIZING THE MATERIALS IN TOPOLOGY OPTIMIZATION

It is essential to notice that the materials typically utilized in topology optimization of mechanical applications are considerable in mechanical design. This is due to the propose of topology optimization is to remove materials to minimize the weight of components and improve the performance of models, particularly in complex geometries. Therefore, the most common utilized materials are as follows:

- Metals:

  - Aluminum alloys – are used in automotive and aerospace engineering [63] due to their best strength-to-weight ratio.
  - Titanium alloys – are well suited for employ in aerospace industries and biomedical [64-65] as a result of their exceptional resistance to corrosion and strength.
  - Steel and stainless steel – owing to their superior strength and long-lasting durability [66], they are highly endorsed for utilize in structural components and bearing.
  - Nickel-based superalloys are utilized in specialized applications for components that tolerate thermal stresses and mechanical such as turbine blades and engine parts [67-68].
- Polymers:
  - Plastics (e.g., PLA [69-70] and ABS [71-72]) are extensively employed for general prototyping purposes and manufacturing robotic components [73-74].
  - Composite – utilized when there is a requirement to balance weight with strength and flexibility, as in sports equipment and automotive. In these cases, composite materials need improvement by reinforcement with carbon and glass fibers. As a results, topology optimization aligns these fibers inside the material [75-76].
- Biomaterials – extensively utilized in the domain of medical engineering, including in applications such as scaffolds and implants [77-78].

As mentioned above, metals, such as steel, titanium alloys, and aluminum, along with plastics, are frequently utilized in topology optimization in the mechanical engineering field. Furthermore, designers have the flexibility to choose materials regarding to performance requirements processes, manufacturing, and cost considerations.

THERMAL EMPLOYMENT IN MECHANICAL ENGINEERING

In spite of this review mainly classifies the topology optimization of models subjected to mechanical loads, such as pressure, force, and moment, and validates the results through stress analysis, there are other fields within mechanical engineering that focus on thermal applications [79-80]. The targets of these applications to improve thermal performance, such as fluid dynamics in heat exchangers and heat transfer, cooling systems, heat sinks, switches, actuators, and diodes. Some of these applications are integrated with mechanical structures to endure both mechanical stresses and thermal, thereby enhancing both structural strength and thermal properties. This is particularly important due to thermal effects could influence mechanical deformation in different applications, particularly diodes and switches [81-82]. In conclusion, engineers might be able to provide lighter designs that accomplish their functions, which conventional optimization approaches may not achieve.

CONCLUSIONS

From this review, the following conclusions were obtained:

1. The manufacturing technique can be expedited by employing optimization software to minimize materials use, energy, costs, and transportation.
2. Reducing waste and carbon dioxide emissions can enhance the environment.
3. Integration between 3D printing techniques and topology optimization can create intricate geometries.
4. Due to the advantages of topology optimization in terms of removing materials, it is widely utilized in diverse engineering fields, particularly in the biomedical components.
5. The ANSYS platform is commonly used for topology optimization compared to other software, in spite of it needs an analysis of the static structure of the design before applying the topology optimization technique.
6. However, SolidWorks is realized for its user-friendly interface and efficiency in task completion, its potentials in topology optimization have not been commonly recommended. It is suggested that this software be employed for the design of the mechanical models.
7. ABAQUS is adept at multi-objective problems, handling complex; however, it needs substantial computational resources and does not contain integrated postprocessing techniques.
8. The Altair Inspire is strongly effective in removing mass and providing rapid computation, making it perfect for the enhancement of lightweight bionic structures.
9. The integration between topology optimization and 3d printing technique enables the designers to achieve complex geometries by this type of optimization.

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