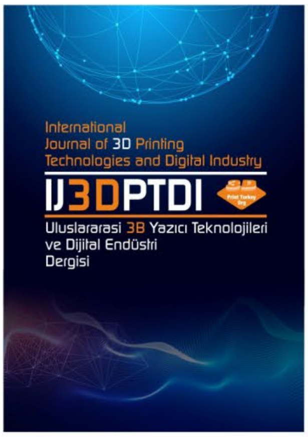

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MECHANICAL SHAFT OPTIMIZATION: A STUDY ON STATIC STRUCTURAL ANALYSIS AND TOPOLOGICAL OPTIMIZATION IN ANSYS

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ABSTRACT

Shafts are extensively used in engineering fields, serving roles in power transmission and rotational movement, thus holding significant importance. This study focuses on analyzing the structure of a selected shaft model derived from research. Subsequently, topology optimization is applied based on the obtained findings. ANSYS software is utilized for performing analysis and optimization analysis. Following the completion of these analyses, the results are thoroughly examined. The optimization process resulted in a reduction of about 2.65% in the maximum stress and approximately 2.46% decrease in the maximum strain, indicating improved mechanical performance. However, an increase of about 33.24% in maximum deformation was observed, which warrants further consideration. Most notably, the weight of the shaft decreased significantly by approximately 57.81%, resulting in the creation of a much lighter model. These outcomes highlight the potential of topology optimization, demonstrating the ability to create lighter and stronger models while utilizing resources efficiently. Consequently, it becomes imperative to explore these outcomes further by modifying selected parameters to achieve optimal results and enhance the model's performance. This study successfully showcases the potential of topology optimization, paving the way for the creation of lighter and stronger models in engineering applications.

Keywords: Shaft, Topology Optimization, Structural Analysis, Resource-Efficient Engineering.

1. INTRODUCTION

Shafts are very important and fundamental components of mechanical engineering [1]. They are used in many areas, such as automotive, mining, energy systems, and structures, and are of great importance in these areas [2-4]. They have different properties in machine structures; for example, they make rotational movement in these machine systems, transmit power, and help to support loads [1]. The design, construction, and analysis of shafts are important and require a thorough understanding of their mechanical behaviors, failure mechanisms, and appropriate support structures [5]. It is important to explain the use and importance of shafts. In mining engineering, shafts are involved in many roles, such as safety transport and underground access. Vertical shafts are used in mining engineering. The strength and stability of vertical shafts are critical for safety, sustainability, and productivity in mining systems and operations [6]. In mechanical engineering, shafts are used for many purposes in mechanical systems such as engines, turbines, and pumps. They enable the correct operation of the systems by transmitting rotational motion and power between different parts. Mechanical properties of shafts, such as bending-torsion resistance, and vibration properties, are important criteria for the reliability and performance of shafts [7-8]. Shafts used in energy systems are used in wind turbines and compressed air energy storage systems. Shafts convert wind energy into electrical energy by transmitting the rotational motion to the generator in wind turbines [9]. Shafts can be found in different types, such as crankshafts, eccentric shafts, and balance shafts, in automotive engineering and are very vital components of automotive structures. Again, taking the rotational motion from the engine and transferring it to various automotive structures allows the vehicle to operate correctly [10]. In addition, shafts are frequently used in different fields and systems, such as civil engineering, materials science, and manufacturing. The importance of shafts lies in providing structural support, transmitting rotational motion and power, improving safety, increasing efficiency, and ensuring the proper functioning of various systems and processes. Thus, the design of shafts, analysis, and optimization of their mechanical behaviors are crucial to improving their performance and efficiency. Topology optimizations can be applied to shaft design to increase efficiency and reduce weight while maintaining structural integrity [11].

Static analysis and topology optimization are very important in the design and improvement of mechanical components. Static analysis allows the evaluation of elements such as moments, forces, and thermal effects by ignoring the dynamic responses of a structure. By applying structural static analysis to the shafts, the stresses, deformations, and displacements of the shaft models under different loads can be found. Thus, as a result of the analysis, it can be ensured that the shafts can withstand the applied loads without excessive deviation or error. In addition, as a result of these analyses, the structural integrity of the shaft is improved by identifying areas of excessive stress or weak points in the model [12-13]. Topology optimization is a design tool that optimizes the distribution of materials that make up the design to achieve the desired performance while trying to minimize the weight of the part or maximize the stiffness using certain parameters [14-16]. Topology optimization removes unnecessary material from the part or model, resulting in an optimized structure or model that meets the specified criteria. [17-18]. Thus, topology optimization is used to improve the efficiency and performance of shafts and other mechanical parts by preserving structural integrity and functionality and saving material [19-20]. By combining static analysis and topology optimization, engineers can design parts that are lighter, stronger, and more suitable for load conditions [21-22].

