



Topology Optimization-Based Lightweight Chassis Design: A Case Study on Structural Efficiency Enhancement for an Autonomous Scale Vehicle

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ABSTRACT

This study aims to enhance structural efficiency and achieve material savings by employing the topology optimization method for the lightweight design of an autonomous model vehicle chassis. During the design process, the penalty-based Solid Isotropic Material with Penalization (SIMP) method, available within ANSYS Academic software, was utilized. Initially, a structural analysis of the chassis was conducted, followed by the application of topology optimization based on the finite element method (FEM) results. Through iterative solutions under specified loading conditions and boundary constraints, a mass reduction of approximately 27% was achieved compared to the initial geometry. Despite the reduction in mass, the design maintained its structural integrity. Graphical analyses indicated that the optimization process reached convergence after the fifth iteration, with a stabilized distribution of material. The results demonstrate the potential of topology optimization to develop low-cost, lightweight, yet robust structural solutions, emphasizing its effectiveness as an engineering tool in systems where weight reduction is critical, such as autonomous model vehicles.

Introduction

In contemporary engineering design processes, the scope has expanded beyond merely fulfilling functional requirements. It now encompasses multi-dimensional criteria such as efficient resource utilization, lightweight construction, structural integrity, and manufacturability. These considerations are especially critical in sectors such as automotive, aerospace, defense, and structural engineering, necessitating the adoption of more comprehensive design approaches. Among the various methods developed to address these needs, topology optimization has emerged as a prominent strategy. Topology optimization is an engineering approach that aims to determine the optimal distribution of material within a given design domain. It goes beyond traditional sizing and shape optimization by enabling the discovery of non-intuitive, high-performance structural layouts. This study focuses on the design process of a chassis intended for use in an autonomous model vehicle, employing

topology optimization to achieve both weight reduction and cost efficiency. Within this context, topology optimization stands out as a numerical method that seeks the most effective material distribution under predefined loading and boundary conditions.

With the advancement of computational techniques, topology optimization has evolved through integration with the Finite Element Method (FEM), isogeometric analysis, and artificial intelligence-based algorithms, thereby facilitating innovative engineering solutions. In this study, the effects of topology optimization across various application domains are evaluated in light of leading works in literature.

Numerous studies have explored the applicability of topology optimization to a wide range of engineering problems. For instance, Chen et al. [1] integrated FEM and BEM techniques with isogeometric analysis to achieve broadband optimization in structural-acoustic interactions, significantly improving computational efficiency. In the

automotive sector, Mete and Başak [2] optimized a critical safety component the tie rod while Nazlı and Özsoy [3] reported up to 57% weight reduction in a control arm. Karamert and Demir [4] analyzed the correlation between torsional stiffness and topological structure in commercial bus chassis to propose design improvements. In aerospace applications, Saraç and Koçak [5] demonstrated that topology optimization in aircraft engine bracket design could yield nearly 80% material savings without compromising structural adequacy. Korkut et al. [6] conducted composite-based structural design for aircraft wing sections using Hypermesh-assisted analysis. From a manufacturing technology perspective, studies by Çalık and Uzun [7] and Canlıdınç [8] have shown that combining metal additive manufacturing with topology optimization yields positive impacts on both production flexibility and material efficiency. Furthermore, Arat et al. [9] reported a 35% weight reduction and a 42% improvement in structural efficiency through topology optimization of pneumatic gripper systems. A study by Cai et al. [10] employing mixed-integer programming addressed the effects of kinematic instability in lattice structures, contributing mathematical formulations to the field. Tuğsal and Deniz [11] investigated the structural behavior of industrial storage rack systems with varying heights under seismic loading and evaluated the contribution of beam-to-column connections to overall system safety. The results obtained from both linear and nonlinear analyses revealed that the detailing of beam-to-column joints plays a critical role in ensuring seismic safety.

