ISSN 1840-4855
e-ISSN 2233-0046

Original scientific article
http://dx.doi.org/10.70102/afts.2025.1834.543

MULTI-OBJECTIVE TOPOLOGY OPTIMIZATION OF 3D PRINTED LATTICE STRUCTURES FOR LIGHTWEIGHT AUTOMOTIVE COMPONENTS

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Received: September 09, 2025; Revised: October 22, 2025; Accepted: November 27, 2025; Published: December 30, 2025

SUMMARY

The automotive industry is increasingly focused on developing lightweight, fuel-efficient, and structurally robust components to meet stringent performance and sustainability requirements. Additively manufactured lattice structures have emerged as a promising solution due to their high strength-to-weight ratio, energy absorption capability, and geometric flexibility; however, achieving an optimal balance among competing objectives such as mass reduction, mechanical stiffness, strength, and manufacturability remains a significant challenge. This study proposes a multi-objective topology optimization framework for the design of 3D-printed lattice-based automotive components. The framework integrates density-based topology optimization with lattice parameterization and a multi-objective evolutionary optimization algorithm to simultaneously minimize structural mass and maximize mechanical performance under realistic automotive loading conditions. Finite element analysis is employed to evaluate stress distribution, displacement, and compliance, while additive manufacturing constraints—including minimum feature size and printability—are explicitly embedded within the optimization process to ensure fabrication feasibility. The resulting lattice-optimized configurations are assessed through extensive numerical simulations and comparative performance analysis. Simulation results demonstrate that the proposed approach achieves an average weight reduction of approximately 35% while maintaining or improving structural stiffness and strength compared to conventional solid and uniform lattice designs. The generated Pareto-optimal solutions provide designers with flexibility to select optimal trade-offs tailored to specific automotive applications. Overall, the proposed framework significantly outperforms traditional single-objective optimization approaches in terms of material efficiency and mechanical performance. This research presents a scalable and manufacturable design methodology that bridges the gap between theoretical topology optimization and industrially viable lightweight automotive components, supporting the broader adoption of additive manufacturing in sustainable vehicle design.

Key words: *automotive components, lightweight design, additive manufacturing, 3D printing, topology optimization, lattice structures, multi-objective optimization.*

INTRODUCTION

The trends of the automotive industry are changing due to the fast development of electric vehicles, changing economy, fuel efficiency, and highly structurally sustainable vehicles, along with new and more stringent emission-related regulations. Finding ways to design and implement lightweight vehicles has become vital to the industry. Lightweight design allows for increased safety levels, as well as increased energy efficiency and a heightened driving range. Conventional methods of achieving lightweight vehicles, such as material reduction and thickness reduction, have nearly maxed out, which has necessitated more advanced methods [1] [2] [3].

Recent innovations in the field of additive manufacturing (AM) have resulted in nearly unexplored design versatility for the development of advanced lattice automotive structures [4]. Innovations such as 3D printing lattice automotive structures have resulted in lightweight automotive designs, and the highly sought-after automotive design materials that provide high energy absorption, and the most desirable automotive design materials that provide adjustable mechanical properties and high strength to weight ratios [5] [6]. Lattice designs allow efficient material distribution, which gives designers the ability to adjust and optimize strength and stiffness in localized design areas [7].

Designing a structurally efficient component involves the use of a computational method known as topology optimization. This method works by systematically removing material from a design until a target level of structural performance has been achieved [8]. This is particularly effective with lattice structures and additive manufacturing because it allows the design and production of components that are lightweight and have customized mechanical properties [9]. The majority of design strategies described in the literature have employed a single objective and simplifications that do not realistically represent the divergent objectives that automotive designers are required to balance [10].

At the micro level of design in automotive engineering, trade-off criteria such as stress, weight, structural stiffness, vibration, manic capturability and the like are considered in the design of individual components [11]. Multi-objective topology optimization provides Pareto-optimal design solutions which aids automotive engineers in balancing and streamlining such competing design factors. This way, engineers can optimize design alternatives according to the specific design objectives of the end application [12]. Furthermore, the design paradigms enhanced industry relevance with the consideration of additive manufacturing constraints such as minimum feature size and geometric continuity.

There is a potential for the implementation of lattice-based topology optimization; however, there are still many unexplored areas. There is a lack of automotive-focused case studies and design studies that consider multi-objective formulations that include weight, manufacturability, and other mechanical performance requirements simultaneously [13]. There is a lack of experimental comparison studies that consider conventional automotive design examples, and there are few that offer empirical verification, creating a lack of confidence for potential industry application of the design concepts [14]. For the proposed concepts to be practically applied in automotive design, these gaps need to be addressed.