The result you want to achieve is to analyze the structural behavior of the specified mechanical shaft model and then improve the model using topology optimization. In this research, a static analysis is carried out on the specified shaft model by analyzing its mechanical response under the applied boundary conditions. After this basic analysis, a design model that is resistant to the previously applied load conditions with optimum weight and material usage is obtained by using topology optimization with reference to the static analysis. In order to see the accuracy and effectiveness of the optimization, the optimized model is again structurally analyzed to verify the results. This comparative analysis aims to check the structural analysis of the optimized model and the previous model. This research aims to contribute to achieving sustainable engineering practices for more efficient use of resources.

The goal of this research is to set an example for more conscientious and optimal resource use by recognizing that the world's resources are limited. The requirements for structural durability, material use efficiency, and weight optimization were examined in this study. The findings of this study promote more environmentally friendly and energy-saving systems by allowing for more effective material utilization in mechanical part design.

2. LITERATURE REVIEW

This research was conducted by Neslihan et al. [23] Utilized topology optimization and structural analysis to decrease the weight of a mobile handling robot. The main goal was to reduce the weight of the robot to enhance its payload capacity and minimize energy consumption. Initially, the researchers created a CAD model of the robot. Performed analysis using CAE software. Based on the analysis results topology optimization was employed to decrease the weight of the robot. Topology optimization is a technique that reduces weight without compromising payload capacity. By minimizing the amount of material used in its design this method successfully reduced the weight of the robot by 25%. Consequently, this led to an increase, in payload capacity and a reduction, in energy consumption. In conclusion, this study demonstrates that topology optimization can effectively enhance the efficiency of mobile handling robots.

In this research study, Ahu and Halil [24] conducted an analysis to compare the application of topology optimization, in manufacturing and machining methods. Topology optimization aims to enhance part performance and lower manufacturing expenses by minimizing material waste and making parts lighter. The study compared the performance of parts designed for manufacturing and machining using topology optimization techniques. As a result of the optimizations carried out in this study the desired reduction in mass was achieved. After the round of optimization, the design saw a reduction of approximately 63% in terms of mass when compared to its initial state. The part, which originally weighed 300 grams was successfully reduced to 100 grams while maintaining its structural integrity. Moreover, there was a decrease, in volume well. In conclusion, this research affirms that topology optimization can effectively cut down costs associated with manufacturing while enhancing part performance through reduction and lightweight strategies.

Orhan et al. [25] Conducted a study, on the electron beam melting method for manufacturing aircraft parts. The objective was to reduce the weight of the parts by 30% and achieve designs with geometry. The study utilized the method for design and topology optimization allowing for the optimization of shapes and reduced weights of the parts. Additionally, they analyzed deviations in structures made from maraging steel material. As a result, the weight of aircraft parts manufactured using electron beam melting was successfully reduced by 30%. Furthermore, topology optimization led to designs featuring geometry. These findings hold promise for producing more durable aircraft components, in the aerospace industry.

Yeswanth and Abraham [26] aimed to carry out a study using ANSYS Workbench 14.0 to analyze the parametric optimization of conventional steel drive shafts used in automobiles. This study aims to replace the driveshaft with different composite materials. Different composite materials, such as high-modulus carbon/epoxy or E-glass polyester, were selected, and the drive shaft was modeled using CATIAV5R20. Then, an analysis of the subject was carried out using ANSYS. As a result of the study, it is stated that the optimization of composite drive shafts provides high strength and reliability, as well as a reduction in weight. In this way, it is aimed at reducing the weight of the vehicles with composite shafts and, as a result, increasing fuel consumption and the overall performance of the vehicle.

