Balancing Sustainability and Performance: A Multi-criteria Comparison of Recycled, Bio-Based and Low-Carbon Materials Using the Analytic Hierarchy Process (AHP)

João Zambujal-Oliveira[1,2(✉)] and Debora Anelli[3]

[1] NOVA LINCS (FCT), Universidade Nova de Lisboa, Lisbon, Portugal
[2] Faculdade de Ciências Sociais, Universidade da Madeira, Funchal, Portugal
joliveira@staff.uma.pt
[3] Department of Architecture and Design, Sapienza University of Rome, Rome, Italy
debora.anelli@uniroma1.it

Abstract. Material selection in engineering and manufacturing increasingly requires balancing technical performance, economic feasibility and environmental sustainability. This paper presents a structured multi-criteria decision-making (MCDM) framework based on the AHP to compare three broad classes of materials: Recycled (A), Bio-based (B), and Low-carbon virgin (C). Each representing a family of real-world alternatives that share a defining sourcing or production characteristic. Five key criteria are considered: carbon footprint, availability, cost, technical performance and circularity. Baseline input values are drawn from established life-cycle assessment databases and published industry benchmarks, and are intended to represent typical class-level performance. Raw indicator values are transformed into benefit scores, used to construct consistent pairwise comparison matrices, and aggregated into global priority scores. Results show recycled materials ranking highest under balanced baseline weights, while sensitivity analysis reveals critical trade-offs when environmental or technical priorities dominate. The proposed framework offers repeatability and clear managerial guidance for sustainable procurement decisions, and is designed to be parameterised as organisation-specific data become available.

Keywords: Sustainable material selection · Analytic Hierarchy Process · Circularity

1 Introduction

Material selection is a critical activity in engineering and manufacturing, as it directly influences product performance, cost structure, supply-chain resilience, regulatory compliance and environmental footprint. Traditional approaches, such

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2027
O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16764, pp. 116–131, 2027.
https://doi.org/10.1007/978-3-032-30533-6_8

as Ashby charts (Fig. 1) and performance indices [2], excel at trading off mechanical, thermal and chemical properties but often overlook sustainability and circular economy dimensions [30].

The growing demand for low-impact materials has highlighted the need for integrated decision-support tools, capable of handling quantitative indicators (e.g. life-cycle emissions, cost) and qualitative aspects (e.g. supply reliability, strategic alignment). MCDM methods, particularly the AHP, have proven effective in reconciling such objectives [6,42].

Despite increasing emphasis on the circular economy, organizations face difficulty comparing heterogeneous material alternatives that differ in economic, environmental, and operational attributes. Existing evaluation approaches address these dimensions separately, limiting consistent decision-making.

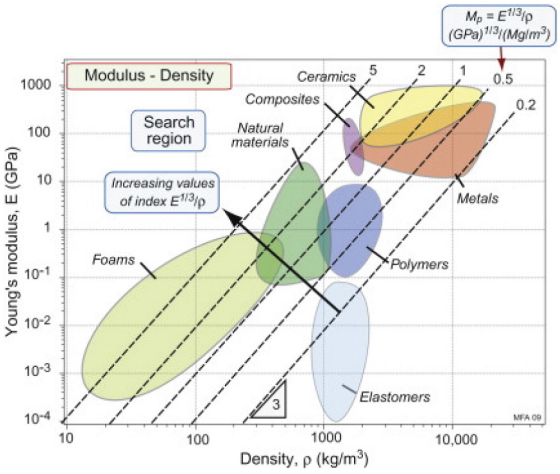

Fig. 1. Distribution of material classes plotted by Young's modulus (E) versus density (ρ) [2].

Consequently, there is a need for a framework capable of integrating quantitative and qualitative criteria to support robust comparison. This study addresses the following research question: How can heterogeneous material alternatives be quantitatively and qualitatively compared within a unified decision-support framework that supports circular economy objectives?

This study aims to develop a decision-support framework to compare recycled, bio-based, and low-carbon virgin materials. The primary objective is to demonstrate an AHP-based template for ranking material alternatives across sustainability, economic, and technical criteria, with a sensitivity analysis to assess its robustness.

2 Literature Review

Engineering material selection has relied on tools such as Ashby-type charts and performance indices, which trade off properties including mechanical strength, thermal behaviour, and chemical resistance [30]. More recent sustainability-oriented extensions of these approaches have begun to incorporate life-cycle assessment (LCA) indicators, such as recyclability, allowing environmental performance to be considered alongside traditional criteria [1,29].

Among multi-criteria decision-making methods applied to materials, the AHP continues to enjoy widespread use thanks to its hierarchical structure, its capacity to handle both qualitative and quantitative criteria, and its built-in mechanism for checking the consistency of judgments [42]. While other techniques, such as TOPSIS, VIKOR, and PROMETHEE, are employed for final ranking tasks, AHP is particularly valued for its ability to derive consistent criteria weights directly from expert judgments or quantitative indicators [6] (Fig. 2).

