A FRAMEWORK FOR CIRCULAR BUILDING RENOVATION: INTEGRATING LCA, C2C, 10R, AND STAKEHOLDER ENGAGEMENT

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ABSTRACT

Background and aim. Circular economy (CE) practices in the built environment require integrating strategies such as life cycle assessment (LCA), cradle-to-cradle (C2C) principles, stakeholder collaboration, and the 10R framework to enhance resource efficiency and minimize environmental impacts across the entire building. However, existing research lacks a comprehensive framework that systematically combines these elements while demonstrating their practical application and addressing stakeholder alignment in real-world scenarios. The aim of this study is to propose a novel framework that integrates LCA, C2C principles, the 10R framework, and stakeholder engagement to advance CE practices in building renovation.

Methods and Data. By applying a mixed-methods approach, this study combines qualitative and quantitative analyses to evaluate CE strategies. The qualitative analysis involves material suitability for reuse, refurbishment, or storage, and explores stakeholder roles within the 10R and C2C frameworks. The quantitative analysis, based on LCA, measures GHG emissions comparing two scenarios using new and reused materials, highlighting potential carbon savings. A case study of a single-family building renovation from Sweden illustrates the practical application of these strategies and emphasizes the importance of stakeholder collaboration in overcoming barriers.

Findings. The findings underscore the importance of strategic material selection and the transformative role of material reuse in achieving long-term carbon savings and minimizing GHG emissions. Incorporating reused materials into building renovation practices can lead to a substantial 94% reduction in GHG emissions compared to using newly produced materials.

Theoretical / Practical / Societal implications. The study demonstrates how circular economy strategies can drive a low-emission building sector, offering practical insights and replicable method for real building projects.

KEYWORDS: Circular economy, Cradle-to-cradle, Life cycle assessment, Reuse, Stakeholder engagement

1 INTRODUCTION AND RESEARCH CONTEXT

The built environment plays a crucial role in the global push toward sustainability, as it is responsible for a significant portion of resource consumption, waste generation, and greenhouse gas (GHG) emissions (Joensuu et al., 2020). The European Union (EU) has introduced various programs and initiatives to encourage stakeholders to transition from a linear to a circular economy (CE), acknowledging the building sector as the largest waste producer and a significant consumer of resources (Giorgi et al., 2022). Both the European Commission and EU member states actively support the adoption of circular strategies, with a goal of full implementation by 2050 (Al-Obaidy, Courard, & Attia, 2022). As such, the transition from a linear economy, characterized by a "take, make, dispose" model, to a CE has become essential for mitigating environmental impacts in this sector (Illankoon & Vithanage, 2023). CE principles aim to optimize the use of resources by designing systems that minimize waste and allow for the

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continuous reuse and recycling of materials. This transition is especially urgent in the building sector, which accounts for nearly 42% of final energy use and approximately 36% of EU-wide GHG emissions (Fabbri et al., 2023). While the potential of CE principles to transform the built environment is increasingly recognized, their practical implementation remains limited, especially to addressing the entire lifecycle of buildings (AlJaber et al., 2023).

To illustrate the practical application of CE strategies, this study focuses on a single-family house building as a case study. Single-family houses represent a significant share of the built environment, contributing notably to resource consumption, energy use, and GHG emissions due to their prevalence and specific design and material requirements (Arceo, 2023; Soust-Verdaguer et al., 2016).

Central to advancing circular practices in the built environment is the application of Life Cycle Assessment (LCA), a widely used methodology that evaluates the environmental impacts of buildings throughout their lifecycle—from material extraction and construction to operation and eventual demolition. LCA provides a comprehensive understanding of a building's environmental footprint, helping stakeholders identify opportunities to reduce resource consumption and minimize negative environmental impacts (Yadav et al., 2024). However, traditional LCA approaches have focused primarily on new buildings and often fail to account for CE principles such as material reuse and recycling (Larsen et al., 2022). Furthermore, LCA is typically confined to system boundaries that do not capture long-term environmental benefits, such as the effects of material recovery and reprocessing (Xing et al., 2022). Consequently, there is a need to expand LCA methodologies to fully integrate CE strategies, particularly in assessing the environmental performance of buildings under circular scenarios.