Akdağ and Çelebi [12] performed weight optimization of a three-phase, 50 Hz, 50 kVA, 34.5/0.4 kV, delta-wye connected oil-type transformer using the Firefly Algorithm. Based on 200 repeated simulations conducted in the MATLAB environment, optimization of the current density and core cross-section suitability factor resulted in an approximately 1% reduction in the transformer's weight. Parla et al., [13] focused on maximum power control and optimization in 8/6 pole switched reluctance generators (SRG) operating under variable wind conditions. In the study conducted in the MATLAB/Simulink environment, it was reported that optimal angles and MPPT control strategies increased power output and ensured system stability. Dündar, İzci et al., [14] improved the Levy Flight Distribution (LFD) algorithm using the Nelder-Mead (NM) method and developed three different strategies. These strategies optimized the balance between global and local search, enhancing performance in function optimization problems, which was validated through statistical tests. Altay and Altay [15] examined the performance of the Slime Mould Algorithm (SMA) and its hybrid versions in global optimization problems. It was found that hybrid methods such as LSMA and ESMA mitigated SMA's slow convergence and local optima entrapment issues, achieving higher success rates in CEC2020 test functions.

This study addresses a notable gap in the literature by integrating topology optimization into the design of an autonomous vehicle chassis an area where structural optimization applications for lightweight model vehicles remain significantly underexplored. The novelty of the work lies not only in the combined application of FEM-based analysis and the SIMP method, but also in the detailed graphical analysis of the optimization process, including iteration-based convergence observations. While existing research has predominantly focused on aerospace and civil engineering applications, this paper provides an original contribution by presenting a cost-effective and lightweight chassis solution tailored for ground vehicles. The achievement of a 27% mass reduction without compromising the safety factor demonstrates that structural efficiency and material economy can be attained simultaneously. This finding sets the study apart from prior work and highlights the effectiveness of topology optimization in lightweight vehicle design.

The primary aim of this study is to develop a lightweight and structurally efficient chassis design for an autonomous model vehicle by employing the topology optimization method. Using the SIMP approach integrated into the finite element framework, the study focuses on reducing the overall mass of the chassis while ensuring that its load-carrying capacity, stiffness, and safety factor remain within acceptable limits. By doing so, this work seeks to demonstrate the practical applicability of topology optimization in ground vehicle design, highlighting its potential as a cost-effective and computationally efficient engineering tool for achieving material savings without compromising structural integrity.

Optimization

Fundamentally, optimization refers to the process of finding the best solution(s) to one or more problems under a set of predefined conditions. It provides a systematic framework to enhance performance, reduce costs, and ensure efficiency in engineering applications. Today, both classical and heuristic methods are commonly employed to solve such problems [16]. Classical approaches such as linear and nonlinear programming are effective for continuous and differentiable functions, whereas heuristic and metaheuristic methods including Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization offer robust solutions for complex and nonlinear problems. Depending on the problem, optimization can also be classified as deterministic or stochastic, single- or multi-objective, and discrete or continuous. Among these approaches, topology optimization has emerged as a particularly powerful method, as it determines the optimal material distribution within a design domain rather than merely adjusting size or shape.

This capability enables the development of lightweight, high-performance structures in manufacturing, aerospace, and automotive engineering. In this manuscript, topology optimization is used to lightweight a model autonomous vehicle chassis.

A. Topology Optimization

Topology optimization methods not only provide optimal geometries but also minimize material usage, thereby offering cost-effective solutions [17]. An illustration of the topology optimization process is presented in Fig. 1.

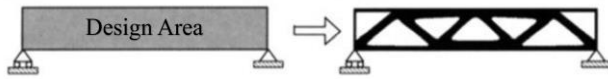


Figure 1. Topology optimization

Topology optimization is one of the most advanced structural design methods, aiming to automatically determine the optimal material layout within a design domain under specified loading conditions and design constraints [18]. The first general and numerical approach in this field was introduced by Cheng and Olhoff [19] for the optimal design of solid elastic plates. Following the seminal work of Bendsøe et al. [20], topology optimization gained significant momentum, introducing a homogenization-based perspective to the methodology. In subsequent years, several numerical techniques have been developed and widely adopted, including the penalty-based Solid Isotropic Material with Penalization (SIMP) method [21,22]. Evolutionary Structural Optimization (ESO) [23,24], and the Level-Set approach [25,26]. In this manuscript, the penalty-based SIMP method is adopted and implemented for structural optimization purposes.