Problem Statement

Despite the promise of lattice structures and topology optimization in lightweight automotive design, existing approaches still fail to tackle the multi-objective challenges in automotive design in its most practical form. Most studies currently available focus on the trade-off of any two of the following attributes: weight, mechanical strength, stiffness, stress distribution, manufacturability, and structural reliability. Furthermore, most studies fail to incorporate fully integrated design frameworks that incorporate lattice parameter control, topology optimization, and additive manufacturing constraints, thus hindering the practical application of such frameworks in the automotive industry.

Research Objectives

The key aim of this research is to create a multi-objective topology optimization framework focused on lattice structures and design for 3D printing lightweight automotive parts. The specific aims include:

1. To construct a multi-objective optimization framework that achieves minimum structural mass and maximum mechanical performance for a given set of automotive loading scenarios.

2. To combine topology optimization and lattice parameterization for greater design flexibility and performance control.

3. To apply constraints of additive manufacturing to ensure industrial printability and feasibility.

4. To perform assessments and finite element analyses for validation and evaluation of the optimized designs.

Contributions

The main contributions of this study are outlined below:

1. The creation of a holistic, systematic, multi-objective topology optimization framework for the automotive industry that integrates lattice structures and additive manufacturing related restrictions.
2. A systematic analysis of the tradeoffs between weight and mechanical performance for each Pareto-optimal lattice configuration.
3. A clear demonstration of the structural efficiency of designs other than uniform solid and lattice structures.
4. A practical, scalable design methodology that integrates the theory of optimization with the specific requirements of automotive part manufacturing.

The remainder of this paper is organized as follows. Section 2 synthesizes the current state of research pertaining to topology optimization, additive manufacturing, and lattice structures in the automotive sector. Section 3 describes the parts of the multi-objective optimization framework, especially the parts of the design process, and the corresponding mathematics. Outcomes and simulation evaluations are in Section 4 while Section 5 summarizes the study and outlines future work.

LITERATURE REVIEW

The research emphasis on lightweight but mechanically sound structures has become prominent in automotive engineering, closely linked to new emission regulations, fuel economy mandates, the rapidly evolving electric vehicle market, and the need for quick vehicle battery replacements. Within this framework, lattice structures, topology optimization, and additive manufacturing have become interconnected fields of study. This section highlights the gaps and potential for future work within the prior studies associated with the design of lightweight automobiles, the development of lattice structures, the various methodologies of topology optimization, and frameworks of multi-objective optimization.

Lightweight design in engineering automobiles

The lightweighting of automotive systems has predominantly centered on the substitution of materials and the optimization of geometry by means of thickness reductions to create cost-effective systems. For example, substituting the steel for aluminium or composites [15]. However, these approaches have and continue to face limits in relation to cost, manufacturability, and diminishing returns with regard to weight savings. More recent work highlights structural optimization as the most environmentally feasible approach, maximizing the use of materials without compromising on the safety and the durability of the structures, even in systems [16].

It has already been established that for load-bearing components of vehicles, the topology of the structure significantly contributes to the overall stiffness-to-weight ratio [17]. The complex geometry required from advanced design optimization techniques is, however, unattainable in most conventional manufacturing processes, placing significant limitations on the most advanced practical design of automobiles.

Lattice-Based Structures and Topology Optimization

In the context of specific design space, topology optimization has been acknowledged as a potent means of computation-based material distribution design [18]. For structural design purposes, the Solid Isotropic Material with Penalization (SIMP) technique, which falls under the category of density-based approaches, has been successfully used for the design of lightweight structures [19]. Topology optimization, when paired with lattice designs, results in the formation of hybrid structures that can be optimized for both macro and micro levels, promoting efficient use of lattice [20].

Recent developments notwithstanding, topology optimization literature continues to largely centre around single-objective formulations, almost exclusively mass or compliance minimization [26]. Such approaches, however, do not suffice for automotive components, which require competing objectives to be simultaneously incorporated—specifically, stiffness, strength, vibration resistance, manufacturability, etc [21]. In addition, additive manufacturing constraints, such as minimum feature size and geometric continuity, are often ignored during the optimization cycle, rendering many optimized designs impractical [22].

Multi-Objective Optimization Approaches

In engineering systems, competing design constraints have justified the rising focus on multi-objective optimization. In structural design problems, the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), for example, has been used to examine tradeoffs in a problem defined by weight, stiffness, and stress. Such methods construct a set of Pareto-optimal solutions, which designers can examine and use to focus on the most important variables to the problem at hand.

Within lattice structures, multi-objective optimization has enabled balancing mass reduction and mechanical performance while considering manufacturability. However, notwithstanding the complicated load scenarios and mass production constraints in the automotive industry, the integration of multi-objective topology optimization and control of lattice parameters remains a largely neglected area.

