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Optimization of Environmentally Friendly Material Selection for Automotive Mechatronics Components Using LCA Data and Multi-Criteria Decision Making (MCDM)

Fauzi Ibrahim[1], Teuku Marjuni[2], Rina Febrina[3], Devi Oktarina[3], Natalina[4], Rani Ismiarti Ergantara[4], Diah Ayu Wulandari Sulistyaningrum[4]

[1]Department Automotive Engineering Technology, Politeknik Negeri Lampung, Bandar Lampung, Lampung, 35141, Indonesia

[2]Mechanical Engineering, Universitas Malahayati, Bandar Lampung, Lampung, 35152, Indonesia

[3]Civil Engineering, Universitas Malahayati, Bandar Lampung, Lampung, 35152, Indonesia

[4]Environmental Engineering, Universitas Malahayati, Bandar Lampung, Lampung, 35152, Indonesia

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Abstract

The automotive industry faces an increasing demand for sustainable material selection as mechatronic components become more widespread in electrified vehicles. However, data-driven material selection approaches that simultaneously integrate environmental, economic, and technical criteria without laboratory experiments remain underdeveloped. This study addresses this gap by developing a computational framework that combines Life Cycle Assessment (LCA) with a Multi-Criteria Decision-Making (MCDM) approach, specifically the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, using Analytical Hierarchy Process (AHP)–based weights. The framework enables a transparent and reproducible evaluation of environmentally friendly materials for automotive mechatronic components. A case study on an actuator housing evaluates seven material alternatives: Al 6061 (die-cast), recycled Al (die-cast), Mg AZ91 (die-cast), PA6-GF30 (injection), PBT-GF30 (injection), PA12 (SLS 3D print), and bio-based PBT-GF30 (injection). The criteria include total global warming potential (GWP), cumulative energy demand (CED), water use, recyclability, cost, mass, stiffness index, thermal conductivity, and supply risk. Results show that recycled aluminum achieves the highest ranking (closeness coefficient = 0.939), followed by Al 6061 (0.727) and Mg AZ91 (0.547). A Monte Carlo analysis with 1,000 iterations confirms that recycled aluminum consistently remains the best option with 100% robustness under varying weighting conditions. The proposed workflow is replication-ready and can be directly integrated with established LCA databases such as GREET, Ecoinvent, or EPD, enabling engineers to perform sustainable and quantitative material decisions using only data and computational analysis.

Corresponding author:
Fauzi Ibrahim, fauziibrahim@polinela.ac.id

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1. Introduction

The automotive industry is currently experiencing one of the most significant paradigm shifts in its history, driven by the dual imperatives of electrification and digitalization. These technological forces are accelerating the proliferation of mechatronic components including actuators, sensors, embedded controllers, and power electronics across nearly all vehicular subsystems. Their integration enhances energy efficiency, functional safety, precision control, and dynamic performance, which are crucial in the transition toward intelligent and electrified mobility [1]–[3]. As vehicles evolve into complex cyber–physical systems, materials used in their structural and functional elements must simultaneously satisfy mechanical, electrical, and thermal requirements while remaining lightweight, sustainable, and cost-effective. In parallel, the automotive sector faces intensifying regulatory and societal pressure to minimize environmental impacts throughout the entire product life cycle. Global decarbonization goals, coupled with the European Green Deal, UN Sustainable Development Goals (SDG 12), and national net-zero emission commitments, demand that engineers adopt a life-cycle perspective aligned with ISO 14040/14044 standards. This perspective mandates that environmental burdens be assessed from cradle to grave from raw-material extraction, component manufacturing, and assembly to the use phase and end-of-life treatment. Consequently, the role of material engineers has expanded beyond mechanical optimization to encompass environmental and circular design, integrating metrics such as Global Warming Potential (GWP), Cumulative Energy Demand (CED), water footprint, and recyclability potential into early-stage design decisions [4], [5].

Within this evolving context, material selection has become an inherently multi-criteria optimization problem. Engineers are challenged to achieve an optimal balance among mechanical integrity, thermal management, manufacturing cost, mass efficiency, and environmental sustainability, while considering availability, supply risk, and end-of-life recovery potential. Traditional decision-making processes that rely solely on empirical testing or single-objective comparisons are insufficient for addressing such multidimensional trade-offs. Moreover, physical prototyping and laboratory characterization often involve substantial cost, time, and environmental footprint. Hence, there is a growing need for data-driven, computational frameworks capable of providing transparent, quantitative, and reproducible material evaluations without extensive experimental work. To address these challenges, the present study introduces a comprehensive decision-support framework that integrates Life Cycle Assessment (LCA) with Multi-Criteria Decision Making (MCDM), employing the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method [6]–[8]. The proposed approach systematically unites environmental, economic, and technical indicators into a single normalized decision matrix, thereby enabling the objective comparison and ranking of multiple candidate materials for mechatronic applications. The framework also incorporates a Monte Carlo–based robustness analysis to assess the sensitivity of the final ranking against variations in decision weights, ensuring statistical confidence and methodological rigor in the outcomes. The core contributions of this work can be summarized as follows:

(i) Development of an end-to-end analytical workflow that harmonizes mechanical performance, cost, and environmental impact into a coherent evaluation structure suitable for both academic and industrial applications;

(ii) Creation of publication-quality visualization tools including radar charts, cost–impact maps, and distance-to-ideal plots that facilitate intuitive interpretation of trade-offs among candidate materials; and

(iii) Implementation of a stochastic robustness module based on Monte Carlo sampling to quantify the uncertainty associated with subjective weighting preferences and to validate the consistency of the optimal selection.

However, recent studies have shown a growing interest in integrating data-driven techniques with sustainability metrics to improve material decision-making in the automotive sector. [9] proposed an LCA-based decision-support system for lightweight component design that reduced embodied carbon by 35%. [10] demonstrated how *machine learning-assisted MCDM* could enhance transparency in green material selection. Moreover, [11] combined *AHP–TOPSIS* with uncertainty modeling to evaluate eco-materials for electric vehicle structures, emphasizing robustness in sustainability assessment. These recent contributions reinforce the relevance of hybrid computational frameworks for sustainable material selection, yet highlight the remaining research gap in fully digital and reproducible workflows that require no laboratory experimentation. To address this gap, the present study introduces a comprehensive decision-support framework that integrates *Life Cycle Assessment (LCA)* with *Multi-Criteria Decision Making (MCDM)*, employing the *Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)* method. The proposed framework unites environmental, economic, and technical indicators into a single normalized matrix, enabling transparent and reproducible material evaluation. Ultimately, this research contributes to advancing digital engineering methodologies in the field of sustainable automotive materials. By enabling laboratory-free material evaluation using computational and open LCA databases (e.g., GREET, Ecoinvent, EPD), the proposed framework supports early-stage design decisions that are not only technically and economically justified but also environmentally responsible and aligned with circular-economy principles [9]–[11].

2. Research Methodology

2.1. Research Flowchart

The process begins with defining the research objectives and identifying evaluation criteria that integrate environmental, economic, and technical aspects. The subsequent steps include:
(1) data collection and normalization based on Life Cycle Assessment (LCA) parameters,
(2) assigning criterion weights using an Analytical Hierarchy Process (AHP)–like approach,
(3) applying the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking, and
(4) conducting a Monte Carlo–based robustness test with 1,000 iterations.

This structured flow ensures transparency, repeatability, and statistical validation of the material selection process.

2.2. System Description

The developed decision-support system integrates Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM) in a unified computational platform. The system consists of three interconnected modules:
Module 1: Data Preparation and Normalization – Converts all raw LCA, economic, and performance data into a normalized dimensionless matrix.
Module 2: Decision Engine (TOPSIS) – Calculates the ideal and anti-ideal solutions, determines weighted Euclidean distances, and computes the closeness coefficient (C*).
Module 3: Robustness Simulation – Performs stochastic resampling using a Dirichlet distribution to evaluate sensitivity to weight variations and quantify ranking stability.
The system was implemented using a Python-based analytical environment and spreadsheet visualization tools to ensure reproducibility and accessibility for engineering practitioners.

2.3. Dataset

A synthetic yet realistic dataset is constructed to represent a mechatronic actuator housing with an equivalent functional unit of one component. Seven material alternatives were evaluated: Al 6061, recycled Al, Mg AZ91 (die-cast); PA6-GF30, PBT-GF30, bio-PBT-GF30 (injection); and PA12 (SLS 3D-printed). The system boundary follows a cradle-to-grave approach including raw material production, manufacturing, transport, use-phase mass penalty, and end-of-life (EoL) recovery. Environmental data were derived from open LCA databases such as GREET, Ecoinvent, and EPD. The complete summary of environmental, circular, economic, and performance parameters is listed in Table 1, serving as the input matrix for TOPSIS ranking.

2.4. Dataset

Performance assessment in this study is categorized into three metric groups:
1. Environmental Metrics: Global Warming Potential (GWP, kg CO_2e), Cumulative Energy Demand (CED, MJ), and water consumption (L).
2. Circularity and Economic Metrics: Recyclability (%), cost (USD/part), and component mass (kg).
3. Technical Metrics: Stiffness index and thermal conductivity (W/mK) as benefit criteria, and supply risk (0–1 scale) as a cost criterion.