B. OPTIMIZATION PROBLEM WITH SIMP

This section briefly introduces the topology optimization problem involving both topology and thickness control, which will be addressed in numerical examples. The penalized Solid Isotropic Material with Penalization (SIMP) approach is a topology optimization technique based on variable density methods. In this method, the design domain is discretized into a finite element mesh composed of isotropic solid microstructures.

The density field (ρ) of the structure is used to transform the topology optimization into a structural continuity optimization problem. The objective of the optimization is to minimize structural compliance under a prescribed volume constraint.

Within the SIMP framework, the optimization problem is mathematically expressed as follows [27].

$$\min: f(\Omega, \rho) = U^t K U = \sum E_e(\rho_e) u_e^t k_e^o u_e \quad (1)$$

Subject to: $KU = F$

$$\sum \rho_e u_e \leq V_{max}$$

$$0 \leq \rho \leq 1$$

Here,

- Ω denotes the structural design domain, which defines the region where the material distribution is to be optimized.
- ρ is the density field of the structural finite element mesh, representing the relative material presence in each element (0 for void and 1 for solid material).
- U represents the global displacement field obtained from the finite element analysis, describing the deformation of the entire structure under applied loads.
- F is the external load vector, which contains the forces or boundary conditions applied to the design domain.
- K is the global stiffness matrix, relating nodal displacements to applied loads in the finite element formulation.
- u_e is the displacement vector of an individual element, extracted from the global displacement field.
- k_e^o is the element stiffness matrix corresponding to unit Young's modulus, which is later scaled by the penalized material properties.
- ρ_e is the elemental density variable that controls whether material exists in a specific element.
- V_{max} represents the upper bound of the total allowable volume, enforcing the volume constraint during optimization.

The density penalization model is expressed by the following equation:

$$E_e(\rho_e) = E_{min} + (\rho_e)^p (E_0 - E_{min}) \quad (2)$$

$$\rho_e \in [0,1]$$

Here,

- E_0 represents the stiffness of the base material
- E_{min} is the artificial minimum stiffness value assigned to void elements to prevent singularities in the numerical solution.
- p is the penalization factor, which pushes intermediate densities toward either 0 (void) or 1 (solid), thereby promoting a clear black-and-white design.
- $\rho_e \in [0, 1]$ defines the range of possible material densities, from fully void (0) to fully solid (1).

In the initial preparation stage, the design domain, loading conditions, boundary constraints, and initial design variables are defined. Based on this setup, a numerical solution is performed to determine the structural behavior of the system—typically using the Finite Element Method (FEM).

Following the structural response analysis, a sensitivity study is carried out to assess the influence of design variables on the objective function (e.g., compliance or stiffness), thereby defining the optimization direction. Numerical instabilities that may arise from discretization or interpolation are subsequently mitigated using

techniques such as filtering or penalization to maintain the physical validity of the solution. The design variables are then updated according to the optimization algorithm, and the new configuration is evaluated for convergence. If convergence is not achieved, the process iterates until the optimized material distribution is obtained. The overall SIMP optimization procedure is illustrated in Fig. 2.

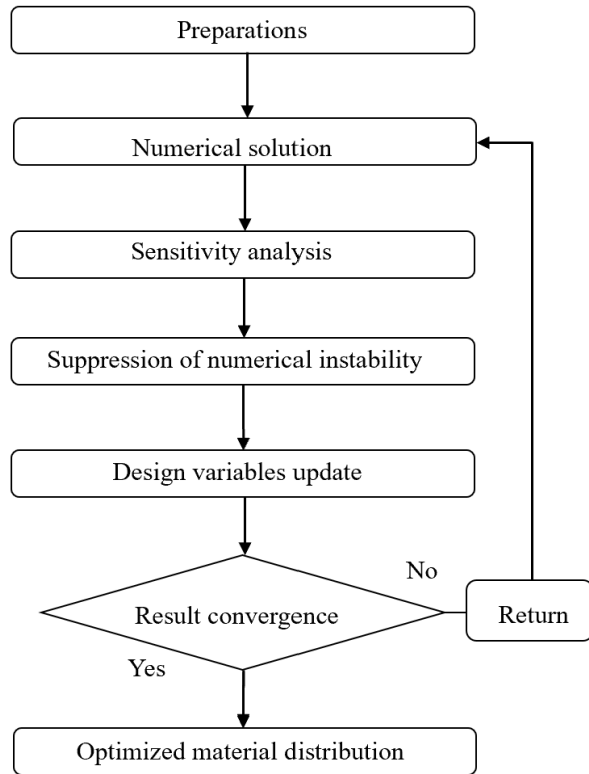


Figure 2. SIMP Flowchart

The stages in Figure 2 are detailed step by step below.