In fact, the LCA of building materials serves as a valuable tool for addressing this issue and can be applied within different system boundaries (Silvestre et al., 2014). First, "Cradle-to-Gate" focuses on the impacts associated with the production process of building materials. Second, "Cradle-to-Grave" encompasses the impacts of production, the transportation, the operational phase, and the disposal. Finally, "Cradle-to-Cradle" extends to include all impacts from production to the end-of-life, involving avoided emissions beyond the system boundary, as captured in the D module (Petrovic et al., 2024).

Minunno et al. (2020) conducted a study comparing the environmental benefits of reusing and recycling building components, revealing that reused components can reduce GHG emissions by up to 88% compared to recycling. While the recycling of materials such as steel, concrete, and plasterboard is well-established and regulated by policies in several countries, reuse practices offer even greater contributions to a CE. It can be noticed that components designed for disassembly can achieve reuse rates of up to 95%, allowing these products to be restored and reintroduced to the market at the end of their previous service life (Galvez-Martos et al., 2018). Recent LCA studies highlight the critical role of building materials in the overall life cycle of buildings. Consequently, the end-of-life (EOL) phase has gained prominence in the building industry, as currently only 20–30% of construction and demolition waste is reused or recycled (Honic et al., 2021).

A promising framework for supporting the CE transition in buildings is Cradle-to-Cradle (C2C) design, which emphasizes the continuous reuse of materials without degradation (Futas et al., 2019). While C2C principles have been applied to individual building materials and products, their integration into the entire building lifecycle—covering design, construction, and material recovery—remains undiscovered (Allam & Nik-Bakht, 2023). C2C principles could significantly enhance the environmental performance of buildings by ensuring that all materials are reclaimed, reused, or recycled at the end of their service life, thus supporting the broader goals of circularity in construction.

Another critical factor in driving the transition to a CE is effective stakeholder engagement (Munaro & Tavares, 2023). The built environment is inherently fragmented, involving multiple stakeholders, including architects, engineers, contractors, suppliers, policymakers, and building owners. Each stakeholder has distinct interests, expertise, and incentives, which can create barriers to collaboration and hinder the implementation of circular practices (Kaewunruen et al., 2024; Lee et al., 2024). While stakeholder engagement is widely recognized as essential for promoting sustainability, research on integrating diverse perspectives into decision-making—particularly in LCA and C2C contexts—is limited (Larsen et al., 2022; Lee et al., 2024).

Despite the growing emphasis on stakeholder engagement, there is a lack of research on structured methodologies that integrate stakeholder input with established CE assessment tools. Specifically, limited studies explore how stakeholder-driven decision-making can be systematically embedded within LCA and C2C frameworks to facilitate circularity in the built environment.

This paper addresses these gaps by proposing a novel framework that integrates LCA, C2C principles, stakeholder engagement, and the 10R framework to advance CE practices in the built environment. Unlike previous studies, which typically focus on either technical assessments or stakeholder perspectives separately, this research bridges the two by embedding stakeholder collaboration directly into the LCA process, ensuring that decision-making aligns with both environmental performance and practical feasibility.

To demonstrate the framework's applicability, this study evaluates GHG emissions in a real-world case building renovation project, comparing scenarios that utilize new versus reused building materials. Using LCA , the study assesses carbon savings and resource efficiency achieved through material reuse across different lifecycle stages. A

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real-world case study of a single-family house renovation demonstrates the practical application of this integrated approach, presenting how circular strategies—such as refuse, reduce, reuse, refurbish, and recycle—can be implemented in building practices. Furthermore, the study emphasizes the critical role of stakeholder collaboration in overcoming practical barriers and aligning diverse interests, offering actionable insights toward achieving a sustainable, low-carbon built environment.

2 METHODOLOGICAL APPROACH

This study involves a mixed-methods approach, integrating both qualitative and quantitative analyses to evaluate circular strategies for the built environment. The qualitative aspect focuses on assessing the suitability of materials for reuse, refurbishment, or long-term storage within circular scenarios. It also considers the roles of key stakeholders and broader frameworks such as the 10R and C2C principles to provide contextual insights. The quantitative aspect, driven by LCA, offers measurable data on environmental impacts such as GHG emissions and material efficiency. Combining these approaches ensures a comprehensive understanding of the potential environmental, practical, and strategic benefits of transitioning to circular practices in the building sector. This integrated methodology enables a holistic evaluation of the case study, emphasizing both the technical feasibility and the broader implications of circular strategies. This study adopts a multi-faceted approach to evaluate the environmental benefits of integrating circular economy (CE) principles into building renovation processes. A combination of quantitative and qualitative methods is used to analyze greenhouse gas (GHG) emissions and stakeholder roles across the building lifecycle. The methodology includes LCA, application of the 10R framework, and stakeholder mapping to comprehensively assess circular renovation strategies.