In the context of the circular economy, material strategies emphasise high reuse, recycling, and recovery rates. Contemporary decision-support models therefore tend to integrate data from established LCA databases (Ecoinvent, GaBi) and regional trade statistics, creating real-world evaluation frameworks [16].

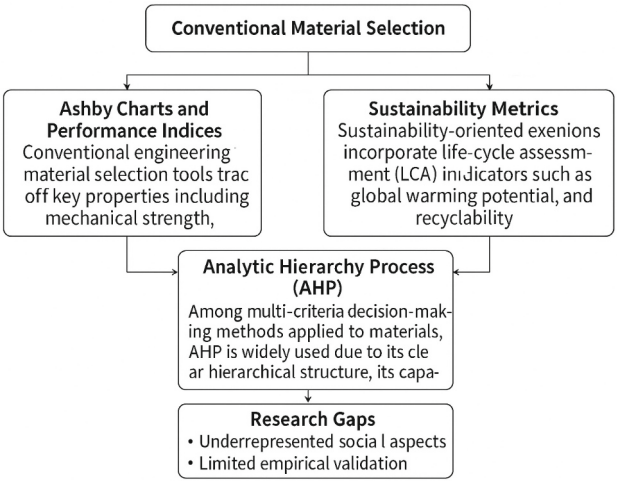

Fig. 2. Conceptual framework linking conventional material selection, sustainability metrics, and AHP.

Despite advancements in integrating sustainability methods, such as LCA and MCDM, into material selection processes, several critical research gaps remain in the literature. Many studies focus predominantly on environmental

and economic dimensions while underrepresenting social aspects (e.g., labor conditions and community impacts) within circular economy frameworks for engineering materials [3,36].

Additionally, although hybrid MCDM approaches address uncertainty criteria, there is limited empirical validation of these models in real-world, sustainable procurement scenarios that incorporate regional material availability and comprehensive circularity indicators [28,37].

Persistent methodological challenges and insufficient integration of normalized mechanisms for comparable evaluations across diverse material types, highlight the need for more robust and practically oriented frameworks that bridge these limitations to support consistent decision-making in pursuing circular material strategies [27,37].

2.1 Research Hypotheses

The following hypotheses guide the development of the framework:

- **H1:** Defining clear material alternatives enhances consistency in MCDM judgements [13].
- **H2:** Integrating quantitative life-cycle indicators with qualitative expert inputs yields more robust prioritization [43].
- **H3:** Normalised indicators and ratio-based pairwise comparisons enable comparability across heterogeneous materials [25,42].

The research hypotheses are formulated to address persistent gaps in the existing literature on sustainable material selection within circular economy contexts. While recent advancements have expanded MCDM applications, particularly through hybrid methods (e.g., fuzzy AHP-TOPSIS), to better incorporate uncertainty, many studies still prioritize economic criteria at the expense of integrated social dimensions, comprehensive circularity metrics, and practical validation [36,37].

Moreover, methodological limitations such as rank reversal in TOPSIS, subjectivity in weighting, and insufficient emphasis on normalized mechanisms for cross-material comparability hinder the development of adaptive frameworks that can support decision-making across engineering applications [3,27]. By testing H1 through enhanced alternative definition, H2 via balanced quantitative-qualitative integration, and H3 with improved normalization techniques, the proposed framework aims to bridge these gaps, contributing to more holistic MCDM tools aligned with circular economy goals.

3 Methodology

3.1 Material Alternatives and Evaluation Criteria

Three classes of materials are evaluated in Table 1. Each class is defined as a category of alternatives, representing a family of real-world materials that share a

defining sourcing or production characteristic. Recycled materials (A) encompass secondary-stream inputs such as recycled aluminium and post-consumer plastics; bio-based materials (B) include plant-derived and agricultural by-product inputs; and low-carbon virgin materials (C) refer to primary materials produced through low-emission processes, including hydrogen-based steels. The class-level framing is intentional, enabling procurement decision-makers to screen strategic material categories, and aligns with how sustainability strategies are formulated at the portfolio level [32].

Table 1. Classification of materials by source and carbon intensity.

Class of Materials	Explanation	Examples
Recycled materials (A)	Obtained from secondary raw materials, recovered from waste streams.	Recycled aluminium; post-consumer recycled plastics
Bio-based materials (B)	Derived from renewable biomass such as plants or agricultural by-products. Reduce dependence on fossil inputs and may be biodegradable.	PLA; natural-fibre composites
Low-carbon virgin materials (C)	Primary materials produced via low-emission processes. Incorporate renewable energy, electrification, or hydrogen.	Low-emission steel; green aluminium

The comparison is structured around five key criteria, with the direction of preference and data sources summarised in Table 2. Data are drawn from LCA databases (Ecoinvent [9], GaBi [14]), industry cost benchmarks [21], and circularity certification frameworks [38].

