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CAD/CAE WORKFLOW FOR THE TOPOLOGY OPTIMIZATION AND GEOMETRIC RECONSTRUCTION OF A STRUCTURAL COMPONENT

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ABSTRACT

This paper presents a study on the topological optimization of a structural component and the conversion of the optimized result into a manufacturable geometric model. The initial model was developed in a CAD environment and imported into the finite element analysis software, where boundary conditions and loading constraints were applied. The optimization process aimed to minimize structural compliance while reducing material usage and maintaining adequate stiffness. Different volume fractions and design parameters were investigated to identify a suitable optimized configuration. The obtained topology optimization results were analysed in terms of structural continuity, manufacturability, and clarity of the load-bearing features. Since the raw optimized geometry often contains irregular surfaces and complex shapes that are difficult to manufacture directly, the result was further reconstructed using NURBS and PolyNURBS modelling techniques. This stage allowed the creation of a smoother, continuous, and closed geometric model suitable for further analysis and production. Lattice structures are also integrated inside the reconstructed model to reduce mass while maintaining mechanical performance. The proposed workflow shows how CAD/CAE tools can transform an optimized conceptual design into a manufacturable structural component. The results emphasize the importance of post-processing, geometric reconstruction, and manufacturability checks in topology optimization.

KEYWORDS: topology optimization, PolyNURBS, lattice structure, CAD/CAE

1. Introduction

The development of lightweight, efficient and manufacturable structural components represents an important objective in modern mechanical engineering. In fields such as automotive engineering, aerospace, robotics and additive manufacturing, structural components must meet increasingly complex requirements regarding stiffness, strength, mass reduction and technological feasibility. Conventional design methods are usually based on the gradual modification of an initial geometry, which may limit the possibility of obtaining an efficient material distribution. In contrast, topology optimization provides a numerical design method that determines the most effective distribution of material within a predefined design domain, according to the applied loads, boundary conditions and design constraints [1-2].

Topology optimization has become strongly connected with additive manufacturing, which allows complex and lightweight geometries to be fabricated more easily than by conventional manufacturing. The integration of topology optimization and additive manufacturing can lead to improved stiffness-to-weight ratios, reduced material consumption and increased design freedom [2-4]. However, raw optimization outputs may contain irregular surfaces, discontinuities, thin members or geometrical details that are difficult to manufacture directly. Therefore, manufacturability constraints, minimum feature size control and post-processing operations are essential for transforming numerical optimization results into practical engineering components [5-7].

The integration of manufacturing constraints into topology optimization has been widely investigated. Mhapsekar *et al.* [5] proposed additive manufacturing constraints in topology optimization to improve manufacturability, especially by reducing support-related limitations. Other studies have considered overhang constraints, build direction limitations, distortion control and process-related restrictions to obtain designs that are more suitable for additive manufacturing [6, 7]. Another important aspect is the conversion of the optimized topology into a clean and manufacturable CAD model. Reconstruction methods, including feature-based approaches, NURBS-based modelling and automated CAD reconstruction, can generate smoother and editable models suitable for further analysis and manufacturing [8-10]. NURBS and PolyNURBS modelling techniques are relevant because they allow rough topology-optimized geometries to be converted into smoother closed CAD models while preserving the main structural load paths.

Lattice structures represent another important direction in lightweight structural design. Due to their cellular architecture, lattice structures can reduce mass while maintaining or improving mechanical performance, especially when combined with additive manufacturing technologies [11-15]. In topology-optimized components, internal lattice structures can be introduced to further reduce mass while preserving the main load-bearing regions of the optimized geometry.

The main objective of this paper is to demonstrate how CAD/CAE tools can be combined to transform a topology-optimized conceptual design into a practical, continuous and manufacturable structural component.

2. Experimental procedure

The experimental research was carried out to define a CAD/CAE workflow for the topology optimization of a structural component and for the reconstruction of the optimized result into a manufacturable geometric model. The workflow included finite element analysis, topology optimization, NURBS/PolyNURBS reconstruction and lattice structure generation. The initial component was designed in a CAD environment and imported into the finite element analysis software. The geometry was checked before analysis to ensure proper meshing. The component was fixed at the cylindrical mounting interface, while a vertical force corresponding to a mass of 7.70 kg, approximately 75.5 N, was applied to the free region of the model. The initial finite element analysis was used to determine the displacement and von Mises stress distributions. These results allowed the identification of the main deformation zones, stress concentration regions and load transfer paths. They were then used as a reference for defining and interpreting the topology optimization process.