Shahane and Pawar [27] carried out the optimization of the crankshaft design of an internal combustion engine using finite element analysis. Firstly, they performed finite element analysis for the optimization of the crankshaft under static and dynamic conditions using ANSYS software. Then, the crankshaft was optimized as a result of these analyses. It was shown that the weight of the optimized crankshaft was reduced by 4.37%. It is also explained that the optimized crankshaft is safe under both static and dynamic boundary conditions, which are the previously applied boundary conditions. Thus, it is explained that weight reduction after optimization can provide a positive increase in engine performance and efficiency. Finally, it is suggested to verify the optimization based on different boundary conditions, such as fatigue analysis.

Li Xue and colleagues [28] conducted a study to explore the application of topology optimization in determining the shape of crane mounting brackets. They utilized ANSYS software to perform an analysis of the bracket's topology. The research findings demonstrated that the optimized design proved both successful and safe. Furthermore, it was highlighted that topology optimization plays a role in ensuring strength and durability under specified conditions while also enhancing efficiency and cost-effectiveness through weight reduction.

Lei et al. [29] stated that they used topology optimization to improve mechanical performance and extend the service life of the gearbox. In the study, a three-dimensional CAD model of the gearbox was created using CREO 3.0 software. Then, the optimization simulation of the gearbox was performed using ANSYS software. As a result, it is explained that there is a reduction in stress concentration as a result of optimization.

Jayanaidu et al. [30] used ANSYS software to optimize the drive shaft for automobile applications. It was aimed at using and analyzing titanium alloy instead of the structural steel material used in the drive shaft. The high specific stiffness and low weight of titanium led to a reduction in the weight of the car. In this way, the car with reduced weight will provide an advantage, and it is stated that the deformation of titanium alloy is less than that of steel, making it a more optimum option.

3. MATERIAL AND METHOD

In this study, a series of steps are applied for the optimization of the shaft model. First, the model is selected for the study. Then, the drawing of the selected model is carried out using CAD programs. Then, static analysis is applied to evaluate the structural performance of the model under boundary conditions. After this step, topology optimization is performed based on the static analysis. The optimized model is then drawn again. Static analysis is performed again on the optimized and redrawn model, and the structural properties of the new model are examined. Finally, the analyses of the initial and final models are compared. The flow chart of the study is shown in Figure 1.

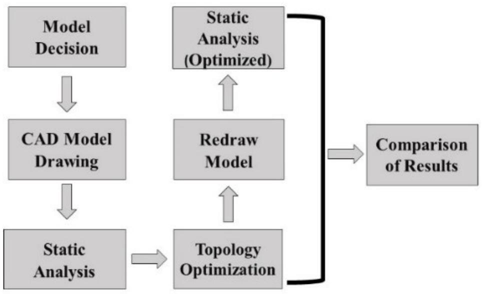

Figure 1. Flow chart of the study.

3.1. Finite Element Modelling of the Shaft

Ansys is a comprehensive engineering software used for product modeling and simulation of the modeled product. It is frequently used in different fields such as aerospace, defense, automotive, and biomedical. Ansys SpaceClaim is a three-dimensional modeling software that allows you to create designs or quickly edit designed models, as well as modify and repair models. The three-dimensional model of the shaft was created, and then the model was checked in the Check Geometry section for model control. The checked model was transferred to Workbench. The material of the shaft model was selected as structural steel. Structural steel material properties are shown in Table 1.

Table 1. Structural steel material properties.

Properties	Unit	Value
Density	*kg/m³* → kg/m^3	7850
Young's Modulus	*GPa*	200
Poisson's Ratio	-	0,3
Tensile Ultimate Strength	*MPa*	460
Tensile Yield Strength	*MPa*	250
Isotropic Thermal Conductivity	*W/mm°C*	0,060500

Mesh operation is very important for simulation. A more detailed mesh structure can be obtained by choosing a smaller mesh size. However, a smaller mesh size requires more computational power, and the analysis time may be longer. In this study, a 2 mm mesh size and the tetrahedron mesh method were selected. When a smaller mesh size is selected, the analysis time is very long, and the computer used is difficult, so the mesh size is selected as specified. As a result of the shaft model mesh, a total of 1165075 nodes and 777526 elements were formed, as shown in Figure 2.