Table 2. Main criteria, preference direction and data sources

Criterion	Preference	Example data sources
Carbon footprint	lower better	LCA (kg CO_2e/kg)
Availability	higher better	% local/reliable supply
Cost	lower better	\$/kg (CAPEX + OPEX)
Technical performance	higher better	normalised index (0–1)
Circularity	higher better	% recyclable/recoverable

3.2 AHP Framework

Figure 3 illustrates the fundamental steps and mathematical structure of the AHP applied in this study. The diagram presents the hierarchical decomposi-

tion of the decision problem into goal, criteria, and alternatives, alongside the corresponding pairwise comparison matrices.

The calculation of the priority vector as the normalized principal eigenvector of the comparison matrix is shown, as well as the evaluation of judgment consistency through the consistency ratio (CR). This representation clarifies the workflow from qualitative judgments to quantitative priority weights, providing a foundation for the multi-criteria evaluation of circular material alternatives.

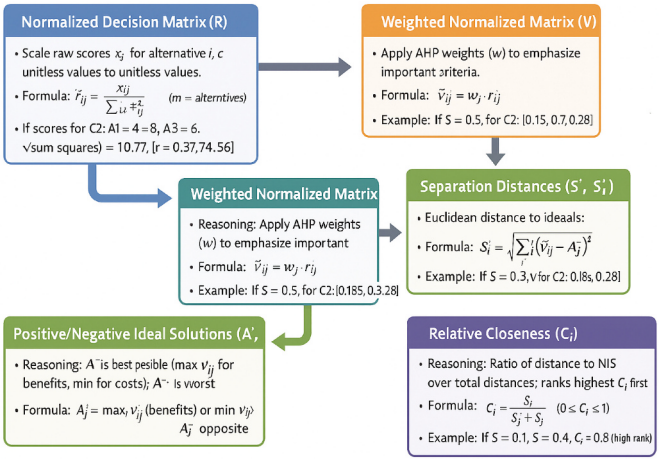

Fig. 3. Mathematical structure of the AHP

3.3 AHP Procedure

The AHP procedure consists of five steps (Fig. 4). Raw values are first transformed into benefit scores: the raw value is used directly for higher-better criteria (*Availability, Technical performance, Circularity*), while the reciprocal (benefit = inverse of raw value) is applied for lower-better criteria (*Carbon footprint, Cost*).

Each benefit vector is then normalised to obtain local priorities. Pairwise comparison matrices are constructed using ratios of benefit scores ($a_{ij} = b_i/b_j$), resulting in consistent matrices by design. Global priorities (G_k) are computed as the weighted sum of local priorities:

$$G_k = \sum_{j=1}^{5} w_j \cdot p_{k,j}, \tag{1}$$

where w_j is the criterion weight and $p_{k,j}$ is the local priority of alternative k on criterion j. Finally, sensitivity analysis is performed by varying criterion weights to assess ranking stability.

