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Embodied carbon meets payback: Stakeholder-driven MCDM for selecting renovation scenarios

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Abstract

Ambitious European building sector's decarbonization goals require significant increase in renovation rates, yet the success of these initiatives relies on aligning technical goals with stakeholder priorities. This study offers a novel perspective by quantitatively comparing how building owners and experts prioritize renovation outcomes using multi-criteria decision-making (MCDM) to shed a light on the potential disagreements and barriers in renovation processes. The work carried out includes an assessment of building owners and experts' perception using pairwise comparisons through the Analytical Hierarchy Process (AHP) to determine the relative significance of each criterion to evaluate renovation scenarios via Simple Additive Weighting (SAW) and Multiplicative Exponential Weighting (MEW) methods. Five key criteria (i) improvement lifespan, (ii) payback period, (iii) operational energy demand, (iv) energy saved, and (v) global warming potential (embodied carbon), were defined to capture a holistic performance of renovation alternatives. To demonstrate the practical applicability of the approach, the stakeholder-derived weights were also applied to a real single-family building case-study, where four renovation scenarios were evaluated using the same MCDM framework. The results showed a strong disagreement between building owners and experts in prioritising renovation criteria. However, application of MCDM methods allowed to assess and select alternative which provides a matching point for stakeholders. These findings contribute to the field of sustainable architecture and civil engineering by highlighting the importance of stakeholder-inclusive MCDM approaches, thereby enhancing the adoption of deep energy retrofits in line with European Green Deal targets.

Keywords: building renovation, multi-criteria decision-making, experts, building owners, decarbonization.

1. Introduction

The building sector accounts for a significant share of global energy consumption and greenhouse gas (GHG) emissions, in 2023 building sector accounted for 32% of the EU's energy use and 34% of energy-related GHG emissions (United Nations Environment Programme, 2025). The numbers account for operational emissions as well as the embodied carbon in building materials. However, currently only about 1%

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of EU buildings undergo energy-efficient renovation annually, even though 85% were built before 2000 and many perform poorly in terms of energy performance (European Commission, 2025). To tackle this issue, the European Green Deal established ambitious targets, including a 55% emissions reduction by 2030 and achieving climate neutrality by 2050 (European Commission, 2024). As a part of this vision, Renovation Wave Strategy (European Commission, 2024) aims to renovate 35 million buildings by 2030. To support the efforts, the revised Energy Performance of Buildings Directive (EPBD) (European Commission, 2025) mandates national strategies, including minimum energy performance standards for the worst-performing buildings and primary energy reduction targets applicable to both residential and non-residential sectors**.** Even though continuous efforts to improve the efficiency of new constructions and existing buildings have resulted in a 34% reduction in GHG emissions in the EU, further progress will require accelerated renovation efforts.

Multi-Criteria Decision-Making (MCDM) methods are becoming increasingly important for supporting the evaluation of renovation scenarios by enabling structured analysis across multiple criteria (Pinzon Amorocho & Hartmann, 2022). Recent study confirms this growing trend in building renovation and material selection contexts (Villalba et al., 2024). For instance, Analytical Hierarchy Process (AHP) has been applied across energy-sustainable renovation projects, including façade upgrade decisions in residential building envelopes in the EU (Golić et al., 2023; Theilig et al., 2025). Reviews of MCDM applications further indicate that AHP is most often used for criteria weighting (Bajwa et al., 2025), while the Simple Additive Weighting (SAW) method is frequently applied in constructing vulnerability indices (Villalba et al., 2024). This method was summarized by MacCrimmon (MacCrimoon, 1968), and the main principles are presented in the works of other authors (Churchman & Ackoff, 1954; Klee, 1971; Zanakis et. al., 1998) Among other MCDM methods, the MEW (Multiplicative Exponential Weighting) method is a multi-criteria decision-making approach that is more sensitive to poor performance in any single criterion (Medineckiene & Björk, 2011). This characteristic is particularly valuable in sustainability assessment, where trade-offs between economic, energy, and environmental factors must be carefully balanced.