2.1 CASE STUDY OVERVIEW

The methodology is demonstrated through a case study of a single-family building with a gross floor area (GFA) of 182 m^2, constructed in the 1970s, located in the city of Växjö, Sweden. The house is of generic classification and has been selected as a representative example of common residential typologies of that era. The building (Figure 1) is currently inhabited and features bearing and non-bearing elements such as partitions, finishes, and cladding, which present significant opportunities for reuse, refurbishment, or recycling.

Figure 1: Exterior view of the case study building.

Comprehensive data, including the building's blueprints in Figure 2 and a draft material quantity in Table 1, provides a foundation for evaluating its material composition and identifying circular strategies.

2.2 SCENARIO DEFINITION

A cradle-to-cradle (C2C) system boundary is used to quantify GHG emissions across all stages of the building lifecycle. Two renovation scenarios are defined for comparative analysis:

- Scenario 1 (Conventional): Utilizes all newly produced materials except concrete.
- Scenario 2 (Circular): Assumes the building is composed of all reused materials, aligning with CE principles.

This approach allows for a comparison of the environmental impacts of new versus reused materials in the building following the C2C approach. Further, Scenario 1 explores how the GHG emissions from newly produced building materials vary between different lifecycle stages. In Scenario 2, the study evaluates GHG emissions from reused materials across different lifecycle stages. This scenario incorporates CE principles and the 10R framework to explore strategies that minimize waste and extend material lifecycles. The environmental impacts of these circular strategies are analyzed using LCA, comparing them to conventional renovation practices in Scenario 1 to highlight the potential benefits in reducing GHG emissions. Both scenarios are developed to align with C2C design principles, emphasizing the circularity of materials without degradation.

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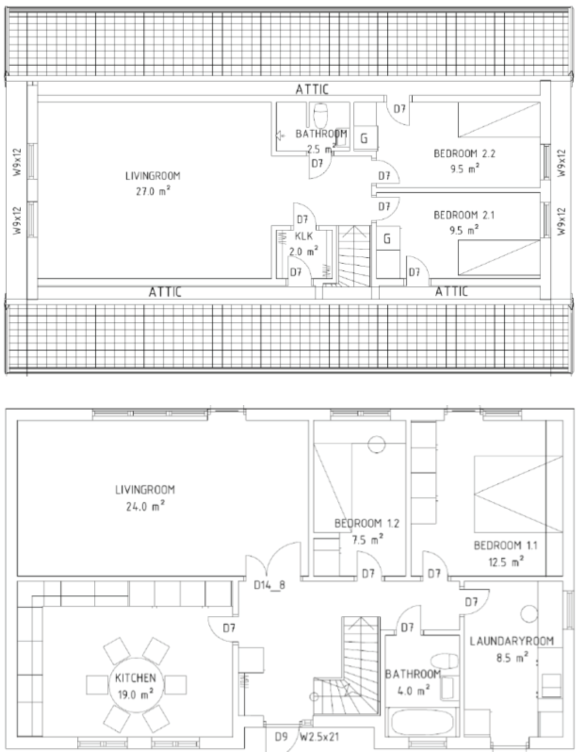

Figure 2: Drawings including first floor and ground floor.

The analysis is conducted using One Click LCA software following the C2C system boundary, assess GHG emissions across all life cycle stages, including production (A1-A3), transport (A4), construction waste (A5), material replacement and refurbishment (B4-B5), end-of-life processes (C2-C4), and avoided emissions (D).

The lifespan chosen for assessment is 50 years. Only windows (40 years), asphalt layer (30 years) and PE layer (20 years) were assumed to be replaced during the building's lifetime. Further, the construction waste percentage and the end-of-life waste treatment for each material is based on Swedish market practices, including energy recovery scenario for all materials that were incinerated (Table 1).