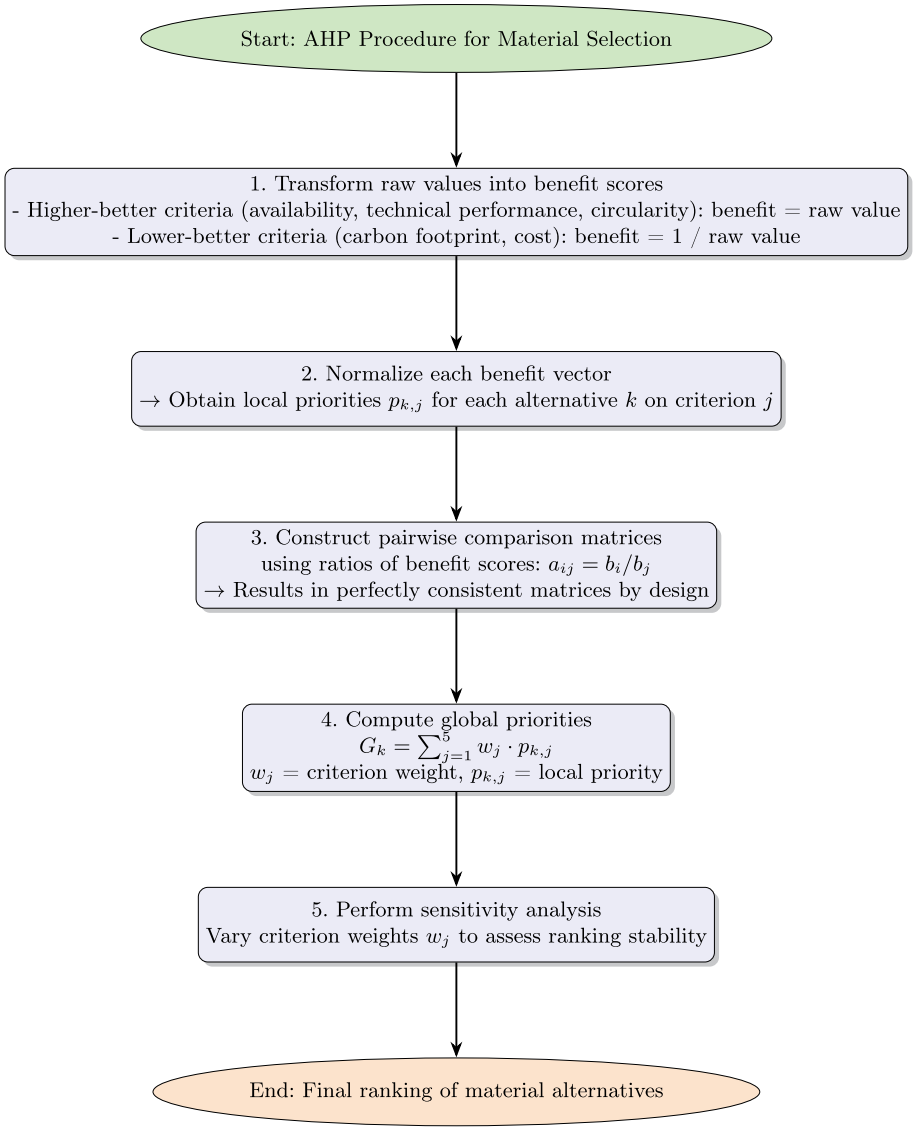

Fig. 4. Flowchart of the adapted AHP procedure.

4 Quantitative Model and Results

4.1 Selection of Baseline Input Values

The analysis uses raw performance values for the three material alternatives: Recycled (A); Bio-based (B), and Low-carbon virgin (C). Table 3 reports class-representative values aligned with LCA databases. Carbon footprints are

2.0kg,CO_2e/kg (recycled), 3.5kg,CO_2e/kg (bio-based), and 1.5kg,CO_2e/kg (low-carbon virgin), consistent with Ecoinvent and GaBi ranges for secondary aluminium/plastics, PLA biopolymers, and hydrogen or renewable-electricity-based primary production [9,14].

Recycled aluminium typically ranges from 0.5–3.0kg, CO_2e/kg, making 2.0kg, CO_2e/kg a reasonable mid-range value. The 1.5kg,CO_2e/kg low-carbon virgin estimate aligns with emerging routes such as Hybrit, whose near-zero pilot results support a broader 1.0–2.0kg,CO_2e/kg range [19,33]. Availability scores (60%, 40%, 30% for A–C) reflect EU procurement and secondary market evidence. Recycled materials benefit from mature collection systems; bio-based supply is limited by seasonality and processing capacity; low-carbon virgin depends on early-stage hydrogen and carbon capture infrastructure [5,39].

Cost benchmarks (2.5, 3.0, 4.0 $/kg for A–C) reflect industry surveys showing secondary materials' cost advantage and packaging [5,26]. Technical scores (0.7, 0.6, 0.8) capture performance: low-carbon virgin aligns with virgin specs; bio-based is limited in strength [22,35]. Circularity (85%, 60%, 50%) reflects recovery rates from certification frameworks [38]. Criterion weights (Carbon: 0.30; Cost: 0.25; Technical: 0.20; Availability: 0.15; Circularity: 0.10) define a balanced baseline where no criterion dominates. This reflects multi-stakeholder settings prioritising cost and emissions, and serves as a reference for sensitivity analysis. The baseline criterion weights, which sum to 1.00, are as follows: *Carbon footprint* is assigned a weight of 0.30, *Cost* 0.25, *Technical performance* 0.20, *Availability* 0.15, and *Circularity* 0.10. To enable consistent comparison across criteria with different directions of preference, the raw values are first transformed into benefit scores.

Table 3. Baseline raw values and preference direction for each criterion

Criterion	Unit	Recycled (A)	Bio-based (B)	Low-carbon virgin (C)
Carbon footprint	kg CO_2e/kg	2.0	3.5	1.5
Availability	% local	60	40	30
Cost	$/kg	2.5	3.0	4.0
Technical performance	index (0–1)	0.7	0.6	0.8
Circularity	% recyclable	85	60	50

For criteria where lower values are preferred (*Carbon footprint* and *Cost*), the benefit score is computed as the reciprocal of the raw value. For criteria where higher values are preferred (*Availability*, *Technical performance*, and *Circularity*), the benefit score is set equal to the raw value itself. The resulting approximate benefit scores after transformation are presented in the Table 4. These benefit values are then normalised within each criterion by dividing each individual benefit score by the sum of the benefit scores for that criterion, yielding

local priority weights that reflect the relative attractiveness of each alternative with respect to the specific criterion.

Table 4. Benefit scores for each criterion and alternative

Criterion	A (Recycled)	B (Bio-based)	C (Low-carbon virgin)
Carbon footprint	0.50	≈ 0.286	≈ 0.667
Availability	60	40	30
Cost	0.40	≈ 0.333	0.25
Technical performance	0.7	0.6	0.8
Circularity	85	60	50

Under the baseline weights, the resulting global priority scores are approximately 0.385 for Recycled materials (A), 0.338 for Low-carbon virgin materials (C), and 0.278 for Bio-based materials (B). This yields a clear ranking of A > C > B. Recycled materials (A) achieve the highest overall priority primarily due to their strong performance in *Availability*, *Cost competitiveness*, and *Circularity*, even though they do not lead in direct carbon reduction or technical performance index.