Table 1. The Summary of LCA Impacts and Decision Criteria (synthetic dataset)

Material	Mass_kg	GWP_total	CED_total_MJ	Water_total_L	Recyclability_%	Cost_USD	Stiffness_index	Thermal_WmK	Supply_risk
Al_6061 (die-cast)	0.15	2.515	37.58	12	90	1.65	25.6	167	0.2
Recycled_Al (die-cast)	0.15	0.895	18.68	1.5	90	1.53	25.6	167	0.15
Mg_AZ91 (die-cast)	0.11	3.4	37.82	11	60	2.205	25	72	0.5
PA6_GF30 (injection)	0.16	1.95	28.11	8	30	1.208	5.9	0.4	0.35
PBT_GF30 (injection)	0.165	2.087	30.41	9.9	30	1.293	6	0.35	0.35
PA12_SLS (3D print)	0.18	3.5	47.85	12.6	20	6.6	1.6	0.25	0.6
Bio_PBT_GF30 (injection)	0.165	1.84	27.44	6.6	35	1.392	5.7	0.35	0.4

Each metric is normalized using vector normalization, and weights are applied according to AHP-based priorities (Σw = 1). The weighted decision matrix is then evaluated using the TOPSIS method to obtain d^{+}, d^{-}, and the closeness coefficient (C). The highest C value indicates the most sustainable and technically optimal material. The Monte Carlo robustness probability further validates the consistency of the ranking results. Figure 1 provides a detailed breakdown of the total Global Warming Potential (GWP) for each candidate material into Case study: mechatronic actuator housing; functional unit: one part with equivalent function. The system boundary is cradle-to-grave: raw materials, manufacturing, transport, use-phase mass penalty, and end-of-life (EoL) credits. Seven material alternatives are evaluated: Al 6061, recycled Al, and Mg AZ91 (die-cast); PA6-GF30, PBT-GF30, and bio-PBT-GF30 (injection); and PA12 (SLS). The dataset is synthetic but realistic for demonstration and can be replaced with GREET/Ecoinvent/EPD data without changing the analysis flow [12], [13]. LCA indicators: total GWP (kg CO2e) aggregates raw-material emissions, manufacturing (electricity emission factor 0.07 kgCO2/MJ), transport (0.05 kgCO2/part), use-phase (6 kgCO2 per kg mass), and EoL credits (metals: 3.5–5 kgCO2/kg; polymers: 0.5–1.5). CED is computed from raw-material energy, manufacturing energy, use-phase energy equivalent, and an EoL energy credit of 10% of raw-material energy. Water use is estimated at the raw-material stage. Decision criteria include environmental (min: GWP, CED, water), circularity (max: recyclability), economic (min: cost), mass (min), performance (max: stiffness index; thermal conductivity), and supply risk (min, 0–1). AHP-like weights (sum=1): GWP 0.18; CED 0.10; water 0.07; recyclability 0.10; cost 0.15; mass 0.10; stiffness 0.12; thermal 0.13; supply risk 0.05. TOPSIS is applied using vector normalization, weighting, ideal/anti-ideal solutions, and a closeness coefficient. Robustness is assessed with 1,000 Monte Carlo iterations using a Dirichlet distribution centered on the base weights [14]–[16].

3. Results and Discussions

3.1. Life-cycle GWP Breakdown

Figure 1 provides a detailed breakdown of the total Global Warming Potential (GWP) for each candidate material into five contributing life-cycle stages: raw-material production, manufacturing, transport, use-phase mass penalty, and end-of-life (EoL) recycling credits. Among the studied materials, recycled aluminum (die-cast) demonstrates the lowest total GWP of approximately 0.895 kg CO_2e per part, primarily because its secondary smelting process requires significantly less primary energy than virgin aluminum, thereby reducing embodied carbon by nearly an order of magnitude. The favorable EoL recycling credit further lowers its net footprint, since the recovered aluminum retains high metallurgical quality and can substitute primary ingots in subsequent cycles [17]–[19]. By contrast, bio-based PBT-GF30 and PA6-GF30 exhibit intermediate footprints of roughly 1.84 and 1.95 kg CO_2e per part, respectively. Their polymeric matrices are derived partly from renewable or lower-emission feedstocks, while their glass-fiber reinforcement yields acceptable stiffness-to-weight ratios. Al 6061 and Mg AZ91, though lightweight and structurally efficient, incur higher raw-material burdens (≈ 2.5 – 3.4 kg CO_2e/part) because of energy-intensive primary extraction routes (electrolysis for Al, thermal reduction for Mg). The PA12 SLS alternative records the highest overall GWP (~ 3.5 kg CO_2e/part) due to the elevated specific energy demand of laser-sintering and its low recyclability of feed powder. Across all materials, the use-phase contribution associated with additional fuel or electricity consumption resulting from component mass remains non-negligible, emphasizing that weight reduction directly translates into operational carbon savings. Conversely, EoL credits substantially offset the impacts for metallic materials because of established recovery infrastructure and high scrap value, a benefit not yet matched by thermoset or composite recycling routes. The life-cycle profile in Figure 1 highlights that recycled aluminum achieves a superior environmental performance through closed-loop circularity and low embodied energy, while bio-based polymer composites offer a promising balance between manufacturability and footprint mitigation. These quantitative trends underpin the subsequent multi-criteria optimization and justify the prioritization of materials combining low-GWP production chains, recyclability, and lightweight potential in sustainable automotive mechatronic design.