- **Preparations**

In this initial stage, the design domain is defined, including the applied loads, boundary conditions, and material properties. The finite element mesh is generated, and an initial density distribution is assigned across the elements. In addition, the optimization parameters such as the volume fraction, penalty factor, and filter radius are specified to ensure a stable and well-posed problem.

- **Numerical solution**

Based on the current material distribution, a numerical analysis is performed, most commonly using the finite element method. This step provides the system response, such as displacements, stresses, or strain energy, which forms the basis for evaluating the performance of the design.

- **Sensitivity analysis**

The sensitivities of the objective function and the constraints with respect to the design variables are computed. This analysis indicates how the material distribution influences the structural response and guides the optimization algorithm in updating the design variables effectively.

- **Suppression of numerical instability**

To eliminate potential numerical instabilities, such as checkerboard patterns or mesh dependency, filtering or projection techniques are applied. These stabilization measures ensure that the resulting material distribution is physically meaningful and manufacturable.

- **Design variables update**

The design variables (element densities) are updated according to the sensitivity information obtained in the previous step. This iterative update process progressively improves the material layout toward the optimal solution.

- **Result convergence**

Convergence criteria are checked by monitoring changes in the objective function and design variables between successive iterations. If the variation falls below a predefined threshold, the solution is considered converged. Otherwise, the process returns to the numerical solution step and continues iteratively.

- **Optimized material distribution**

Once convergence is achieved, the final optimized material distribution is obtained. This distribution represents the most efficient structural layout within the defined design space and constraints.

Material and Method

A. Material

PLA-based polymer material was used for the vehicle chassis to ensure manufacturability using a 3D printer. The dimensions of the chassis are $10 \times 75 \times 210$ mm. The technical information provided by the manufacturer is indicated in Table 1 [28]. The 3D model of the vehicle chassis is presented in Fig. 3.

Table 1. Mechanical properties of polylactic acid (PLA) [28]

Mechanical Property	Value
Yield strength	60 MPa
Elongation at break	6%
Tensile modulus	3600 MPa
Flexural strength	83 MPa
Flexural modulus	3800 MPa

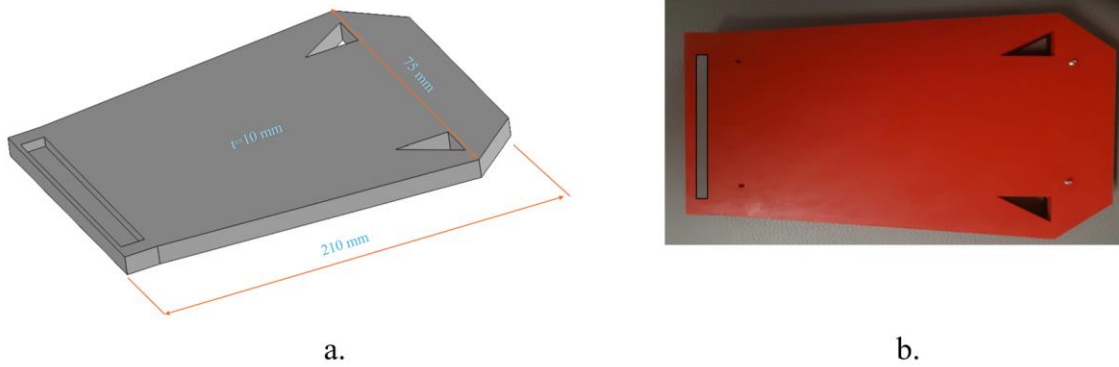


Figure 3. Vehicle chassis model (a) 3D CAD design (b) Physical model fabricated using a 3D printer.

