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Article

A Life Cycle Carbon Assessment and Multi-Criteria Decision-Making Framework for Building Renovation Within the Circular Economy Context: A Case Study

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Abstract: Applying circular economy principles to the renovation of existing buildings is increasingly recognized as essential to achieving Europe's climate and energy goals. However, current decision-making frameworks rarely integrate life cycle carbon assessment with multi-criteria evaluation to support circular renovation strategies. This paper introduces an innovative framework that combines life cycle carbon assessment with multi-criteria decision analysis to identify and sequence circular renovation measures. The framework was applied to a residential case study in the Netherlands, using IES VE for operational carbon assessment and One Click LCA for embodied carbon assessment, with results evaluated using PROMETHEE multi-criteria analysis. Renovation measures were assessed based on operational and embodied carbon (including Module D), energy use intensity, cost, payback period, and disruption. The evaluation also introduced the embodied-to-operational carbon ratio (EOCR), a novel metric representing the proportion of embodied carbon, including Module D, relative to operational carbon savings over the building's lifecycle. The homeowner's preferences regarding these criteria were considered in determining the final ranking. The findings show that circular insulation options involving reused materials and designed for disassembly achieved the lowest embodied carbon emissions and lowest EOCR scores, with reused PIR achieving a 94% reduction compared to new PIR boards. The impact of including Module D on the ranking of renovation options varies based on the end-of-life scenario. The framework demonstrates how circular renovation benefits can be made more visible to decision-makers, promoting broader adoption.

Keywords: circular economy; building renovation; life cycle assessment; multi-criteria decision-making; circular renovation; net zero; retrofit

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1. Introduction

In Europe, buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions, stemming from both operational and embodied carbon. European countries have made efforts to tackle operational carbon emissions, either through more stringent building standards for new constructions or by renovating existing housing stocks. However, the latter aspect is still lagging in many countries [1]. On the other hand, emissions related to the embodied carbon of buildings are often not addressed by legislation in Europe despite the fact that embodied carbon represents a significant portion of carbon emissions associated with a building during its life cycle [2]. However, it is a subject that generates a lot of debate. Across Europe, many voluntary standards have been developed for embodied carbon, and it is expected that soon building regulations will incorporate such targets. Examples of voluntary standards include France's HQE (Haute Qualité Environnementale) certification, which encourages sustainable building practices by incorporating the assessment of embodied carbon [3]. Similarly, Germany's DGNB (German Sustainable Building Council) offers a certification system that includes life cycle assessments to evaluate embodied carbon in construction materials [4]. The Netherlands has implemented a national standard to regulate embodied carbon in new buildings through the "MilieuPrestatie Gebouwen" (MPG) [5].

One of the main strategies to reduce embodied carbon in buildings is to apply the principles of the circular economy. Several European initiatives and research projects are actively promoting the circular economy within the building sector. For instance, CIRCuIT (Circular Construction in Regenerative Cities) aimed to demonstrate how cities can transition to a circular construction sector by implementing circular construction practices at scale [6]. Also, FCRBE (Facilitating the Circulation of Reclaimed Building Elements in Northwestern Europe) focused on increasing the amount of reclaimed building elements being circulated in Northwestern Europe [7].

The circular economy is defined by the Ellen MacArthur Foundation [8] as a system where materials never become waste and nature is regenerated. David Cheshire, in his book The Handbook to Building a Circular Economy [9], suggests practical methods to apply this concept to buildings. He suggests that retaining, refurbishing, and refitting existing buildings is the best option for reducing embodied carbon. When this is not possible, and it often is not due to financial, technical, or administrative reasons, the priority should be to reclaim or remanufacture components, with recycling as the last resort.

The renovation of existing buildings inherently applies the principles of a circular economy to the built environment by retaining and repurposing existing structures, thereby preserving the embedded carbon and value within them, rather than constructing new buildings. Numerous studies have highlighted that renovations are generally more advantageous in terms of overall carbon emissions when compared to new construction, further underscoring their environmental benefits [10]. However, even within renovation projects, additional circular economy principles can be implemented, transforming them into circular renovation as described in Densley [11]. Up to 50% of materials extracted during renovations could be recirculated, preventing 200–500 Mt of CO_2e annually at a global scale [12]. Strategies such as design for disassembly can be incorporated, enabling materials to be recovered, reused, refurbished, or recycled at the end of a building's life cycle. These approaches extend the life of materials and reduce waste, offering significant opportunities to minimize embodied carbon and maximize resource efficiency in renovation projects. With materials making up roughly 60% of renovation costs, circular approaches offer both environmental and financial benefits. Circularity is not only key to achieving carbon goals but also represents a $600 billion opportunity in diverted materials by 2050 at a global scale [12]. There is clear momentum for circular renovation, especially in Europe, to decarbonize the residential building stock, and existing initiatives such as the Circular Economy Action Plan [13] and the Renovation Wave [14] may provide synergies that help mainstream circular renovation approaches.

Many studies have explored the implementation of circular economy principles in renovation projects to reduce embodied carbon emissions. For instance, Densley [11] examined the challenges and implications of incorporating circularity into building retrofits. Similarly, Sáez-de-Guinoa et al. [1] proposed frameworks for integrating circular economy models into building renovation projects. Other initiatives, such as the Dutch research project REHA, for instance, developed solutions, pilots, and demonstrator studies to test and showcase new technologies for circular retrofits [15].

As indicated in the recent report published by the World Economic Forum and the literature review below, a key barrier to circular renovation is limited decision-making frameworks; the report calls for tools that support lifecycle performance evaluation [12]. Current decision-making frameworks are not adapted to circular renovation and rarely integrate life cycle carbon assessment with multi-criteria evaluation to support circular renovation strategies. This paper responds to this gap by developing and applying an innovative decision-making framework that supports circular renovation by integrating life cycle carbon assessment with multi-criteria analysis in order to identify the best renovation package and generate a step-by-step renovation plan.

2. Literature Review

Despite the importance of circular economy in the built environment, scientific research on circular economy is still an emerging topic in the building renovation sector, as argued by Sáez-de-Guinoa et al. [1].

Many research projects and papers focused on the development of innovative solutions to implement a circular economy in renovation projects have been developed [16]. For instance, the EU 'Drive 0' research projects sought to showcase the possibilities of swiftly reducing carbon emissions in housing by utilizing modular circular renovation solutions [17]. The renovation incorporated modular wall panels, which were an adaptation of an existing steel structural wall system into a demountable, pre-finished wall panel embodying circularity principles. Many other European projects investigated modular renovation façade technologies; 4RinEU developed prefabricated multifunctional timber-frame façades [18], and PLUG-N-HARVEST, an EU-funded project, investigates a modular facade system for the retrofitting of existing buildings [19]. The modular renovation systems for facades are often combined with other technologies and toolkits. For instance, the European project EASEE utilized 3D laser scanning techniques for acquiring a very detailed model of buildings for anchoring systems installation onsite [20]. It can be noted that most research on modular technologies for circular renovation focused on external wall insulation through modular façades, while options such as internal wall insulation [20] and roof insulation received less traction [21].

Another stream of research has focused on developing circularity indicators tailored to renovations. For example, Bergmans et al. [17] introduced a quantitative design for disassembly (DfD) indicator that evaluates an element's or material's potential for end-of-life disassembly. This indicator takes into account factors such as connection type, connection accessibility, and layer independence. Along similar lines, other scholars [22] proposed more holistic indicators for assessing the circularity of renovations. One such approach extends beyond the DfD aspect by also considering materials' origin (MO) and reusability (RU). This method aligns with widely used tools—such as the circularity index in the One Click LCA tool—and provides a simplified framework for renovation projects, facilitating its adoption in mainstream assessment methods.

Several studies focused on creating frameworks that integrate circular economy principles into building renovations. These frameworks typically use a step-by-step methodology to assess the circularity of renovation options, often relying on a circularity index as the principal performance metric. An example is a proposed six-stage framework for circular refurbishment developed by Fernandes and Ferrão [23] that incorporates mapping, selective disassembly, and material recovery, providing actionable steps to align with circular procurement policies. This framework emphasizes collaboration between local authorities and stakeholders and integrates lifecycle analysis to reduce embodied carbon emissions. In developing countries, similar frameworks have been adapted to local contexts, emphasizing strategies like design for disassembly (DfD) and design for adaptability (DfA) [24]. These approaches facilitate the reuse of materials, reduce dependency on virgin resources, and minimize waste at the end of a building's lifecycle. Tools like One-Click LCA [25] are often used to assess material circularity and optimize design choices. However, challenges such as regulatory gaps, technical limitations, and the fragmentation of industry stakeholders complicate the broader adoption of these frameworks.

