

Identification of Parameters for Sustainability Assessment of Chassis Frame Based on Material Selection Across Life Cycle Phases

Amit Patel

Indian Institute of Technology Delhi, Department of Design
Hauz Khas, New Delhi 110016, India
Amit.patel@design.iitd.ac.in

Sumer Singh

Indian Institute of Technology Delhi, Department of Design
Hauz Khas, New Delhi 110016, India
Sumer.Singh@design.iitd.ac.in

ABSTRACT

Informed decision-making is necessary for sustainability in the automotive sector at every stage of a vehicle's life cycle. The chassis frame is a crucial part of any automobile, and the choice of material has a big impact on sustainability results. This study offers a methodology to assist in choosing materials for car chassis frames based on a systematic evaluation of sustainability throughout the manufacturing, usage, and end-of-life stages of the life cycle. The four main aspects of sustainability i.e environmental, economic, social, and technical & performance, are taken into account. To find pertinent parameters under each dimension, a thorough literature review was carried out. The relative importance of these four criteria in relation to sustainable chassis frame design was then determined through a quantitative analysis. A more balanced and data-driven approach to decision-making is made possible by this weighting, which offers crucial insights into the ways in which various sustainability factors influence material evaluation. The final framework is meant to serve as the basis for a decision support system (DSS) that helps stakeholders, such as manufacturers, designers, and legislators, choose materials that support sustainability objectives without sacrificing functionality. Expanding the parameter set and confirming the framework with expert input such as Delphi studies will be the main goals of future development. By encouraging life cycle thinking and providing a clear framework for including sustainability considerations early in the design process, this research advances sustainable mobility. It makes it easier for automotive engineers to choose materials in a more responsible, knowledgeable, and comprehensive manner.

KEYWORDS: Decision support system, Sustainability, Automobile, Chassis frame

1. Introduction

The automobile chassis frame is a critical structural component that forms the foundation of a vehicle, supporting essential mechanical systems such as the engine, axles, suspension, braking, and steering mechanisms (Prasad et al., 2020). It serves as the structural backbone of the vehicle, providing rigidity, strength, and stability under diverse operational conditions (Mounika et al., 2021). Traditionally, chassis frames have been manufactured using steel due to its mechanical robustness and cost-effectiveness. However, in the context of increasing environmental concerns and regulatory pressures, there is a growing emphasis on re-evaluating material choices to enhance the overall sustainability of automotive components (Jasiński et al., 2016).

Sustainable material selection for chassis frames has emerged as a key focus area in automotive engineering, with attention shifting toward lightweight alternatives such as aluminium, advanced high-strength steels (AHSS), and composite materials. These alternatives contribute to reduced vehicle weight, improved fuel efficiency, and lower greenhouse gas emissions over the vehicle's lifecycle. Moreover, the choice of chassis material has implications for environmental performance and economic viability, social acceptability, and technical functionality. In this context, assessing sustainability parameters spanning manufacturing processes, in-use performance, and end-of-life recyclability has become essential in guiding material selection decisions. Therefore, a sustainable chassis frame must strike a balance between performance requirements and long-term environmental and economic goals, aligning with the broader objective of sustainable mobility.

Previous studies have demonstrated the importance of material selection in achieving sustainability goals and used life cycle assessment (LCA) methodologies to evaluate the environmental performance of various vehicle types, emphasising that upstream material decisions largely determine downstream ecological impacts. Similarly, (Othman et al., 2018) explored the use of lightweight materials like aluminium and carbon-fibre-reinforced plastics (CFRPs), which significantly reduce vehicle weight and thus fuel consumption. However, these studies often prioritise environmental aspects and fail to adequately consider economic, social, and technical dimensions.

The current literature often treats sustainability dimensions in isolation. For instance, (Das et al., 2010) discussed the economic benefits of aluminium but did not adequately account for its high energy consumption during processing. Similarly, (Risaliti et al., 2025) highlighted the mechanical advantages of alternative materials but did not incorporate social factors such as worker safety or community impact. Studies like those of (Singh et al., 2009) and (Forcellese et al., 2021) have examined recyclability and end-of-life processes but lack cost and technical feasibility integration.

