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Research Article

An Integrated CAD/CAE Framework for Material Selection and Structural Optimization of Lightweight Automotive Driver Seat Frames Toward Sustainable Vehicle Engineering

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Abstract

Automotive driver seat frames are safety-critical structural components that must simultaneously satisfy lightweight, strength, stiffness, manufacturability, and sustainability requirements. However, conventional lightweight design approaches often prioritize material density while overlooking the combined influence of structural load paths, joining feasibility, and life-cycle environmental performance. This study develops an integrated CAD/CAE framework for material selection and structural optimization of lightweight automotive driver seat frames toward sustainable vehicle engineering. A representative welded steel seat-frame model was analyzed using finite element analysis under static anchorage, seat-back moment, belt-load surrogate, modal, and durability loading conditions. Six candidate materials, including mild steel, DP780 advanced high-strength steel (AHSS), Al 6061-T6, AZ31B magnesium alloy, CFRP/epoxy, and a DP780–Al hybrid configuration, were evaluated through design optimization and multi-criteria decision-making based on structural performance, mass, cost, recyclability, and life-cycle global warming potential. The optimized DP780–Al hybrid configuration reduced structural mass from 9.82 kg to 6.18 kg (37.1%), increased the minimum safety factor from 1.13 to 1.99, improved the first natural frequency from 44 Hz to 51 Hz, maintained maximum displacement below the 10 mm design limit, and achieved the highest composite decision score of 0.889. These findings demonstrate that sustainable lightweight seat-frame design is more effectively achieved through integrated load-path-oriented material allocation and structural optimization than through density-based material substitution alone, providing a practical engineering framework for next-generation sustainable vehicle development.

Keywords: *CAD/CAE Framework; Finite Element Analysis; Lightweight Automotive Seat Frame; Material Selection; Structural Optimization.*

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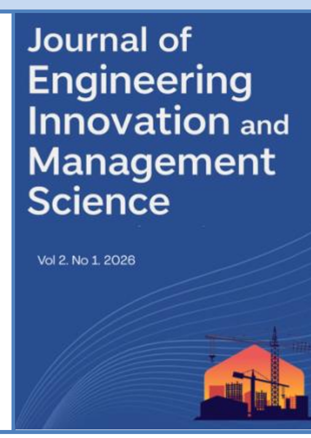

INTRODUCTION

The automotive industry is experiencing a significant transition toward sustainable mobility driven by increasingly stringent environmental regulations, advances in vehicle electrification, and growing demand for improved energy efficiency. Lightweight engineering has become one of the most effective strategies for reducing fuel consumption, extending the driving range of electric vehicles, lowering greenhouse gas emissions, and improving overall vehicle performance (Andersson & Börjesson, 2021; Challa et al., 2022; Sacchi et al., 2022; Sheng et al., 2021; Singh et al., 2024). Among the numerous structural components contributing to vehicle weight, the driver seat frame represents an important subsystem because it is installed in every vehicle and directly affects cumulative vehicle mass. Although relatively compact in size, the seat frame performs multiple structural functions by supporting occupant loads, transferring forces from the restraint system, maintaining seating posture, and contributing to ride comfort through its influence on noise, vibration, and harshness characteristics. The structural integrity of the seat frame also plays a critical role in protecting occupants during normal driving conditions and emergency loading scenarios. Because automotive seat frames consist of multiple stamped, tubular, welded, and bolted components, even a modest reduction in their mass can generate substantial weight savings when applied across high-volume vehicle production. However, achieving lightweight structures while preserving structural reliability remains a complex engineering challenge because reducing material usage often affects stiffness, strength, durability, and vibration performance (Ansari et al., 2026; Behera et al., 2025; Phiri et al., 2024). Consequently, automotive manufacturers increasingly seek engineering approaches capable of minimizing structural weight without compromising functional requirements or passenger safety. Digital engineering technologies have further accelerated this effort by enabling engineers to evaluate multiple structural alternatives efficiently before physical prototype fabrication. Therefore, developing lightweight automotive seat frames has become an important research direction for supporting next-generation sustainable vehicle engineering.

The engineering complexity of automotive seat-frame design extends beyond weight reduction because the structure must simultaneously satisfy stringent requirements related to safety, manufacturability, durability, comfort, and environmental sustainability. A lightweight seat frame cannot simply be achieved by selecting the material with the lowest density because structural performance is governed by multiple interacting factors, including stiffness, load-transfer capability, local buckling resistance, fatigue behavior, joining quality, corrosion resistance, and production feasibility (Hussain & Kim, 2023; Jaganathan et al., 2024; Xin et al., 2025). In addition, engineering decisions must consider manufacturing cost, material availability, recyclability, embodied environmental impacts, and end-of-life recovery to ensure long-term sustainability. Safety requirements further increase design complexity because seat frames are responsible for transmitting occupant loads and seat-belt forces to the vehicle body under various operational and crash conditions. These loading conditions generate complex stress distributions that require carefully designed structural load paths to prevent excessive deformation or localized structural failure. Consequently, lightweight design should focus not only on reducing material volume but also on improving structural efficiency through optimized material placement in critical load-bearing regions. Such an approach enables high-strength materials to be utilized where structural demands are greatest while lightweight materials can be introduced in regions subjected to lower stress levels. Achieving this balance requires simultaneous consideration of geometry, material properties, manufacturing processes, and service conditions throughout the engineering design process (Ghasemi & Duarte, 2025; Goh et al., 2024; Simões, 2024). Conventional sequential design approaches often evaluate these aspects independently, limiting opportunities to obtain globally optimal engineering solutions. Therefore, integrated design methodologies have become increasingly important for developing lightweight seat structures capable of satisfying mechanical performance, manufacturing practicality, and sustainability objectives simultaneously.