4.2 Sensitivity and Robustness Analysis

Sensitivity analysis indicates that the ranking structure is primarily driven by the relative weight allocation between *Carbon footprint*, *Technical performance*, and the jointly reinforcing operational criteria (*Cost* and *Availability*). The model exhibits a non-linear response to changes in environmental prioritisation.

A sensitivity analysis on the *Carbon footprint* weight reveals a switching point at $w_{CO_2} \approx 0.50$, beyond which Low-carbon virgin materials (C) overtake Recycled materials (A) in priority. This threshold is not symmetric: reductions in w_{CO_2} below the baseline (0.30) strengthen the dominance of A only marginally, while increases above the threshold induce a rank reversal, reflecting the convex structure of the weighted aggregation.

A one-way sensitivity analysis on *Technical performance* shows a weaker but consistent effect. Even when the weight of this criterion is increased up to 0.40 (double its baseline value), Low-carbon virgin materials (C) narrow the gap with A but do not overtake it unless accompanied by a increase in environmental weight. This indicates that technical superiority alone is insufficient to compensate for the cost–availability disadvantage of C under current parametrisation.

To formalise interaction effects, a two-dimensional sensitivity region analysis was conducted over (w_{CO_2}, w_{TP}) while rescaling remaining weights proportionally. The results define three stable regions:

- **Region I (Operational dominance)**: A remains optimal when $w_{CO_2} < 0.45$ and $w_{TP} < 0.35$. This region reflects procurement regimes dominated by cost efficiency, supply security, and circularity objectives.

- **Region II (Transitional regime)**: C becomes competitive but not dominant when $0.45 \leq w_{CO_2} \leq 0.55$, provided $w_{TP} \leq 0.35$. In this region, ranking inversion is sensitive and small perturbations in weights can lead to rank reversal between A and C.
- **Region III (Decarbonisation dominance)**: C dominates when $w_{CO_2} > 0.50$ jointly with $w_{TP} \geq 0.30$, reflecting policy-driven procurement settings with binding emissions constraints.

Across all configurations, Bio-based materials (B) remain rank-stable in third position. This result is robust even to extreme weight scenarios, indicating structural inferiority under industrial performance parameters rather than sensitivity to weighting assumptions.

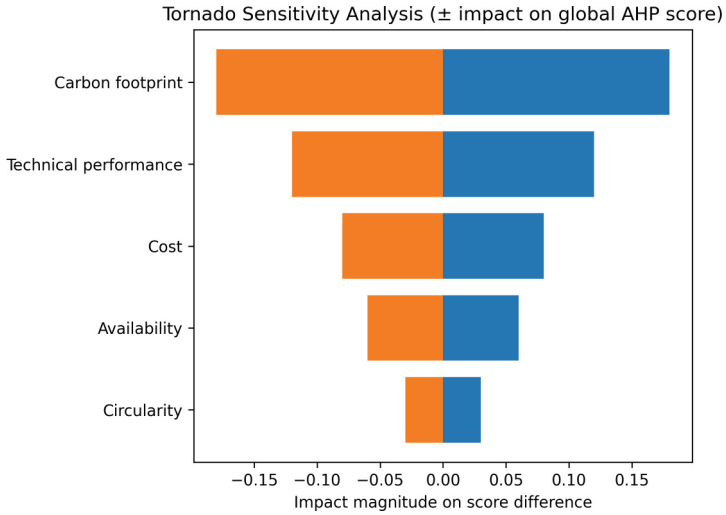

Fig. 5. Tornado sensitivity analysis of global AHP scores under ±10% variation in criterion weights. Bars represent the impact range of each criterion on the global priority difference between alternatives. Criteria are ordered by decreasing influence on ranking stability.

The tornado diagram in Fig. 5 provides a one-way sensitivity decomposition of the AHP-based global priority scores under bounded perturbations of ±10% in each criterion weight. The analysis quantifies the marginal effect of each criterion on the stability of the ranking structure A $\succ$ C $\succ$ B.

The results show that the *Carbon footprint* is the main sensitivity driver, generating the largest score variation between Recycled (A) and Low-carbon virgin (C). This confirms that environmental weighting drives rank reversals, consistent with the identified switching threshold at $w_{CO_2} \approx 0.50$. Increasing the carbon weight favors C, while decreasing it reinforces the dominance of A.

Technical performance is the second most influential criterion. Its effect is asymmetric: higher weights improve C's position but do not overturn the baseline

ranking without stronger carbon emphasis, indicating a complementary rather than substitutive role.

By contrast, *Cost* and *Availability* stabilise the ranking. Changes in their weights consistently reinforce the dominance of Recycled materials (A), reflecting their strong performance on both criteria and anchoring the ranking against environmental reweighting.

Finally, *Circularity* shows the lowest marginal impact among all criteria. While it contributes positively to the score of Recycled materials, its limited dispersion across alternatives results in low leverage over ranking outcomes. This suggests that circularity, as operationalised in the present model, functions primarily as a secondary reinforcing criterion rather than a decisive differentiator.