B. METHOD

All components of the vehicle were modeled in 3D using the student version of SolidWorks. For topology optimization, the academic version of ANSYS software was utilized. The optimization process was carried out using the topology optimization module available within the structural optimization environment of ANSYS. The method employed was the Solid Isotropic Material with Penalization (SIMP) technique, which is integrated into the software. In this study, force and moment distributions were applied in a manner that realistically reflects actual driving scenarios.

Results and Discussion

Topology optimization was employed in the design of the vehicle chassis. This approach enabled a reduction in structural weight while maintaining durability and overall performance. The topology optimization analyses were performed using ANSYS software.

A. Structural Analysis Result

Prior to conducting topology optimization, a structural analysis of the vehicle was performed. The analysis utilized 15,096 elements and 76,871 nodes. Subsequently, a Quality Mesh Analysis was conducted, yielding a minimum mesh quality value of 0.31446, which is considered acceptable for the model vehicle chassis. The mesh structure is illustrated in Fig. 4.

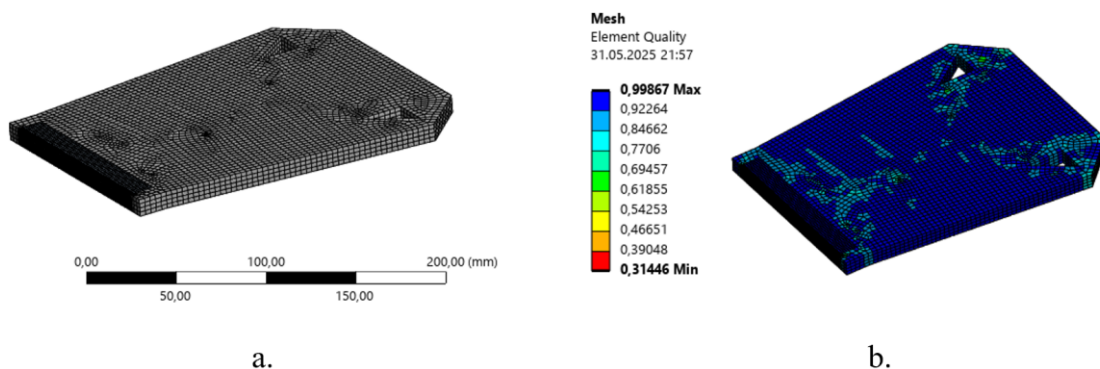


Figure 4. Mesh detail (a) Mesh design (b) Mesh element quality

For the structural design of the vehicle chassis, fixed supports were applied at the base points where the wheel axles are mounted. A 5 N vertical load was applied from

the top, and the analysis was performed accordingly. The results showed a maximum deformation of 0.00065133 mm. The von Mises stress ranged from a minimum of 5.2505×10^{-5} MPa to a maximum of 0.31043 MPa.

These values indicate that the system operates with a safety factor of approximately 15, confirming its structural safety. Details of the analysis are illustrated in Fig. 5.