Topology optimization was performed using a density-based method, with the objective of minimizing compliance and increasing structural stiffness. Several volume fractions were investigated to identify a suitable compromise between material reduction, structural continuity and manufacturability. Based on the comparison of the investigated volume fractions, the 40% volume fraction was selected for further reconstruction because it provided clearer and more continuous load-bearing paths.

The optimized geometry selected from the volume-fraction comparison was imported as an STL model and used as a reference for CAD reconstruction. NURBS and PolyNURBS tools were applied to rebuild the main structural surfaces, smooth the geometry and obtain a closed solid model. The cylindrical mounting interface was preserved as a functional region and integrated into the reconstructed body.

After reconstruction, an internal tetrahedral lattice structure was generated to further reduce mass while maintaining adequate stiffness. The lattice members were assigned a uniform thickness of 1.5 mm, selected as a compromise between manufacturability, stiffness and lightweight design.

3. Results and discussion

The results obtained in this study are grouped into four main stages: the initial finite element analysis, the topology optimization results, the reconstruction of the optimized geometry, and the generation of the internal lattice structure.

The initial finite element analysis was performed to evaluate the structural response of the original component before topology optimization. A vertical force corresponding to a mass of 7.70 kg, approximately 75.5 N, was applied to the model. The analysis focused mainly on the displacement distribution and the von Mises stress distribution, because these results indicate the critical regions and the main load transfer paths. The displacement results show that the highest deformation appears in the regions located farther from the fixed support. This behaviour is expected, since the fixed mounting area restricts movement, while the free regions of the structure are more affected by the applied vertical load. The stress distribution indicates the zones where the material is more intensively loaded and therefore

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must be preserved during the optimization process. These results were used as a basis for defining the topology optimization problem and for interpreting the optimized material distribution. Figure 1 shows the displacement distribution of the initial component under the applied vertical load. The figure is included to identify the regions with the highest deformation before topology optimization. Figure 2 shows the von Mises stress distribution of the initial component. This result is important because it identifies the highly stressed regions that must be preserved during the topology optimization process.