Other studies have taken a more strategic perspective, exploring the challenges, barriers, and opportunities associated with circular renovations. The topic is drawing growing interest, and although numerous technical solutions are emerging, many remain at the pilot stage. A key obstacle is the financial burden: innovative solutions typically involve higher capital costs than conventional retrofits. Some authors propose incremental retrofitting—where costs are spread over several years—as one way to boost uptake [1]. Beyond financial factors, social, political, and organizational barriers also hinder the adoption of circular retrofits [11]. From a social standpoint, homeowners are already hesitant to invest in standard energy-saving measures, making it even more challenging to convince them of the benefits of circular renovation and the importance of embodied carbon savings. This highlights the need to raise awareness and demonstrate clear advantages. Politically, the main added value of circular renovations, which is the reduction of embodied carbon, may not drive widespread application unless regulations explicitly target embodied carbon and circularity in renovation projects. Furthermore, an agile supply chain is essential to facilitate the implementation of these solutions. Nevertheless, circular renovations offer considerable potential if these hurdles are addressed.

On the other hand, very few studies have examined the embodied carbon impacts of circular renovation strategies [17,22]. Those that did relied on cradle-to-gate assessments (A1–A3) to compare circular retrofit solutions with conventional alternatives. However, because they focused solely on product-level emissions and excluded other lifecycle stages (such as end-of-life), their results sometimes showed higher embodied carbon for circular solutions than for traditional renovations [17].

To the best knowledge of the author, none of the existing studies propose a decision-making tool that combines life cycle carbon assessment with multi-criteria analysis to identify the most appropriate circular renovation package and to develop a corresponding step-by-step renovation plan. Moreover, most carbon assessments of circular renovation strategies are limited to cradle-to-gate emissions (A1–A3), thereby neglecting end-of-life stages and material recovery potential, which are critical for capturing the full environmental value of circular approaches.

To date, no comprehensive decision-making framework exists that evaluates circularity in renovation across the entire life cycle, including module D, in a way that meaningfully informs renovation decision-making. Additionally, the literature lacks a practical, comparative metric that allows for the evaluation of circular renovation options based on both embodied impacts across all life cycle stages and operational carbon savings over the building's lifetime.

This paper addresses these gaps by proposing an innovative decision-making framework that integrates life cycle carbon assessment with multi-criteria analysis to support circular renovation. The framework enables the identification of the most effective renovation package and the development of a phased renovation strategy. It also introduces a novel comparative indicator, the embodied-to-operational carbon ratio (EOCR). The framework is not specific to anyone building typology or stakeholder context and is therefore universally applicable.

3. Materials and Methods

The methodology consists of several sequential steps (see Figure 1). It is anticipated that a renovation manager will be responsible for overseeing the implementation of the framework to ensure smooth coordination and execution.

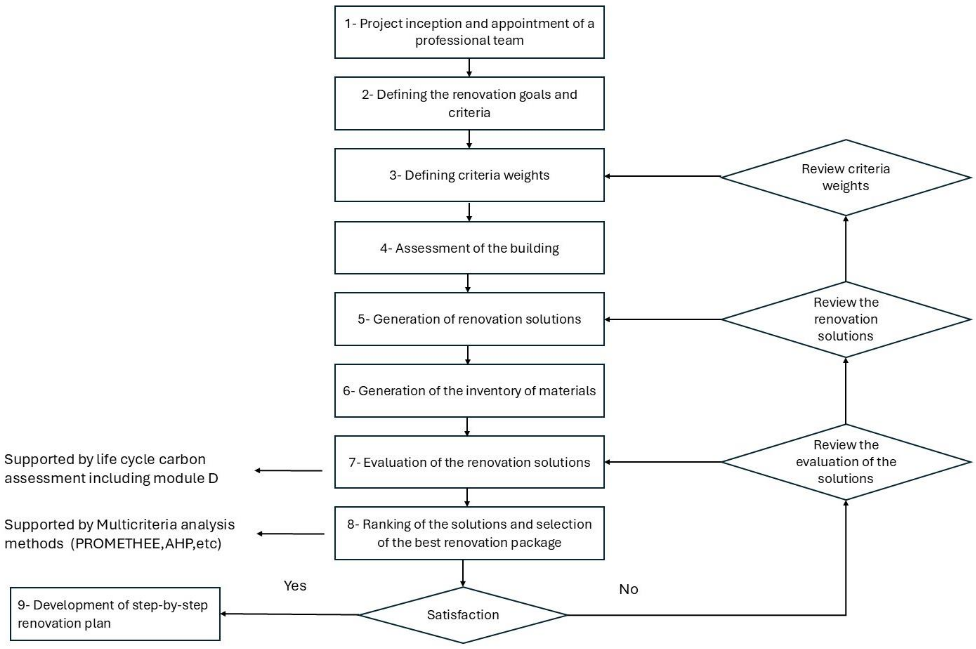

Figure 1. Proposed framework for circular renovations.

3.1. Project Inception and Appointment of a Professional Team

The project inception phase represents the preliminary step in the circular renovation process. It typically involves direct engagement between the client(s) and a renovation lead professional or renovation project manager, who is responsible for the implementation of the proposed framework. At this early stage, typically specialist consultants are not yet involved. Instead, the focus is on establishing a high-level understanding of the project's feasibility and objectives.

3.2. Defining the Renovation Goals and Criteria

This step involves setting the objectives of the renovation project. In this framework, a novel approach is proposed compared to previous studies. To assess circular renovation strategies, the paper advocates for the use of a life cycle carbon assessment rather than limiting the scope to cradle-to-gate emissions (A1–A3), which has been the focus of several researchers looking at circular renovation assessment [17,22]. Instead, this framework recommends considering all life cycle stages including A1–A5 (product and construction stages), B1–B6 (use stage), C1–C4 (end-of-life stage), and Module D (beyond the system boundary). This paper specifically recommends that when considering circular strategies, module D should be included in the calculation of the total embodied carbon, as suggested by many scholars [26–28].

Module D is particularly emphasized, as it captures the potential environmental benefits or burdens from reusing, recovering, or recycling materials at the end of life—key aspects of circularity. In the context of circular renovation, this module is crucial because it allows the assessment to account for the avoided impacts resulting from material recovery and reuse, effectively crediting strategies that prioritize disassembly, material reuse, and design for recyclability. Without including Module D, the long-term environmental benefits of circular retrofit strategies would be underestimated, and materials that are reusable or recyclable at the end of life would not be properly valued in the decision-making process. For instance, in a study comparing circular renovation solutions to traditional approaches, the circular renovation option appeared to have higher embodied carbon emissions [17]. The primary reason for this was that only A1–A3 emissions (cradle-to-gate) were considered, placing the circular renovation at a disadvantage. Circular design strategies often require additional materials or processes at the production stage, such as incorporating fasteners, treatments, or modular design elements that increase initial embodied carbon. However, these early carbon investments are intended to facilitate disassembly, reuse, or recycling at the end of life. Without the inclusion of Module D, which accounts for these future avoided impacts, the full circular value and long-term carbon efficiency of such interventions cannot be properly assessed.

In addition to incorporating module D to account for end-of-life emissions and recovery benefits, the framework emphasizes the importance of material reuse, a core principle of the circular economy. Reusing existing building materials reduces the demand for virgin resources. In alignment with recommendations from One Click LCA specifically the version Whole life carbon assessment, GLA/RICS/Green Mark including EN15804 +A2 [25], the framework adopts the following assumptions: when materials are reused in a renovation project, emissions associated with Modules A1–A3 and A5 (raw material extraction, manufacturing, and construction-stage impacts) are excluded from the embodied carbon calculation. Additionally, when reused materials are sourced locally, emissions from Module A4 (transport to site) are also excluded.

The framework suggests calculating both embodied carbon emissions (including module D) and operational carbon savings over a 60-year period. Furthermore, it introduces a new metric: the embodied-to-operational carbon ratio (EOCR). This metric represents the proportion of embodied carbon (including Module D) relative to operational carbon savings over the building's lifecycle, expressed as a percentage. The formula for this metric is as follows:

$$\mathrm{EOCR}(\%) = \frac{\text{Embodied Carbon }(\mathrm{A1}-\mathrm{A5}, \mathrm{B1}-\mathrm{B5}, \mathrm{C1}-\mathrm{C4}, \text{incl.D})}{\text{Operational Carbon Savings }(\text{B6 over 60 years})} \times 100$$

A low EOCR (<50%) indicates that the embodied carbon investment is relatively small compared to the operational savings, suggesting that the measure is highly carbon-efficient over its lifecycle. A medium EOCR (50–100%) implies that operational savings still outweigh embodied carbon, but the embodied carbon is significant enough to warrant careful consideration of the intervention's long-term carbon efficiency. A high EOCR (>100%) indicates that the embodied carbon load exceeds the operational carbon savings, suggesting that the intervention may not be carbon-efficient over the building's lifetime and may require reassessment or optimization to justify its environmental impact. This metric builds upon the relative embodied carbon concept proposed in the previous literature [29], but importantly, the inclusion of Module D reflects the circularity benefits or burdens, making the metric more relevant for circular renovation evaluations. In cases where the operational carbon savings over the 60-year period are negative, the relative embodied carbon ratio becomes inapplicable. This situation may arise when certain retrofit measures do not directly reduce energy consumption but are nonetheless essential to the overall renovation strategy, such as the installation of centralized mechanical ventilation systems. These systems may slightly increase energy use due to fan power or added ventilation load, especially if not paired with heat recovery. In such scenarios, there are no net operational carbon savings to offset the embodied carbon of the intervention, and in fact, the total operational emissions may increase. As a result, calculating a ratio of embodied carbon to operational carbon savings is not meaningful, since it would involve dividing by a negative or zero value. Therefore, these cases should be clearly flagged in the evaluation as scenarios where the relative embodied carbon ratio cannot be applied.