However, despite that EU strategies such as the European Green Deal and Renovation Wave emphasize accelerating energy efficiency improvements, an important dimension often remains overlooked: the perspectives of building owners. Owners of single-family houses in particular tend to rely heavily on the professional advice (European Environment Agency, 2023) however, their priorities may differ. Although there is growing use of MCDM tools in renovation decision-making, existing research rarely examines how building owners' priorities differ from those of experts, leaving owners' perspectives underrepresented in evaluations that increasingly shape EU renovation and decarbonisation policies. This study directly compares owners' and experts' weighting of identical criteria and demonstrates how these differences influence the ranking of actual renovation scenarios.

Therefore, the aim of this study is to analyze how building owners evaluate and prioritize renovation criteria and compare their views with experts' opinion. By applying the same MCDM framework to both groups, the study identifies areas where owners' and experts' evaluations agree or differ, offering insights into how decision-support tools can better incorporate stakeholder diversity. The findings of this study help bridging the gap in understanding between expert-driven assessments and building owners' perspectives, clarifying different priorities that might influence renovation decision-making.

2. Methodology

This study utilized MCDM methods to evaluate renovation scenarios priorities from the perspective of both experts and building owners. The study consisted of three main stages: (i) definition of evaluation criteria, (ii) collection of stakeholder assessments, and (iii) application of MCDM methods to compare the results of prioritisation.

2.1. Defining the criteria

The criteria selected in this study are widely discussed and adopted in renovation and sustainability research area. Improvement of lifespan reflects the durability of retrofit measures, an aspect emphasized in life-cycle–oriented studies that highlight how extending component or building service life reduces environmental impacts and increases long-term renovation value (Marsh, 2016). The payback period remains one of the most influential factors for building owners, who often prioritise short-term financial feasibility. Medineckiene and Björk (2011) demonstrated that homeowners consistently rate payback and investment cost as central criteria when considering energy improvements. However, as payback time alone tends to favor less expensive measures (Malmgren & Mjörnell, 2015), it should be supported by life-cycle financial indicators to ensure balanced decision-making. Both energy demand and energy savings are core operational performance metrics in renovation assessments. They are widely used to evaluate the effectiveness of insulation, window replacement, and HVAC upgrades, with numerous MCDM applications relying on these indicators to rank retrofit scenarios (Golić et al., 2023; Kamari et al., 2018). Energy savings also align with EU policies targeting reductions in operational energy use, making them a central measure of renovation success. Finally, GWP captures the climate impact of renovation measures and is increasingly recognised as essential due to the growing share of embodied emissions in energy-efficient buildings. Recent studies integrate embodied and operational GWP into decision frameworks, demonstrating that solutions with high energy savings may still perform poorly environmentally if material-related emissions are high (Seddiki & Bennadji, 2025). Additionally, complementary indicators are used in literature and include life-cycle cost (LCC), embodied energy, CO_2 emissions reduction, indoor environmental comfort, disruption level, while each providing additional dimensions important for holistic renovation assessment (Malmgren & Mjörnell, 2015; Kamari et al., 2018). However, within the aim of this work, five criteria were selected and defined that reflects the procedures commonly utilized in renovation processes – energy audit, operational performance assessment and life cycle assessment. In addition, these criteria aimed to cover a more comprehensive approach, taking into account not only economic aspect but also energy efficiency and environmental impact.

(K1) Improvement lifespan (years) – the expected service life of implemented energy-efficiency measures - the period during which they remain functional and effective without major maintenance, repair, or replacement. Lifespan can be referred from standards (e.g., EN 15459-1:2017) or product technical documentation.

(K2) Payback period (years) – a criterion that reflects financial viability - the time it will take for the investment to recover its initial cost through savings achieved by implemented energy efficiency improvement measures.