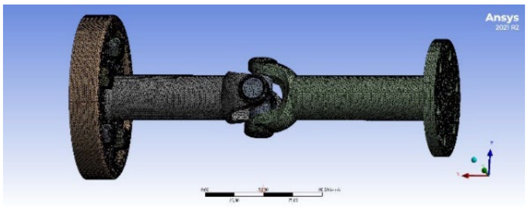

Figure 2. Static mesh of shaft.

3.2. Boundary Conditions

Since the shaft is connected by bolt parts, the part with the bolt connection is selected as the fixed support. Momentum is applied to the disc on the opposite side. The applied boundary conditions are shown in Figure 3.

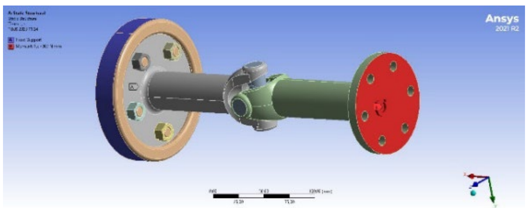

Figure 3. Boundary conditions applied to the shaft.

3.3. Topology Optimization Analysis Parameters

Topology optimization is considered a design methodology in which various scenarios are examined and aims to optimize a model. This study was carried out using Ansys software. After the static analysis was completed, the structural optimization process was started. At this stage, necessary adjustments were made, and the optimization process was performed for 500 iterations. During the optimization process, the regions that should be excluded from the model were determined in the "Optimization Region" section, and parts such as connection points or screws were excluded from the optimization process. In addition, the response weight was selected from the "Response Constraint" section, and it was decided to keep it at 35%.

4. RESULT

4.1. Static Structural Analysis Results

After the prescribed boundary conditions and loads were applied, the shaft model was statistically analyzed. The analysis aimed to measure the structural integrity of the model and its ability to withstand mechanical stresses in the real environment. Stress is a quantity that allows the identification of forces that resist deformation. Stress is generally defined as the force per unit area. There are different types of stress. The stress that occurs when forces pull an object is called tensile stress, and the stress that occurs when forces compress an object is called compressive stress. Figure 4 shows the stress distribution in the shaft model.

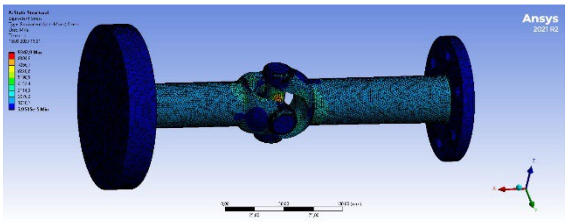

Figure 4. Stress in the shaft model under boundary conditions.

The deformation or shape change that occurs in a material subjected to various forces is called strain. There are many different types of strain, such as compressive strain, shear strain, and shear stress. Figure 5 shows the strains in the model.

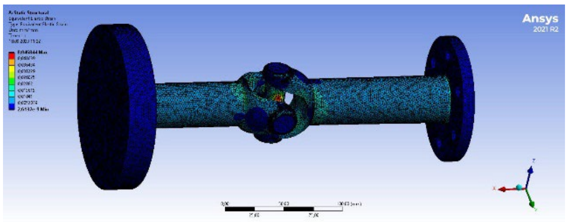

Figure 5. Strain in the shaft model under boundary conditions.

The shape or size of the material to which different external loads are applied is known as deformation. Deformation can occur in various ways. Elastic deformation is the return of the material to its former shape after deformation. Continuous deformation of the material indicates that it is permanently deformed. Figure 6 shows the deformation in the model.

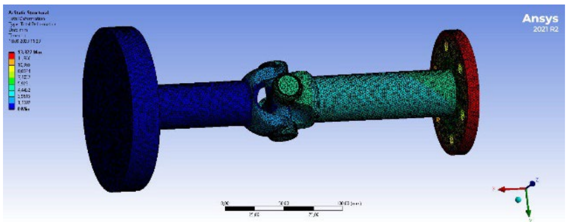

Figure 6. Deformation in the shaft model under boundary conditions.

4.2. Topology Optimization Results

After finishing the static analysis, topology optimization parameters were determined based on the results of the static analysis. Following that, the optimization analysis began, encompassing a grand total of 26 iterative phases. Nevertheless, the outcomes achieved in the 27th iteration did not satisfy the predetermined optimization standards, resulting in the dismissal of the model. As a result of this optimization procedure, a new model was generated, as shown in Figure 7.