Furthermore, there is a noticeable scarcity of studies incorporating stakeholder input through structured methodologies like multi-criteria decision-making (MCDM). Most frameworks lack flexibility and fail to reflect industry-specific or region-specific sustainability priorities. This fragmentation in the literature presents a clear gap for a comprehensive, integrative approach to material selection that accommodates diverse sustainability indicators and stakeholder preferences.

This research seeks to bridge these gaps by developing a holistic framework for sustainable material selection, explicitly focusing on automotive chassis frames. The proposed model considers sustainability's environmental, economic, social, technical & performance dimensions across the vehicle life cycle. Applying the Analytic Hierarchy Process (AHP), expert opinion is systematically incorporated to assign relative importance to each sustainability dimension. This enables a balanced, data-driven material evaluation process. The outcome of this research contributes a practical decision support system (DSS) that can

guide automotive engineers, manufacturers, and policymakers in selecting materials that align with sustainability goals while maintaining performance standards.

2. Background and Literature Review

In recent years, a growing emphasis on sustainability in the automotive industry has been driven by environmental regulations, resource depletion concerns, and consumer awareness. Sustainability in automotive design is inherently multi-dimensional, incorporating environmental, economic, social, and technical perspectives (Wellbrock et al., 2020). The challenge lies in balancing these often conflicting dimensions, especially when selecting materials for components such as the chassis frame, which plays a critical structural role and contributes significantly to the vehicle's overall weight and environmental footprint.

Environmental impacts of materials have traditionally been assessed using Life Cycle Assessment (LCA), a method popularised by ISO 14040 standards (International Organization for Standardization, 2006). LCA-based studies, such as those by (Burchart-Korol & Folęga 2019), have shown that emissions during the production stage can outweigh use-phase savings if high-energy materials like aluminium or CFRP are used without adequate recycling strategies. (Das et al., 2010) emphasised that although lightweight metals reduce operational emissions, their extraction and processing are often energy-intensive and polluting, making end-of-life management crucial.

Economic considerations in material selection have often focused on raw material costs and manufacturability. (Zhou et al., 2015) developed a cost-optimisation model for automotive parts but did not integrate sustainability criteria. Moreover, though conceptually strong, life cycle costing approaches often lack practical implementation in early design due to data limitations. Recent advances, such as those by (Hariram et al., 2023), suggest that economic models must be integrated with sustainability metrics to reflect the long-term value of material decisions.

Social sustainability has historically been underrepresented in engineering design literature. Parameters such as worker safety, labour rights, and community impact are rarely quantified or incorporated into material selection decisions (Karlewski et al., 2019). This exclusion creates blind spots that may affect long-term brand reputation, regulatory compliance, and ethical operations. The Global Reporting Initiative (GRI) and the United Nations Sustainable Development Goals (UN SDGs) increasingly encourage manufacturers to consider social criteria in design and procurement processes. Yet, systematic tools for doing so remain limited.

Technical performance parameters—such as strength, stiffness, corrosion resistance, and fatigue life—have long been the focal point in materials engineering. Studies such as (Risaliti et al., 2025) and (Singh et al., 2009) have demonstrated the advantages of high-strength steel and magnesium alloys in meeting vehicle performance standards. However, these studies often evaluate performance in isolation from other sustainability concerns. A lack of multi-dimensional frameworks means that materials optimal in one category may perform poorly in others, leading to sub-optimal or unsustainable design decisions.

Multi-Criteria Decision Making (MCDM) approaches have emerged to fill this gap, offering techniques to integrate various performance indicators. Methods like TOPSIS, VIKOR, and AHP have been utilised in broader sustainability assessments (Ding et al., 2021; Oliveira et al., 2014). While useful, many of these implementations are not specific to chassis design and lack parameter standardisation, which limits their transferability. Moreover, few studies have actively involved experts from different domains (e.g., manufacturing, environmental science, policy) to ensure that the criteria and weightings used reflect real-world priorities.

The present study addresses these limitations by developing a decision support framework explicitly tailored to the sustainability-oriented material selection of chassis frames. It employs AHP to incorporate expert judgment in a structured manner and considers a comprehensive set of parameters spanning the environmental, economic, social, and technical domains. This research builds on and extends the literature by providing a replicable methodology, validated parameter set, and customisable decision-support interface for use in academia and industry.