(K3) Energy demand (kWh) – reflects the total energy required for building operation and can be categorized by type (e.g., thermal, electrical). It can be calculated and/or measured before and after implementing energy efficiency improvement measures.

(K4) Energy saved (kWh) – a direct outcome of the planned or implemented energy efficiency improvement measures. Similarly, as for energy demand, it can be calculated and/or measured. It can also be categorized by the type of energy. This criterion is generally assessed in order to quantify the effectiveness of the modernisation measures under consideration.

(K5) Global warming potential (kg CO_2 eq.) – expresses the environmental impact of the measures in terms of greenhouse-gas emissions. In LCA it is a major criterion for alternatives comparison. Within the renovation scope, it reflects the differences in carbon dioxide emissions of different building improvement scenarios.

In this study, all the criteria were expressed in absolute terms (e.g., total energy saved, total GWP, total operational demand). While this is a common approach in MCDM applications, it naturally tends to prioritise larger renovation measures, which tend to deliver higher absolute savings and impacts. However, this is not the only possible way to evaluate renovation alternatives. Other studies normalize performance indicators using relative or intensity-based metrics, such as energy per m^2, energy per occupant, GWP per m^2, cost per kWh saved, etc. (Šikšnelytė-Butkienė et. al., 2021; Spudys et. al., 2023). Such approaches would allow comparison of projects of different scales on a comparable basis.

2.2. Data collection

To gather data for the comparative assessment of building owners' and experts' perception of renovation outcomes priorities, a survey was conducted. The research sample consisted of 11 participants per group, which is considered sufficient for deriving meaningful qualitative insights.

- The expert group included scientists, technical supervisors, and other specialists all of whom combined academic qualifications with practical professional experience. The experts' focus is geographically limited to Europe, and their opinions were gathered using questionnaires. Selected professionals met the following requirements:

  - At least 5 years of experience in applying BIM methodology in the civil engineering field;
  - Holding at least master's degree in civil engineering;
  - Certified as a civil engineer (e.g., technical supervisor, project manager, BIM coordinator, designer, or similar) or researcher in civil engineering;
  - Knowledge and application of local and European level construction technical and legal documents.
- The group of building owners was selected to ensure diversity in terms of age, gender, and building type, capturing a broader range of perspectives and decision-making preferences. Consistent with the criteria applied in selecting experts, the geographical representation was focused to Europe.

Respondents were asked to evaluate the relative importance of each criterion using a structured questionnaire based on the AHP. Using AHP, respondents compared indicators in pairs, evaluating their relative importance using the fundamental scale (Saaty, 1977), which ranges from 1 (equal importance) to 9 (one criterion is incomparably more important than another), with intermediate values. The procedure was explained in detail before starting a survey to ensure quality of responses.

The survey collected information from building owners and experts, including basic contextual data, as well as a completed prioritization table reflecting their evaluation of renovation criteria. Since the study involved stakeholders' participation, even if the collection of their perspectives does not require sensitive personal data, the authors ensure that the process and collected information were handled in accordance with the highest ethical standards.

2.3. MCDM application

After completion of the survey for both target groups, the next step was to determine the significance of the five defined criteria. The collected pairwise comparison matrices were processed to derive the relative weights of each criterion. Consistency of responses was checked by calculating the Consistency Index (CI) and Consistency Ratio (CR), where $CR \leq 0.10$ was considered acceptable. All matrices satisfied this threshold. Group consensus was measured using Kendall's W coefficient, which indicated moderate-to-strong agreement (W values in the range 0.4–0.6, $p < 0.05$) (Kendall, 1970). As responses consistency was confirmed, the individual weights provided by each group of respondents were combined to obtain the final significance coefficients (q_j) for the five criteria. This aggregation was performed by calculating the average of the normalized weights in each group, following established AHP procedures (Kendall, 1970). The resulting q_j values represent the relative importance of each criterion, reflecting the overall view of experts and building owners, while also taking into account individual variations in priorities.