2.3 MATERIAL ANALYSIS

A detailed material inventory is created by analyzing the draft material quantities shown in Table 1. This inventory identifies non-bearing elements by type—such as brick, wood, gypsum, concrete and metal—and evaluates their condition and suitability during the end-of-life processes. Each material is assessed against the 10R framework, prioritizing strategies such as reuse, refurbishment, and recycling to maximize circularity. Factors such as the ease of disassembly, material durability, and the potential for repurposing are considered to determine their viability within the two scenarios. This material analysis serves as a critical input for both the environmental impact evaluation and the proposed circular strategies.

Table 1: Input materials and waste processing.

Building material	Volume (m^3)	Mass (kg)	Construction Waste %	End of life process
Brick	12,36	24712	5,0	Crushed to aggregate
Particle board	1,77	1219	16,7	Incineration
Concrete (foundation)	11,10	26633	0	Crushed to aggregate
Windows	0,04	93	Not available	Not available
Gypsum	13,44	10753	12,5	Recycling
Metal stairs	0,04	287	7,5	Recycling
Glass wool insulation	78,12	10156	8,0	Landfilling
PE Layer	0,28	252	10,0	Landfilling
Roof ceramic tiles	3,73	7464	5,0	Crushed to aggregate
Asphalt layer	0,93	970	Not available	Not available
Timber	22,11	12379	17,9	Incineration
Wood Board	24,92	16694	17,9	Incineration

2.4 INTEGRATION OF LCA, C2C, AND THE 10R FRAMEWORK

LCA method is used to quantify the environmental impacts of the two scenarios, with system boundaries extending from cradle-to-grave to cradle-to-cradle. The analysis emphasizes GHG emissions, resource efficiency, and waste generation, providing a quantitative basis for comparing circular renovation strategies with traditional practices. C2C principles guide the design of these strategies, ensuring that materials are reused or recycled in a manner that avoids degradation and reduces reliance on virgin resources. The 10R framework further informs the analysis by mapping circular strategies—such as refusal, reduction, reuse, refurbishment, and recycling—across each stage of the building lifecycle. Together, these frameworks enable a comprehensive evaluation of CE potential within the case study.

2.5 STAKEHOLDER CONSIDERATION IN SCENARIOS

Although this study does not engage stakeholders directly, it identifies key participants and their roles are essential for implementing circular strategies. Key stakeholders are identified and their roles are analyzed across lifecycle phases: production, transport, construction, use, and end-of-life. Stakeholders include architects, designers, contractors, deconstruction specialists, homeowners, material banks, and policymakers. Their contributions are evaluated based on their influence on material choices, resource management, and emissions control. Collaborative strategies are proposed to align stakeholder actions with CE objectives.

In the renovation scenario, architects and designers are responsible for incorporating reused or refurbished materials into the renovation plan while maintaining the building's functional and aesthetic quality (Passoni et al., 2021). Contractors play a critical role in disassembling and preparing materials for reuse (Dams et al., 2021), while homeowners influence the adoption of circular practices as the primary decision-makers (Kaewunruen et al., 2024). In the future renovation scenario, deconstruction specialists ensure the careful recovery of materials to preserve their quality, and material banks facilitate long-term storage and tracking of reusable components (Oliveira et al., 2024). Policymakers and regulators are also highlighted as pivotal in creating standards and incentives to support material reuse (Nußholz et al., 2019). These considerations provide a framework for understanding the collaborative nature of circular practices in the building sector, even without direct engagement.

2.6 EVALUATION METRICS

The evaluation of the two scenarios is based on a combination of quantitative and qualitative analysis, derived from a structured analysis of material use, environmental impact, and circularity potential. The quantitative analysis evaluates GHG emissions and explores their reduction potential by comparing two renovation scenarios. Using the LCA method, the study provides a comprehensive, data-driven evaluation of positive (released) and negative (avoided) impacts.
Qualitative metrics, informed by literature and established frameworks such as the 10R and C2C principles, assess the practicality and circularity potential of the proposed strategies. This includes evaluating factors such as the feasibility of material recovery, storage, and reuse based on typical practices in the building sector, as well as alignment with industry standards and policy trends. By integrating these perspectives, the analysis provides a comprehensive evaluation of the scenarios, highlighting their technical, environmental, and strategic implications without relying on direct stakeholder input.