The tornado analysis confirms that the decision model exhibits a structured sensitivity hierarchy, with environmental and technical criteria acting as primary volatility drivers, and economic and logistical criteria acting as stabilising forces. This asymmetric sensitivity structure explains the observed robustness of Recycled materials (A) under most weight perturbations, while simultaneously highlighting the conditional dominance of Low-carbon virgin materials (C) under carbon-intensive policy regimes.

4.3 Discussion and Managerial Implications

The results underscore a trade-off that decision-makers in procurement and circularity must carefully manage. Recycled materials (A) demonstrate clear advantages in operational efficiency, supply-chain resilience, and circularity metrics, consistent with prior studies emphasizing the energy and material savings associated with secondary raw material loops [15,23]. These materials reduce dependence on primary extraction, lowering both environmental impact and exposure to raw-material price volatility.

Empirical evidence from industrial practice reinforces these findings. In the steel sector, Electric Arc Furnace (EAF) production based on scrap inputs has been shown to reduce energy consumption by approximately 60–75% and CO_2 emissions by 70–90% relative to blast furnace routes [26]. Similarly, in aluminium production (e.g., Hydro's recycling operations in Europe [18], secondary aluminium exhibits energy savings of up to 95% compared to primary smelting, significantly improving both cost efficiency. In the construction sector, recycled aggregates in road sub-bases have been documented in Dutch infrastructure projects to replace up to 30–50% of virgin aggregates without compromising structural performance [12] (Table 5. Strategic recommendations therefore depend on the organisation's primary objectives:

1. Choose Recycled (A) when supply-chain robustness and circular economy alignment represent strategic priorities. This is relevant in metals, packaging, and construction materials sectors, where industrial evidence shows cost reductions of 10–25% and volatility hedging benefits in input markets.
2. Choose Low-carbon virgin (C) when regulatory carbon-reduction targets are non-negotiable; in such cases, the combined weight of Carbon footprint and

Table 5. Synthesis of material classes with empirical industrial evidence and observed trade-offs across sectors.

Material Class	Industrial Evidence	Trade-offs
Recycled (A)	Steel [20]: 60–75% energy reduction and 70–90% CO_2 reduction vs. BF route; Aluminium recycling: up to 95% energy savings; Construction aggregates: 30–50% substitution in infrastructure projects [7,8,11,12].	Quality variability in feedstock; dependency on collection systems; limited suitability for high-spec aerospace-grade applications
Low-carbon virgin (C)	Hybrit steel: 90–95% CO_2 reduction [19]; CCS cement: 80–90% reduction potential [31]; Renewable-powered aluminium: ∼75% lower footprint vs. global average production [18].	High CAPEX and infrastructure dependence (hydrogen/renewables); limited scalability in short term; residual reliance on virgin extraction
Bio-based (B)	PLA bioplastics: limited composting infrastructure coverage (<30%) [8]; Bio-composites in automotive interiors: 10–15% weight reduction but hybrid reinforcement required [41]; packaging pilots in FMCG sector [12].	Mechanical performance constraints; higher unit cost and supply instability; end-of-life treatment limitations; need for hybridisation with synthetic materials

Technical performance should exceed approximately 60% of the total weighting to shift the ranking in C's favour. This reflects observed adoption patterns in steel and aerospace supply chains, where compliance requirements dominate procurement decisions.

3. Bio-based materials (B) should be considered only after development efforts have demonstrably improved their performance on cost and availability. Current evidence suggests their optimal use is limited to packaging and consumer goods unless supported by subsidies or technological breakthroughs in biorefining and composite engineering.

A novelty of the present work lies in the application of a ratio-based AHP structure to circular-economy procurement decisions. By constructing consistent pairwise comparison matrices directly from transformed benefit scores, the approach provides a fully quantifiable risk assessment for a multi-faceted sourcing choice. This is consistent with decision-support frameworks adopted in consulting practice [5,26], where multi-criteria scoring systems are increasingly used to map material substitution pathways under carbon and supply constraints.

5 Conclusions and Future Work

The AHP-based framework developed in this study offers a structured and replicate method for comparing heterogeneous sustainable material alternatives under environmental, technical, and economic objectives. Under balanced baseline weights, Recycled materials (A) provide the most attractive compromise.

However, when environmental performance, particularly greenhouse-gas reduction, is assigned substantially higher priority, Low-carbon virgin materials (C) emerge as the best choice.

Moreover, methodological limitations such as rank reversal in TOPSIS and subjectivity in weighting, ratio-based mechanisms for cross-material comparability hinder the development of robust, adaptive frameworks capable of supporting decision-making across diverse management and engineering applications [3,27]. By testing H1 with a stronger definition, H2 with a better mix of quantitative and qualitative methods, and H3 with improved comparison, the framework fills gaps and supports more reliable MCDM tools for circular economy goals.

Several directions for future refinement are proposed. These include implementing dynamic weighting mechanisms to better reflect evolving regulatory pressures and technology maturity curves; integrating full Life Cycle Costing into the cost criterion to account for end-of-life management expenses from secondary material recovery; extending the model to handle uncertainty using fuzzy AHP or Monte Carlo simulation of weights; and conducting validation through procurement case studies, thereby strengthening confidence in the framework's practical utility.