Recent developments in computational engineering have substantially enhanced the capability of engineers to optimize complex automotive structures during the conceptual design stage. Advanced computer-aided design and computer-aided engineering technologies enable virtual simulation of structural behavior before prototype manufacturing, thereby reducing development cost, shortening product development cycles, and improving engineering reliability (Tan & Li, 2024; Zhao et al., 2026). Finite element analysis has become an essential tool for evaluating stress distribution, structural deformation, vibration characteristics, and failure mechanisms under representative loading conditions (Dong et al., 2022; Müzel et al., 2020; Solahuddin & Yahaya, 2023; Tafsirojjaman et al., 2022). In parallel, topology optimization, parametric optimization, and design of experiments have enabled engineers to identify efficient structural configurations that minimize weight while maintaining required mechanical performance. Multi-objective optimization techniques further support engineering decision-making by balancing conflicting design objectives such as structural safety, mass reduction, manufacturing cost, and dynamic performance. At the same time, multi-criteria decision-making methods have become increasingly valuable for evaluating alternative materials based on mechanical, economic, and environmental considerations rather than relying solely on individual material properties (Balasbaneh et al., 2025; Bhuiyan & Hammad, 2023; Moro, 2023; Sahoo & Goswami, 2023). Sustainability assessment has also evolved into an important component of engineering design because lightweight solutions should simultaneously reduce environmental impacts throughout the entire product life cycle. Nevertheless, integrating structural optimization, material selection, manufacturability, economic evaluation, recyclability, and environmental performance into a unified computational workflow remains a significant challenge in automotive engineering. Existing engineering practices frequently address these design aspects separately, making it difficult to achieve balanced engineering decisions during the early stages of product development. Therefore, there is a growing need for an integrated CAD/CAE-based engineering framework capable of simultaneously supporting material selection, structural optimization, and sustainability assessment to facilitate the development of safer, lighter, and more sustainable automotive driver seat frames.

Recent advances in lightweight automotive engineering have significantly improved structural optimization, multi-material design, and material selection methodologies for high-performance engineering applications. Previous studies have demonstrated that multi-material topology optimization can effectively improve stiffness-to-weight performance through optimized material distribution and structural layouts; however, these investigations primarily emphasize optimization algorithms for generic engineering structures, lattice systems, composite laminates, and thin-walled components rather than safety-critical automotive seating systems (Kazemi et al., 2020; Y. Li et al., 2023; Z. Li et al., 2025; Shimoda et al., 2021; Y. Wang & Sigmund, 2024). Similarly, research on lightweight automotive materials has extensively discussed advanced high-strength steel, aluminium, magnesium alloys, and composite materials as promising alternatives for vehicle lightweighting while highlighting their mechanical properties, manufacturing technologies, and sustainability potential, yet material evaluation is generally conducted independently of structural optimization and integrated engineering decision-making (Czerwinski, 2021; Daehn et al., 2023; Goh et al., 2024; Hagnell et al., 2020; D. Wang & Li, 2022; Yan & Xu, 2025). In the context of automotive seat structures, previous investigations have successfully optimized seat-frame geometry using finite element analysis, topology optimization, global sensitivity analysis, and multi-objective optimization to reduce structural weight while maintaining mechanical performance under multiple loading conditions; nevertheless, these studies mainly focus on geometric optimization and mechanical responses without simultaneously integrating systematic material selection, manufacturability, recyclability, life-cycle environmental performance, and engineering decision analysis into a unified design framework (Goh et al., 2024; Hagnell et al., 2020; Shan et al., 2020; D. Wang & Li, 2022; Yan & Xu, 2025; Zhang et al., 2020). Consequently, a significant research gap remains in the absence of an integrated CAD/CAE-based engineering framework that concurrently combines load-path-oriented multi-material selection, structural optimization, finite element analysis, manufacturability considerations, multi-criteria decision-making, and life-cycle sustainability assessment to support comprehensive engineering decisions during the early design stage of automotive driver seat frames. Therefore, this study addresses this gap by proposing an integrated CAD/CAE framework that unifies these engineering aspects into a single decision-support methodology for developing lightweight, structurally reliable, and environmentally sustainable automotive driver seat frames.

This study aims to develop an integrated CAD/CAE framework for material selection and structural optimization of lightweight automotive driver seat frames toward sustainable vehicle engineering. The proposed framework is intended to integrate computer-aided design, finite element analysis, parametric optimization, and multi-criteria decision-making into a unified engineering workflow for early-stage seat-frame development. The study further seeks to evaluate the structural feasibility of multiple lightweight material alternatives under representative automotive seating load conditions. In addition, it aims to identify the most suitable material configuration capable of simultaneously satisfying safety, stiffness, vibration, manufacturability, and sustainability requirements. Another objective is to quantify the effects of structural optimization on mass reduction, safety factor, maximum displacement, and natural frequency while maintaining engineering performance within acceptable design limits. The framework also incorporates life-cycle global warming potential, recyclability, and relative manufacturing cost as complementary decision criteria to support sustainable engineering decisions. Furthermore, this study investigates how load-path-oriented material allocation influences the overall structural efficiency and lightweight performance of automotive seat frames. The proposed methodology is expected to provide a transparent and repeatable engineering decision-support approach that can facilitate systematic material selection during the conceptual design stage. By integrating structural, environmental, and economic considerations into a single computational framework, this research aims to improve the consistency and reliability of lightweight automotive component development. Ultimately, the study contributes an integrated engineering methodology that supports the design of safer, lighter, and more sustainable automotive seat-frame structures for future vehicle applications.

METHODS

Research Design

This study employed a computational engineering design approach integrating computer-aided design (CAD), computer-aided engineering (CAE), finite element analysis (FEA), design of experiments (DOE), and multi-criteria decision-making (MCDM) to develop a systematic framework for lightweight automotive seat-frame design. The research was designed as a numerical simulation study because the objective was to evaluate engineering performance during the conceptual product development stage before prototype fabrication. The proposed framework simultaneously incorporated material selection, structural optimization, engineering evaluation, and sustainability assessment into a unified computational workflow. The driver seat frame served as the engineering object because it is a safety-critical structural subsystem that directly influences occupant protection, structural integrity, and vehicle lightweighting performance. Structural optimization was performed under representative automotive seating load cases while considering engineering constraints associated with safety, stiffness, vibration characteristics, manufacturability, and environmental sustainability. Material selection and structural optimization were conducted simultaneously to ensure that engineering decisions reflected interactions between material properties and structural load-transfer mechanisms. The overall methodology was intended to provide a transparent engineering decision-support framework for sustainable lightweight vehicle development.