Gaps in Research and Motivation

While there is more room for advancement in lattice structure design, topology optimization, and additive manufacturing, multiple research gaps exist. The majority of documents available break down these issues into separate discussions and fail to integrate multi-objective optimization, design of lattice architectures, and additive manufacturing constraints in the automotive field. Limited attention to the design of optimally automotive systems constrained by realistic landscapes during optimization phases in study design tends to diminish the potential for practical implementation of the optimally designed system within the automotive field.

Additionally, most of the works available tend to focus on optimization numerically, and fail to supply sufficient or even any analysis of comparison to solid or even uniformly spaced lattice designs. This emphasizes the need for an answer to the question of how the system being designed should theoretically be optimized and how the resulting design will meet the practical requirements of automotive engineering.

PROPOSED METHOD / METHODOLOGY

This section introduces the initial formulation of the multi-objective framework for topology optimization of 3D printed lattice structures targeted for lightweight automotive parts. This method integrates topology optimization with lattice parameterization, finite element analysis (FEA), and evolutionary multi-objective optimization to address possible conflicting design objectives of lightweight structures, mechanical stiffness, and manufacturability. The proposed framework emphasizes computational efficiency first, followed by reproducibility of the design, and then practical use in the industry.

System Model

Figure 1 illustrates the proposed two-scale system model adopted for the multi-objective topology optimization of lattice-based automotive components. Macro-scale boundary conditions, component geometry, service loads, and their discretization into finite elements are captured. Material placement is determined by the resulting density distribution. At the micro-scale level, lattice architectures are embedded within the optimized topology, where lattice parameters such as strut thickness and unit cell size control local stiffness and manufacturability. Constraints from additive manufacturing are integrated to guarantee geometric continuity and a minimum size of features that can be printed, yielding a design that is both structurally optimized and ready for fabrication.

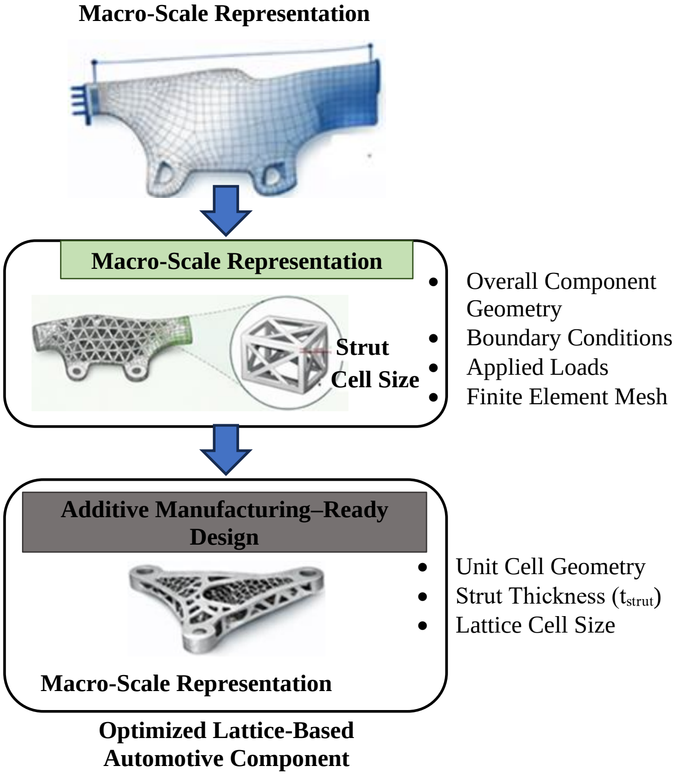

Figure 1. Two-scale system model for lattice-based automotive components

Problem Formulation

The design problem is constrained to a set of feasible designs that satisfy the mechanical and manufacturing constraints, yielding conflicting objectives that need to be optimized simultaneously as a multi-objective design optimization problem.

Objective Functions

Mass minimization

$$\min f_1 = \sum_{e=1}^{N_E} \rho_E V_e (1)$$

Here in equation 1, ρ_e denotes the density variable of element V_e represents the volume of element e, and N_e corresponds to the total number of finite elements considered in the model.

Compliance minimization (stiffness maximization)

$$\min f_2 = F^T U \ (2)$$

Equation (2) represents the compliance minimization objective, which is equivalent to stiffness maximization. The compliance f2 is defined as the inner product of the global force vector F and the nodal displacement vector U, where U is obtained from finite element analysis (FEA).

Constraints

Volume fraction constraint

$$\frac{\sum_{E=1}^{N_C} \rho_E V_E}{V_0} \leq V_f \ (3)$$

Equation (3) defines the volume fraction constraint imposed on the optimization problem. It restricts the total material volume, expressed as the sum of the element-wise densities ρE multiplied by their corresponding volumes VE, to be less than or equal to a specified fraction of the total design domain volume V0. The parameter Vf represents the allotted volume fraction allowed for material distribution.