3. Results and Discussion

The results of the AHP-based expert survey provided crucial insights into how professionals from diverse backgrounds perceive the relative importance of sustainability dimensions in the context of automotive chassis frame material selection.

3.1 Sustainability Dimension Weightage

Based on responses from the 36 validated experts, the aggregated relative weights of the four sustainability dimensions were presented in figure 1.

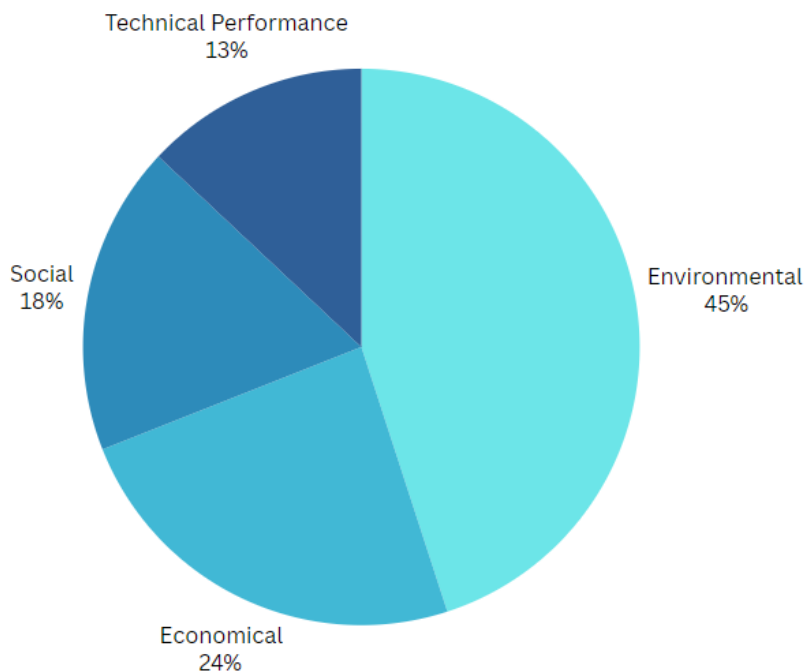


Figure 1: Weightage of sustainability Dimensions after AHP calculation.

These results indicate that environmental considerations are currently the most critical factor influencing material choices, followed closely by economic. While less prioritised, social dimensions and technical performance remain integral to a well-rounded sustainability assessment.

This weighting pattern is consistent with the automotive industry's push toward carbon neutrality, light-weighting, and circular economy strategies. It also reflects the regulatory emphasis on environmental reporting and lifecycle emissions, such as those mandated by the EU's End-of-Life Vehicles Directive and the U.S. Corporate Average Fuel Economy (CAFE) standards.

3.2 Selected Sustainability Parameters and Sub-Parameters

The following parameters in Table 1 were finalised for inclusion in the decision support framework. Each is discussed in brief based on its relevance, assessment method, and impact on sustainability outcomes.

3.3 Comparative Assessment: Steel, Aluminium, CFRP

When these characteristics were evaluated across three commonly used materials for automobile chassis frames—high-strength steel (HSS), aluminium alloys (such as AA7075), and carbon fibre-reinforced polymers (CFRP)—distinct advantages and limitations were observed. High-strength steel offers a balanced combination of strength, cost-effectiveness, and recyclability. Although it adds to the overall weight of the vehicle, it remains the most established material in automotive applications, supported by mature supply chains and minimal social or environmental risks during production and recycling. Aluminium, in contrast, is significantly lighter and relatively affordable, contributing to improved fuel efficiency. However, its production process is energy-intensive, and while it offers reasonable mechanical strength, its fatigue resistance is moderate compared to other alternatives. CFRP stands out in terms of exceptional strength-to-weight ratio, delivering substantial weight reductions and superior mechanical performance. Nevertheless, its widespread application is constrained by high costs, energy-intensive manufacturing processes, and significant challenges in recycling at the end of the product's life cycle. These comparisons highlight the necessity for a comprehensive, multi-criteria sustainability framework for material selection. A material that performs exceptionally well in one dimension, be it environmental, economic, social, or technical, may demonstrate shortcomings in another. Therefore, the proposed sustainability assessment framework facilitates a balanced evaluation of such trade-offs, enabling more informed and responsible decision-making in the context of sustainable automotive design.