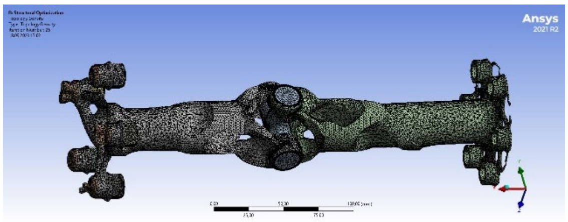

Figure 7. Optimized shaft model.

The optimized model was examined, and as a result of the analysis, it was concluded that the model should be redrawn and the errors should be eliminated. Two screws in the model were found to be cut, and it was determined that these screws were no longer required and should be removed from the model. Therefore, the model was exported in STL format. The main model was redesigned according to the optimized model. The redesigned model is shown in Figure 8 and was used for the static analyses.

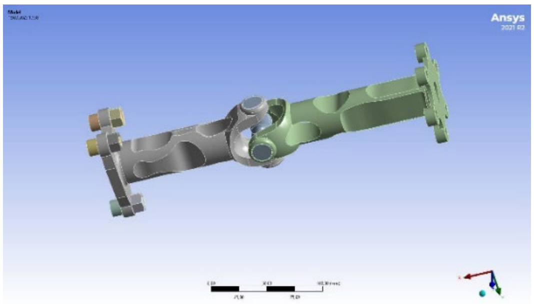

Figure 8. The redesigned model according to the optimized model.

The final version of the design was subjected to static analysis using the same mesh structure, boundary conditions, and settings in Ansys software for comparison and control purposes. The results of this analysis can be seen in Figure 9 for stress results, Figure 10 for strain results, and Figure 11 for deformation results.

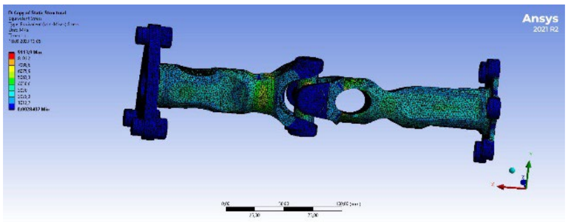

Figure 9. Stress in the optimized shaft model under boundary conditions.

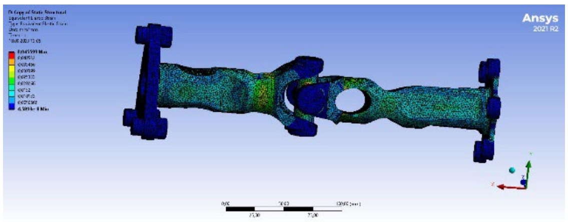

Figure 10. Strain in the optimized shaft model under boundary conditions.

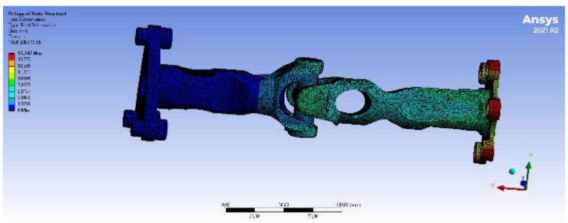

Figure 11. Deformation in the optimized shaft model under boundary conditions.

Table 2. Comparison table of shaft model optimization results.

Target Variable	A	B	C	W
Before optimization	0,04684	9342,9	13,327	5,9
After optimization	0,04559	9113,9	17,747	2,5

Formula 1 (PC: Percentage Change, Bf: Before, Af: After) was used to calculate the percentage change for each target variable:

$$PC = ((Bf - Af)/Bf) \times 100 \quad (1)$$

Table 2 (A: Maximum Strain(mm), B: Maximum Stress (MPa), C: Maximum Deformation(mm), W: Weight (Kg)) shows the comparison table of the shaft model before and after optimization. A reduction of about 2.65% in the maximum stress was observed. The maximum strain decreased by approximately 2.46%. In contrast, the maximum deformation increased by about 33.24%. The weight of the shaft decreased by a significant amount of approximately 57.81%. This shows that a much lighter model was created as a result of the optimization process.

5. CONCLUSIONS

Topology optimization enables the optimal allocation of material, enhancing the model's utility, efficiency, and structural performance. Topology optimization enables the attainment of lighter designs and enhances mechanical benefits. This research study focuses on the optimization of the shaft model. Conclusions were drawn concerning the model and the subject based on this research.