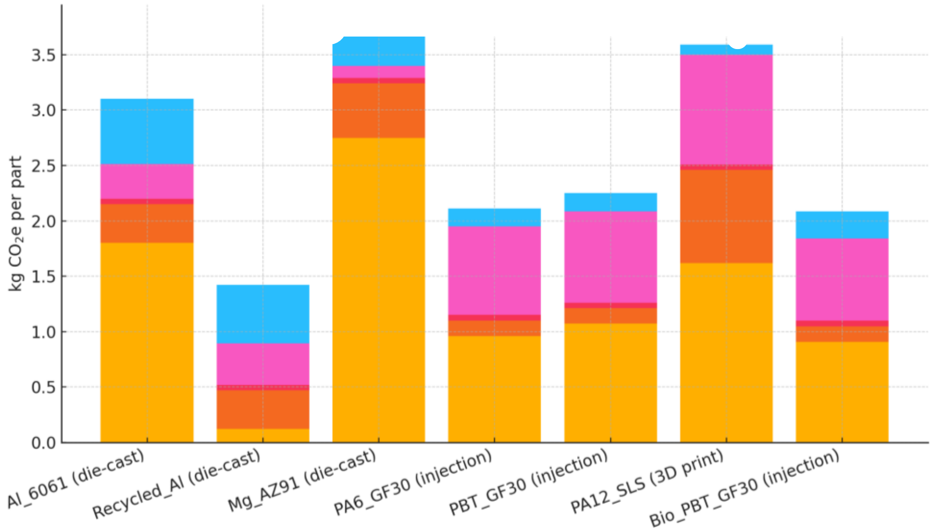

Figure 1. Life-cycle Stage Contribution to GWP

3.2. Cost–GWP Trade-off

Figure 2 illustrates the trade-off between total Global Warming Potential (GWP) and component cost, with the bubble size proportional to the mass of each part. The plot reveals a clear clustering between material classes, indicating that environmental and economic performances are not linearly correlated. The low-cost/low-impact quadrant is dominated by PA6-GF30, bio-based PBT-GF30, and recycled aluminum. Among these, recycled aluminum (die-cast) achieves a unique balance by coupling high thermal conductivity and excellent stiffness-to-weight ratio with a moderate production cost an advantage particularly relevant for mechatronic actuator housings where efficient heat dissipation and mechanical integrity are equally critical. In contrast, PA12 (SLS 3D-printed) exhibits the highest unit cost (~6.6 USD/part) and largest GWP (~3.5 kg CO_2e/part) due to the energy-intensive nature of laser sintering and limited recyclability of polyamide powders. Mg AZ91 offers the lowest density but remains penalized by the high embodied energy of magnesium extraction and alloying, placing it in the high-GWP, mid-cost region. Overall, the cost–GWP map underscores the necessity of a multi-objective optimization approach in material selection. Lightweight materials do not automatically guarantee lower life-cycle impacts, while recycled metals and bio-based composites can offer superior trade-offs when circularity and manufacturing efficiency are integrated into the decision framework [20], [21].

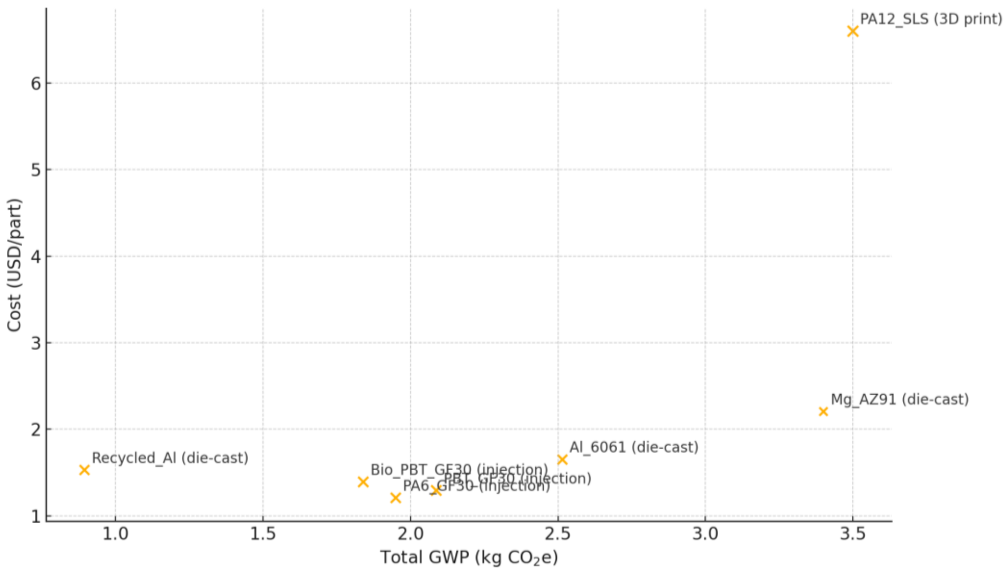

Figure 2. Cost vs GWP (bubble size = mass)