The following key criteria are stipulated for evaluating circular renovation strategies:

3.2.1. Embodied Carbon Emissions

Product and construction stages (A1–A5), in-use embodied emissions (B1–B5), end-of-life emissions (C1–C4), and module D (reuse, recycling, and recovery benefits beyond the system boundary) are included.

3.2.2. Operational Carbon (B6)

Total operational emissions of the building over a 60-year period.

3.2.3. Embodied-to-Operational Carbon Ratio (EOCR)

The percentage ratio of embodied carbon (including circularity benefits in module D) to operational carbon savings.

3.2.4. Impact on Energy Use Intensity (EUI)

Energy use intensity (EUI) represents the annual energy consumption of a building normalized by its floor area, typically expressed in kWh/m^2/year. It reflects the overall energy efficiency of the building and its technical systems. In this framework, EUI should account for delivered energy as well as on-site renewable generation. Therefore, any on-site generation is accounted for within the EUI itself and not in module D of the life cycle assessment. The impact on EUI is expressed as a percentage change compared to the baseline (pre-retrofit) scenario. Negative values indicate a reduction in energy use (improved performance), while positive values indicate an increase in energy use compared to the base case.

3.2.5. Investment Cost (€)

The total installed cost (materials and labor) of each measure or package of measures.

3.2.6. Energy Bill Savings (€/Year)

$$\text{Energy Savings (€/year)} = (\text{energy consumption before renovation} - \text{energy consumption after renovation}) \times \text{energy cost (€ per kWh)}$$

3.2.7. Payback Period

$$\text{Payback Period(years)} = \frac{\text{Capital Cost of the EEM or package of EEMs}}{\text{Annual cost savings}}$$

In addition to the core set of prescribed criteria, the framework is designed to accommodate additional factors, including qualitative dimensions such as inconvenience caused by renovation work, impact on building aesthetics, or improvements in indoor comfort. These criteria can be easily integrated into the evaluation process and are intended to be defined through discussion with the decision-maker(s) during this step. While some studies propose structured consensus-building techniques such as the Delphi method [30] to define criteria, this framework deliberately avoids such resource-intensive processes to remain accessible and practical for real-life renovation projects.

At this stage, the framework also encourages the team to define performance targets, for example, aiming for standards such as EnerPHit [31], and to clarify any budgetary constraints that should influence decision-making.

3.3. Defining Criteria Weights

Another original feature of the proposed framework is that it allows decision-makers to assign weights to each criterion, ensuring that the most important factors are prioritized to achieve the best compromise. While this approach is not new in the context of renovation projects, it is innovative for circular retrofitting. The framework does not require a specific weighting technique, such as the SWING method [32] or analytic hierarchy process (AHP) [30], as it aims to remain user-friendly. Instead, decision-makers, whether working individually or in groups, can assign importance to each criterion on a scale from 0 to 1, where 1 represents "extremely important" and 0 means "not important at all".

3.4. Assessment of the Existing Building

The aim of this step is to assess the existing property to gather comprehensive data. This assessment should culminate in the development of an energy model, alongside other critical information such as occupant comfort, ventilation, potential defects, occupancy patterns, and the building's structural or historical significance. This paper does not aim to provide a detailed methodology for conducting the assessment, as such procedures are already outlined in various building standards such as PAS 2035 [33] and BS 40104 [34].

During this step, sufficient information should be collected to create a reliable energy model. The research does not prescribe a specific tool for this purpose. The model can be generated using static tools (e.g., the Passive House Planning Package, PHPP, developed by the Passive House Institute) or dynamic simulation tools like IES VE or Design Builder. The choice of tool should depend on the project's requirements and scale.

In large or complex projects, technologies such as laser scanning and building information modeling (BIM) can significantly enhance the speed and accuracy of the assessment process. This is particularly valuable for circular renovation projects where solutions are often prefabricated off-site [35].

3.5. Generation of Renovation Solutions

This stage involves generating renovation strategies, including circular renovation options. The type of solution will primarily depend on the property assessment and the goals established by decision-makers in the previous steps. At this stage, the solution must be detailed enough to allow for the quantification of materials, which is crucial for the subsequent steps in the process. In order to have a fair comparison between circular and non-circular strategies, all scenarios should aim for the same performance. To reduce the number of potential combinations when forming renovation packages, the grouping of measures should take place after individual solutions have been evaluated. This approach ensures that only the most effective and feasible options are considered for inclusion in packages, streamlining the decision-making process and avoiding unnecessary complexity.

3.6. Generation of the Inventory of Material

This step involves quantifying the proposed solutions to enable the calculation of embodied carbon in the following stages. Since this is a renovation context, the paper adopts the approach implemented by Mohammadpourkarbasi et al. [36] and Prabatha et al. [10], where only the added materials are considered in the embodied carbon calculations. Existing materials and components already present in the building do not need to be included in the assessment, as they are not newly introduced within the scope of the retrofit.

3.7. Evaluation of the Renovation Solutions

Once the solutions are generated, they should be evaluated individually and grouped in renovation packages to account for potential interactions between different measures.

The evaluation should be based on the criteria established in the previous step. This process could accommodate both quantitative and qualitative assessments. Quantitative evaluations may include tools such as One Click LCA for life cycle carbon assessment or PHPP for operational carbon calculations. The paper also recommends using energy performance modeling tools such as PHPP, Design Builder, and IES rather than relying on compliance tools, as these allow for a more accurate assessment of the real performance of the building [37]. In addition, qualitative criteria, such as the level of disturbance caused by the retrofit work or the impact on the building's aesthetic aspects, should also be considered if required by the team.

3.8. Ranking of the Solution and Selection of the Best Renovation Package

Once the evaluation is completed, the proposed solutions need to be ranked to determine the best renovation package. At this stage, the framework recommends using a multi-criteria decision-making (MCDM) method [38]. However, it does not prescribe any specific tool, such as PROMETHEE (preference ranking organization method for enrichment evaluation) [30] or AHP, allowing flexibility for decision-makers to use whatever tool is available and suitable for their needs. Although these tools may vary in their methodologies [30], they all facilitate identifying the best-performing solutions by considering multiple criteria. Importantly, they also account for the preferences and priorities of one or multiple decision-makers, ensuring a balanced and informed decision-making process. This flexibility allows the framework to remain adaptable and user-friendly, accommodating different project requirements and stakeholder preferences.

At this stage, if the team is satisfied with the identified renovation package, the next step would be to develop a step-by-step renovation plan. However, if the results are not satisfactory, the framework recommends an iterative review process. The first step is to revisit the evaluation of the proposed options, allowing the team to reassess their performance and ensure all inputs and assumptions are valid. If the results remain unsatisfactory, the next phase involves reconsidering the set of renovation solutions included in the assessment. As a final step, the team may review and adjust the weighting of the evaluation criteria, particularly if project priorities have shifted or were not fully captured in the initial scoring.

3.9. Development of Step-by-Step Renovation Plan

The aim of this step is to develop a step-by-step plan to bring the building to the appropriate level of decarbonization. The rationale behind this phased approach is that financial resources for a full-scale retrofit are often limited, making incremental implementation more practical and realistic. The plan should prioritize the implementation of measures based on the rankings provided by the multi-criteria decision-making tools, while also ensuring that the execution of one measure does not hinder the future implementation of others and that future measures will not compromise or damage previously installed measures [39]. In scenarios where digital building logbooks are adopted, the step-by-step renovation plan developed through the framework would be documented within the logbook.

4. Application of the Proposed Methodology

In order to test and assess the developed framework, this paper used a case study approach. The use of a single case study has been widely applied in the buildings' renovation literature to test new methodologies, including in previous investigations conducted by the authors [30,32]. In this paper the case study is located in the town of Groningen in The Netherlands. The case study is a residential building constructed in 1930 (see Figure 2). The building has been selected mainly because the owners of the house were planning to renovate their property and were willing to participate in this research. The proposed methodology is not developed for a specific building type in mind but with the aim to be applied in any kind of renovation project. The stakeholders included in the project included the owner of the house and the authors of this paper, who acted as retrofit professionals and were responsible for the implementation of the proposed framework (step 1).

Figure 2. Residential building selected as a case study (building on the right).