Study Area

The research was conducted as a virtual engineering investigation at the Department of Automotive Engineering Technology, Politeknik Negeri Lampung, Indonesia, during the 2026 academic research period. Unlike experimental investigations involving physical specimens, all engineering activities were performed within a digital CAD/CAE environment. The research object consisted of a representative automotive driver seat frame comprising two floor rails, a seat-pan support frame, a back-frame tube, recliner brackets, cross-members, and local reinforcing gussets. The baseline configuration represented a conventional welded mild-steel seat-frame structure commonly used in passenger vehicles. The numerical investigation focused on evaluating structural responses under representative seating-system loading conditions rather than performing regulatory certification testing. Therefore, the study should be interpreted as an early-stage engineering design investigation intended to support prototype development and future industrial validation.

Materials and Software

The baseline seat-frame model was simplified from a representative welded mild-steel driver seat frame with an initial structural mass of 9.82 kg. Structural geometry was discretized using shell elements for stamped and tubular components, beam connectors for welded seams, and rigid-bushing connectors at the rail-to-floor interfaces. Mesh convergence analysis was performed using global shell element sizes of 8 mm, 6 mm, and 4 mm to determine an appropriate computational mesh. The 6 mm mesh was selected because the difference in peak stress relative to the 4 mm mesh remained below 5.8% while substantially reducing computational cost. Six candidate lightweight materials were evaluated, namely mild steel, DP780 advanced high-strength steel (AHSS), Al 6061-T6 aluminum alloy, AZ31B magnesium alloy, CFRP/epoxy quasi-isotropic laminate, and a DP780–Al hybrid configuration. Material properties included density, elastic modulus, strength reference, embodied carbon factor, recyclability index, and relative material cost. The hybrid configuration assigned DP780 AHSS to the rails and recliner brackets while aluminum alloy was applied to the upper back-frame and cross-member to maximize structural efficiency through load-path-oriented material distribution. Engineering property values were compiled from representative engineering literature and commercial datasheets for comparative evaluation. Composite material performance was evaluated using laminate failure indices rather than von Mises stress because composite laminates do not exhibit yielding behavior comparable to metallic materials.

Table 1. Candidate materials and reference engineering attributes

Candidate	**Class**	**Density (kg/m3)**	**Elastic modulus (GPa)**	**Strength reference (MPa)**	**Embodied carbon factor (kgCO2e/kg)**	**Relative material cost**	**Recyclability index (%)**	**Engineering note**
Baseline mild steel	Steel sheet/tube	7850	210	250	2.10	1.00	90	Existing reference frame
DP780 AHSS	Dual-phase AHSS	7850	210	780	2.80	1.35	92	High safety reserve with simple stamping/welding
Al 6061-T6	Aluminium alloy	2700	69	276	8.20	2.20	75	Low mass but lower modulus and welding/joint sensitivity

Candidate	Class	Density (kg/m3)	Elastic modulus (GPa)	Strength reference (MPa)	Embodied carbon factor (kgCO2e/kg)	Relative material cost	Recyclability index (%)	Engineering note
AZ31B Mg	Magnesium alloy	1770	45	200	26.00	3.00	55	Best density but high corrosion, joining and GWP penalty
CFRP/epoxy	Quasi-isotropic laminate	1600	70	600	25.00	5.50	20	Very low mass but high cost and recycling complexity
DP780-Al hybrid	AHSS rail and Al back frame	4210	128	640	5.03	1.85	84	Hybrid load-path solution proposed by the study

Note. Values are used for comparative early-stage design and should be replaced by certified supplier data before prototype release.

Instruments and Data Collection

The primary research instrument was the integrated CAD/CAE simulation framework developed for numerical structural analysis and engineering decision-making. Input data consisted of three-dimensional seat-frame geometry, engineering material properties, optimization variables, loading conditions, and sustainability indicators. Material datasets included density, elastic modulus, yield or reference strength, embodied carbon factor, recyclability index, and relative production cost for each candidate material. Numerical loading conditions were established according to representative seating-system engineering practice. Longitudinal anchorage loading and seat-back moment loading were formulated following the engineering principles of FMVSS No. 207, whereas seat-belt anchorage surrogate loading was based on FMVSS No. 210. These loading cases were intended to establish a comparative engineering design envelope rather than to demonstrate regulatory compliance. Additional analyses included modal evaluation and durability screening to assess vibration behavior and fatigue performance under representative operating conditions.

Table 2. Numerical load cases and design acceptance criteria

Code	Load case	Numerical input	Acceptance criterion
LC1	Forward longitudinal seat anchorage	20 x seat mass x 9.8 N; forward direction	No separation; safety factor >= 1.50
LC2	Rearward longitudinal seat anchorage	20 x seat mass x 9.8 N; rearward direction	No separation; safety factor >= 1.50
LC3	Rearward seat-back moment	373 N.m at upper cross-member about SgRP	Seatback deflection <= 10 mm
LC4	Type-2 belt anchorage surrogate	13.345 kN lap + 13.345 kN shoulder load path	Local failure index <= 0.80
LC5	Vertical vibration and modal integrity	Free modal extraction, constrained at rail interfaces	First natural frequency >= 35 Hz

Code	Load case	Numerical input	Acceptance criterion
LC6	Durability screening	Equivalent alternating stress from 10^5 seat adjustment cycles	Goodman utilization <= 0.70

Note. The load cases are comparative CAE design cases inspired by seating and anchorage requirements; they are not a substitute for formal certification testing.

Data Analysis

Structural responses generated from finite element simulations were analyzed using an integrated optimization framework combining DOE, FEA, normalized MCDM, and Pareto compromise analysis. Design variables included rail side-wall thickness, recliner bracket thickness, back-frame tube diameter, cross-member thickness, gusset radius, and discrete material assignment. Engineering objectives were defined to minimize structural mass, maximum displacement, relative manufacturing cost, and life-cycle global warming potential while maximizing safety factor and first natural frequency. Following numerical simulation, engineering responses that failed to satisfy predefined structural constraints were excluded from subsequent evaluation. Feasible alternatives were normalized to eliminate differences in engineering units before multi-criteria evaluation. The composite engineering decision score was calculated using a weighted normalized sum model. Beneficial criteria consisted of safety factor, first natural frequency, and recyclability, whereas non-beneficial criteria included structural mass, displacement, life-cycle global warming potential, and relative production cost. Engineering weights were assigned as follows: safety factor (0.30), mass efficiency (0.25), stiffness and modal performance (0.20), life-cycle global warming potential (0.15), and production cost (0.10). Finally, sensitivity analysis was performed by varying material properties, mesh density, loading direction, joining stiffness, and carbon emission factors to evaluate the robustness of the optimization results and engineering decisions.