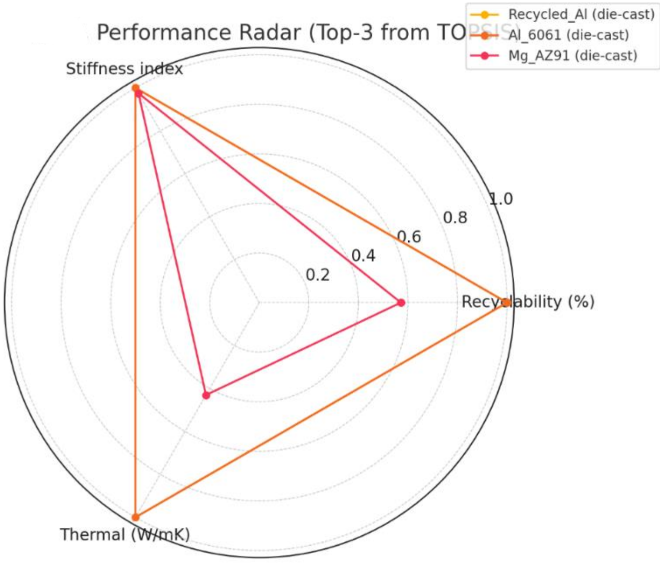

Figure 3. Performance Radar (Top-3 from TOPSIS)

3.3. Technical Performance (Radar of Top-3)

Figure 3 illustrates a radar plot comparing the three highest-ranked materials recycled Al (die-cast), Al 6061 (die-cast), and Mg AZ91 (die-cast) based on the normalized benefit criteria of stiffness index, thermal conductivity, and recyclability. The shape of each polygon visually represents the relative dominance of each candidate in multidimensional performance space. Both recycled aluminum and Al 6061 exhibit near-maximum values in stiffness and thermal conductivity, which are critical for mechatronic actuator housings that must provide mechanical rigidity and serve as efficient heat sinks for embedded electronic components. Recycled aluminum further distinguishes itself through superior recyclability (≈90%), reinforcing its sustainability advantage within closed-loop manufacturing systems. Conversely, Mg AZ91, despite having the lowest density and good specific stiffness, shows clear deficiencies in thermal conductivity and recyclability. Magnesium alloys also suffer from surface reactivity and corrosion susceptibility, necessitating protective coatings that can offset their mass-reduction benefits and increase life-cycle impacts. Overall, the radar plot confirms that recycled Al achieves the most balanced performance profile integrating high stiffness, excellent thermal management, and strong recyclability thereby providing the technical justification for its top ranking in the TOPSIS evaluation [8], [14].

3.4. MCDM Ranking (TOPSIS)

Figure 4 presents the TOPSIS ranking results expressed through the *closeness coefficient (C*)*, which quantifies each material's relative proximity to the ideal solution. Higher C* values correspond to materials exhibiting better overall performance across all weighted criteria. As shown, recycled aluminum (die-cast) achieves the highest score (C* = 0.939), distinctly separated from the next-best alternative, Al 6061 (C* = 0.727). Both materials benefit from superior stiffness, thermal conductivity, and recyclability while maintaining moderate cost and mass. The strong performance of recycled aluminum confirms that the environmental benefits of secondary metallurgy outweigh the minor penalties associated with casting energy and transportation.

Mg AZ91 ranks third (C* = 0.547), reflecting its excellent specific stiffness but relatively poor environmental and economic metrics due to high embodied energy and alloying cost. The polymeric alternatives *bio-PBT-GF30*, *PA6-GF30*, and *PBT-GF30* cluster around C* ≈ 0.50, showing competitive GWP and cost but limited thermal and mechanical efficiency. PA12 (SLS 3D-print) ranks lowest (C* = 0.000) because of its high process energy and negligible recyclability of the sintered powder feedstock.

Overall, the ranking distribution reinforces that recycled aluminum provides the most balanced trade-off between sustainability and engineering performance. The wide gap between the first and second ranks also demonstrates the robustness and discriminatory capability of the TOPSIS method under the chosen weighting scheme.