The second step consisted of defining the evaluation criteria (step 2). In addition to the criteria prescribed by the framework, the homeowner expressed their desire to include one additional criterion in the evaluation process: the level of disruption caused by the renovation works. This aspect was captured using a qualitative scale, allowing the homeowner to assess the degree of inconvenience or disturbance that each proposed solution would entail during implementation. Disruption factors may include the duration of works, noise levels, dust, the need for temporary relocation, and impacts on daily routines. By using a simple 5-level qualitative scale (very low to very high disruption), the framework allows these less tangible but highly relevant considerations to be integrated into decision-making. Following a discussion with the homeowner, it was agreed that the renovation solutions should, where realistically feasible, aim to meet at least the same performance standards required for new buildings under current Dutch regulations. Specifically, the following U values were targeted: roofs ≤ 0.16 W/m^2·K, external walls ≤ 0.21 W/m^2·K, and windows ≤ 1.65 W/m^2·K. To ensure a fair comparison between design options, all similar building envelope insulation scenarios were designed to achieve these same U values [40]. The homeowner was then asked to assign a weight to indicate the importance given to each objective, using a scale from 0 to 1, where 1 represents extremely important and 0 means not important at all (step 3). The weights assigned by the homeowner for each criterion are shown in Table 1.

The fourth step entailed a thorough assessment of the building (step 4). This was carried out by the authors. Depending on the context and the projects, this can be performed by other types of professionals, such as renovation assessors, coordinators, and so on. The assessment included sufficient data to create an energy model and allowed the design of renovation options. The information gathered included detailed measurements of the house, data on the type of walls, U values, ventilation type, heating, occupancy pattern, and so on. The main characteristics of the building are presented in Table 2. The dynamic software IES Virtual Environment (version 2024.0.0.0) was used to create the energy model (see Figure 3), which was calibrated using energy bill data provided by the owner. The calibration allows us to obtain more accurate results; for instance, during the calibration and discussion with the homeowner, it was found that the upper floor, the attic, was not always heated by the client, although it was in the heated envelope areas, and this played an important role in the assessment of the energy consumption and associated savings.

Table 1. Evaluation criteria.

	Embodied Carbon Including Module D	Operational Caron Savings	Embodied-to-Operational Carbon Ratio	Impact on Energy Use Intensity	Total Cost	Yearly Savings	Payback Period	Level of Disruption
Codes	C1	C2	C3	C4	C5	C6	C7	C8
Units	kg CO_2e	kg CO_2	%	%	€	€	Years	qualitative
Weights of Criteria	0.5	0.5	0.5	1	1	1	1	0.6

Table 2. Characteristics of the case study.

Building Characteristics	Performance
Existing External wall	Non insulated cavity wall U value 1.7 W/m^2·K
Double glazed window	U value 2.94 W/m^2·K
Door	U value 2.9 W/m^2·K
Existing pitched roof	U value 2.06 W/m^2·K
Airtightness	Assumed 5 ach after calibration
Heating	Gas powered central heating system
Ventilation	Intermittent fans in the bathroom and kitchen
Hot water consumption	1.5 L/h/person
Total volume	361.6982 m^3
Total floor area	148.18 m^2
External wall area	35.4 m^2
External opening Area	28.6 m^2
Sloping roof	62.1 m^2

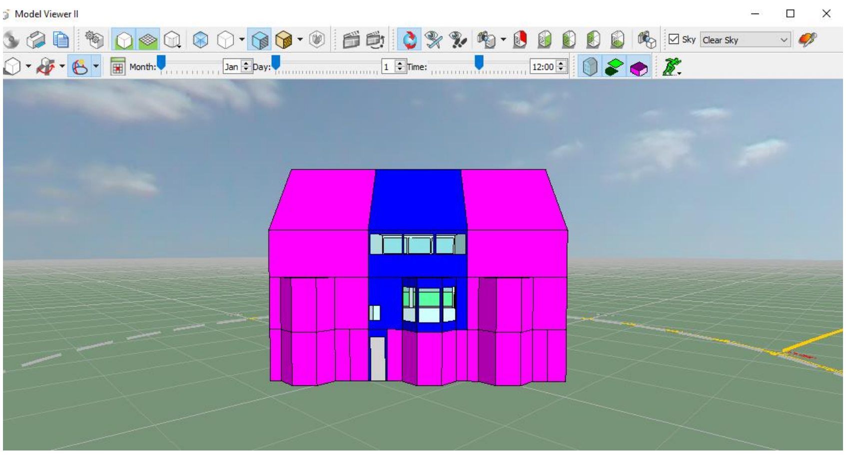

Figure 3. IES model of the case study.

Once the assessment of the building was completed, the next step involved generating renovation options (step 5). These included both traditional and circular solutions, targeting the building's roof, external walls, windows, and services. For the roof and wall insulation, four material strategies were considered: conventional insulation materials, natural insulation materials, recycled insulation materials, and reused insulation materials.

For windows, two categories were defined: wooden windows, representing the natural material approach, and UPVC windows, representing the conventional solution. The services strategies included the evaluation of three key systems: air source heat pump (ASHP), mechanical extract ventilation (MEV), and mechanical ventilation with heat recovery (MVHR). After defining the strategies, a material inventory was developed for each renovation option (Step 6). As outlined in the methodology, only new materials added to the existing building were included in the inventory (materials already present were excluded). The quantities of materials for each scenario are presented in Table 3.

Table 3. Inventory of renovation materials.

Retrofit Measure	Resource	Quantity	Thickness (mm)	Service Life (Years)
Internal wall insulation with conventional insulation (92.5 mm PIR plasterboard)	Gypsum plasterboard, 12.5 mm, 10.6 kg/m, 2850 kg/m^3	35.4 m^2	12.5	As building (60 years)
	Timber battens	7.15 m^2	38	As building (60 years)
	PIR insulation panels	35.4 m^2	80	As building (60 years)
	Sawn timber	4.49 m^2	100	As building (60 years)
Internal wall insulation with natural materials	Lime interior plaster	34.5 m^2	15	30 years
	Insulation, wood fiber	34.5 m^2	60	As building (60 years)
	Sheep wool insulation in batts	28.01 m^2	100	As building (60 years)
	Sawn timber	6.56 m^2	100	As building (60 years)
Internal wall insulation with recycled Insulation	Lime interior plaster	34.5 m^2	15	30 years
	Insulation, wood fiber	34.5 m^2	60	As building (60 years)
	Cellulose insulation, blown	27.95 m^2	100	As building (60 years)
Wall insulation with reused materials	Gypsum plasterboard, 12.5 mm, 10.6 kg/m, 2850 kg/m^3	35.4 m^2	12.5	As building (60 years)
	Timber battens	7.15 m^2	38	As building (60 years)
	PIR insulation panels	35.4 m^2	80	As building (60 years)
Roof insulation with conventional insulation	Rock wool insulation bats	51.04 m^2	140	As building (60 years)
	Gypsum plasterboard	62.1 m^2	12.5	As building (60 years)
Roof insulation with natural materials	Sheep wool insulation in batts	51.04 m^2	140	As building (60 years)
	Gypsum plasterboard	62.1 m^2	12.5	As building (60 years)
Roof insulation with recycled materials	Cellulose insulation, blown	51.04 m^2	140	As building (60 years)
	Gypsum plasterboard	62.1 m^2	12.5	As building (60 years)
Roof insulation with re-used materials	PIR insulation panels	51.04 m^2	100	As building (60 years)
	Gypsum plasterboard	62.1 m^2	12.5	As building (60 years)
Wooden frame windows	Wooden frame window, triple glazed, fixed, 36.3 kg/m^2	28.6 m^2	-	40
PVC-U windows	Window, triple glazed, PVC-U frame	28.6 m^2	-	40
Air Source Heat Pump (ASHP)	air/water heat pump for heating and hot water production (P = 10 kW, 206 kg/unit)	1 unit	-	22
	Panel radiators with 8 connections, 600 × 1000 mm	150 kg	-	25
	Thermally insulated flexible pipes, 1.5 kg/m	300 m	-	60
Mechanical ventilation system with heat recovery (MVHR)	Mechanical ventilation system with heat recovery (MVHR) 115 kg/unit	1 unit	-	25
	Flexible ventilation ducting	50 m	-	60
Mechanical Extraction Ventilation (MEV)	Mechanical Extraction Ventilation (MEV) Unit, 7–12 kg/unit	1 unit	-	25
	Flexible ventilation ducting	25 m	-	60

Following the generation of solutions, they were evaluated against the predefined criteria (Step 7). In addition to individual interventions, combinations of measures were also proposed and evaluated in the form of retrofit packages to explore the potential synergies between different solutions. Some evaluations were quantitative, for example, operational carbon savings were calculated using IES Virtual Environment (version 2024.0.0.0), while embodied carbon emissions were assessed using One Click LCA (version whole life carbon assessment, GLA/RICS/Green Mark including EN15804 + A2). Other evaluations were qualitative and based on stakeholder input. For instance, the level of disruption was rated using a five-level scale, ranging from very low to very high. The results of the evaluation of individual renovation solutions and packages of solutions are presented in Tables 4 and 5, respectively.

Table 4. Evaluation of the individual renovation solutions.