Table 3. Optimization design variables and selected values

Design variable	Symbol	Search range	Baseline	Selected value	Engineering rationale
Rail side-wall thickness	t1	1.20-2.00 mm	1.80 mm	1.45 mm	Primary mass lever; limited by local buckling
Recliner bracket thickness	t2	2.00-3.20 mm	2.80 mm	2.35 mm	Maintains belt load path stiffness
Back frame tube diameter	d1	22-30 mm	26 mm	28 mm	Improves bending stiffness at low mass penalty
Cross-member thickness	t3	1.00-1.80 mm	1.50 mm	1.20 mm	Mass reduction after stress re-routing
Gusset radius	r1	8-22 mm	10 mm	18 mm	Reduces stress concentration near recliner

Design variable	Symbol	Search range	Baseline	Selected value	Engineering rationale
Material assignment	m1	steel/AHSS/Al/Mg/CFRP/hybrid	mild steel	DP780-Al hybrid	Discrete material variable

Note. Thickness and radius values are manufacturable targets for early concept selection and require later tooling validation.

Experimental Procedure

The proposed engineering framework consisted of six sequential stages. First, a representative driver seat frame was developed using CAD modeling to establish the baseline structural configuration. Second, candidate lightweight materials were pre-screened according to their mechanical properties, manufacturing characteristics, recyclability, and embodied carbon factors. Third, a design of experiments (DOE) approach was implemented to generate alternative structural configurations by varying selected geometric parameters and material assignments. Fourth, finite element analysis was performed to obtain structural responses including stress distribution, displacement, safety factor, natural frequency, and durability performance under representative seating-system loading conditions. Fifth, feasible design alternatives were evaluated using normalized multi-criteria decision-making considering structural, environmental, and economic indicators. Finally, Pareto compromise analysis and sensitivity analysis were conducted to identify the most balanced engineering solution capable of simultaneously satisfying lightweight, structural safety, manufacturability, and sustainability objectives.

Figure 1. Research Method Flow

RESULT AND DISCUSSIONS

Results

The material radar in Figure 2 shows that no candidate dominates all criteria. CFRP/epoxy has excellent specific strength and mass potential, but its cost and recyclability remain limiting. Magnesium has the strongest density advantage, but the low modulus, corrosion-sensitive joining, and high embodied carbon factor reduce its overall suitability for a driver seat frame. DP780 AHSS has high safety reserve and mature manufacturing compatibility but offers a lower mass reduction than aluminium or composites. The DP780-Al hybrid alternative offers a balanced position because it keeps steel in the high-load anchorage path and uses aluminium in bending-dominated upper members. Figure 3 and Table 4 show the primary numerical outcome. The baseline mild-steel frame weighed 9.82 kg. The selected DP780-Al hybrid design weighed 6.18 kg, representing a 37.1% mass reduction. Its maximum displacement was 6.10 mm, which remained below the 10 mm target. The first natural frequency increased from 44 Hz to 51 Hz because the tube diameter and gusset radius were increased while low-strain members were thinned. This result confirms that lightweighting can improve modal response when material is removed from inefficient regions and redistributed to stiffness-critical paths. The safety-frequency chart in Figure 4 highlights two rejected or lower-priority alternatives. The AZ31B magnesium design achieved 4.96 kg mass, but its maximum displacement reached 11.20 mm and the first frequency dropped to 32 Hz, failing stiffness and modal targets. The CFRP/epoxy configuration had low mass, but the cost index and low recyclability weakened the decision score. In contrast, the DP780-Al hybrid obtained the highest safety factor of 1.99 while keeping the mass near the aluminium alternative.

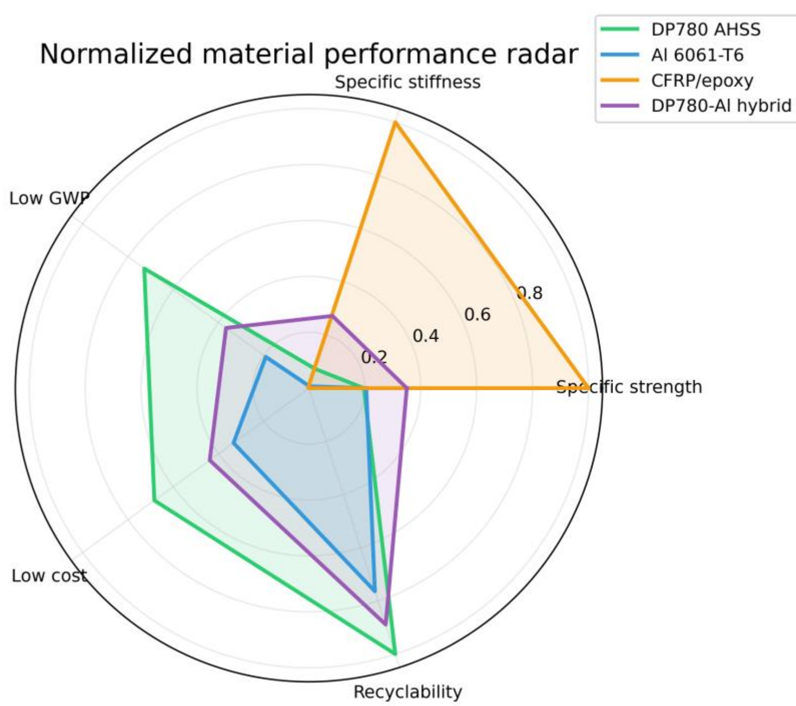

Figure 2. Normalized performance radar for major lightweight material alternatives