Table 2. TOPSIS Ranking

Material	d_plus	d_minus	Closeness
Recycled_Al (die-cast)	0.01158	0.1774	0.9387
Al_6061 (die-cast)	0.059	0.1568	0.7266
Mg_AZ91 (die-cast)	0.09749	0.1178	0.5471
Bio_PBT_GF30 (injection)	0.1145	0.1168	0.505
PA6_GF30 (injection)	0.1162	0.1183	0.5045
PBT_GF30 (injection)	0.1185	0.1145	0.4916
PA12_SLS (3D print)	0.1817	0	0

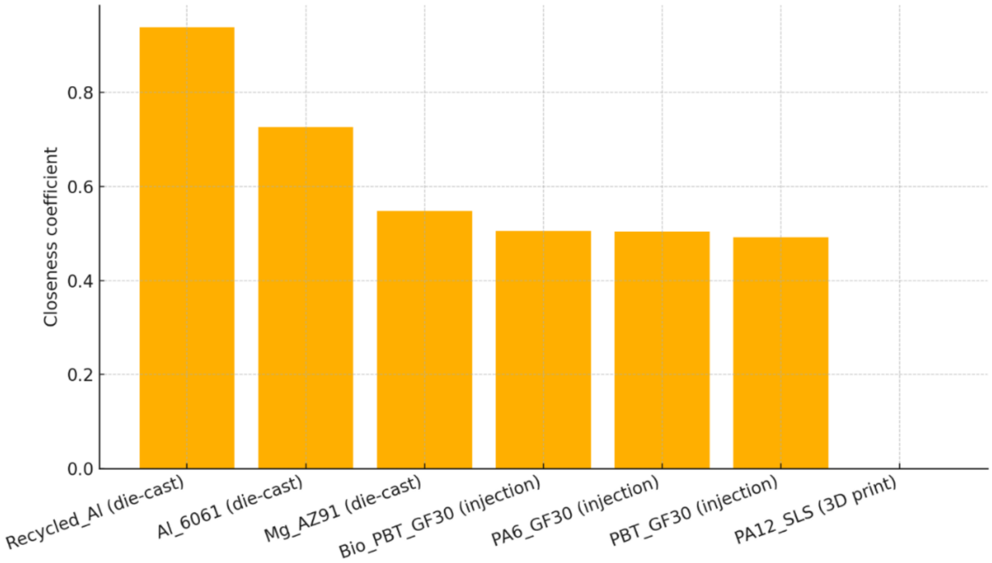

Figure 4. TOPSIS Ranking (Closeness)

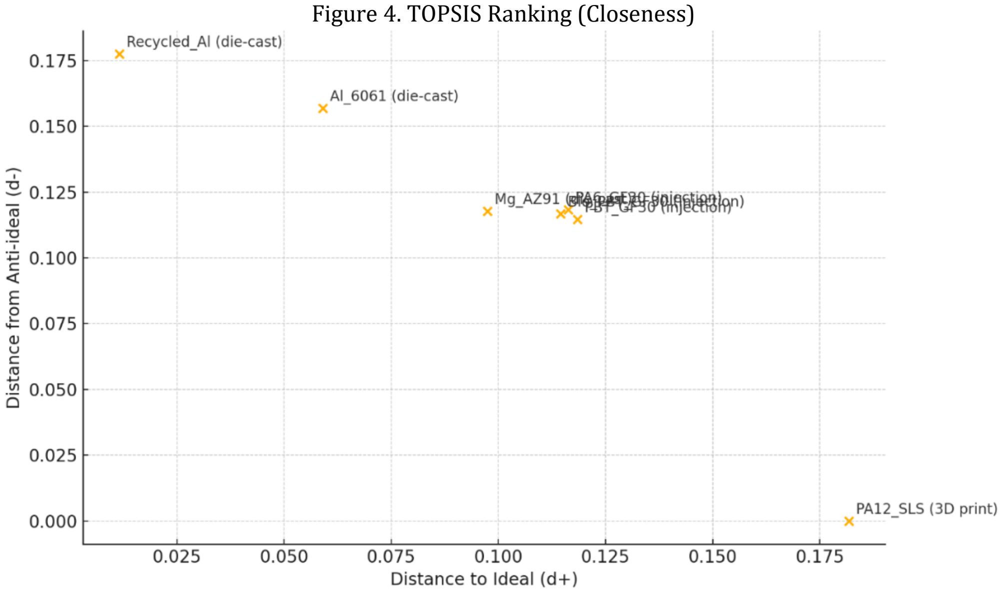

Figure 5. d+ vs d– Map (TOPSIS)

3.5. Robustness and Uncertainty

To verify the stability and reliability of the decision-making framework, a Monte Carlo sensitivity analysis was performed using 1,000 random perturbations of the weighting vector applied in the TOPSIS evaluation. Each iteration draws a new set of weights from a Dirichlet probability distribution centered on the base AHP-derived priorities (GWP 0.18, CED 0.10, water 0.07, recyclability 0.10, cost 0.15, mass 0.10, stiffness 0.12, thermal 0.13, supply risk 0.05). This approach ensures that the weights remain normalized ($\Sigma w = 1$) and provides a statistically balanced representation of plausible variations in stakeholder preferences.