		Embodied Carbon Including Module D (Excluding Module D)	**Operational Caron Savings**	**Embodied-to-Operational Carbon Ratio**	**Impact on Energy Use Intensity**	**Total Cost**	**Yearly Savings**	**Payback Period**	**Level of Disruption**
	Codes	C1	C2	C3	C4	C5	C6	C7	C8
	Units	kg CO_2e	kg CO_2	%	%	€	€	Years	qualitative
	Weights of Criteria	0.5	0.5	0.5	1	1	1	1	0.6
A1	Internal wall insulation with conventional insulation (92.5 mm PIR plasterboard)	488 (581)	33,540	1.45	−22.5	3540	493	7.18	Moderate
A2	Internal wall insulation with natural materials (100 mm flexible wood fiber batt between timber studs, 60 mm fiber board, 15 mm lime plater finish)	309 (537)	33,540	0.92	−22.57	4248	493	8.62	High
A3	Internal wall insulation with recycled Insulation; 140 mm loose cellulose insulation between timber studs, 60 mm fiber board, 15 mm lime plater finish)	218 (448)	33,540	0.64	−22.57%	4035.6	493	8.19	High
A4	Wall insulation with reused materials 100 mm reused PIR installed between studs, 15 mm plasterboard	27 (120)	33,540	0.08	−22.57	2584.2	493	5.24	Moderate
A5	Roof insulation with conventional insulation (140 mm rock wool insulation, 12.5 mm plaster board)	696 (698)	17,940	3.87	−12.06	3850.2	264	14.58	Moderate
A6	Roof insulation with natural materials; (140 mm flexible wood fiber batt between rafters, 12.5 mm plaster board)	474 (476)	17,940	2.64	−12.06	4719.6	264	17.88	Moderate

Table 4. *Cont.*

		Embodied Carbon Including Module D (Excluding Module D)	Operational Caron Savings	Embodied-to-Operational Carbon Ratio	Impact on Energy Use Intensity	Total Cost	Yearly Savings	Payback Period	Level of Disruption
A7	Roof insulation with recycled materials; 140 mm loose cellulose insulation between rafters, 12.5 mm plaster board)	249 (251)	17,940	1.38	−12.06	3922.236	264	14.86	High
A8	Roof insulation with re-used materials; (Total roof insulation 0.16 W/m^2·K)	189 (191)	17,940	1.05	−12.06	4160.7	264	15.76	Moderate
A9	Triple-glazed wooden frame windows	3339 (3361)	40,980	8.14	−27.58	21,450.0	602.00	35.63	High
A10	Triple-glazed UPVC windows	4697 (4720)	40,980	11.46	−27.58	7321.6	602.00	12.16	High
A11	Air source heat pump (SCOP 2.5)	7118 (10,101)	72,600	9.80	−68.19	12,000	1140	10.53	Very high
A12	Mechanical ventilation with heat recovery (MVHR)	955 (1678)	−9300	_	+6.31	5000	−136.00	n/a	Very high
A13	Mechanical extract ventilation	230 (290)	−45,780	_	+30.91	2500	−672.00	n/a	High

Table 5. Evaluation of renovation packages.

Codes		C1	C2	C3	C4	C5	C6	C7	C8
A14	Package 1 (roof insulation with traditional materi-als/ASHP/MVHR)	8769 (12,477)	72,960	12.02	−68.34	20,850.2	1145.00	18.21	Very high
A15	Package 2 all measures/traditional insulation/UPVC windows/ASHP/MVHR	13,954 (17,778)	109,080	12.79	−83.34	31,711.8	1639.00	19.35	Very high
A16	Package 3 all measures/renewable insulation/wooden windows/ASHP/MVHR	12,195 (16,153)	109,080	11.17%	−83.34%	47,417.6	1639.00	28.93	Very high
A17	Package 4 all measures/recycled insulation/wooden windows/ASHP/MVHR	11,879 (15,839)	109,080	10.89	−83.34	46,407.83	1639.00	28.31	Very high
A18	Package 5 all measures/reused insulation/wooden windows/ASHP/MVHR	11,628 (15,451)	109,080	10.66	−83.34	45,194.9	1639.00	27.57	Very high
A19	Package 5 all measures/reused insulation/UPVC windows/ASHP/MVHR	12,986 (16,810)	109,080	11.90	−83.34	31,072.9	1639.00	18.95	Very high

Operational carbon savings, the impact on energy use intensity (EUI), and annual energy cost savings in euros were derived using the dynamic simulation software IES. The following assumptions were applied in the energy and carbon calculations: carbon emission factors (electricity: 0.328 kg CO_2/kWh, natural gas: 0.202 kg CO_2/kWh) and energy prices (electricity: €0.2695/kWh (including taxes), natural gas: €0.178/kWh). The embodied carbon of renovation measures was calculated using One Click LCA, a widely used lifecycle assessment software. Cost data were obtained from manufacturers' websites and installer quotes. The level of disruption caused by each retrofit option was evaluated qualitatively, based on input provided directly by the homeowner, using a simple qualitative scale.

At this stage, the multi-criteria decision-making method PROMETHEE was used to evaluate the retrofit solutions against the defined criteria, taking into account the decision-maker's preferences (Step 7). This method was chosen because it supports both quantitative and qualitative criteria and is user-friendly, requiring no coding [41]. The PROMETHEE method ranks solutions based on their net Phi value, which represents the overall preference strength of one alternative over the others, considering both the evaluation of the options with respect to the criteria as well as the preferences of decision-makers. A higher net Phi value indicates a more favorable solution, while a lower or negative value suggests weaker performance relative to the alternatives. By considering both the strengths and weaknesses of each option across all criteria and incorporating the decision-maker's preferences, the net Phi value provides a comprehensive and balanced ranking of the retrofit options. An important feature of PROMETHEE is that it does not allow compensation between criteria—in other words, a poor score on one criterion cannot be offset by a high score on another [30]. As outlined in the methodology, the framework is designed to be flexible regarding the choice of multi-criteria decision-making tools. Any method that allows for the ranking of solutions while integrating the decision-maker's preferences, whether individual or collective, can be adopted within this approach.

Figures 4 and 5, respectively, present the ranking of individual retrofit options and packages of solutions based on their performance across all criteria, considering the preferences of the decision-maker. The solutions are ranked from left to right according to the PROMETHEE results, with the option on the far left representing the best-performing solution and the one on the far right representing the least favorable. Each renovation option is represented by a stacked bar, where the individual contributions of the criteria are visualized using a color-coded scheme. The positive segments of each bar (pointing upward) represent criteria where the option performed well, while the negative segments (pointing downward) highlight weaker performance areas. This visualization helps to clearly identify the trade-offs and dominant features of each retrofit option, making it easier to understand the reasoning behind the ranking outcomes.

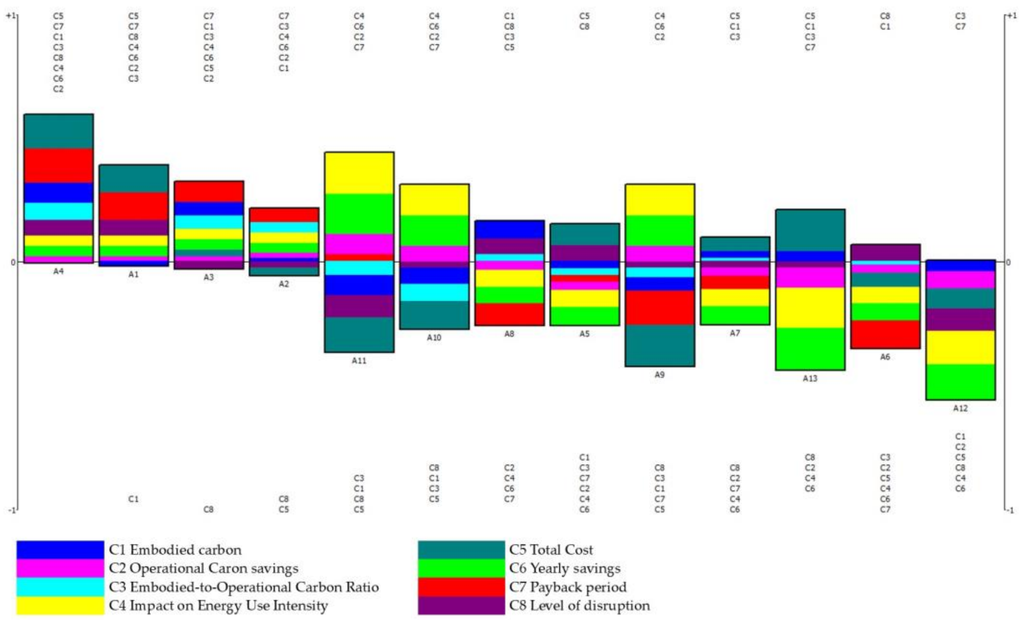

Figure 4. Ranking of individual renovation solutions (ranked from left to right).