3 FINDINGS

3.1 ANALYSIS OF SELECTED SCENARIOS

The results presented in Figure 3 compare GHG emissions across LCA stages using new materials (Scenario 1) versus reused materials (Scenario 2). The production process (A1-A3) significantly contributes to emissions in Scenario 1, while Scenario 2 demonstrates a significant reduction in this stage due to the use of reused materials and used cut-off method. The transport emissions and construction waste emissions are zero as the Scenario 2 assumes that all materials from the existing building are reused. Thus, the total impact is substantially lower in Scenario 2, representing 94% reduction and highlighting the environmental benefits of material reuse. Additionally, the D module (avoided emissions) offsets emissions in Scenario 1 (new materials) by accounting for the avoided impacts of future material recycling, reusing and using as energy substitution in district heating after incineration process. However, in Scenario 2 (reused materials), the D module does not account for additional avoided emissions, as the credits are already allocated during for primarily used materials. This underscores the long-term carbon savings potential of material reuse compared to the reliance on newly produced materials.

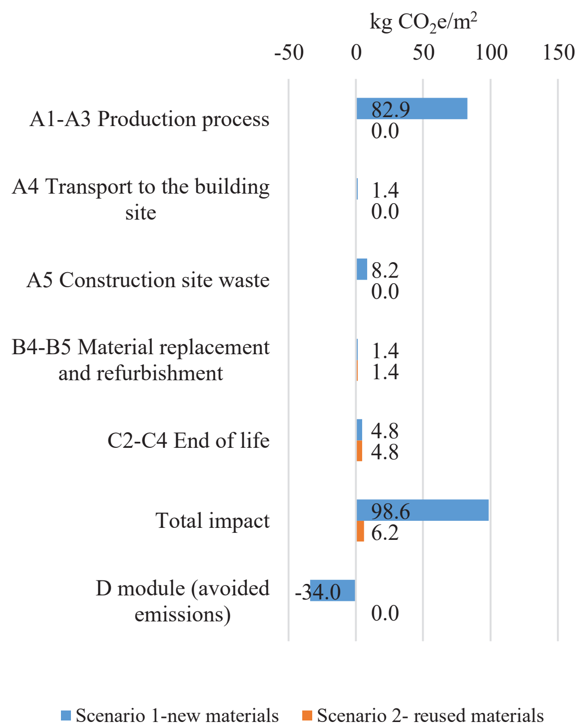

Figure 3: Comparison of GHG emissions between new and reused materials across different LCA stages.

Figure 4 shows GHG emissions across LCA stages for new materials in Scenario 1. The production stage (A1-A3) is the largest contributor, especially for brick, gypsum, and roof ceramic tiles. The only material that is not changed during renovation is concrete installed in the foundation. Transport (A4), construction waste (A5), replacement (B4-B5) and end-of-life (C2-C4) stages have relatively minor emissions. The D module indicates avoided emissions for materials such as timber, wood board and metals, highlighting potential future benefits through recycling or energy recovery. This emphasizes the importance of material choice in minimizing GHG impacts.

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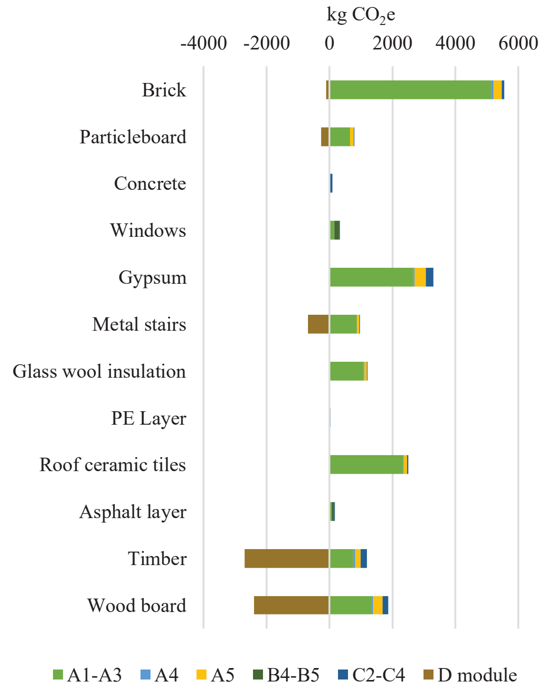

Figure 4: Scenario 1 - GHG emissions across LCA stages for new materials.