Table 1 Selected Parameters for Sustainability Assessment Based on Material Selection Across Life Cycle Phases

	Parameters Category	Metric	Phase of assessment	Description
Environmental Sustainability	Energy consumption	MJ/Kg	All Phases	The energy required to extract, process, and fabricate the material into components, energy consumed by the element during use and at the EOL energy needed to recycle or recover
	Emissions	Co ₂ -eq/kg	All Phases	GHG emissions generated during manufacturing, operation of vehicles and at the EOL
	Water Usage	Liters/Kg	Manufacturing and EOL	Water used in the processing and manufacturing of components and at the EOL is required to be recycled or recovered.

	Vehicle weight contribution	% weight reduction	Use	It influences the total vehicle weight reduction and emissions during use.
	Waste generation	%	Manufacturing and Use	Total waste generated during the processing of material for making a component, and waste generated at the EOL
	Recyclability	%	EOL	At the EOL, how much material gets recycled
	Ecotoxicity	-	All Phases	Environmental harm during the material life cycle
	Biodegradability	-	EOL	To check the landfill impact of the material at the end of its life
	Resource scarcity	-	All Phases	Concern over rare and non-renewable material
Economic Sustainability	Material Cost	\$/Kg	Manufacturing	The cost of raw materials varies depending on the availability
	Processing Cost	\$/component	Manufacturing	Fabrication costs like casting and machining.
	Capital equipment Cos/Investment	%/unit	Manufacturing	Cost of special processing equipment.
	Lifecycle Operating Cost	\$/Lifetime	Use	Fuel, repair, and maintenance costs.
	Disposal Cost	\$/kg	EOL	Safe disposal costs of the material at the EOL
	Value retention	\$/unit	Use and EOL	The resale value of the product during use and at the EOL should have some value
Social Sustainability	Worker Safety	Risk Score	Manufacturing	Hazards in material processing.
	Labor Rights Compliance	ILO/SA8000	Manufacturing	Ethical sourcing and fair labour.
	Occupational Health Impact	LTIFR	Manufacturing	Health burden on workers.
	Consumer Safety	Crash safety, fire resistance	Use	End-user safety impacts.
	Noise & Vibration	dB levels	Use	Comfort and operator health.
	Community Impact	EJ Index	End-of-Life	Effects on local communities from waste.

	Transparency & Traceability	Audit Availability	All Phases	Supply chain traceability.
Technical & Functional	Machinability	Tool wear, cutting speed	Manufacturing	Ease and precision of machining.
	Weldability	Heat input, distortion	Manufacturing	Material behaviour in welding.
	Formability	Elongation %	Manufacturing	Complexity of shapes is formable.
	Mechanical Properties	Strength, Modulus	Use	Tensile, yield, and stiffness.
	Thermal Properties	Conductivity, expansion	Use	Heat dissipation and deformation resistance.
	Fatigue Resistance	Fatigue life	Use	Performance under cyclic loading.
	Creep & Wear Resistance	Wear coefficient	Use	Heat and wear performance.
	NVH Performance	Natural frequency	Use	Noise, vibration, harshness properties.
	Durability Index	Years	All Phases	Resistance to corrosion and fatigue.
	Repairability	Ease of repair	All Phases	Maintenance and part availability.

3.4. Implementation and Application

The sustainability evaluation framework developed in this study is designed as an academic exercise and a practical tool to support real-world decision-making in the automotive industry. The framework's modular design and reliance on measurable sustainability indicators allow it to be implemented as part of a Decision Support System (DSS). This digital platform can be integrated into early-stage vehicle design and material selection processes. A mock-up model is presented in Figure 2.

3.4.1 Integration into a Decision Support System (DSS)

The envisioned DSS will allow manufacturers, engineers, and policymakers to input various chassis frame materials and assess their sustainability based on pre-defined and customisable parameters. The system will consist of the following modules:

Input Interface: Enables users to select materials and enter data such as production region, processing technology, and recycling capabilities. The interface can also accommodate user-defined weightings for each sustainability dimension, enabling the system to reflect different priorities across companies or regulatory environments.