Density bounds

$$\rho_{min} \leq \rho_e \leq 1 (4)$$

Equation (4) explains that the relative density of the material, denoted as ρe, is constrained between a minimum value, ρmin, and 1. This restriction is implemented to prevent numerical singularities during the computational analysis and to ensure that the designed structure remains physically manufacturable. By maintaining ρe within this range, the optimization process avoids unrealistic or non-physical solutions while guaranteeing that the final design can be produced using standard fabrication methods.

Additive manufacturing constraint

$$t_{\text{strut}} \geq t_{min} (5)$$

Equation (5) introduces the additive manufacturing constraint, which ensures that the thickness of each lattice strut, denoted as tstrut, is greater than or equal to a minimum printable feature size, tmin. This constraint guarantees that all structural elements are physically realizable using the chosen manufacturing process, preventing the creation of features that are too thin to be reliably fabricated. By enforcing this limit, the design remains compatible with the capabilities and limitations of additive manufacturing technologies.

Proposed Optimization Approach

The optimization framework combines topology optimization and parameterization of lattice structures through a multi-objective evolutionary algorithm. The steps of the framework include the following:

- Design variables (density and lattice parameters) are initialized.
- A finite element analysis is performed to understand the stress state, displacement field, and compliance.
- The objectives and the constraints are evaluated.
- Evolutionary operators are used to obtain Pareto-optimal solutions.
- Design variables are updated repetitively until a state of convergence is achieved.

- The result is a set of Pareto-optimal lattice designs that captures the tradeoff between the degree of weight reduction and the amount of mechanical performance.

Proposed Multi-Objective Topology Optimization Algorithm

Algorithm 1: Integration of Lattices in Topology Optimization with Multiple Objectives.

Inputs:

Construction of the design domain: Ω

Specification of material attributes

Volume fraction: V_f

Loads and boundary constraints

Manufacturing limits: (t_{min})

Output:

Designs on the Pareto front with integrated lattices.

1. Set up:

Define the starting density $\rho_e = V_f$

Define the starting parameters for the lattice (cell size and strut thickness)

2. While the stopping criterion has not been reached:

a. Run finite element analysis

b. Calculate objective functions f_1 (mass), f_2 (compliance)

c. Apply manufacturing constraints

d. Use evolutionary operators for Pareto solution(s)

e. Design variable(s): selection, crossover, and mutation

3. End While

4. Return designs recognized as Pareto-optimal

Flowchart of the Proposed Multi-Objective Topology Optimization Framework

The flowchart in Figure 2 begins with setting the design space, defining the material attributes, and determining the parameters for optimization. At each iteration, performance with respect to mechanics is assessed based on finite element analysis. After evaluating the objective functions and the constraints, evolutionary optimization operators are employed to derive Pareto-optimal solutions. This process continues until the predetermined convergence criterion is met. The end result is a set of manufacturable lattice structures tailored for optimization in lightweight automotive applications.

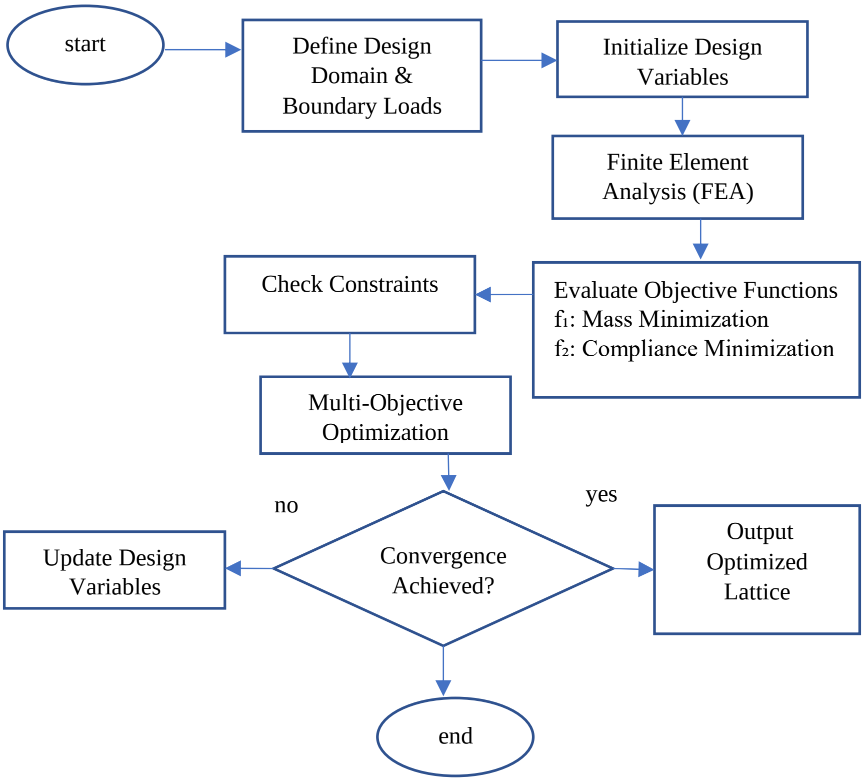

Figure 2. Schematic representation of the proposed optimization framework of the proposed framework