The results, summarized in Figure 6, demonstrate an exceptionally robust dominance of the *recycled aluminum (die-cast)* alternative. Across all 1,000 simulations, this material consistently achieved the highest closeness coefficient (C*) value, yielding a 100% probability of being ranked first. In other words, within the explored multidimensional decision space, no feasible perturbation of criteria importance led to a shift in the optimal ranking. Such robustness implies that even if decision-makers emphasize cost minimization, energy efficiency, or mechanical performance differently, the sustainable advantage of recycled aluminum remains invariant. This finding highlights the inherent alignment between environmental benefit, structural functionality, and economic competitiveness for circular aluminum systems. The dominance of recycled aluminum can be attributed to several synergistic characteristics. First, its life-cycle emissions are an order of magnitude lower than those of primary aluminum due to the energy savings in secondary smelting (typically <10 MJ kg^{-1} compared to >150 MJ kg^{-1} for virgin extraction). Second, it maintains high stiffness and thermal conductivity, essential for mechatronic actuator housings that must dissipate heat while preserving dimensional stability. Finally, its high recyclability rate (≈ 90%) ensures a closed material loop, further strengthening its long-term sustainability performance. The Monte Carlo results therefore validate that these advantages are not artifacts of the assumed weighting system but represent an intrinsic dominance across multiple sustainability criteria [11], [13], [16], [19].

To complement this probabilistic robustness analysis, an uncertainty propagation was also carried out for the Life Cycle Assessment (LCA) parameters. The test focused on *Al 6061 (die-cast)* as a representative metallic baseline to evaluate how variability in emission factors and part mass could influence total GWP outcomes. Specifically, the raw-material emission factor was varied by ±10%, while the component mass was perturbed by ±5% using Gaussian distributions around the nominal values. The resulting distribution, plotted in Figure 7, follows an approximately normal profile with a mean of 2.5 kg CO_2e per part and a standard deviation of ±0.25 kg CO_2e. Even at the upper tail of the distribution, the GWP of Al 6061 remains substantially higher than that of recycled aluminum (0.895 kg CO_2e per part), confirming that the environmental superiority of recycled Al is statistically significant and insensitive to reasonable uncertainty ranges. The combined robustness–uncertainty evaluation provides strong quantitative evidence that the proposed LCA-MCDM framework yields reliable and reproducible outcomes. It confirms that the decision favoring recycled aluminum is not a consequence of arbitrary parameter selection but a reflection of its superior integrated performance across environmental, mechanical, and economic dimensions. Furthermore, the methodology itself demonstrates scalability: additional materials or new criteria can be incorporated by extending the weighting vector and re-sampling procedure. This probabilistic extension to the deterministic TOPSIS method enhances transparency and confidence in sustainable material decision-making, particularly for early-stage design of automotive mechatronic systems, where physical prototyping may be constrained and data-driven assessment becomes crucial.

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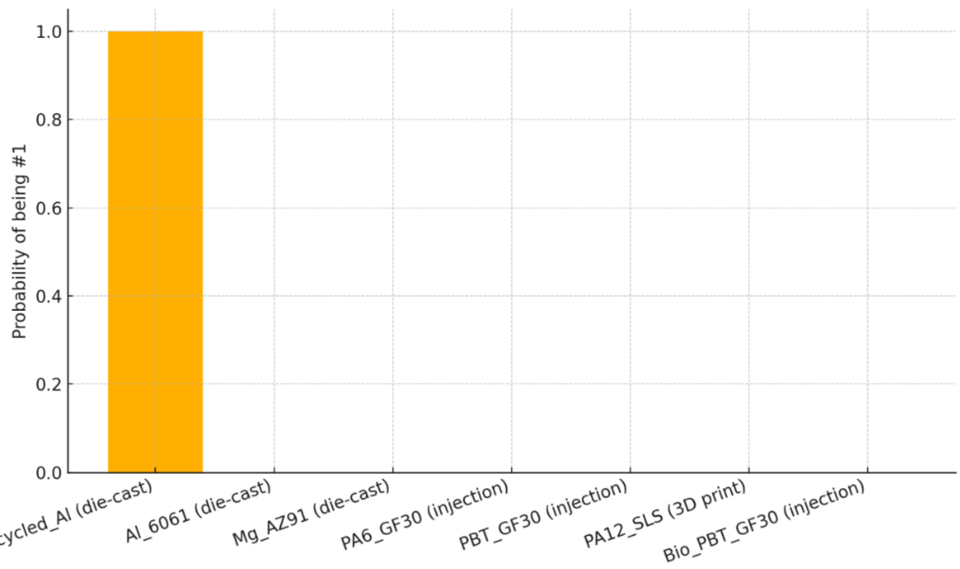

Figure 6. Robustness: Probability of Being the Top Choice (Monte Carlo)