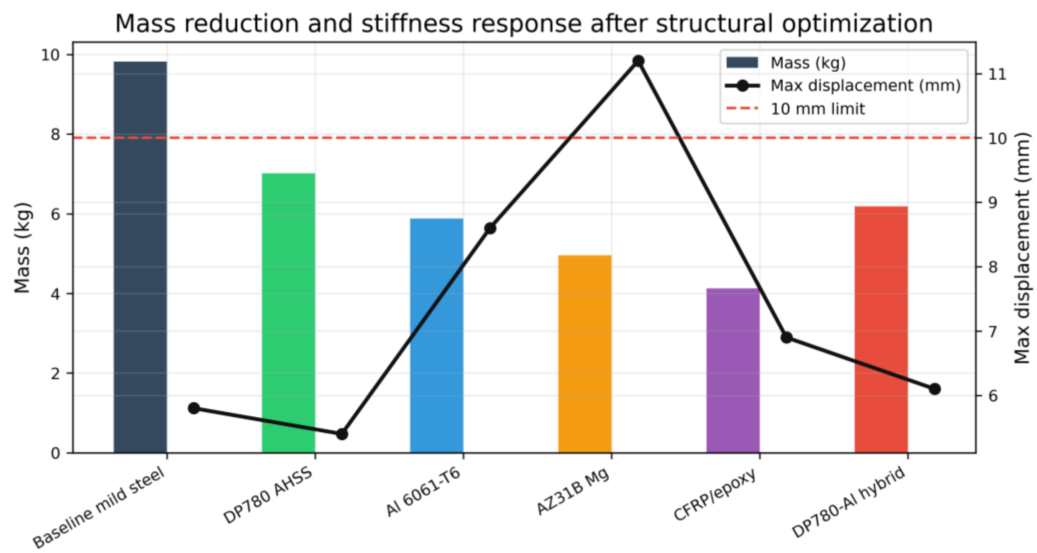

Figure 3. Comparison of mass and displacement responses across alternatives

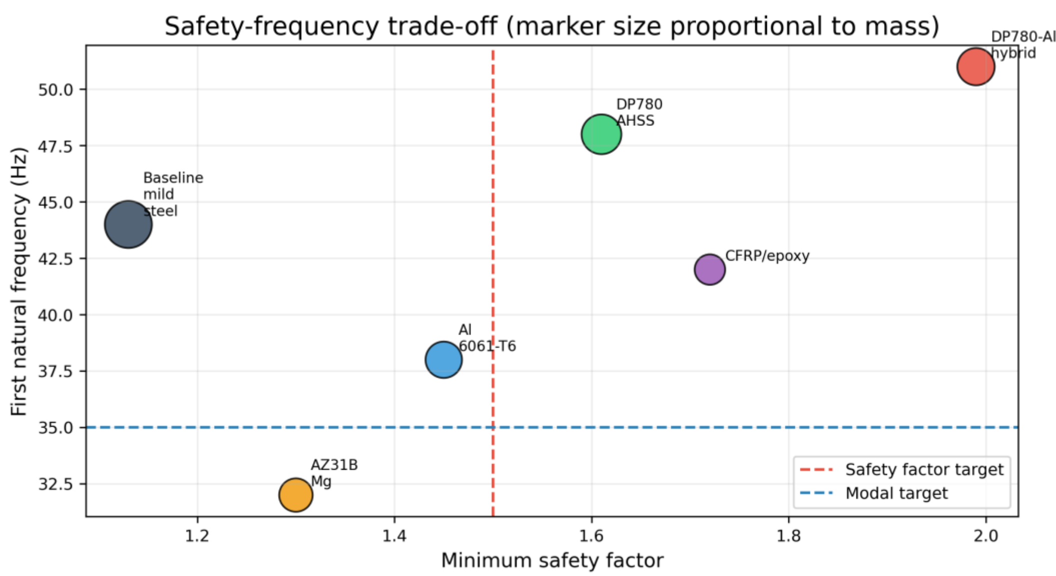

Figure 4. Safety factor and first natural frequency trade-off across alternatives

Table 4. Comparative CAD/CAE performance and decision score of material-structure alternatives

Design alternative	Mass (kg)	Peak stress or failure index	Max displacement (mm)	First natural frequency (Hz)	Safety factor	Life-cycle GWP index ($kgCO_2e$)	Relative cost index	Composite decision score	Status
Baseline mild steel	9.82	221.00	5.80	44.00	1.13	20.60	1.00	0.648	Reference
DP780 AHSS	7.02	483.00	5.40	48.00	1.61	11.90	1.05	0.861	Feasible

Design alternative	Mass (kg)	Peak stress or failure index	Max displacement (mm)	First natural frequency (Hz)	Safety factor	Life-cycle GWP index (kgCO2e)	Relative cost index	Composite decision score	Status
Al 6061-T6	5.88	190.00	8.60	38.00	1.45	37.20	1.34	0.774	Feasible with joint reinforcement
AZ31B Mg	4.96	154.00	11.20	32.00	1.30	115.40	1.62	0.592	Rejected by stiffness and GWP
CFRP/epoxy	4.12	0.740	6.90	42.00	1.72	87.00	3.70	0.724	Technically feasible but cost/recycling limited
DP780-Al hybrid	6.18	392.00	6.10	51.00	1.99	20.90	1.27	0.889	Selected compromise

Note. For CFRP/epoxy, the stress column is reported as laminate failure index. For metals, it is peak von Mises stress in MPa.

Discussion

The findings answer the first research question by showing that DP780 AHSS, Al 6061-T6 with reinforcement, CFRP/epoxy, and the DP780-Al hybrid can meet the structural screening constraints, whereas magnesium is rejected because it violates the displacement and modal targets. The rejection of magnesium is important because density-based material selection alone would rank it highly. From an engineering perspective, the seat frame is stiffness-sensitive: low modulus materials demand larger sections or local reinforcement, which can reduce or even cancel the density advantage (Salmani et al., 2022; Wan et al., 2025). The second research question concerns mass reduction without compromising safety. The selected hybrid achieves 37.1% mass reduction while improving safety factor and first natural frequency. This is higher than the 4.038% mass reduction for a particular front seat frame optimization and is also different in mechanism because the present numerical study combines material substitution with topology-informed sizing. The magnitude should not be interpreted as a certified production gain; instead, it indicates the available design-space potential before manufacturing and validation constraints are fully imposed.