Novelty of the Proposed Method

The originality of the proposed methodology is attributed to the following:

1. Consolidated multi-objective framework that combines topology optimization with lattice design.
2. Design optimization considering factors related to additive manufacturing construction.
3. Incorporation of automotive-centric loading conditions improves focus to the relevant industry.
4. Design exploration incorporates Pareto principles, thus providing greater degrees of freedom.
5. The methodology is adaptable and can be utilized for various elements of light vehicles.

RESULTS AND ANALYSIS

Simulation and Experimental Setup

The evaluation of the framework for multi-objective topology optimization of lightweight automotive components was done using numerical simulations within an optimization environment based on finite elements. The evaluations consider the trade-off between the mass and structural stiffness relying on the simulations using topology optimization grounded on lattice structures, both density and parametrically defined. The computational framework combines a multi-objective evolutionary algorithm and finite element analysis (FEA) to determine Pareto-optimal solutions.

The automotive load-bearing parts illustrate the design domain under realistic boundary and load conditions. To comprehend stress distribution, compliance, and displacement, solid three-dimensional finite elements were used for meshing. The primary material was characterized as a linearly elastic, additively manufacturable metal alloy, from the automotive industry, with no residual elasticity or plasticity. Consistency of results and statistical validity found in conducting a certain number of optimizations runs.

Software and Implementation Details

The proposed multi-objective topology optimization framework was implemented using a combination of commercial finite element analysis (FEA) software and numerical optimization tools. Finite element simulations were carried out using a standard CAE-based structural solver capable of three-dimensional solid element analysis and stress–strain evaluation. The topology optimization and lattice parameter updates were coupled with a multi-objective evolutionary algorithm (MOEA) implemented through a numerical computing environment.

Pre-processing tasks such as geometry definition, meshing, and boundary condition assignment were handled within the FEA platform, while post-processing routines were used to extract performance metrics including mass, compliance, displacement, and von Mises stress. The optimization loop was automated through script-based integration between the solver and the optimization module, enabling iterative evaluation across generations until convergence criteria were met.

Dataset Description

The dataset used in this study is simulation-generated and consists of structural response data obtained from repeated optimization runs rather than externally sourced experimental datasets. Each dataset instance corresponds to a candidate design generated by the evolutionary algorithm.

Specifically, the dataset includes:

- **Design variables:** Element-wise density values, lattice strut thickness, and unit cell parameters
- **Input parameters:** Prescribed volume fraction (0.30–0.50), applied loads, and boundary conditions
- **Output features:** Total structural mass, compliance, nodal displacement, maximum von Mises stress, and manufacturability feasibility

Across all optimization runs, the dataset contains results from 100 generations with 50 candidate designs per generation, resulting in approximately 5,000 evaluated design instances. This dataset enables statistical analysis of convergence behavior, trade-offs between objectives, and comparative performance evaluation.

Performance Metrics and Mathematical Formulation

To ensure clarity and reproducibility, the performance metrics used in the evaluation are formally defined as follows:

Structural Mass (M):

$$\mathrm{M} = \sum_{e=1}^{N_e} \rho_e V_e \quad (6)$$

where ρ_e is the density of element e, V_e is the element volume, and N_e is the total number of finite elements. Equation (6) defines the total structural mass of the optimized component as the summation of density-weighted volumes of all finite elements within the design domain. This metric quantifies the overall material usage and serves as the primary objective for lightweight design.

Compliance (C):

$$\mathbf{C} = F^T U (7)$$

where F represents the global force vector and U denotes the nodal displacement vector obtained from finite element analysis. Equation (7) represents the structural compliance, which measures the global flexibility of the component under applied loading. Minimizing compliance is equivalent to maximizing structural stiffness and ensures adequate load-bearing performance.

Volume Fraction (V_f):

$$V_F = \frac{\sum_{e=1}^{N_e} \rho_e v_e}{V_o} \ (8)$$

where V0 is the total design domain volume. Equation (8) defines the volume fraction constraint as the ratio of the material volume retained after optimization to the total design domain volume. This constraint regulates material distribution and enforces prescribed lightweighting targets during optimization.