Acknowledgements. This work is supported by NOVA LINCS (UID/04516/2025) with the financial support of FCT, I.P. (DOI: https://doi.org/10.54499/UID/04516/2025).

References

1. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: International Symposium: New Metropolitan Perspectives, pp. 690–701. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65
2. Ashby, M.F.: Materials Selection in Mechanical Design, 4th edn. Butterworth-Heinemann, Oxford, UK (2011). ISBN: 978-1-85617-663-7
3. Bajwa, A.U.R., Siriwardana, C., Shahzad, W.M., Naeem, M.A.: Material selection in the construction industry: a systematic literature review on multi-criteria decision making. Environ. Syst. Decis. **45**(1), 8 (2025). https://doi.org/10.1007/s10669-025-10001-w
4. Balali, A., Hakimelahi, A., Jahangiri, M.H.: Multi-criteria ranking of green materials according to the goals of sustainable development. Sustainability **12**(22), 948 (2020). https://doi.org/10.3390/su12229482
5. Feth, M., Healy, G., Polunin, K., von Szczepanski, K., Van Der Weck, M.: A Faster Path to Sustainability in the Materials and Process Industries. Boston Consulting Group (BCG) (2023). https://www.bcg.com/publications/2023/path-to-sustainability-in-materials-process-industries
6. Bhaskar, A.S., Khan, M.A.: Comparative analysis of hybrid MCDM methods in material selection for dental applications. Expert Syst. Appl. **209**, 11826 (2022). https://doi.org/10.1016/j.eswa.2022.118268

7. Høibye, L., Sand, H.: Circular Economy in the Nordic Construction Sector: Identification and Assessment of Potential Policy Instruments. Nordic Council of Ministers, TemaNord 2018:517 (2018). https://norden.diva-portal.org/smash/get/diva2:1188884/FULLTEXT01.pdf
8. European Commission. A European Strategy for Plastics in a Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2018) 28 final, Brussels, 16 January 2018 (2018). https://www.europarl.europa.eu/RegData/docs_autres_institutions/commission_europeenne/com/2018/0028/COM_COM(2018)0028_EN.pdf
9. Ecoinvent Association. Ecoinvent Database, version 3.x. Zürich, Switzerland (2025). https://ecoinvent.org/
10. European Environment Agency (EEA). Resource Efficiency and the Circular Economy in Europe 2019 – Even More from Less. EEA Report No 26/2019. Publications Office of the European Union, Luxembourg (2020). https://circulareconomy.europa.eu/platform/sites/default/files/26_2019_resource_efficiency_2019_th-al-20-007-en-n.pdf
11. European Environment Agency. Construction and demolition waste: Challenges and opportunities in a circular economy. EEA (2020). https://www.eea.europa.eu/publications/construction-and-demolition-waste-challenges
12. Ellen MacArthur Foundation. Completing the picture: How the circular economy tackles climate change. Ellen MacArthur Foundation (2019). https://www.ellenmacarthurfoundation.org/completing-the-picture
13. Emovon, I., Oghenenyerovwho, O.S.: Application of MCDM method in material selection for optimal design: a review. Results Mater. **7**, 10011 (2020). https://doi.org/10.1016/j.rinma.2020.100115
14. Sphera Solutions. GaBi Database. Leinfelden-Echterdingen, Germany (2025). https://sphera.com/
15. Geyer, R., Jambeck, J.R., Law, K.L.: Production, use, and fate of all plastics ever made. Sci. Adv. **3**(7), e170078 (2017). https://doi.org/10.1126/sciadv.1700782
16. Hafner, A., Ott, S., Winter, S.: Recycling and end-of-life scenarios for timber structures. In: Materials and Joints in Timber Structures: Recent Developments of Technology, pp. 89–98. Springer (2014). https://doi.org/10.1007/978-94-007-7810-8
17. Hosseinijou, S.A., Mansour, S., Shirazi, M.A.: Social life cycle assessment for material selection: a case study of building materials. Int. J. Life Cycle Assess. **19**(3), 620–64 (2014). https://doi.org/10.1007/s11367-013-0658-1
18. Norsk Hydro. Environmental product declaration: Hydro REDUXA 4.0 aluminium extrusion ingot (NEPD-1840-768-EN). Norsk Hydro ASA (2020). https://www.hydro.com/globalassets/download-center/certificates/nepd-1840-768-hydro-4.0-aluminium-extrusion-ingot.pdf
19. Hybrit Development AB. HYBRIT: Fossil-free steel initiative. SSAB, LKAB, & Vattenfall (2021). https://www.hybritdevelopment.se/en/
20. International Energy Agency. Aluminium. IEA (2022). https://www.iea.org/energy-system/industry/aluminium
21. International Organization for Standardization. ISO 59020:2024: Circular economy — Measuring and assessing circularity performance, 1st edn. ISO (2024). https://www.iso.org/standard/80650.html
22. Jha, S., Akula, B., Enyioma, H., Novak, M., Amin, V., Liang, H.: Biodegradable biobased polymers: a review of the state of the art, challenges, and future directions. Polymers **16**(16), 226 (2024). https://doi.org/10.3390/polym16162262