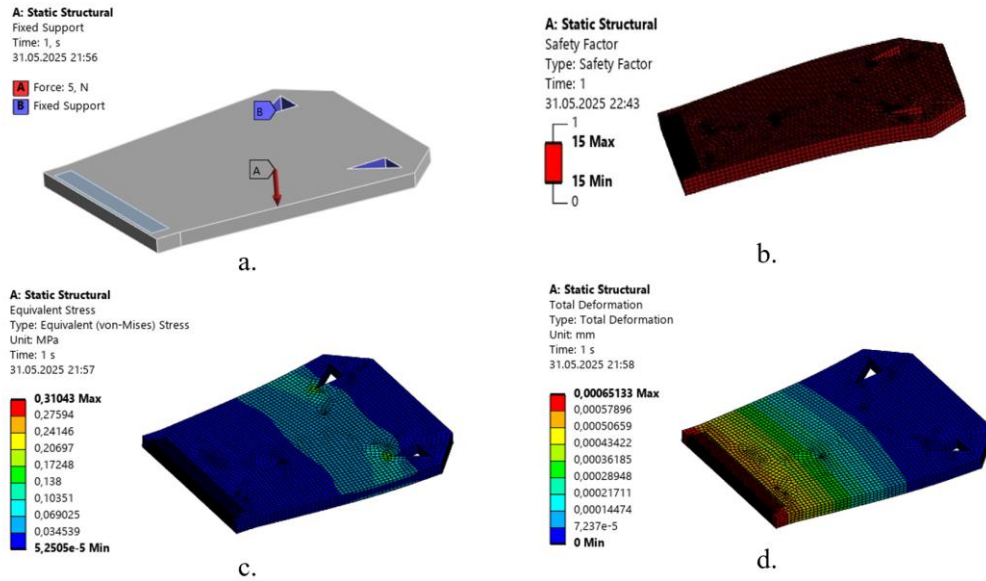


Figure 5. Analysis detail (a) Boundary conditions (b) Safety Factor (c) Von-Mises Stress (d) Total deformation

B. Topology Optimization Result

Following the structural analysis, the results were transferred to the Structural Optimization module within the ANSYS software. The design setup and integration details are presented in Fig. 6.

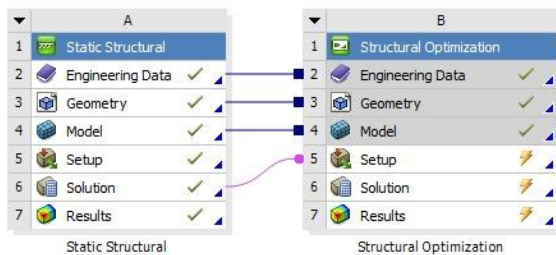


Figure 6. Design detail

From this point onward, topology optimization was performed using the SIMP method, while keeping the boundary conditions and mesh settings unchanged. The results of the topology optimization are presented in Fig. 7.

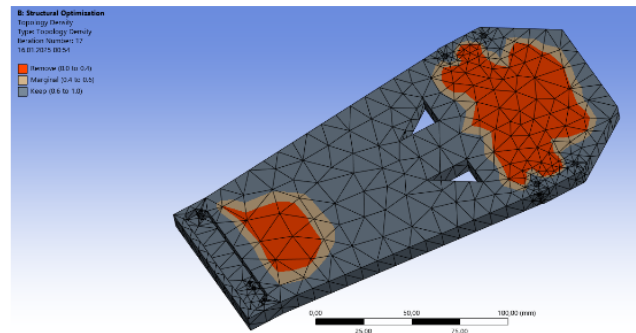


Figure 7. Topology optimization result screen

Based on the results of the topology optimization, a 27% reduction in mass was achieved after 15 iterations compared to the initial model. The optimized design produced lower maximum stress under the same loading conditions compared to the conventional solid chassis. Graphical analyses revealed that the optimization process reached convergence starting from the 5th iteration, indicating a stabilized material distribution. On average, each iteration required approximately 30 seconds, resulting in a total optimization time of about 7.5 minutes. In terms of computational cost, the analyses were performed on a standard workstation equipped with an Intel i7 processor (3.40 GHz) and 16 GB RAM, using ANSYS Academic software. The finite element model consisted of 15,096 elements and 76,871 nodes, which indicates that the proposed topology optimization framework is computationally efficient and feasible for lightweight

design applications. The plot of iteration versus topology density is presented in Fig. 8.

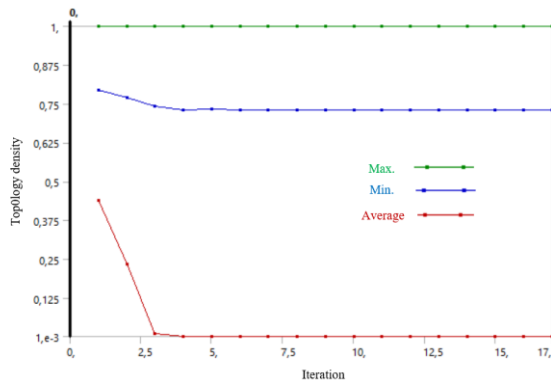


Figure 8. Iteration – Topology density

The graph demonstrates that unnecessary material was effectively removed during the mass optimization process, while material density remained constant in critical regions to preserve structural integrity.

These findings indicate that the applied topology optimization was effective and that further iterations beyond a certain point did not yield additional improvements.

The results of this study were observed to be consistent with the literature [29,30]. A comparison of the literature is shown in Table 2.