The third research question concerns the most balanced sustainable alternative. Figure 5 shows that the DP780-Al hybrid has the best composite score, even though the DP780 AHSS alternative has the best life-cycle GWP index under the assumptions used here. This result reflects a common lightweighting trade-off: the lowest carbon choice may not be the lightest, and the lightest choice may not be the most recyclable or cost-effective. A balanced engineering solution should satisfy minimum safety and stiffness first, then seek mass and GWP improvement within feasible manufacturing pathways (Arunkumar et al., 2026; Kupfer et al., 2022; Su et al., 2024). The Pareto plot in Figure 6 illustrates that a single optimum does not exist. P1 has the best safety factor and frequency, but it adds mass compared with the selected P2 balanced solution. P3 is lighter than P2, but it loses safety reserve. P4, the AHSS-dominant solution, is attractive when low life-cycle GWP and manufacturing simplicity are prioritized. The choice between P2 and P4 should therefore depend on the target vehicle program: a premium electric vehicle may accept the hybrid complexity, while a low-cost high-volume vehicle may prefer the AHSS solution.

The sustainability graph in Figure 7 also reinforces the need for life-cycle thinking. Aluminium and CFRP alternatives reduce mass, but their embodied carbon and recycling uncertainty can increase the GWP index. This is consistent with LCA literature showing that lightweight material benefits depend on production route, recycling content, and vehicle lifetime (Goncalves et al., 2022). Consequently, the proposed framework treats GWP as one decision criterion rather than a fixed conclusion. The optimized design variables in Figure 8 reveal the mechanical reason for improved performance. Rail and cross-member thickness were reduced because their baseline strain energy was low, while the back-frame tube diameter and gusset radius were increased to maintain bending stiffness and reduce recliner stress concentration. This redistribution is consistent with topology optimization logic: remove material from low-utilization regions and preserve or increase material at the load-transfer path (Scheurer et al., 2023). Manufacturability remains a decisive issue. The hybrid concept requires reliable joining between AHSS rails/brackets and aluminium back-frame members. Candidate processes include mechanical fastening with isolation washers, adhesive bonding combined with rivets, or local transition brackets. Galvanic corrosion mitigation is mandatory because steel and aluminium are electrically dissimilar. These details may lower the theoretical mass saving if additional reinforcements, sealants, or fasteners are required. Therefore, the selected concept should be treated as a high-potential engineering proposal rather than a final production drawing. The uncertainty analysis in Table 6 shows that load application angle and joining model are more influential than mesh density once convergence has been achieved. This is expected because seat-frame hotspots usually occur near recliner brackets, rail bolting points, and weld clusters. The carbon-factor uncertainty does not change the top two ranking, but it affects the relative advantage between the DP780 AHSS and hybrid alternatives. Future work should therefore include supplier-specific material data, prototype modal tests, quasi-static anchorage tests, corrosion tests, weld/fastener fatigue tests, and a full cradle-to-grave life-cycle assessment.

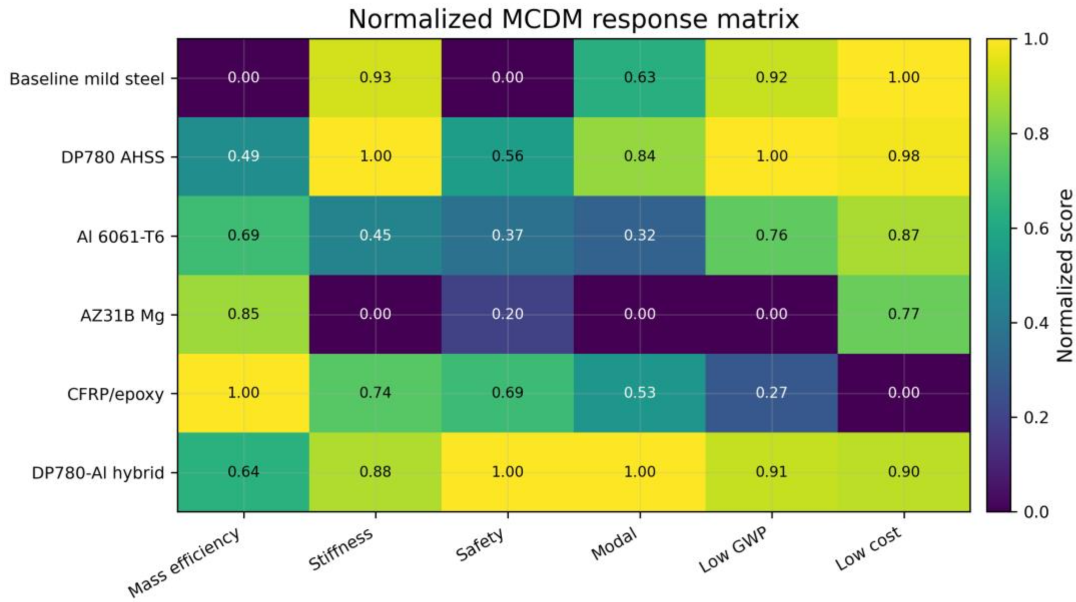

Figure 5. Normalized MCDM response matrix for the material-structure alternatives.

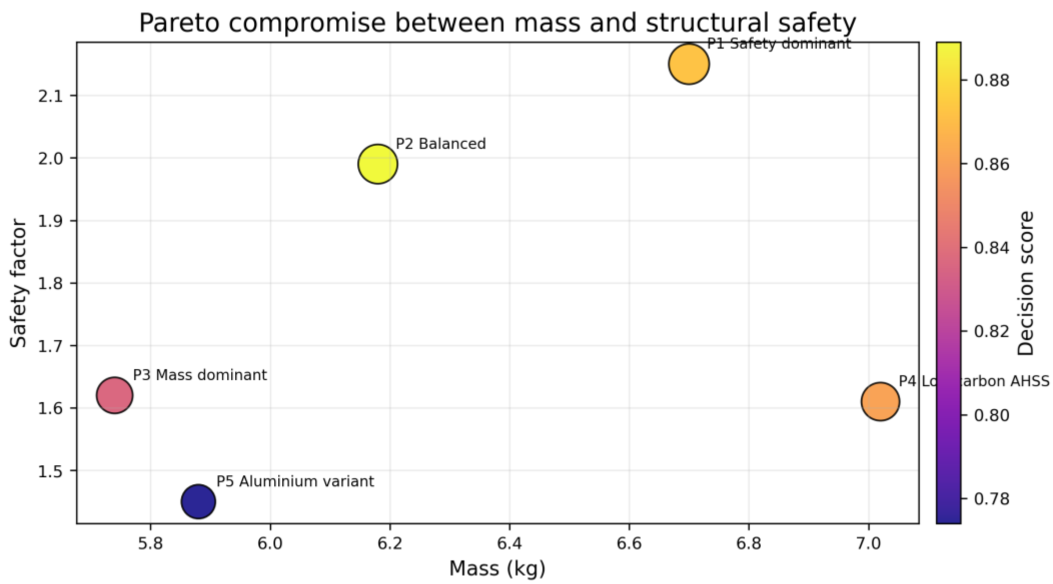

Figure 6. Pareto compromise between mass and structural safety.