23. Kirchherr, J., Reike, D., Hekkert, M.: Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour. Conserv. Recycl. **194**, 10700 (2023). https://doi.org/10.1016/j.resconrec.2023.107001
24. Mardina, Z., et al.: CM3D: a circular materials multi-criteria decision-making tool for medical devices. Mater. Des. **254**, 11401 (2025). https://doi.org/10.1016/j.matdes.2025.114015
25. Mardina, Z., Turnbull, R.P., Rahimifard, S., Bibb, R., Culmer, P.: CM3D: a circular materials multi-criteria decision-making tool for medical devices. Mater. Des. **254**, 11401 (2025). https://doi.org/10.1016/j.matdes.2025.114015
26. McKinsey & Company. Decarbonizing the world's industries: A net-zero guide for nine key sectors. McKinsey & Company (2023). https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonizing-the-world-industries-a-net-zero-guide-for-nine-key-sectors
27. Meng, L., Osmani, M., Glass, J.: A probabilistic multi-criteria framework for assessing circularity and sustainability in modern methods of construction. Smart Sustain. Built Environ. (2025). https://doi.org/10.1108/SASBE-04-2025-0185
28. Mlybari, E.A.: Smart sustainability in construction: an integrated LCA-MCDM framework. Sustainability **17**(21), 965 (2025). https://doi.org/10.3390/su17219650
29. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021)
30. Mussatto, A., Bradley, D., Toso, G., Bártolo, P.J., O'Halloran, S.: Advanced production routes for metal matrix composites. Eng. Rep. **3**(5), e1233 (2021). https://doi.org/10.1002/eng2.12330
31. Norcem. Brevik CCS Project: Carbon Capture and Storage in Cement Production. Brevik, Norway (2020). https://www.norcem.no/en/brevikccs/
32. Pagell, M., Wu, Z.: Building a more complete theory of sustainable supply chain management using case studies of 10 exemplars. J. Supply Chain Manag. **45**(2), 37–5 (2009). https://doi.org/10.1111/j.1745-493X.2009.03162.x
33. Pei, M., Petäjäniemi, M., Regnell, A., Wijk, O.: Toward a fossil free future with HYBRIT: development of iron and steelmaking technology in Sweden and Finland. Metals **10**(7), 97 (2020). https://doi.org/10.3390/met10070972
34. Poulikidou, S., et al.: Material selection for minimizing life cycle environmental impact of vehicles. Mater. Des. **83**, 704–71 (2015). https://doi.org/10.1016/j.matdes.2015.06.079
35. Shelly, D., et al.: Mechanical performance of bio-based fiber reinforced polymer composites: a review. Polym. Compos. (2025). https://doi.org/10.1002/pc.30000
36. Soliman, M.H., Mohammed, A.B., Zaki, A.A.: Sustainable building materials: a critical literature review. Discov. Mater. **6**(1), 3 (2026). https://doi.org/10.1007/s43939-025-00485-3
37. Tighnavard Balasbaneh, A., Aldrovandi, S., Sher, W.: MCDM approaches for circular economy and cost assessment. Sustainability **17**(11), 500 (2025). https://doi.org/10.3390/su17115007
38. World Business Council for Sustainable Development & One Planet Network. Global Circularity Protocol for Business (Version 1.0). WBCSD & UNEP (2025). https://www.wbcsd.org/resources/a-global-framework-to-measure-manage-and-communicate-business-circularity/
39. World Economic Forum. The Net-Zero Industry Tracker. Geneva, Switzerland (2022). https://www.weforum.org/reports/the-net-zero-industry-tracker

40. World Steel Association. Sustainability Indicators 2023. Brussels, Belgium: World Steel Association (2023). https://worldsteel.org/wp-content/uploads/Sustainability-indicators-report-2023.pdf
41. Yan, L., Xu, H.: Lightweight composite materials in automotive engineering: state-of-the-art and future trends. Alex. Eng. J. **118**, 1 (2025). https://doi.org/10.1016/j.aej.2024.12.002
42. Zakeri, S., et al.: A decision analysis model for material selection. J. Eng. Appl. Sci. **70**(1), 5 (2023). https://doi.org/10.1038/s41598-023-35405-z
43. Zambujal-Oliveira, J., Fernandes, C.: Sustainable packaging in circular food supply chains. Packag. Technol. Sci. **37**(6), 443–45 (2024). https://doi.org/10.1002/pts.2802
44. Zambujal-Oliveira, J., Duque, J.: Stochastic carbon taxes and capital turnover. Results Eng. (2026). https://doi.org/10.1016/j.rineng.2026.109902
45. Zou, R.X., Mayfield, E.N.: Lifecycle greenhouse gas emissions of raw steel production plants in the US. Environ. Sci. Technol. (2026). https://doi.org/10.1021/acs.est.5c01504