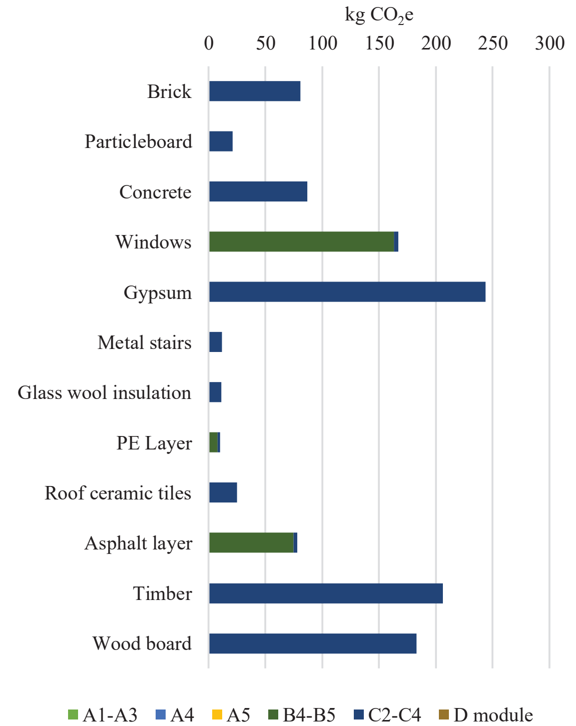

Figure 5: Scenario 2 - GHG emissions across LCA stages for reused materials.

Figure 5 presents GHG emissions across LCA stages for all reused materials in Scenario 2. The production stage (A1-A3) has zero emission contribution as the cut-off method is used. Further, the transport emissions (A4) and construction waste emissions (A5) remain zero as the reused materials are inserted from the existing building. The highest emissions are noticed at the end of life (C2-C4) for gypsum, timber, and wood board during the waste processing stage, followed by the replacement of materials (B4-B5). The D module remains zero as the benefits during recycling/reusing/energy recovery processes are counted in the newly produced products.

3.2 INTEGRATION OF THE 10R FRAMEWORK AND STAKEHOLDER CONSIDERATION IN SCENARIOS

To assess the environmental impacts across the building lifecycle in our different scenarios, we have analysed the application of circular strategies, framed within the 10R principles. The primary objective was to identify and map theoretically how different stakeholders contribute to achieving the environmental benefits of material reuse, as opposed to new material use, while integrating the principles of Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. Each stakeholder's role is aligned with specific stages of the building lifecycle, ensuring that the implementation of these strategies is both practical and effective.

The identification of relevant stakeholders was informed by insights gained from the literature review and an understanding of common practices in the building industry. The focus was on stakeholders typically involved in the design, construction, operation, and demolition of a single-family house. These include architects, designers, contractors, deconstruction specialists, homeowners, material banks, and policymakers. The selection of these stakeholders was based on their established influence over material choices, resource management, waste reduction, and emissions control at each lifecycle stage, as identified in previous studies and industry reports. By considering their roles, it was possible to link specific circular strategies to each stakeholder's influence on the project's environmental outcomes.

3.2.1 Production Phase

Including the principles of Reduce, Reuse, and Repair, the industry can significantly lower energy consumption, minimize waste, and cut GHG emissions, fostering a more sustainable and efficient construction process. Table 2 summarizes these principles, compares emissions across two scenarios, and highlights key stakeholders in sustainable material production. It emphasizes the significant impact of material choices on emissions and underscores the role of stakeholders in promoting practices that reduce the environmental footprint of the building industry.

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Table 2: Production phase strategies and impacts.

Element	Description
Principles	**Reduce**: Minimize the need for new materials by choosing alternatives such as reused materials. **Reuse**: Use materials that are still in good condition, recovered from demolition or deconstruction. **Repair**: Restore damaged or deteriorated materials instead of replacing them, extending the life of existing materials.
Scenario 1	Relies on new materials, leading to high emissions due to energy-intensive manufacturing processes and raw material extraction.
Emissions Impact (Scenario 1)	Significant emissions from material production (A1-A3) and raw material extraction, contributing to a large environmental footprint.
Scenario 2	Utilizes reused materials, reducing the need for new production and lowering emissions.
Emissions Impact (Scenario 2)	Major reduction in emissions from material production.
Stakeholders	**Architects and designers**: Incorporate reused and refurbished materials into designs. **Contractors**: Reuse materials locally to minimize transport emissions and contribute to disassembling buildings for reuse. **Deconstruction specialists**: Recover reusable materials from existing structures. **Policymakers**: Support circular production processes and incentivize the use of reused materials to reduce emissions.