Table 2. Comparison of the literature

Feature	This Study	Eröss and Markovits [29]	Güney and Uzun [30]
Material	PLA	Ti6Al4V Titanium Alloy	Aluminum alloy (UAV frame structure)
Method	SIMP Topology Optimization	Stiffness-based topology optimization	SIMP-based and BESO (Bi-directional Evolutionary Structural Optimization) methods
Mass Reduction (%)	27% (depending on boundary condition and load case)	Approximately 70–80% (depending on boundary condition and load case)	24–33% (depending on boundary condition and load case)
Number of Iterations	15 (converged after 5)	100 iterations (converged after 10)	40–60 (SIMP converged after 40, BESO after 60)
Maximum Stress	Reduction	Reduction	Reduction in all load cases; stress concentration minimized near support regions
Computation Time	7.5 minutes (standard hardware)	Variable depending on algorithmic and hardware improvements	8–10 minutes (ANSYS Workbench, mid-range CPU)
Software	ANSYS Workbench 2024 R2	Unspecified	ANSYS Workbench 2022 R2
Field	Structural optimization	Structural optimization	UAV lightweight structural optimization
Optimization Type	Single-objective (stiffness maximization)	Single-objective (stiffness and weight trade-off)	Multi-objective (mass minimization and stiffness maximization)
Boundary Conditions	Fixed supports, distributed load	Fixed–cantilever beam constraint	Clamped UAV arm with distributed lift forces
Mesh/Element Size	Medium density mesh (~10 ⁵ elements)	High-resolution mesh (~10 ⁶ elements)	Variable mesh density (~10 ⁵ –10 ⁶ elements)
Validation Method	FEA-based convergence validation	Numerical validation with AM compatibility check	FEA and literature-based comparison
Manufacturing Method	FDM (3D printing validation)	SLM (Selective Laser Melting)	CAD-integrated topology optimization (AM-oriented design)
Performance Improvement (%)	Stress reduction ≈12%, weight reduction 27%	Stiffness improvement ≈15%, mass reduction up to 80%	Strength-to-weight ratio improved by ≈20–25%
Objective Function	Minimize compliance (maximize stiffness)	Minimize compliance subject to volume constraint	Minimize compliance and displacement under load constraints

A comparative analysis of the present study with the works of Eröss and Markovits [29] and Güney and Uzun [30] reveals significant variations in material selection,

optimization methodology, and computational performance. In this study, PLA material was used, whereas Ti6Al4V titanium alloy and aluminium alloy were

employed in the referenced works for additive manufacturing and UAV structural applications, respectively. The use of PLA in this study highlights a focus on polymer-based lightweight modelling and rapid validation through additive manufacturing, contrasting with the metal-based optimization strategies adopted in the other two studies.

From a methodological standpoint, this research utilizes the SIMP topology optimization technique, while Eröss and Markovits [29] applied a stiffness-based topology optimization, and Güney and Uzun [30] integrated both SIMP and BESO (Bi-directional Evolutionary Structural Optimization) methods. The combination of SIMP and BESO in [30] provides a hybrid framework capable of balancing material distribution and element addition–removal strategies, enhancing convergence precision.

In terms of mass reduction, the current study achieved 27%, which is moderate compared to the 70–80% reported by Eröss and Markovits [29] and the 24–33% range found by Güney and Uzun [30]. The relatively higher mass reduction in [29] is attributed to the use of high-strength titanium alloys and the allowance of greater material removal under similar boundary constraints. In contrast, the mass reduction range obtained by Güney and Uzun [30] reflects a balance between lightweight design and maintaining UAV structural rigidity.

Regarding convergence performance, the present study reached stability after five iterations out of fifteen total, whereas Eröss and Markovits [29] required approximately ten iterations out of one hundred, and Güney and Uzun [30] reported convergence between forty and sixty iterations depending on the optimization method (SIMP or BESO). This outcome indicates a faster convergence trend in the current study, primarily due to simpler geometric constraints and reduced mesh complexity.

All studies demonstrated stress reduction as a key result, though with varying degrees of improvement. The maximum stress reduction observed in the current work is about 12%, while Eröss and Markovits [29] and Güney and Uzun [30] achieved greater reductions due to the utilization of metallic materials with higher stiffness and optimized boundary configurations. Moreover, in [30], the stress concentration near support regions was effectively minimized by combining SIMP and BESO strategies.