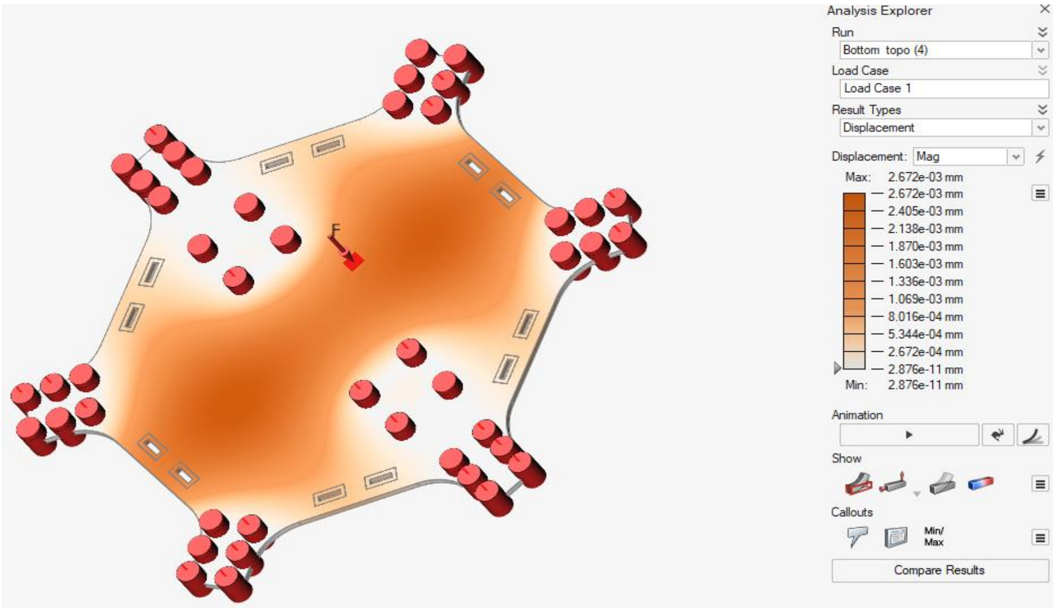

Fig. 1. *The displacement distribution of the initial component*

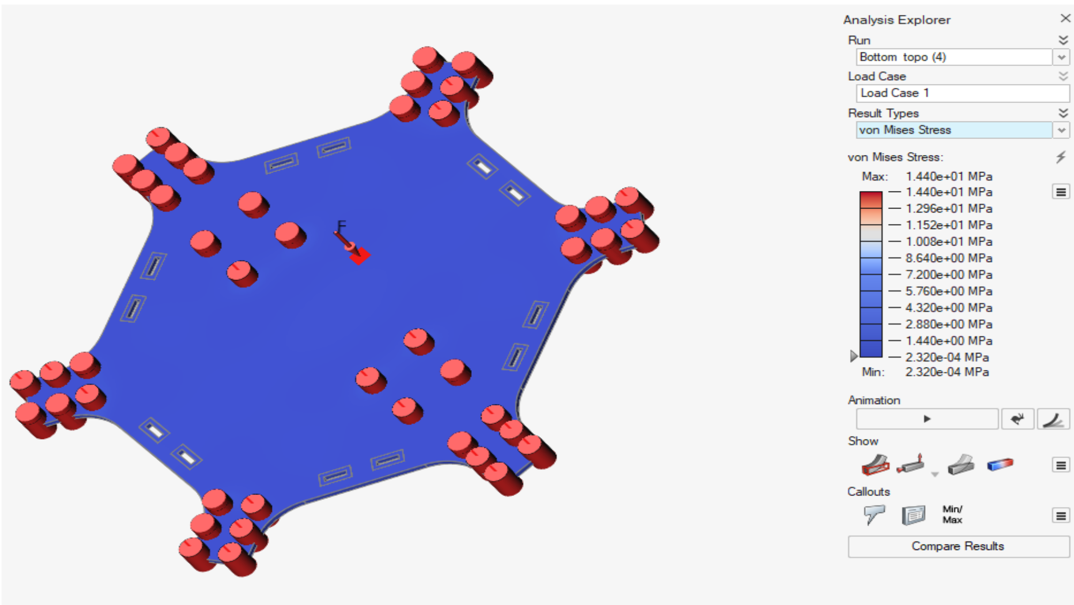

Fig. 2. *Von Mises stress distribution of the initial component*

The topology optimization results indicate that material is mainly retained along the principal load paths between the applied load region and the fixed mounting interface.

Low-density regions indicate material that can be removed without significantly affecting the global stiffness of the component. However, not all optimized configurations are suitable for manufacturing. Some volume fractions produced

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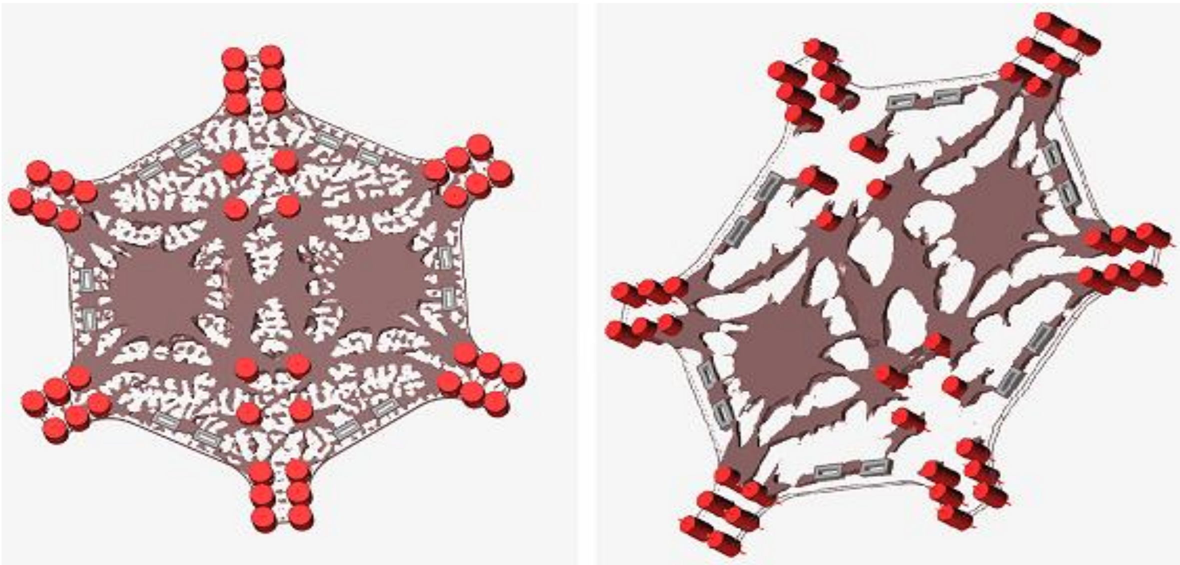
discontinuous or poorly defined structural members, which could not be directly converted into a reliable CAD model.