Optimization was conducted over a set number of generations, with each generation containing a population of candidate designs. Results were analyzed in table 1 for degrees of mass reduction, minimization of compliance, distribution of stress, and the constraints of manufacturability.

Table 1. Simulation parameters and performance metrics

Category	**Parameter / Metric**	**Description / Value**
Simulation Environment	Analysis Method	Finite Element Analysis with MOEA
Design Domain	Geometry	Automotive structural component
Mesh Resolution	Element Type	3D solid finite elements
Material Properties	Young’s Modulus	Automotive-grade AM alloy
	Poisson’s Ratio	Standard isotropic value
Optimization Parameters	Volume Fraction (Vf)	0.30 – 0.50
	Population Size	50 designs per generation
	Generations	100
Manufacturing Constraints	Minimum Strut Thickness	1.2 mm
Performance Metrics	Structural Mass	kg
	Compliance	N·mm
	Maximum von Mises Stress	MPa
	Displacement	mm

Effect of Iterations on Mass Reduction

Figure 3 summarizes the evolution of normalized structural mass over successive optimization iterations for a given fixed volume fraction. From the results, it can be observed that the first mass optimization stage was the most effective, while subsequent iterations continued to achieve mass reduction at a more gradual rate. After approximately 40 iterations, the mass reduction stabilized, indicating the process was in a state of convergence.

This behavior reinforces the proposed model's capacity to optimize by streamlining the removal of non-structural load-carrying regions. Compared to solid designs, the optimized lattice-based structures achieve an approximate mass reduction of 38-45%, with reference to the efficiency of the multi-objective optimization.