Criteria were normalized to ensure comparability for benefit-type criteria (Improvement lifespan, Energy saved), normalization used (MacCrimoon, 1968):

$$\bar{x}_{\mathrm{ij}} = \frac{x_{\mathrm{ij}}}{x_{\mathrm{i}}^{\max}} \quad (1)$$

and for cost-type criteria (Payback period, Energy demand, GWP) (MacCrimoon, 1968),

$$\bar{x}_{\mathrm{ij}} = \frac{x_{i}^{\min}}{x_{\mathrm{ij}}}. \quad (2)$$

This ensured that higher values always indicated more desirable outcomes.

Two MCDM methods were then applied (MacCrimoon, 1968):

- Simple Additive Weighting (SAW):

$$S_{\mathrm{i}} = \sum_{j=1}^{n} \bar{x}_{\mathrm{ij}} \cdot q_{\mathrm{j}} , \quad (3)$$

a compensatory method where strong results can offset weak ones .

- Multiplicative Exponential Weighting (MEW) (Zanakis et. al., 1998):

$$L_{\mathrm{i}} = \prod_{j=1}^{n} \left(\bar{x}_{\mathrm{ij}} \right)^{q_{\mathrm{j}}} , \quad (4)$$

a non-compensatory method that penalises poor performance in any criterion. This makes MEW particularly relevant in sustainability assessments where a single weak point (e.g., very high GWP) undermines overall performance.

To establish a benchmark for normalizing criteria across renovation scenarios, optimal values were applied. For benefit-type criteria (e.g., improvement lifespan, payback period, energy saved), the optimal value corresponds to the maximum observed performance, while for environmental criteria (e.g., energy demand, GWP) it corresponds to the minimum observed performance. Expressing each scenario's performance relative to these optimal values ensures comparability across criteria with different units and scales, enabling their integration into the MCDM analysis. Further on these values were utilised as input data for the MCDM analysis of the renovation scenarios for the case study building.

In addition, a preliminary sensitivity analysis was performed by perturbing the criteria weights by ±15 % to evaluate ranking stability. Results confirmed that the relative positions of the top alternatives (Scenarios 3 and 4) remained unchanged, indicating robustness of the findings.

To build on previous research on enhanced building improvement sustainability assessment, the authors employ a case study with corresponding results (Table 1) from a comprehensive analysis of a residential single-family building renovation scenarios with the same defined criteria (Spudys et al., 2025). The table provided includes the 'Optimal value' row that indicates the best observed performance for each criterion, while the 'min/max' row specifies the preferred direction of evaluation.

Table 1
Renovation scenarios of case study building

Scenario	Improvement Lifespan, year	Payback Period, year	Energy Demand, kWh	Energy Saved, kWh	GWP, kg CO_2 eq.
Scenario 1. Additional 50 mm thermal insulation of external walls	100	104.32	8018.41	297.3	66600.00
Scenario 2. Additional 50 mm thermal insulation of external walls and windows/doors replacement	100	121.31	7917.53	398.18	69600.00
Scenario 3. Additional 150 mm thermal insulation of roof structure	60	29.13	7800.81	514.9	67100.00
Scenario 4. Additional 150 mm thermal insulation of roof structure and windows/doors replacement	60	42.2	7494.32	821.39	70000.00
Optimal value	100	29.13	7494.32	821.39	66600.00
min/max	max	min	min	max	min

Source: designed by the authors.

3. Results and discussion

The weighting results obtained from the pairwise comparison reveal clear differences between building owners' and experts' priorities in their evaluation of renovation criteria importance. Table 2 presents the relative significance (q_j) and ranking of each criterion for both groups, alongside a comparative interpretation. The findings highlight areas of agreement, such as the importance of energy savings, as well as notable contradictions. In particular, different priorities can be observed regarding payback period and environmental impact of energy efficiency improvement measures implemented (GWP). Additionally, Fig. 1 visually depicts different perspectives of renovation stakeholders described in Table 2.