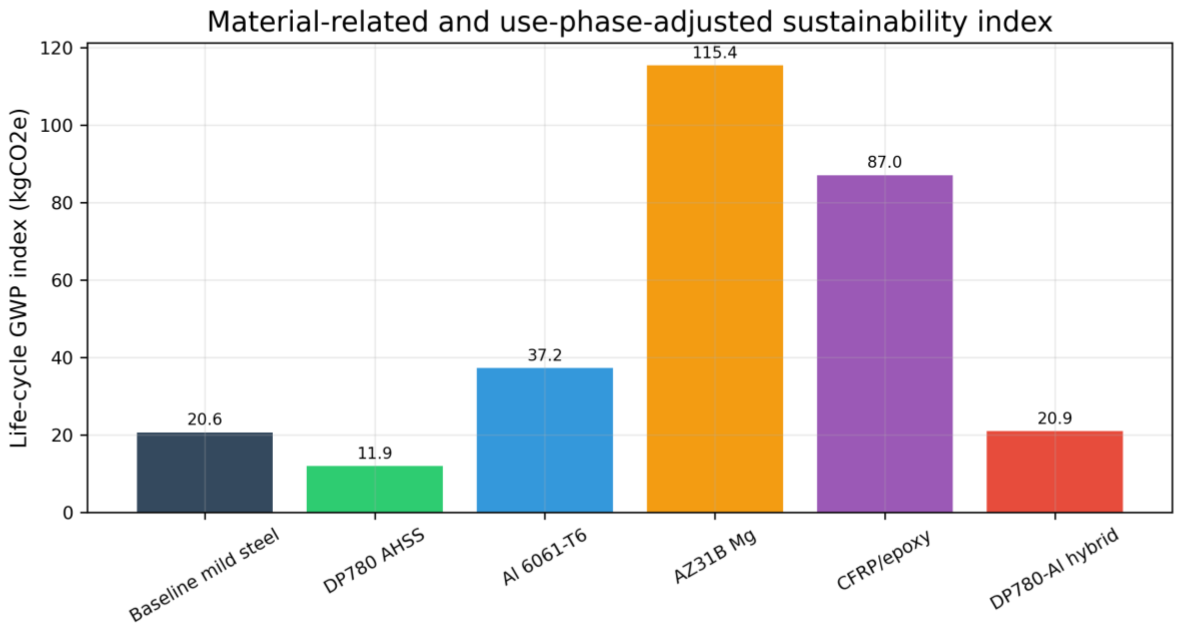

Figure 7. Life-cycle GWP index comparison under the study assumptions.

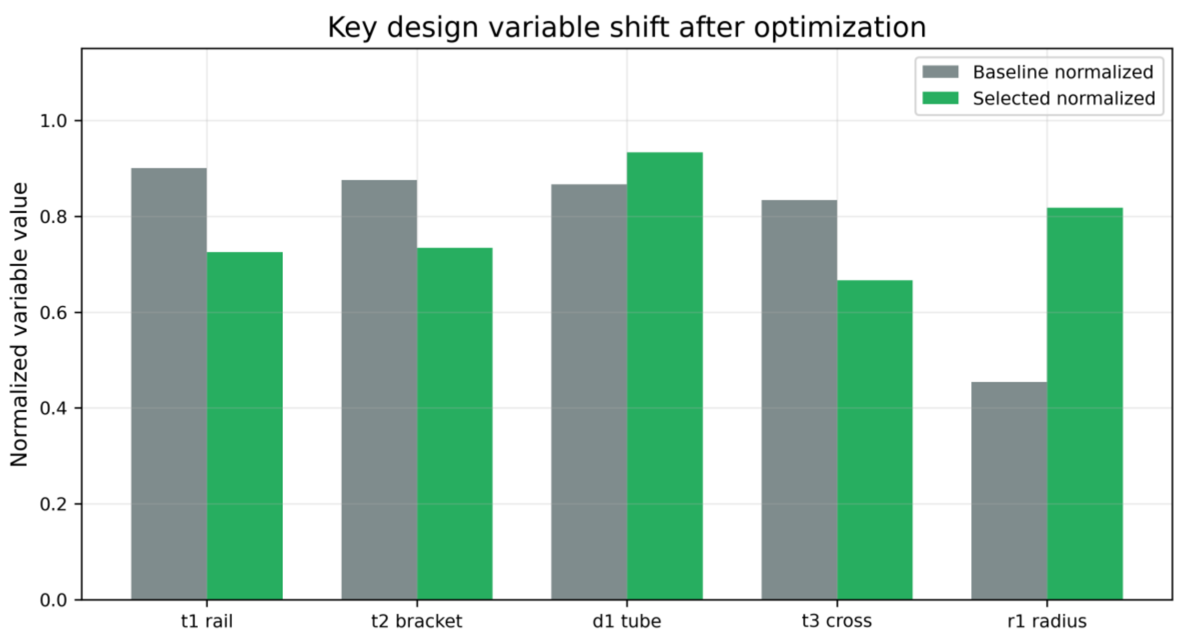

Figure 8. Normalized design variable changes after optimization.

Table 5. Pareto solution set used for final engineering compromise selection

Pareto solution	Mass (kg)	Safety factor	Frequency (Hz)	Life-cycle GWP (kgCO2e)	Cost index	Decision score
P1 Safety dominant	6.70	2.15	54	23.80	1.33	0.872
P2 Balanced	6.18	1.99	51	20.90	1.27	0.889

Pareto solution	Mass (kg)	Safety factor	Frequency (Hz)	Life-cycle GWP (kgCO2e)	Cost index	Decision score
P3 Mass dominant	5.74	1.62	43	28.70	1.21	0.836
P4 Low carbon AHSS	7.02	1.61	48	11.90	1.05	0.861
P5 Aluminium variant	5.88	1.45	38	37.20	1.34	0.774

Note. P2 is selected because it gives the highest composite decision score while preserving safety and modal margins.