Initially, the chosen shaft model undergoes static structural analysis and a torsion test in this study. The torsion test findings were linked to the structural optimization, and subsequently, topological optimization was conducted. The model derived from topology optimizations was reconfigured. The new model underwent structural analysis and torsion testing under identical conditions. The findings are displayed in Table 1 and in visual representations. One notable achievement noted in the improved shaft model during this investigation is the significant weight reduction, amounting to a 57.81% decrease. Furthermore, a notable decrease in stress and tension was also seen.

These advancements are expected to enhance the energy and operating efficiency of machine shafts. Due to the decrease in weight, it is believed that it can aid in achieving more sustainable resource management and enhance the exploitation of raw materials accordingly.

The findings of this research exhibit notable resemblances and disparities when compared to analogous studies in the existing literature. Initially, the use of topology optimization led to notable enhancements in our desired parameters. Specifically, the mechanical shaft model experienced a weight reduction of 57.81%, which aligns with the findings of Neslihan et al.'s [23] research on a mobile handling robot and Ahu and Halil's [24] study comparing component manufacturing and machining techniques. Furthermore, the endeavor by Orhan et al. [25] to diminish the mass of airplane components by 30% aligns with reduced weight in the optimization of mechanical shafts. Topology optimization aligns with Ahu and Halil's [24] research, which seeks to enhance component performance and minimize expenses by simultaneously lowering weight. However, the study conducted by Shahane and Pawar [27] on the optimization of the crankshaft in an internal combustion engine demonstrates the favorable outcomes of a 4.37% reduction in crankshaft weight, leading to enhanced engine performance. The research conducted by Li Xue et al. [28] on topology optimization for defining the shape of crane mounting supports demonstrates that optimization plays a crucial role in enhancing durability, strength, efficiency, and cost-effectiveness. Within this particular framework, the present study demonstrates that investigating the optimization of the mechanical shaft model might yield beneficial outcomes for the objectives of reducing weight and improving performance in engineering applications.

6. DISCUSSION

The primary aim of this study is to prioritize the conservation of materials and enhance the effectiveness of components and models employed in engineering. By mitigating stress and strain, we may prolong the lifespan of machine components while simultaneously enhancing their efficiency. This optimization process not only yields advantages but also exerts a favorable influence on the environment. Furthermore, the lowering of weight also contributes to the promotion of sustainable engineering techniques.

Mechanical shafts play a crucial role in various engineering applications and ensure the proper functioning of machines, equipment, and systems in different industries. Their important functions in the transmission of electricity, rotational movement, and structural reinforcement underline their importance in engineering design. Given the increasing demand for improved efficiency, conservation of resources, and sustainable engineering techniques, optimizing mechanical shafts becomes imperative. This research was born out of the necessity to address the issues associated with the optimization of mechanical shafts. Traditional diagnostic and optimization techniques often face limitations, making it difficult to increase mechanical efficiency while reducing weight. Our work on this topic attempts to address this shortcoming by introducing a new technique for the optimization of shafts. We aim to improve the performance and resource efficiency of mechanical shafts by combining static structural analysis with topological optimization in ANSYS. The reasons for this are based on the search for a lighter, stronger, and more ecologically sustainable model. This not only advances engineering practice but also aligns with the broader goal of sustainable resource management. This study provides a distinct opportunity to explore unexplored areas of shaft optimization, improve the efficiency of our machines, and promote environmentally sound engineering methods.

The possible enhancements achieved in the research are quite significant. Nevertheless, it is crucial to be aware of the adverse circumstances that arise in the model and to guide future investigations. The decrease in weight, tension, and strain is a beneficial advancement. Nevertheless, the augmentation in deformation needs careful consideration. Hence, it is crucial to minimize distortion and enhance the model once again.

In future research, other materials can be employed to enhance the potential force, strength, and performance of the optimized model. The materials in question might either be composite materials that have been previously mentioned in the literature or titanium materials. In order to mitigate the increasing deformation and get a more optimal model, it is advisable to thoroughly evaluate the response constraint value of 35% and repeat the model analysis. By doing so, one can achieve more optimal settings for the model. To summarize, this study elucidates that topology optimization may enhance efficiency, provide savings, and promote mindful usage of resources.

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