Tables 3 and 4 present the evaluation of four renovation scenarios based on the five defined criteria using weights (qj) derived from both groups' perception. It consists of normalized performance values of each scenario for each respective criterion – 1 indicates that the scenario achieved the optimal performance. Furthermore, the higher the value, the better result of performance, while values closer to 0 means a weaker performance result compared to the benchmark. Column "MEW Value" presents the results of MEW – a non-compensatory method that penalizes poor performance in any single criterion. While "SAW Value" presents the results of SAW – a compensatory method where high performance in one criterion can offset weaker performance in another. Respectively, for each method resulting ranks of the scenario are provided.

Table 2
Comparison of the significance of criteria for two groups of respondents

Criterion	Owners (qj, Rank)	Experts (qj, Rank)	Comparison
Improvement Lifespan	0.249; Rank 3	0.109; Rank 3	Both groups place moderate importance on building improvement lifespan. Building owners value long improvement lifespan more than twice as much as experts, which reflect their concern about the durability and usability of renovation measures. Experts clearly consider it significantly less important than GWP and energy saved.
Payback Period	0.282; Rank 1	0.071; Rank 4	Major difference, as owners tend to prioritize short-term financial feasibility, while experts assign relatively little importance to payback period. This reflects the important difference of the renovation stakeholders' priorities.
Energy Demand	0.178; Rank 4	0.030; Rank 5	Both groups rank energy demand as relatively negligible, but owners concern it more than experts. This suggests that owners associate high energy demand with higher long-term operational costs.
Energy Saved	0.256; Rank 2	0.336; Rank 2	Strong alignment: both groups rank energy savings as highly important. Owners prioritize this criterion due to expectations to reducing energy costs, whereas experts emphasize its contribution to energy efficiency and broader sustainability objectives. Therefore, it can be considered as a bridge between economic aspects and environmental priorities.
GWP	0.035; Rank 5	0.454; Rank 1	Highest contradiction. Owners assign minimal importance to GWP, whereas experts see it as the single most important criterion. This highlights the significant gap between individual financial motivations and expert-driven environmental policy goals.

Source: designed by the authors.

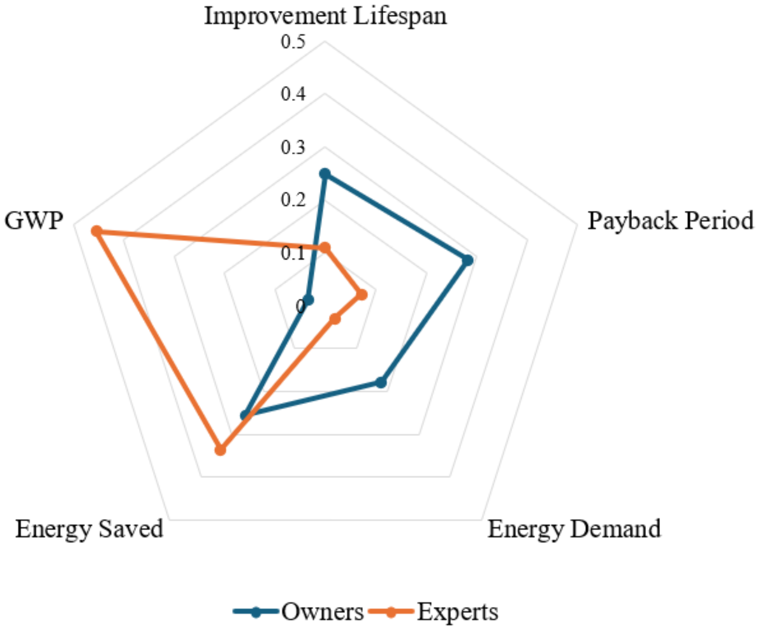

Fig. 1. Comparison of significance coefficients (q_j) based on owners' and experts' perspectives.
Source: designed by the authors.