The results obtained for lower volume fractions showed a higher level of material reduction, but also a greater risk of discontinuities and weak structural regions. In contrast, higher volume fractions produced more continuous geometries, but with a smaller mass reduction.

Therefore, the selection of the final topology was based not only on material saving, but also on the clarity of the structural members and the possibility of reconstructing the geometry into a manufacturable model. Figure 3 compares two topology optimization results obtained for different volume fractions. The comparison shows that the 40% volume fraction provides clearer and more continuous structural members than the 20% volume fraction, which is more prone to discontinuities.



a b

Fig. 3. *Comparison of topology optimization results for different volume fractions: (a) 40% VF and (b) 20% VF*

The optimized geometry was selected by considering three main criteria: structural continuity, manufacturability, and preservation of the main load-bearing paths. The selected topology presents a continuous material distribution and clearly defined structural members. The density distribution indicates that the optimized shape follows the main force transmission directions. This confirms that the optimization process successfully identified the regions where material contributes most effectively to stiffness. The surface of the optimized STL model was rough and contained irregular features. For this reason, the optimized result was used as a design guide for the reconstruction stage rather than as a directly manufacturable part.

The reconstruction stage was necessary to transform the rough topology optimization result into a smooth and closed CAD geometry. The optimized STL model was imported into the modeling environment, where NURBS and PolyNURBS tools were used to create a manufacturable free-form shape. The reconstruction began by creating sections through the optimized model. These sections were used as references for generating NURBS surfaces along the main structural paths. Since the model was symmetrical, only half of the geometry was initially reconstructed. This reduced modelling time and allowed better control of the central region. The half-model was then mirrored, and the coincident vertices were welded to obtain a continuous geometry.

Figure 4 presents the reconstructed PolyNURBS model obtained after smoothing and correction operations. The figure is used to demonstrate that the rough topology optimization result was converted into a continuous and closed manufacturable geometry.

During reconstruction, several geometric issues were observed, including overlapping faces, hidden surfaces, non-welded vertices, and local discontinuities. These defects were corrected by editing vertices, edges, and faces, since a non-closed model cannot be reliably used for additive manufacturing or further finite element analysis. The cylindrical mounting interface was reconstructed separately using a PolyDisk feature and then integrated into the main body to obtain a continuous

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transition between the functional region and the optimized structure.

The final PolyNURBS model was checked using tolerance verification tools to ensure that the reconstructed geometry represented a closed solid. One of the main difficulties encountered during reconstruction was the integration of the cylindrical mounting interface with the optimized design region. The original topology result did not provide a clean transition between the structural body and the mounting cylinder. Therefore, the cylindrical region was reconstructed separately using a PolyDisk feature. The PolyDisk was extruded to the required length and then combined with the main reconstructed body. Several faces were removed, and the remaining edges were connected manually to create a continuous transition. This operation was necessary because the mounting interface is a functional region and must be preserved in the final geometry. The successful integration of the mounting interface is important because discontinuities in this region could generate stress concentrations or manufacturing problems. A single continuous body is preferable to the simple combination of separate design and non-design regions, because the connection zones may otherwise become mechanically weak. After obtaining the closed PolyNURBS geometry, the model was prepared for lattice structure generation. The purpose of the lattice structure was to reduce the mass of the component while maintaining adequate stiffness. The reconstructed geometry was imported as an STL file, and a surface mesh was generated.