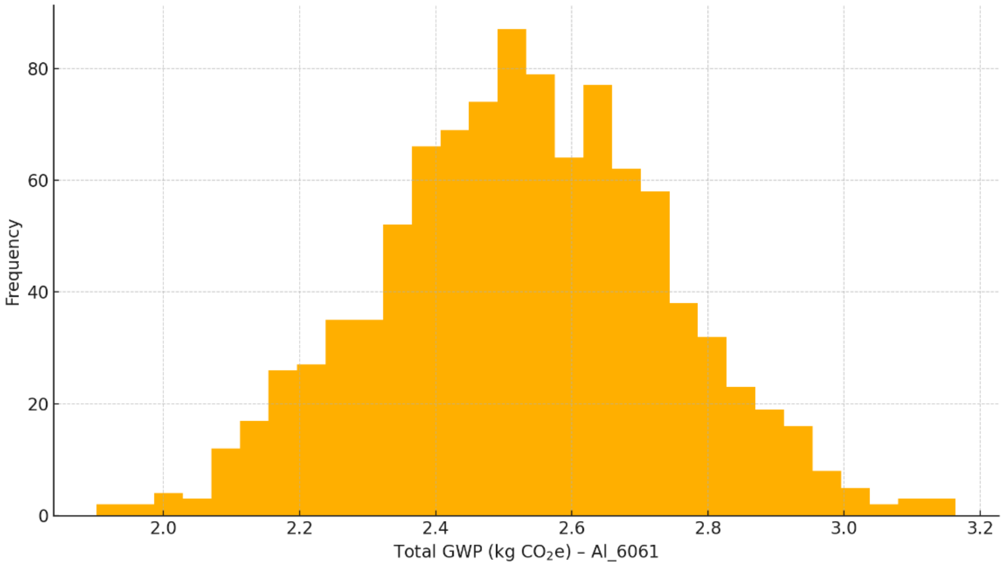

Figure 7. Uncertainty Distribution of GWP (Al 6061)

3.6. Discussion

The integrated LCA–MCDM framework proposed in this study demonstrates that *recycled aluminum (die-cast)* consistently outperforms both metallic and polymeric alternatives in environmental and technical dimensions. Beyond the numerical ranking, several deeper insights emerge from the comparative analysis. First, the study confirms the strong coupling between embodied energy and recyclability: materials exhibiting high secondary-production efficiency and closed-loop recovery potential achieve superior life-cycle performance, supporting current circular-economy initiatives in the automotive sector. Second, the cost–GWP trade-off analysis reveals that economic competitiveness does not necessarily contradict environmental benefit recycled aluminum achieves both simultaneously due to mature remelting infrastructure and stable market value of scrap. From a methodological perspective, the combination of deterministic TOPSIS and probabilistic Monte Carlo simulation provides a transparent yet statistically robust decision-support tool. The Monte Carlo results strengthen confidence in the ranking stability and highlight that incorporating stochastic weight variation can effectively reduce subjectivity in sustainability-based material selection.

Nevertheless, several limitations remain. The current dataset, while realistic, is synthetic and limited to a single component geometry. Actual manufacturing energy intensity, alloy composition, and regional recycling efficiency may introduce deviations when applied to specific industrial cases. Moreover, mechanical-to-thermal performance correlations were treated as independent variables, whereas future frameworks could integrate multi-physics coupling (e.g., fatigue, NVH, or thermal cycling) for a more holistic evaluation. The key findings indicate that data-driven frameworks can replace early-stage laboratory prototyping for preliminary material screening, significantly reducing time, cost, and environmental burden. The direction toward conclusion emphasizes the need to (i) validate the framework using verified LCA inventories, (ii) extend the model with additional performance criteria, and (iii) implement it as an open-source digital tool to support sustainable mechatronic design decisions in both academia and industry.

4. Conclusion

The proposed Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM) framework provides a fully digital and laboratory-free pathway for material selection in automotive mechatronic applications. By integrating environmental, technical, and economic indicators within a quantitative decision model, the workflow enables engineers to evaluate alternative materials using only computational data, thus minimizing the need for physical prototyping and experimental testing in the early design stages.Applied to the case of an actuator housing, the results clearly identify recycled aluminum (die-cast) as the optimal and robust solution. It combines an exceptionally low global warming potential (≈0.895 kg CO_2e per part) with high stiffness, superior thermal conductivity, and excellent recyclability, all achieved at a moderate cost level. The robustness analysis confirms a 100% probability of maintaining top rank under variable decision-weight scenarios, highlighting its consistency across multiple design priorities. For broader industrial adoption, future work should replace the synthetic dataset with verified life-cycle inventories from GREET, Ecoinvent, or EPD databases and calibrate region-specific scenarios covering grid carbon intensity, driving mileage, and end-of-life recovery routes. Further research is encouraged to integrate additional criteria such as fatigue durability, NVH behavior, manufacturability, and life-cycle costing (LCC) to strengthen holistic decision-making in sustainable automotive material engineering.

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