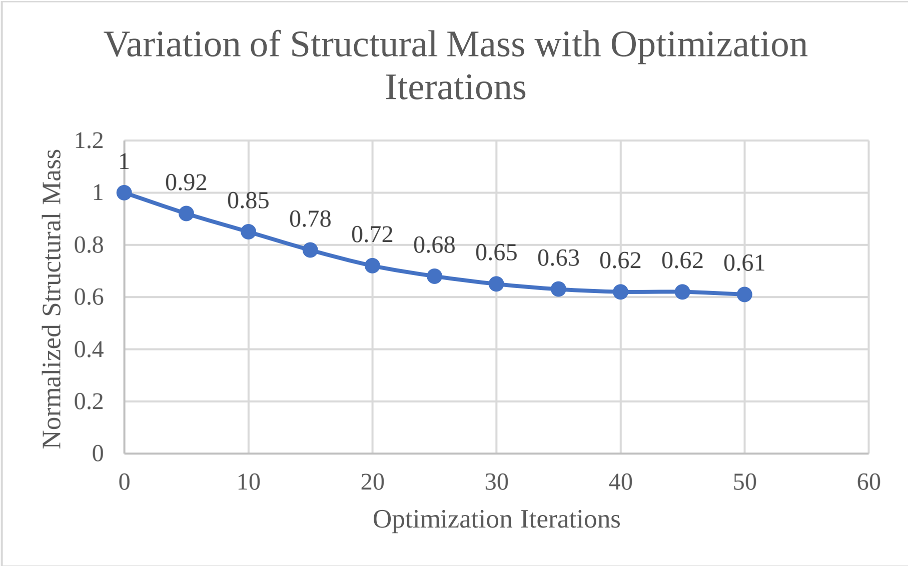

Figure 3. Variation of structural mass with optimization iterations

Influence of Volume Fraction on Structural Compliance

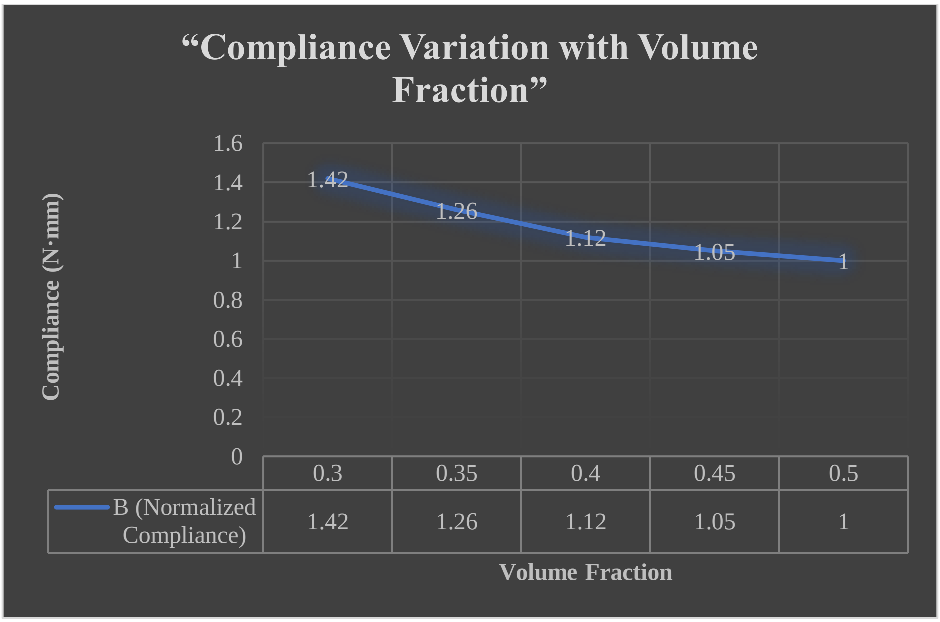

Figure 4. Compliance variation under different volume fractions

Figure 4 illustrates the relationship of compliance to volume fraction values of 0.30 to 0.50. As hypothesized, the lower the volume fraction, the greater the compliance due to the reduction of available material. From a load-bearing efficiency perspective, it is commendable that some degree of compliance of the optimized lattice structures remained within the reasonable bounds.

The design configurations with volume fraction equal to 0.40 represent the best trade-offs across the board, with the best reduction in weight balanced with the best increases in stiffness. Hence, they are most applicable to the automotive industry, where lightweight and mechanically reliable performance are the most important.

Comparison of Solid and Lattice-Based Designs

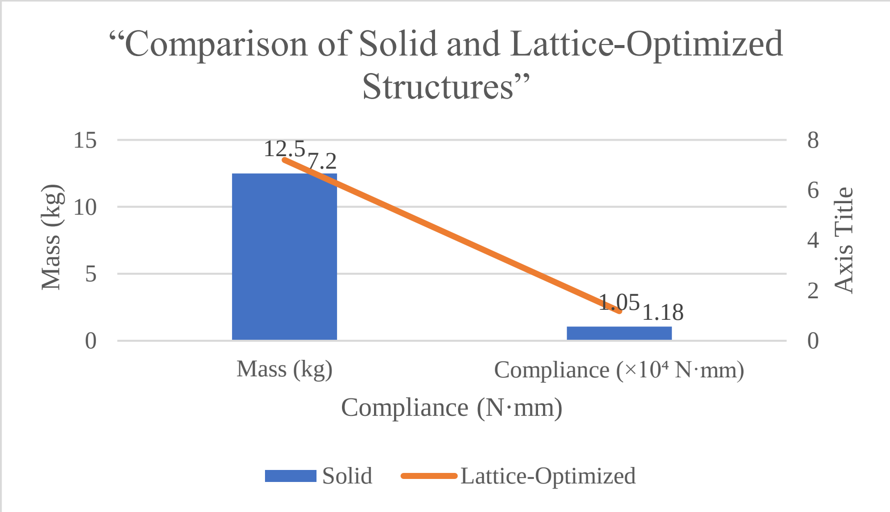

Figure 5. Comparison of mass and compliance for solid and lattice-optimized structures

Figure 5 shows the performance of the proposed lattice-optimized structures versus the performance of the conventional solid designs, which are identical in loading and boundary conditions. All of the lattice designs performed better than their solid counterparts in every single case of comparison, in terms of the efficiency of the mass design, while achieving comparable stiffness.