Table 3
Decision matrix representing the values of the scenario's criteria and their significance, SAW and MEW values and Ranks (Experts' perception)

Scenario	Improvement Lifespan	Payback Period	Energy Demand	Energy Saved	GWP	MEW Value	MEW Rank	SAW Value	SAW Rank
q_j	0.109	0.071	0.03	0.336	0.454				
Scenario 1, Additional 50 mm thermal insulation of external walls	1	0.2792	0.9346	0.3619	1	0.2941	4	0.7325	4
Scenario 2, Additional 50 mm thermal insulation of external walls and windows/doors replacement	1	0.2401	0.9465	0.4848	0.9569	0.3073	3	0.7518	3
Scenario 3, Additional 150 mm thermal insulation of roof structure	0.6	1	0.9607	0.6269	0.9925	0.3639	2	0.8265	2
Scenario 4, Additional 150 mm thermal insulation of roof structure and windows/doors replacement	0.6	0.6903	1	1	0.9514	0.3979	1	0.9124	1

Source: designed by the authors.

Table 4
Decision matrix representing the values of the scenario's criteria and their significance, SAW and MEW values and Ranks (Owners' perception)

Scenario	Improve-ment Lifespan	Payback Period	Energy Demand	Energy Saved	GWP	MEW Value	MEW Rank	SAW Value	SAW Rank
q_j	0.249	0.282	0.178	0.256	0.035				
Scenario 1, Additional 50 mm thermal insulation of external walls	1	0.2792	0.9346	0.3619	1	0.0186	3	0.6218	4
Scenario 2, Additional 50 mm thermal insulation of external walls and windows/doors replacement	1	0.2401	0.9465	0.4848	0.9569	0.0184	4	0.6428	3
Scenario 3, Additional 150 mm thermal insulation of roof structure	0.6	1	0.9607	0.6269	0.9925	0.0269	1	0.7976	2
Scenario 4, Additional 150 mm thermal insulation of roof structure and windows/doors replacement	0.6	0.6903	1	1	0.9514	0.0264	2	0.8114	1

Source: designed by the authors.

Consistent and strong experts' agreement on importance of GWP and energy savings when considering renovation alternatives results in stable scenario rankings across different MCDM methods. Both methods confirm that Scenario 4 is the most favourable option, reflecting its balanced performance across the dominant environmental criteria. In contrast, owners' results vary depending on the method applied. This variability arises because building owners prioritise economic and energy-related criteria more evenly, making the rankings sensitive to whether trade-offs are allowed (SAW) or weaknesses are penalized (MEW). This results that Scenario 4 can be considered as the most favourable using SAW method, while Scenario 3 is preferred under MEW method. However, in both methods the difference between the highest-ranked and the second alternatives is relatively small, indicating close competition among the top-performing scenarios. It is also worth mentioning that even experts strongly prioritised GWP criterion, the scenario with the lowest GWP (Scenario 1) was ranked lowest overall. This reflects the fact that strong performance in one criterion cannot compensate for significantly weak performance in other highly weighted criteria, such as energy saved.

These findings highlight the value of applying MCDM in renovation assessment, as it allows integration of differing stakeholder priorities and reveals trade-offs that would be overlooked in a single-criterion approach. Even owners and experts typically strongly disagree on the relative importance of criteria for most of them – with owners driven mainly by economic considerations and experts by sustainability – both groups generally could agree on the same renovation alternative. This alignment highlights the importance of identifying renovation alternatives that can address both stakeholders' needs, ensuring that measures are attractive to owners for their economic benefits while also meeting experts' environmental priorities.