Parameter Evaluation Engine: This module evaluates the performance of each material against the defined parameters using built-in databases and user inputs. It uses weighted scoring models based on AHP-derived priorities to calculate aggregate sustainability scores.

Visualisation Dashboard: Provides comparative charts, radar plots, and ranking outputs, communicating trade-offs. Stakeholders can easily see which materials score best under specific conditions or how trade-offs manifest across dimensions.

Scenario Modelling Tool: Allows users to explore "what-if" scenarios, such as changes in raw material prices, stricter environmental regulations, or supply disruptions. This anticipatory capability supports strategic planning and risk mitigation.

3.4.2 Benefits of Implementation

Implementing a Decision Support System (DSS) based on this sustainability assessment framework offers several strategic advantages for organisations within the automotive sector. One of the primary benefits is enhanced transparency, allowing stakeholders to understand and justify material selection decisions using objective sustainability data. This is particularly valuable during regulatory audits, certification processes, or communications with investors and customers. Additionally, the DSS provides flexibility through customisation, enabling the adjustment of parameter weights to accommodate regional regulatory requirements, organisational sustainability priorities, or specific vehicle applications such as electric vehicles or heavy-duty commercial vehicles. Another key advantage is regulatory alignment, as the framework assists organisations in proactively meeting evolving standards, including ISO 14040 for life cycle assessment (LCA), ISO 26000 for social responsibility, and increasingly stringent vehicle-specific emissions regulations.

Furthermore, using the DSS significantly improves cost and time efficiency by streamlining the material screening and assessment process, which would otherwise demand extensive expert involvement and prolonged deliberations. Beyond operational efficiency, the framework fosters cross-departmental collaboration by establishing a unified decision-making basis for teams across design, sustainability, procurement, and compliance functions. As a result, the proposed DSS framework supports sustainable material selection and enhances organisational coherence in achieving sustainability goals.

Decision Support System (DSS) for Sustainability Assessment of chassis frame based on the selected material

Section 1: Material selection Panel

Field/Input	Description
Material ID	Auto-generated or user-defined unique material name
Material Name	e.g., Aluminum 6061, High-Strength Steel, CFRP
Source of Material	Recycled / Virgin / Hybrid
Application Type	Passenger / Commercial / Heavy-duty vehicle chassis

Section 2: Parameter Input Grid

Sustainability Dimension	Parameter	User Input Value	Unit	Weight (%)	Weighted Score (Auto)
Environmental	GHG Emissions	8.5	kg CO ₂ -eq/kg	10	0.85
	Energy Consumption	45	MJ/kg	8	3.6
	Recyclability Rate	75	%	7	5.25
.....
Economic	Raw Material Cost	2.5	\$/kg	8	0.2

Social	Worker Safety Index	4	Score (1–10)	5	0.5

Technical & Performance	Tensile Strength	320	MPa	6	1.92

Section 3: Results Panel

Dimension	Score (0–10)	Weighted Contribution
Environmental	6.5	2.275
Economic	7.2	1.44
Social	5.3	0.795
Technical & Performance	8.1	2.43
Total Composite Score		6.94 / 10

Section 4: Recommendation & Output

- Rank of this material: #2 out of 6 candidates
 - Decision Tip: Material meets performance needs with moderate sustainability score; consider alternatives if higher recyclability is needed.

Figure 2: A mock-up model of the Decision Support System (DSS) for the Sustainability Assessment of the chassis frame based on the selected material.

4. Methodology

To estimate weights for sustainability aspects, this study uses a structured scientific approach that consists of four stages: parameter identification, expert selection, a pairwise comparison survey, and AHP analysis. The methodology attempts to develop a comprehensive and transparent framework for selecting sustainable materials in vehicle chassis design.