In terms of computational efficiency, the present analysis required an average of 7.5 minutes on standard hardware, whereas Eröss and Markovits [29] reported variable durations dependent on algorithmic and hardware performance, and Güney and Uzun [30] achieved convergence within 8–10 minutes using ANSYS Workbench on mid-range CPUs. These results confirm that computational time is primarily influenced by material complexity and mesh resolution rather than optimization methodology alone.

From the software and validation perspective, all three studies utilized the ANSYS Workbench environment for simulation and optimization. However, while this study and Güney and Uzun [30] explicitly specified the software versions (2024 R2 and 2022 R2, respectively), Eröss and Markovits [29] did not. Validation methods also differed:

the present study performed FEA-based convergence validation and experimental confirmation via 3D printing, while Eröss and Markovits [29] conducted numerical validation with additive manufacturing compatibility, and Güney and Uzun [30] carried out literature-based and simulation-based validation.

Finally, while all studies pursued structural optimization, the objective functions slightly differed. The present study and Eröss and Markovits [29] aimed to minimize compliance (thus maximizing stiffness), whereas Güney and Uzun [30] conducted a multi-objective optimization balancing both mass minimization and stiffness maximization, which is more suitable for UAV lightweight design requirements.

If further weight reduction is desired without compromising structural stability, alternative optimization constraints or loading scenarios may be considered.

Conclusion

The findings of this research demonstrate the effectiveness of topology optimization in achieving lightweight and structurally efficient chassis designs. The initial finite element analysis, which employed a mesh of 15,096 elements and 76,871 nodes, confirmed the structural adequacy of the baseline design under applied boundary conditions. A maximum deformation of 0.00065133 mm and von Mises stress values ranging from 5.25×10^{-5} MPa to 0.31043 MPa indicated a safety factor of approximately 15, ensuring reliability for practical use.

Subsequently, the application of the SIMP-based topology optimization approach resulted in a 27% reduction in mass compared to the initial geometry. Importantly, this reduction did not compromise the load-carrying capacity or durability of the chassis. Iteration-based analyses revealed that convergence was achieved after 15 iterations, with material distribution stabilizing from the 5th iteration onward. The optimized configuration also exhibited lower maximum stress values compared to the conventional solid chassis, confirming that weight reduction was achieved without sacrificing mechanical performance.

From a computational perspective, the optimization process proved to be efficient. Each iteration required approximately 30 seconds, with a total optimization time of about 7.5 minutes on a standard workstation (Intel i7, 3.40 GHz, 16 GB RAM). This demonstrates that the proposed framework is not only effective but also feasible for real-world engineering applications in terms of computational cost.

Overall, this study confirms that topology optimization can deliver lightweight, cost-effective, and structurally robust solutions for autonomous vehicle chassis design. The method provides a balance between material savings and structural safety, making it highly suitable for engineering applications where weight reduction is a critical design criterion.

In future studies, the optimization framework can be extended in several directions. First, different materials such as composites, lightweight alloys, or advanced

polymers may be investigated to evaluate their influence on the structural performance and manufacturability of the chassis. Second, alternative manufacturing methods, including additive manufacturing or hybrid production techniques, could be explored to validate the practicality of the optimized designs and assess their cost–benefit ratios. Furthermore, multi-objective optimization approaches may be employed to simultaneously consider multiple criteria such as stiffness, weight reduction, vibration performance, and fatigue life, thereby providing a more comprehensive evaluation of design trade-offs. Finally, the integration of experimental validation and hardware-in-the-loop testing will be beneficial to verify numerical predictions and to ensure the real-world applicability of the proposed design methodology.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

Declaration of Ethical Standards

The authors remained faithful to all ethical rules

Credit Authorship Contribution Statement

Taş KA: Software, Investigation, Writing – original draft, Methodology,

Karabıyık MC: Software, Investigation, Writing – original draft, Methodology,

Tanriver K: Writing – review and editing, Validation, Conceptualization,

Ak M: Writing – review and editing, Validation, Conceptualization,

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