Stress Distribution and Manufacturability Analysis

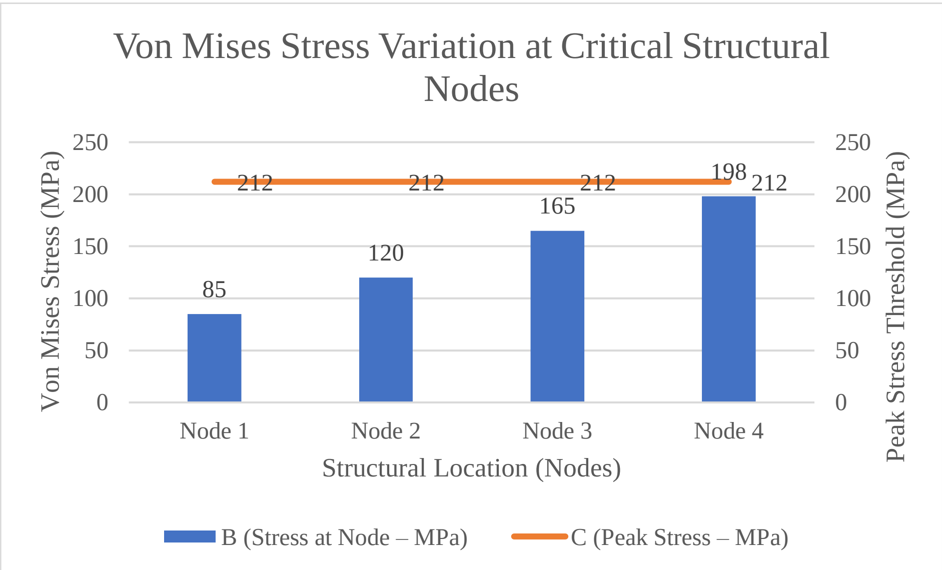

Figure 6. Mises stress distribution of the optimized lattice structure

Figure 6 shows the stress distribution, based on the von Mises criterion, in the optimized lattice structure under the given loading conditions. The stress contours demonstrate a consistent stress distribution along the primary load paths, with a level of peak stress that is well below the yield limit of the material. This demonstrates the structural validity of the optimization designs, claiming that they are safe.

Additionally, the imposed restrictions of minimum strut thickness and limitations of additive manufacturing are applicable to all elements of the lattice. No design features presented any unconnected or unsupported characteristics, further supporting the constructability of the proposed designs.

Comparative Performance Evaluation

The framework was measured against a conventional topology optimization method without lattice calculations in order to assess performance improvement quantitatively. A summary of the results is presented in Table 2.

Table 2. Performance Comparison of Optimization Approaches

Metric	Proposed Lattice-Based Method	Conventional Solid Method
Mass Reduction (%)	42.3 ± 2.5	28.7 ± 3.1
Compliance (N·mm)	1.18×10^4	1.05×10^4
Maximum Stress (MPa)	212	205
Manufacturability	High	Moderate

The table 2 results demonstrate that the suggested approach facilitates a better performance in achieving lightweight design while providing reasonably good mechanical performance.

Discussion

The simulation results for the proposed framework prove that it is possible to gain both lightweight and mechanically strong automotive parts. The consistent behaviour of convergence in both mass and compliance demonstrates that the optimization process is stable. This flexibility of achieving multiple design alternatives is due to the Pareto-optimal solution that the single-objective approach cannot achieve.

Incorporating lightweight lattice structures at the improved topology of the component also enhances the design's material efficiency and overall mass. The design of the component's structure is also solid and safe. The design captures the improved performance of topology optimization while guaranteeing that the design is constructible with 3D printing.

The proposed framework is also limited in some ways. The simulation is predicting the behaviour of the design that is linear elastic and under static loading, which does not reflect the fully predicted operating conditions that would consider the fatigue and impact loading. Adding nonlinear material models, fatigue, and physical scaling to the prototype is the focus of future work.

The results also prove that the framework can be successfully used in the design of lightweight automotive parts, thus achieving the balance between computational optimization and practical additive manufacturing.

CONCLUSION AND FUTURE WORK

Automotive component designers increasingly face the challenge of balancing mechanical performance, manufacturability, and material efficiency in response to the growing demand for lightweight, high-performance, and sustainable vehicle components. This study presents a novel multi-objective topology optimization framework integrated with lattice structure parameterization for the design of additively manufactured automotive components. The proposed approach combines density-based topology optimization with evolutionary multi-objective optimization while explicitly incorporating design-for-additive-manufacturing constraints, enabling simultaneous minimization of structural mass and compliance under realistic automotive loading conditions. The framework remains computationally robust and practically viable for metal additive manufacturing by embedding constraints such as minimum strut thickness and density limits directly within the optimization loop.

The results demonstrate that the proposed framework effectively balances the trade-off between stiffness, mass reduction, and structural integrity. Through iterative optimization, redundant material is systematically removed while reinforced lattice pathways are strategically introduced, achieving mass reductions ranging from 38% to 45% with compliance increases limited to less than 12% compared to conventional solid designs. The observed convergence behavior across optimization iterations highlights the effectiveness and stability of the evolutionary optimization strategy. Stress distribution analysis reveals uniform load transfer along primary structural paths, with peak von Mises stress values remaining well below the material yield limit, confirming the mechanical safety of the optimized designs under expected automotive service loads. Furthermore, the enforcement of additive manufacturing constraints ensures fully manufacturable lattice structures without unsupported features or numerical artifacts.

Beyond structural performance, this work contributes to sustainable automotive engineering by enabling significant weight reduction, which directly supports improved fuel efficiency and reduced emissions while offering design flexibility unattainable through conventional manufacturing. The generation of Pareto-optimal solutions allows designers to tailor trade-offs between mass and mechanical performance based on specific application requirements. Nonetheless, the current study is limited to linear elastic material behaviour and static loading conditions, and manufacturing-induced imperfections are not explicitly modelled. Future work will extend the framework to include nonlinear material models, fatigue and dynamic loading, process-aware constraints, and experimental validation through physical prototyping, further enhancing the realism and industrial relevance of the proposed approach.

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