Furthermore, as GWP in this study reflects the embodied carbon of the energy efficiency improvement measures, results highlight the gap that building owners are not sufficiently informed that sustainability performance and successful renovation depends not only on the reduction of energy consumption, but also on embodied carbon in materials and products that are utilized for building renovation, which seems to be evident to experts. This undervaluation by owners may arise as embodied emissions are not visible in everyday building use, unlike energy bills or comfort levels that provide immediate feedback. Renovation benefits are usually understood through lower costs or better usability, making long-term embodied impacts difficult for owners to perceive. As a result, clearer communication tools and policy measures are needed to help homeowners understand how material choices influence a building's lifetime emissions.

4. Conclusions

This study examined how building owners and experts prioritise renovation criteria and how these priorities impact the ranking of renovation alternatives when evaluated with MCDM methods. By conducting experts and building owners surveys and using pairwise comparison, the results showed a clear difference in criterion prioritisation: owners almost equally emphasized short term economic feasibility and quality of renovation measures implemented (energy saved, payback period and improvement lifespan), while experts significantly prioritised environmental performance and efficiency (GWP, and energy saved). This situation highlights the importance of considering energy efficiency improvement measures assessment holistically, rather than based on individual indicator or target criteria. Despite these contrasts, both groups strongly agreed on the high importance of energy savings, indicating a common path for building renovations.

Owners' rankings were more method-sensitive – SAW favoured the alternative with the strongest energy savings (Scenario 4), whereas MEW preferred the more balanced alternative (Scenario 3). Notably, the difference between the top two scenarios was small in both methods, indicating a close competition and showing that results are sensitive to the choice of method.

Despite this disagreement on criteria importance, MCDM methods allowed finding a matching point between the perspectives of building owners and experts in the field. In particular, scenario's 4 significant energy savings and reduced energy demand, combined with an average payback period and acceptable carbon dioxide emissions made it a credible alternative. Even in cases where owners and experts disagreed on individual criteria, the assessment of multiple criteria indicated that this scenario performs the best overall. The fact that Scenario 1, despite achieving the lowest embodied carbon (GWP), was consistently ranked lowest overall demonstrates that strong performance in a single indicator cannot offset weak results in other highly weighted criteria such as energy savings.

These findings also have implications for both policy and practice. Evident misalignment between owners' and experts' priorities suggests that renovation policies and advisory services should place greater emphasis on communicating embodied carbon and long-term environmental impacts in a more accessible and understandable way. Practical information tools, incentives, or minimum-information requirements could help align homeowners' priorities with broader decarbonisation goals and support more balanced renovation choices in practice.

At the policy level, integrating embodied carbon into renovation standards, certification schemes, and national EPBD implementation plans would help to ensure that sustainability criteria are considered alongside cost and energy performance. Strengthening regulatory visibility of material-related emissions could bridge the gap between homeowners' renovation priorities and EU-level decarbonisation goals.

Considering limitations and future work of this study, current limitation is the modest sample size, yet sufficient for comparative assessment but not for population-level research. Future research could expand stakeholder diversity beyond owners and experts to include financial institutions, contractors, and policymakers, and apply sensitivity analysis (e.g., weight perturbation tests) to check ranking robustness. Another limitation of the study is that the application of the stakeholder-derived weights was demonstrated on a single-building case study, which may limit the generalisation of the scenario-ranking results to other building types or contexts. This would strengthen the applicability of stakeholder-driven MCDM frameworks in guiding renovation strategies towards EU decarbonisation goals.

References

Bajwa, A. U. R., Siriwardana, C., Shahzad, W. & Naeem, M. A. (2025). Material selection in the construction industry: a systematic literature review on multi-criteria decision making. *Environment Systems and Decisions, 45*(1), 8.

Churchman, C. W. and Ackoff, R. L. (1954). An approximate Measure of Value. *Journal of the Operations Research. Informs, 2*(2), 172-187.

European Commission (2025). Energy Performance of Buildings Directive. Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/energy-performance-buildings-directive_en [Accessed 15-Aug-2025].