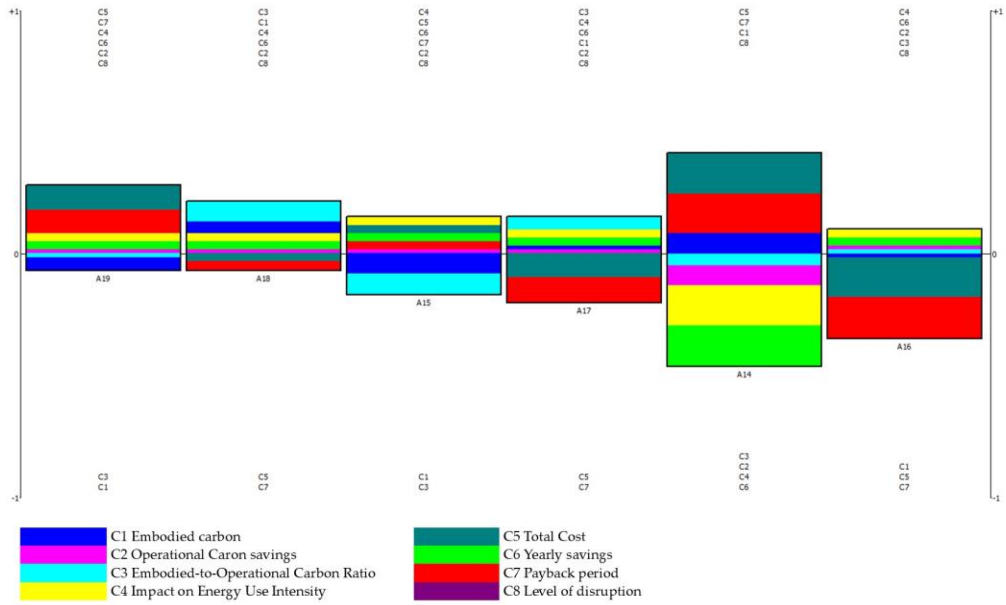

Figure 5. Ranking of renovation packages (ranked from left to right).

Action A4, which consists of internal wall insulation using reused PIR panels, ranked highest among all options. This outcome is due to its strong performance across several key criteria. The solution had a low initial investment cost, as it was assumed that the PIR panels would be sourced second hand, making them significantly cheaper than new materials. In this particular case, the reused PIR was assumed to be leftover stock from other projects commonly available in large quantities due to over-ordering rather than recovered from existing buildings. As a result, the panels were considered unused and therefore assigned a full-service life of 60 years. However, in scenarios where reused PIR originates from materials already installed in a previous building, it would be appropriate to assign a reduced lifespan to better reflect its remaining useful life within the life cycle carbon assessment. Interestingly, the second-, third-, and fourth-ranked actions also involved wall insulation strategies. These alternatives performed particularly well in terms of initial cost, payback period, and embodied carbon. However, they were less effective in reducing operational energy use, annual savings, and energy use intensity. Following the internal wall insulation options, the installation of an air source heat pump (A11) emerged as the next best-performing solution. This measure demonstrated strong performance across several criteria, including carbon savings, impact on energy use intensity, yearly financial savings, and payback period. The next best-performing individual measure after the internal wall insulation and heat pump was the installation of triple-glazed uPVC windows (A10). This solution ranked highly due to its strong performance in operational carbon savings and its significant impact on reducing energy use intensity. Roof insulation using reused PIR (A8) and traditional rock wool (A5) followed, ranking seventh and eighth, respectively. While both options performed reasonably well in terms of embodied carbon, their operational impact was less pronounced compared to other envelope upgrades. At the lower end of the ranking, mechanical extract (A13) ventilation and MVHR (A12) (mechanical ventilation with heat recovery) scored less favorably when evaluated as standalone measures. This is primarily because they do not directly contribute to energy savings, and in some cases, they can even increase overall energy consumption due to fan power demands.

When assessed as a package, the combination of reused PIR insulation for walls and roof, UPVC windows, an air source heat pump, and an MVHR system (A19) emerged as the most preferred solution. This package delivered strong performance in terms of operational carbon savings, impact on EUI, and yearly savings, while also achieving substantial operational savings. The inclusion of reused PIR also contributed to a notable reduction in overall renovation costs. Although mechanical extract ventilation ranked higher than MVHR when assessed individually, primarily due to its lower initial cost and the cost-driven priorities of the homeowner, the decision-maker ultimately agreed to include MVHR in the final renovation package. As a result, the generation of an alternative package excluding MVHR was not considered necessary, as the final package was accepted based on overall performance and alignment with the project's long-term objectives.

Once the best-performing retrofit package was identified by the framework and the outcomes agreed upon by the decision maker, a step-by-step renovation plan was generated (see Table 6). The sequence of steps was determined by considering both the multi-criteria ranking of individual measures and the practical interactions between them. Based on this, the first step selected was the installation of the air source heat pump. Although this measure was technically ranked second, following internal wall insulation, it was considered unsuitable to insulate the walls beforehand due to the need to route pipes through the envelope to connect the external unit. Additionally, wall insulation prior to window replacement would have complicated the later installation of new windows.

Table 6. Step-by-step renovation plan.

Steps	Renovation Measures
1	Air source heat pump (SCOP 2.5)
2	Windows and MVHR
3	Interior wall insulation combined with the roof insulation

The next steps in the sequence were to replace the windows and install the MVHR system. Window replacement, which ranked second overall, was completed before wall insulation to ensure better detailing around the windows and reduce thermal bridging. MVHR installation was also combined with window replacement to ensure that increased airtightness does not cause indoor air quality issues. Finally, internal wall insulation along with roof insulation was the concluding step in the phased renovation plan.

A sensitivity analysis was conducted to assess how the exclusion of module D would affect the ranking of renovation solutions. In the context of this case study, the impact of excluding module D on the overall ranking was relatively limited (see Figure 6). This is primarily because the major contributions to module D came from wood incineration credits, linked to the disposal of timber elements used in insulation and internal structures, rather than high-value material reuse.

An additional scenario analysis was conducted to assess the impact of end-of-life scenarios on the ability of Module D to influence the overall ranking of renovation options. A hypothetical scenario (H20) was generated specifically for sensitivity analysis, focusing on one of the internal wall insulation options (A1). In this scenario, the insulation solution was designed for disassembly, allowing the PIR insulation to be reused at the end of the building's life (see Table 7).

The results of the analysis showed that H20 ranked as the second-best option when Module D was included (see Figure 7) but dropped to third place when Module D was excluded (see Figure 8). This outcome confirms that including Module D can significantly impact the ranking when the renovation solution is designed to enable high-value material reuse.

Table 7. Hypothetical scenario (design for disassembly and reuse).

Codes		C1	C2	C3	C4	C5	C6	C7	C8
H20	Internal wall insulation with reusable conventional insulation (92.5 mm PIR plasterboard)	47 (581)	33,540	0.14	−22.5	3540	493	7.18	Moderate

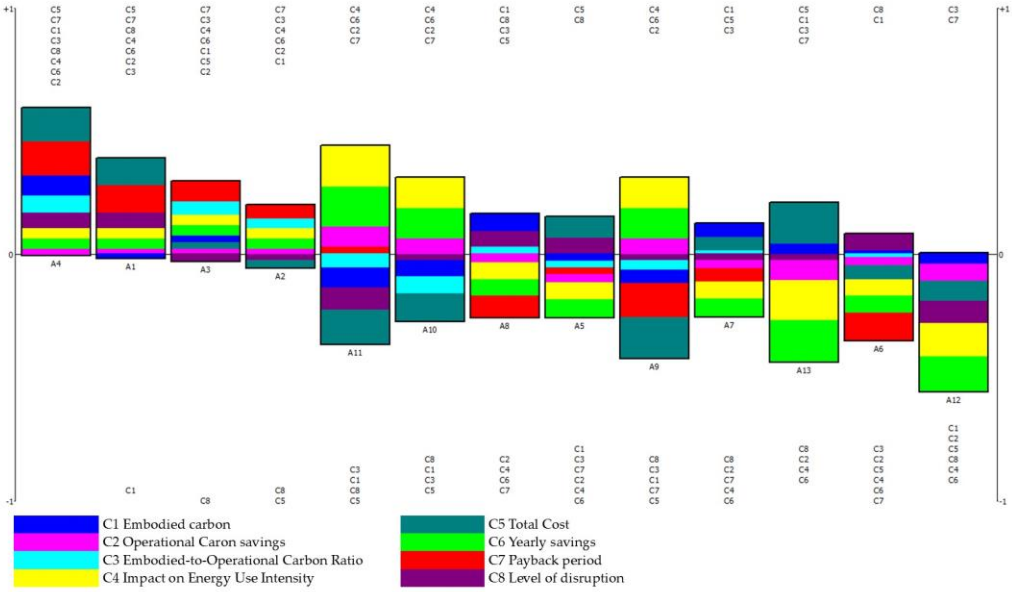

Figure 6. Ranking of the individual renovation solutions excluding module D (ranked from left to right).