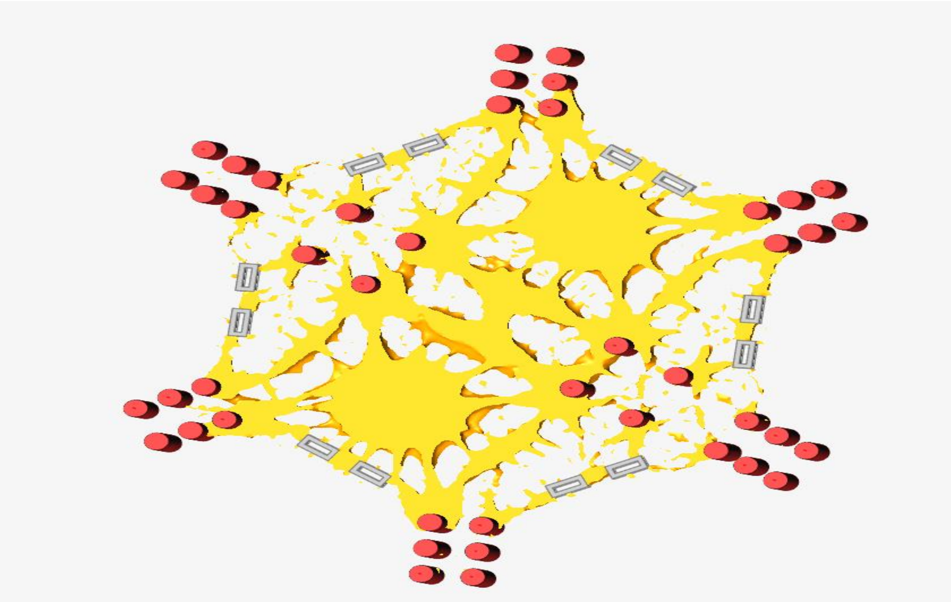

Fig. 4. *Reconstructed PolyNURBS model obtained after smoothing and correction operations*

Before lattice generation, the reconstructed geometry was meshed and remeshed to improve the regularity of the internal lattice. Mesh quality was important because an irregular surface mesh could lead to non-uniform lattice distribution. A tetrahedral lattice structure was selected because it provides good stiffness and is suitable for internal reinforcement. The lattice rule was defined and then applied inside the reconstructed geometry. The internal volume lattice was adjusted so that the members remained inside the component boundary. The lattice members were assigned a uniform thickness of 1.5 mm. This value was chosen to obtain a balance between manufacturability, stiffness and mass reduction. The final lattice-reinforced model was exported for further analysis. Figure 5 presents a detail of the final lattice-reinforced component obtained after applying the tetrahedral lattice inside the reconstructed geometry. This figure highlights the internal lightweight structure prepared for further analysis or additive manufacturing.

The obtained results show that topology optimization is an efficient method for identifying the main load-bearing regions of a structural component. The NURBS/PolyNURBS reconstruction stage proved to be essential for converting the optimized concept into a smooth and manufacturable model. This stage allowed the preservation of the main structural load paths while eliminating surface irregularities and geometric errors. The final reconstructed geometry was more suitable for finite element analysis, STL export and additive manufacturing preparation.

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The integration of lattice structures further improved the lightweight design concept. By replacing part of the internal volume with a

tetrahedral lattice, the component can achieve additional mass reduction while maintaining internal support. Nevertheless, the lattice generation process depends strongly on mesh quality. A non-uniform surface mesh can lead to irregular lattice distribution, while excessive remeshing may alter the external geometry. Therefore, mesh control is an important factor in obtaining reliable lattice-reinforced components.