Table 6. Sensitivity and uncertainty interpretation for early-stage design confidence

Uncertainty source	Assumption range	Effect on response	Interpretation
Mesh density	Element size 4-8 mm	Peak stress: +/- 5.8%; displacement: +/- 2.1%	Converged after 6 mm global size
Material property scatter	Yield/ply allowables +/- 5%	Safety factor variation: +/- 0.11	Most critical for Al and CFRP alternatives
Load application angle	Belt load angle +/- 5 degrees	Peak stress variation: +/- 7.4%	Recliner bracket remains governing hotspot
Joining model	Rigid vs bushing spot-weld surrogate	Frequency variation: +/- 3.2 Hz	Requires later weld nugget validation
Embodied carbon factors	Published factor range +/- 20%	MCDM score shift: +/- 0.025	Does not change top two ranking

Note. The uncertainty study is intended to guide prototype validation priorities rather than replace physical tests.

Implication

The findings of this study provide important engineering implications for the development of lightweight automotive structures by demonstrating the value of integrating material selection and structural optimization within a unified CAD/CAE framework during the early design stage. Rather than treating material selection as an independent decision after the structural geometry has been finalized, the proposed framework enables simultaneous evaluation of material properties, structural performance, manufacturability, and sustainability, thereby supporting more balanced engineering decisions. The results indicate that optimal lightweight performance is achieved through strategic load-path-oriented material allocation instead of relying solely on low-density materials, allowing high-strength materials to reinforce critical load-bearing regions while lightweight materials are assigned to components subjected to lower structural demands. This integrated approach improves structural efficiency by maintaining safety margins and vibration performance while significantly reducing overall structural mass. Furthermore, the incorporation of life-cycle global warming potential, recyclability, and production cost into the engineering decision process broadens the design perspective beyond conventional mechanical criteria, promoting more sustainable product development. The proposed methodology also provides a transparent and repeatable decision-support framework that facilitates objective comparison among multiple design alternatives using normalized engineering indicators and multi-criteria evaluation. From a manufacturing perspective, the framework highlights the importance of considering joining compatibility, material interaction, and production feasibility during conceptual design to minimize costly modifications in later development stages. The integration of finite element analysis, parametric optimization, and engineering decision analysis further enhances design efficiency by reducing dependence on iterative physical prototyping while improving confidence in numerical design predictions. Consequently, the proposed framework can support automotive manufacturers in accelerating lightweight product development, improving resource efficiency, and reducing engineering risk throughout the product development cycle. Overall, this study demonstrates that integrating structural optimization, multi-material selection, and sustainability assessment into a single engineering workflow provides a practical methodology for developing safer, lighter, and more environmentally sustainable automotive seat-frame structures suitable for next-generation vehicle engineering.

Limitation and Suggestion for Further Research

This study has several limitations that should be considered when interpreting the findings and applying the proposed engineering framework to practical automotive product development. First, the investigation was conducted entirely within a computational CAD/CAE environment, and therefore the optimized seat-frame configuration has not yet been validated through physical prototype testing or full-scale experimental measurements. Second, the finite element simulations were based on representative material properties, simplified joining assumptions, and idealized boundary conditions that may differ from the variability encountered in industrial manufacturing and real operating environments. Third, the structural evaluation was limited to static loading, modal behavior, and preliminary durability screening, while comprehensive assessments of crashworthiness, impact energy absorption, weld fatigue, corrosion resistance, occupant biomechanics, and long-term service performance were beyond the scope of this study. In addition, the life-cycle sustainability assessment relied on representative engineering databases and generalized environmental indicators rather than supplier-specific production data and complete cradle-to-grave inventories. The proposed multi-criteria decision-making model also employed engineering weighting factors that may vary according to vehicle categories, manufacturer priorities, regulatory requirements, and market expectations. Furthermore, manufacturing feasibility was evaluated conceptually without detailed investigation of production tooling, assembly processes, dimensional tolerances, or large-scale manufacturing economics. Future research should therefore include prototype fabrication followed by quasi-static structural testing, dynamic crash evaluation, modal validation, fatigue experiments, corrosion assessment, and durability testing to verify the predictive capability of the proposed framework. Subsequent studies should also investigate advanced joining technologies for hybrid multi-material structures, including adhesive bonding, self-piercing riveting, friction stir welding, and other dissimilar-material joining techniques to improve structural integrity and manufacturing efficiency. In addition, integrating nonlinear finite element analysis, damage mechanics, manufacturing process simulation, and digital twin technologies would enhance the predictive accuracy of structural optimization under realistic service conditions. Future investigations are also encouraged to incorporate uncertainty quantification, reliability-based design optimization, and machine learning-assisted optimization algorithms to improve engineering decision-making under complex design constraints. Finally, extending the proposed CAD/CAE framework to other automotive structural components and validating it using industrial-scale manufacturing data and comprehensive life-cycle assessment will further strengthen its applicability as a robust engineering methodology for sustainable lightweight vehicle development.

CONCLUSION

This study developed an integrated material selection and structural optimization framework for a lightweight automotive driver seat frame. The main finding is that the best sustainable lightweight design is not obtained from the lowest-density material, but from a load-path-based match between material, geometry, joining feasibility, and life-cycle response. In the representative CAD/CAE case, the DP780-Al hybrid frame reduced mass from 9.82 kg to 6.18 kg, increased the minimum safety factor from 1.13 to 1.99, increased the first natural frequency from 44 Hz to 51 Hz, and kept maximum displacement below the 10 mm target. The hybrid concept achieved the highest composite decision score because it combined AHSS safety reserve in the rail and recliner load paths with aluminium mass saving in the upper frame. The contribution of the article is a transparent engineering workflow that connects FEA responses, material properties, cost, recyclability, and life-cycle GWP into one decision matrix. The limitation is that the results are based on numerical assumptions and representative geometry; they do not constitute regulatory certification or production validation. Future work should include detailed CAD release, mesh-independent nonlinear FEA, weld and fastener modelling, prototype fabrication, FMVSS/UNECE-equivalent bench testing, fatigue durability, corrosion assessment, and a supplier-specific cradle-to-grave life-cycle assessment.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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