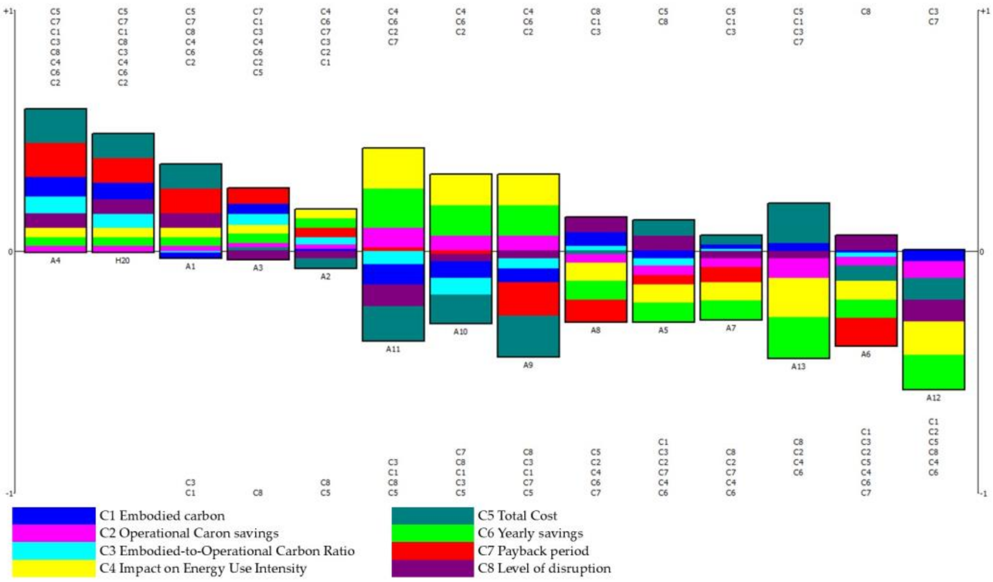

Figure 7. Ranking of the individual renovation solutions, including H20 and module D (ranked from left to right).

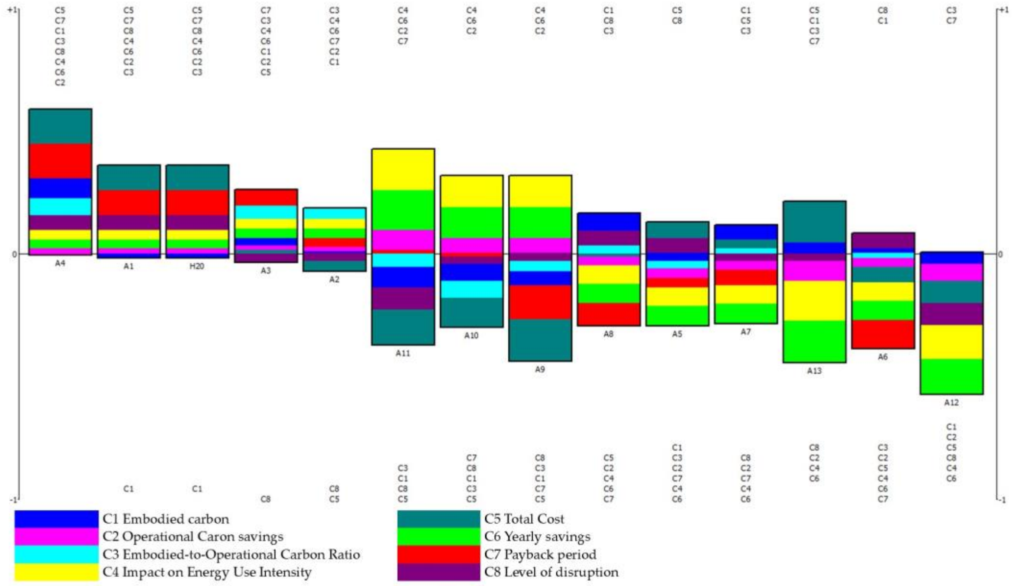

Figure 8. Ranking of the individual renovation solutions, including H20 and excluding module D (ranked from left to right).

5. Discussion

5.1. Interpretation of the Ranking of the Renovation Options

The proposed framework successfully identified the most suitable renovation options, both as individual measures and as part of the final recommended package. Among the highest-ranked individual solutions were the reused PIR internal wall insulation (A4), air source heat pump (A11), and triple-glazed uPVC windows (A10).

The internal wall insulation with reused PIR (A4) stood out for its very low embodied carbon, showing a 94% reduction compared to the conventional PIR boards (A1). This substantial advantage was mainly due to the exclusion of modules A1–A3, which allowed us to account for the avoided emissions from material reuse. Had the assessment not been taken using this approach, other options such as natural or recycled insulation would likely have appeared more favorable. This underlines the importance of having a clear methodological approach to account for reused materials and confirms the findings of recent studies that emphasize the embodied carbon impacts of reusing local materials in residential buildings [42].

The air source heat pump (A11) was another top choice, particularly due to its high coefficient of performance (COP; 2.5), which enabled significant savings in both operational carbon emissions and annual energy bills. Although its embodied carbon was relatively high compared to other measures, with an EOCR of 9.80%, a closer analysis using One Click LCA revealed that a significant portion of those emissions stemmed from the use phase, particularly due to the type of refrigerant used. This finding highlights the importance of selecting low-GWP refrigerants when specifying heat pump systems.

There is ongoing debate in the renovation industry regarding whether heating systems should be installed before or after fabric measures [43]. Some argue that carrying out fabric improvements prior to installing the heat pump can reduce the building's space heating demand, allowing for a smaller system size and potentially enabling the retention of existing radiators, both of which can result in significant embodied carbon savings [39]. Fabric-first advocates also raise concerns about the operating costs of heat pumps in under-insulated buildings, suggesting that without reducing the heating load first, switching from gas to electricity leads to an increase in energy bills [44]. Conversely, others, such as the European Heat Pump Association, advocate for the rapid deployment of heat pumps, stressing their role in the urgent decarbonization of Europe's housing stock. They argue that heat pumps can operate effectively even in moderately inefficient buildings and that delaying installation may postpone carbon savings that could be achieved immediately, which would detrimentally impact targets in terms of the decarbonization of building stocks [45].

The findings of this study suggest that a heat pump should definitely be part of a retrofit package. The timing of heat pump installation depends largely on the criteria being prioritized. In scenarios where carbon reduction is the primary objective, early installation is clearly justified. However, heat pumps can contribute to carbon savings only when the coefficient of performance (COP) of the system, combined with the carbon factor of electricity, results in lower emissions compared to a gas boiler. In other words, the carbon factor of electricity must be sufficiently low for the heat pump's efficiency to offset the emissions associated with gas heating. If initial cost, disruption, or comfort are more heavily weighted, a different sequencing may be more appropriate on a case-by-case basis, underscoring the value of a multi-criteria approach and the proposed framework.

The triple-glazed uPVC windows performed well due to their substantial impact on operational energy use. In the simulated model, these windows reduced the U-value from 2.94 $W/m^2{\cdot}K$ to 0.8 $W/m^2{\cdot}K$, delivering significant operational carbon savings. Given the large proportion of glazing in the building envelope, this improvement had a major impact. Although uPVC has a high embodied carbon, this was largely offset by its operational performance reflected in a favorable EOCR (11.46%). However, it is evident from the evaluation table (see Table 4) that the triple-glazed wooden frame windows achieved a better EOCR (8.14%) and demonstrated approximately 28% lower embodied carbon compared to the triple-glazed uPVC windows. This finding aligns with several studies that highlight the environmental advantages of timber-framed glazing over uPVC alternatives in terms of embodied carbon [46]. Nevertheless, in the context of this study, the uPVC windows were prioritized due to the higher weighting assigned to cost-related criteria, as defined by the decision-maker.

The analysis also revealed that measures such as mechanical extract ventilation and MVHR systems, which performed less favorably in terms of carbon, remain essential for ensuring adequate indoor air quality after retrofit. These results emphasize the multi-faceted nature of retrofit, where technical systems cannot be judged on carbon performance alone. Including additional criteria such as comfort, health, or indoor air quality may have positioned these solutions more favorably in the ranking. This reflects a broader shift in the literature, where scholars increasingly emphasize the co-benefits of retrofit, including comfort and well-being [47].

Overall, the proposed ranking approach offered clarity and structure in evaluating complex retrofit trade-offs. It allowed each solution's strengths and weaknesses to be clearly visualized.

5.2. Impact of Evaluation Criteria and Life Cycle Carbon Metrics

A central contribution of this framework lies in its integration of circular economy aspects in the life cycle carbon and multicriteria assessment.

The decision to exclude emissions from modules A1–A3 when materials are reused and A1–A4 when materials are reused locally plays a crucial role in highlighting the environmental value of circular solutions. For instance, reused PIR insulation (A4) demonstrated a 94% reduction in net embodied carbon compared to new PIR boards (A1), primarily due to the carbon credits from avoided virgin material production. Had the framework not excluded product stage emissions (A1–A3) and transport emissions (A4) from the life cycle carbon assessment of the circular option (reused PIR A4), it would have shown similar carbon performance to that of new PIR boards (A1). This would have misrepresented the environmental benefits of implementing circular strategies in renovation projects, as it would fail to account for the significant carbon savings associated with material reuse. This approach aligns with guidance from recent studies [42], which encourage practitioners to account for upstream environmental benefits when reused materials substitute for new production.