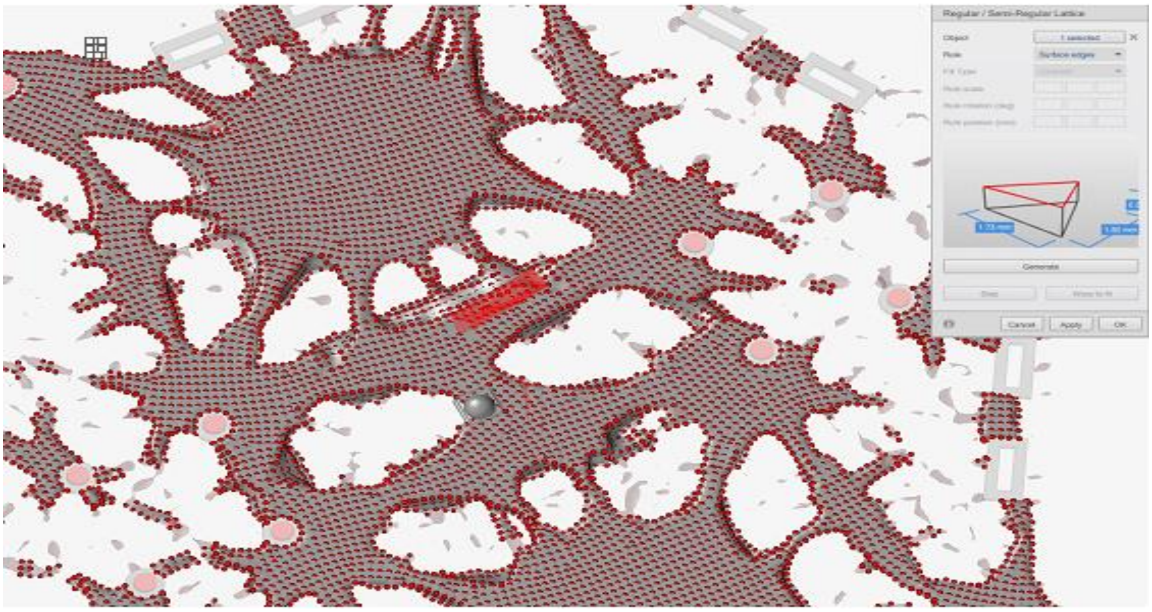

Fig. 5. *Detail of the final reconstructed component with internal tetrahedral lattice structure*

The proposed CAD/CAE workflow transforms a numerical optimization result into a practical structural component that can be further analysed or manufactured.

The topology optimization results obtained for different volume fractions are summarized in Table 1. The results show that lower volume fractions lead to higher material reduction, but they also increase the risk of discontinuities and poorly defined members. The configuration corresponding to a 40% volume fraction was selected because it provided a more continuous geometry and a better basis for NURBS/PolyNURBS reconstruction.

Table 1. *Comparison of topology optimization results for different volume fractions*

Volume fraction [%]	**Material reduction [%]**	**Relative remaining material [%]**	**Structural continuity**	**Manufacturability assessment**
20	80	20	Low	Discontinuous members and poorly defined geometry
25	75	25	Medium	Some load paths are visible, but several regions are difficult to reconstruct
30	70	30	Medium	Improved material distribution, but local discontinuities are still present
35	65	35	Medium-High	More continuous members, but some structural features remain unclear
40	60	40	High	Continuous geometry and clearer load-bearing paths

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4. Conclusions

This paper presented a CAD/CAE workflow for the topology optimization of a structural component and for the conversion of the optimized result into a manufacturable geometric model. The proposed approach included finite element analysis, topology optimization, NURBS/PolyNURBS reconstruction, geometry verification, and lattice structure generation.

The initial finite element analysis allowed the identification of the main displacement and von Mises stress regions, which were used to define and interpret the topology optimization process. The comparison of different volume fractions showed that lower volume fractions can increase material reduction but may also lead to discontinuous or poorly defined structural members. Therefore, the final optimized configuration was selected based on both mass reduction and manufacturability.

The reconstruction stage proved to be essential, since the raw topology optimization result could not be used directly as a final CAD model. By using NURBS and PolyNURBS tools, the optimized geometry was transformed into a smoother, continuous, and closed model while preserving the main load-bearing paths and the functional mounting interface.

The integration of an internal tetrahedral lattice structure provided an additional lightweight design solution. The results also showed that mesh quality and geometric continuity are important factors for obtaining a reliable lattice-reinforced model. The research confirms that topology optimization should be combined with geometric reconstruction and manufacturability verification to obtain a practical engineering component suitable for further analysis and additive manufacturing.

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