European Commission (2024). Renovation Wave. Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/renovation-wave_en [Accessed 10-Aug-2025].

European Commission (2024). The European Green Deal - European Commission. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en [Accessed 11-Aug-2025].

European Environment Agency (2023) Accelerating the energy efficiency renovation of residential buildings - a behavioural approach. Available at: https://www.eea.europa.eu/en/analysis/publications/accelerating-the-energy-efficiency [Accessed 10-Aug-2025].

Golić, K., Kosić, T. & Kosorić, V. (2023). AHP-Based Model for Energy-Sustainable Renovation of Building Envelopes: A Case Study. *Sustainability, 15*(10), 8384.

Kamari, A., Jensen, S. R., & Corrao, R. (2018). A hybrid decision support system for generation of holistic renovation scenarios: Cases of energy, cost, and comfort. *Sustainability, 10*(4), 1255.

Kendall, M. G. (1970). *Rank correlation methods*. London, Griffin.

Klee, J. A. (1971). The role of decision models in the evaluation of competing environmental health alternatives. *Management Science, 18*(2), 52-67

Maccrimon, K. R. (1968). Descriptive and normative implications of the decision – theory postulates. In: Borch K., Mossin J. (eds) Risk and Uncertainty. International Economic Association Conference. London: Palgrave Macmillan.

Malmgren, L., & Mjörnell, K. (2015). Application of a decision support tool in three renovation projects. *Sustainability, 7*(9), 12521–12538.

Marsh, R. (2016). Building lifespan: effect on the environmental impact of building components in a Danish perspective. *Architectural Engineering and Design Management, 13*(2), 80–100.

Medineckiene, M. & Björk, F. (2011). Owner preferences regarding renovation measures - The demonstration of using multi-criteria decision making. *Journal of Civil Engineering and Management, 17*(2), 284–295.

Pinzon Amorocho, J. A. & Hartmann, T. (2022). A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods. *Journal of Building Engineering, 53*, 104596.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15*(3), 234–281.

Seddiki, M., & Bennadji, A. (2025). A Life Cycle Carbon Assessment and Multi-Criteria Decision-Making Framework for Building Renovation Within the Circular Economy Context: A Case Study. *Buildings, 15*(11), 1894.

Spudys, P., Jurelionis, A. & Fokaides, P. (2025). Digitizing buildings sustainability assessment: Integrating energy audits, operational energy assessments, and life cycle assessments for enhanced building assessment. *Energy, 316,* 134429.

Spudys, P., Afxentiou, N., Georgali, P.-Z., Klumbyte, E., Jurelionis, A., & Fokaides, P. (2023). Classifying the operational energy performance of buildings with the use of digital twins. *Energy and Buildings, 290*, 113106.

Šikšnelytė-Butkienė, I., Streimikienė, D., Baležentis, T., & Skulskis, V. (2021). A Systematic Literature Review of Multi-Criteria Decision-Making Methods for Sustainable Selection of Insulation Materials in Buildings. *Sustainability, 13*(2), 737.

Theilig, K., Vollmer, M., Lang, W. & Albus, J. (2025). Multi-criteria decision-making for energy building renovation: Comparing exterior wall structures with the AHP, ANP, utility analysis, and TOPSIS. *Building and Environment, 280*, 113075.

Villalba, P., Sánchez-Garrido, A. J. & Yepes, V. (2024). A review of multi-criteria decision-making methods for building assessment, selection, and retrofit. *Journal of Civil Engineering and Management, 30*(5), 465–480.

United Nations Environment Programme (2025). Global Status Report for Buildings and Construction 2024/25 Not just another brick in the wall. https://doi.org/10.59117/20.500.11822/47214

Zanakis, H. S., Solomon, A., Wishart, N. and Dublish, S. (1998). Multi-attribute decision making: A simulation comparison of selected methods. *European Journal of Operational Research, 107*(3), 507–529.