4.1 Parameter Identification

A comprehensive literature review was undertaken to identify and extract relevant sustainability parameters for material selection for automobile chassis frames. These parameters were systematically categorised into four key dimensions of sustainability: environmental, economic, social, technical, and performance. These parameters were selected by their frequency of appearance in previous scholarly works, their direct relevance to automotive applications, and their potential for quantifiable measurement and assessment. Within the environmental dimension, critical factors such as carbon dioxide (CO₂) emissions, energy consumption during production, recyclability rates, and material scarcity were identified as significant contributors to the sustainability profile of materials. The economic dimension encompassed parameters including raw material costs, processing costs, and life cycle costs, reflecting both immediate and long-term financial implications. Social sustainability parameters focused on aspects such as worker safety during manufacturing, the broader community impact of material sourcing and production, and adherence to labour law regulations. Finally, the technical and performance dimension included key engineering properties such as tensile strength, fatigue resistance, stiffness, manufacturability, and strength-to-weight ratio. Collectively, these parameters provide a holistic representation of both the life cycle impacts and the technical performance requirements associated with materials used in chassis frame manufacturing, thereby forming a robust foundation for sustainability assessment.

4.2 Expert Survey Design

A targeted survey was designed to capture the relative importance of each sustainability dimension. The survey used the AHP methodology, requiring participants to perform pairwise comparisons among the four dimensions. Each comparison was rated on a 1–9 scale to express how much more one criterion matters over another.

4.3 Expert Panel

The study was carried out with the involvement of a carefully selected panel of 36 specialists representing diverse yet complementary areas of expertise. The panel comprised 18 academic researchers with backgrounds in materials science, sustainable engineering, and automotive design, alongside 10 professionals from original equipment manufacturers (OEMs) within the automotive sector, specialising in vehicle design, sustainability integration, and materials sourcing. Additionally, the panel included eight policy experts and sustainability consultants, each bringing specialised knowledge in regulatory frameworks and the social dimensions of sustainability assessments. All participating experts possessed at least four years of relevant professional or academic experience, ensuring credibility and depth in the evaluation process. To further validate the robustness of the pairwise comparison data collected during the study, each respondent's consistency ratio (CR) was calculated. Following established analytic hierarchy process (AHP) guidelines, only responses demonstrating a CR value of less than

0.1 were considered acceptable and were subsequently included in the final analysis. This methodological rigour contributed to the reliability and accuracy of the sustainability parameter prioritisation process.

4.4 AHP Analysis

The AHP approach was used to calculate normalised weights from the verified survey replies. Each expert was assigned a pairwise comparison matrix, and the eigenvalues, consistency index (CI), and consistency ratio (CR) were calculated. After establishing uniformity, the weights of individual experts were combined to provide the final numbers. This quantitative approach provides neutrality and includes a variety of perspectives while balancing academic, industry, and policy factors.

5. Conclusion

This study bridges the gap between life cycle thinking and real-world engineering decision-making by presenting a thorough, multifaceted framework for sustainable material selection in car chassis frame design. The research incorporates technical, social, economic, and environmental performance issues into a structured evaluation approach, acknowledging that the chassis frame is a fundamental component with substantial effects throughout a vehicle's life cycle.

The suggested framework uses the Analytic Hierarchy Process (AHP) to obtain quantitative weightings from expert input and includes comprehensive sustainability parameters for each category. By doing this, objectivity is improved, and material selection aligns with actual industry priorities. According to the findings of the AHP-based expert poll, environmental and economic factors are given the most weight (45% and 24%, respectively), followed by social (18%) and technical performance (13%) factors. This is a reflection of engineering priorities and regulatory pressures in contemporary automotive procedures.

The development of a comprehensive parameter set that encompasses, among other things, greenhouse gas emissions, energy consumption, recyclability, strength-to-weight ratio, worker safety, and life cycle cost is a noteworthy contribution of this work. Through detailed explanations of the interactions between factors, the framework offers a sophisticated basis for the creation of decision support systems (DSS). Stakeholders may now more clearly weigh trade-offs and adjust important choices to meet particular sustainability objectives. Furthermore, the framework can be tailored to different vehicle kinds, business objectives, or area policies thanks to its modular design. Long-term relevance and adaptability are ensured by its capacity to handle changing material technologies, regulatory frameworks, and circular economy efforts.

By providing automotive engineers, designers, and policymakers with a rigorous, flexible, and useful tool, our research advances the sustainable mobility goal. It establishes the foundation for smart DSS tools that support safer, more environmentally friendly, and more commercially feasible car designs. Such integrated approaches will be essential as vehicle technologies develop further to guarantee that material selections support performance as well as the more general objectives of social responsibility, environmental stewardship, and economic resilience.

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