A particular emphasis of the framework is the inclusion of module D in the calculation of embodied carbon, which captures the potential environmental benefits or loads associated with the reuse, recycling, or recovery of materials at the end of life. For instance, recycled insulation (A3) showed a 55% lower embodied carbon impact than its conventional equivalent (A1) when module D was included and a 23% reduction when module D was excluded. However, as mentioned in the sensitivity analysis, the inclusion of module D did not have a significant impact on the total ranking in this case study. This could be explained by the fact that the levels of carbon savings in module D depend greatly on the end-of-life scenario. The most substantial reductions are achieved when materials are reused, which would be the case if the product had been designed for disassembly. In contrast, recycling or incineration, which were the main end-of-life scenarios of the proposed strategies in this paper, typically result in smaller benefits.

While designing for disassembly represents a promising strategy for future renovations, it was not considered in this study as a feasible solution due to the limited availability of mature, demountable internal wall insulation systems. However, as part of the sensitivity analysis, a hypothetical scenario (H20) for one of the internal wall insulations (A1), assuming design for disassembly and future reuse of PIR insulation, showed that including Module D can significantly impact the ranking when the renovation solution is designed to enable high-value material reuse. H20 embodied emissions when including module D were 47 kg CO_2e, representing a 90% decrease compared to the conventional baseline (A1). This potential benefit of including module D is overlooked in many existing renovation evaluation methods, which tend to focus on cradle-to-gate embodied emissions (A1–A3) [17,22]. Without this consideration, many circular strategies are unfairly penalized, appearing less effective than more linear alternatives. This reinforces the argument made in the recent literature that excluding Module D from carbon assessments leads to the systematic undervaluation of circular options, particularly those involving reuse scholars [26–28].

The framework also introduced the embodied-to-operational carbon ratio (EOCR) as a novel decision-support metric to evaluate the carbon efficiency of interventions over their lifecycle. This ratio enabled the consideration of embodied carbon alongside operational savings, making it particularly useful for distinguishing solutions with high embodied carbon impacts but substantial long-term benefits, such as heat pumps or triple-glazed UPVC windows. Moreover, the results clearly showed that circular insulation options had the lowest EOCR, with a descending order typically observed: reused materials performed best (A4) (0.08%), followed by the hypothetical design for disassembly scenario (H20) (0.14%), then recycled (A3) (0.64), afterward natural (A2) (0.92), and finally traditional insulation materials (A1) (1.45), which exhibited the highest EOCR. The EOCR demonstrates significant advantages when addressing circular economy principles and life cycle carbon emissions compared to the more traditionally used carbon payback period (CPP). While the CPP indicates how long it takes for the annual operational carbon savings of a given solution to offset the initial embodied carbon (A1–A3) [48], it falls short in capturing the full life cycle aspects of building materials. Specifically, the CPP does not account for factors such as replacement cycles or end-of-life benefits (Module D), making it less suitable for assessing circular renovation projects. As a result, the number of years indicated by the CPP may not accurately reflect the long-term carbon efficiency of a measure. When compared to the relative embodied carbon [29], the main advantage of the EOCR is its ability to capture the carbon benefits associated with circular economy strategies. Unlike traditional metrics, the EOCR explicitly accounts for end-of-life scenarios, such as design for disassembly and reuse. For instance, if we apply both metrics to two scenarios, one where PIR insulation is designed for disassembly and future reuse and another where new PIR boards are used, the difference becomes evident. The EOCR yields a value of 0.14% for the design for disassembly scenario (H20) and 1.45% for the new PIR boards (A1), clearly reflecting the carbon savings potential of reusing materials. In contrast, the relative embodied carbon metric, which is calculated as embodied carbon (A1–A3) divided by the total carbon savings over the building's life [29], gives a value of 1.61% for both scenarios.

Importantly, the framework's ability to integrate qualitative criteria such as occupant disruption, aesthetic impact, or comfort improvements makes it particularly well-suited to accommodate the co-benefits of retrofit, which are often omitted from traditional assessments. This aligns with the emerging literature [47] advocating for a broader understanding of renovation value that reflects outcomes like improved indoor air quality, health, and well-being.

5.3. Criteria Weights

Another key strength of the proposed framework is its flexible weighting system, which allows decision makers to tailor the evaluation process to their specific project priorities. In this case study, financial considerations, including cost and payback period, were given the highest importance, reflecting the constraints and priorities of a private homeowner. However, in different contexts such as publicly funded renovation programs, municipal housing, or heritage retrofits, stakeholders may assign greater weight to carbon reduction, material reuse, or occupant health and comfort. This case study also highlights the challenge of balancing stakeholder priorities, particularly when private incentives conflict with policy directions. In this instance, the homeowner's prioritization of cost over carbon savings somewhat skewed the results toward conventional solutions, for example, uPVC windows over wooden frames. One way to bridge the gap between cost and carbon considerations is to ensure access to funding that supports the adoption of circular and sustainable solutions, particularly for private households. Many top-down approaches, such as promoting circular economy principles in new and existing buildings through the Circular Economy Action Plan, need to account for the reality that, at the building level, especially for private homeowners, cost is often the primary driver of decision-making. For circular options to be widely implemented, they must be cost-competitive compared to conventional solutions.

The framework's capacity to adjust criteria weights without altering its overall structure makes it highly adaptable to a wide range of building typologies, ownership models, and policy environments. Similar approaches have been promoted in recent studies on participatory renovation decision-making [49], which call for methods that balance expert knowledge with stakeholder engagement.

5.4. Limitations and Future Research Directions

Despite its strengths, the framework also presents several limitations that should be acknowledged. One of the primary challenges is the time investment required for a full application. Because the framework is designed to evaluate a wide range of quantitative and qualitative criteria, gathering the necessary data can be resource intensive. Additionally, obtaining input from the decision-maker(s), including preference weightings and qualitative feedback (e.g., on disruption or aesthetics), can be time-consuming, especially in projects with multiple stakeholders or limited engagement capacity. Another key limitation relates to the level of expertise required to apply the framework effectively. It relies on the integration of life cycle carbon and multicriteria assessments, which often involve different tools, methods, and knowledge domains. Another challenge associated with the inclusion of module D is the uncertainty associated with predicting end-of-life scenarios. Accurately forecasting how materials will be treated decades into the future, whether they will be recycled, reused, or landfilled, depends on numerous variables, including technological advancements, market dynamics, and policy changes. Module D requires assumptions about future processes that may not materialize [50].

Future research could also focus on applying the framework in different contexts, such as non-domestic buildings or larger-scale renovation projects, to test its adaptability and effectiveness across a broader range of building types and stakeholder settings. Moreover, a future automated version of the proposed framework could be effectively integrated within digital building logbooks, which are increasingly recognized as essential for managing building performance and renovation data. The Circular Economy Action Plan [13] recognizes digital building logbooks as key enablers for circularity. Incorporating the framework into these logbooks would enable the automatic generation of customized step-by-step renovation plans based on up-to-date building data while continuously capturing information on energy performance, material use, and carbon impact. Furthermore, integrating this potential automated version of the framework with BIM and digital twins could significantly enhance its functionality. BIM can serve as a centralized data source, automatically feeding building performance data into the framework, enabling the generation of energy models and supporting more accurate scenario analysis. Digital twins would enable real-time monitoring and dynamic updating of the renovation strategy as building performance data changes over time. Additionally, BIM data could be seamlessly linked with life cycle assessment (LCA) tools, such as One Click LCA, which are already compatible with BIM environments. This combined approach would streamline the calculation of embodied carbon and operational savings, making the framework more efficient, adaptable, and practical for large-scale applications.

6. Conclusions

This paper introduced a new decision-making framework that integrates life cycle carbon assessment with multi-criteria analysis to support circular thermal renovation. The framework enables the multicriteria evaluation and ranking of renovation measures and guides the development of a step-by-step renovation plan. Applied to a residential case study, the framework identified a renovation package that included reused PIR panels for walls and roof insulation, UPVC windows, an air source heat pump, and an MVHR system as the most suitable option based on performance and feasibility. Among the key findings, circular insulation options, particularly those involving reused materials and designed for disassembly, achieved the lowest embodied carbon emissions and lowest EOCR scores, demonstrating superior life cycle carbon performance. For example, reused PIR showed a 94% reduction in embodied carbon compared to new PIR boards. It was found that the impact of including Module D on the ranking of renovation options depends on the type of end-of-life scenario associated with circular options. Measures that enable high-value reuse, such as those designed for disassembly, achieve the greatest carbon savings when Module D is considered. In addition to carbon and cost metrics, the framework accommodated qualitative criteria, such as disruption and comfort, essential for capturing renovation co-benefits like health and well-being, which are often overlooked in conventional assessments. The framework is not specific to anyone building typology or stakeholder context and is therefore universally applicable. It can be adapted to suit different building types, ownership models, and decision-making processes. Future research could develop an automated version of the proposed framework and/or apply the framework to non-domestic buildings, including projects involving multiple stakeholders, to test its scalability and flexibility in more complex settings.

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