3.2.2 Transport Phase

By adopting the principle of Reduce, the industry can lower transportation emissions and enhance sustainability. Table 3 compares the emissions of sourcing materials locally versus long-distance transportation. It also identifies key stakeholders involved in reducing transportation emissions, emphasizing the optimization of logistics and the promotion of local sourcing to minimize the overall carbon footprint of construction projects.

Table 3: Transport phase strategies and impacts.

Element	Description
Principle	**Reduce**: Minimize transportation emissions by sourcing materials locally and optimizing logistics, reducing the need for long-distance transportation.
Impact of Reduce	Reduces emissions associated with material transport, lowers the carbon footprint of construction projects, and minimizes inefficiencies in logistics.
Scenario 1 and 2	Sourcing materials locally, reducing the need for long-distance transport and improving logistics to lower emissions.
Emissions Impact (Scenario 1 and 2)	Substantial reduction in transportation emissions through localized sourcing and improved logistics efficiency.
Stakeholders	**Contractors**: Optimize logistics and coordinate local sourcing to minimize transportation emissions. **Logistics managers**: Ensure efficient delivery and minimize fuel consumption. **Policymakers**: Introduce policies that incentivize local sourcing and transportation efficiency to reduce emissions. **Architects & Designers:** Source local reused products/materials to incorporate in their projects to minimize transportation needs.

3.2.3 Construction Phase

By applying the principles of Reuse, Repair, and Refurbish, emissions and resource consumption can be significantly minimized. Table 4 identifies key stakeholders involved in implementing these principles to reduce waste and resource use. Focusing on reusing materials, repairing components, and refurbishing of materials allows the building industry to lower its impacts and contribute to a CE.

Table 4: Construction phase strategies and impacts-integration.

Element	Description
Principles	**Reuse**: Saves materials from previous projects to reduce demand for new resources and prevent waste. **Repair**: Restores or fix building components to extend their lifespan. **Refurbish**: Updates outdated materials to avoid full replacement.
Impact of Principles	**Reuse**: Reduces emissions from material production by avoiding new manufacturing. **Repair**: Saves resources and minimizes waste by extending material lifespans. **Refurbish**: Promotes resource efficiency and reduces the need for new material production.
Scenario 1	Relies on new materials and potential waste during construction phase
Emissions Impact (Scenario 1)	High emissions from material production (A1-A3) and significant contributions from waste generation during construction (A5).
Scenario 2	Integrates reused materials, repairs, and refurbishments to reduce the need for new production, thereby lowering emissions to zero.
Emissions Impact (Scenario 2)	Zero emissions from production phase due to cut-off method, and no waste in (A5) as the all materials are sourced from existing building.
Stakeholders	**Contractors**: Execute repairs and integrate salvaged materials. **Deconstruction specialists**: Salvage and prepare materials for reuse. **Material banks**: Store and track reusable materials.

3.2.4 Use Phase

Using the principles of Reuse, Repair, Refurbish, and Remanufacture, the building industry can significantly reduce the need for new resources, lower emissions, and minimize waste. These practices ensure that materials are maintained, repurposed, and extended in their lifecycle, contributing to sustainability and the promotion of a CE. Table 5 summarizes these principles, outlines their impacts on emissions, compares different scenarios in terms of sustainability, and identifies the stakeholders involved in maintaining and extending the lifecycle of materials.

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Table 5: Use phase strategies and impacts.

Element	Description
Principles	**Reuse**: Ongoing reuse of materials to extend their lifecycle and reduce the need for new resources. **Repair**: Regular repair and maintenance to preserve the functionality of materials. **Refurbish**: Upgrading or improving existing materials to meet modern standards with minimum replacement. **Remanufacture**: Processing old materials into new components to reduce waste and demand for raw materials.
Impact of Principles	**Reuse**: Reduces the need for new material production, lowers emissions and conserves resources by extending the lifecycle of building materials. **Repair**: Minimizes resource consumption and waste generation by repairing rather than replacing. **Refurbish**: Extends the life of existing systems materials, reducing the demand for new materials and if necessary, replacing them with reused options. **Remanufacture**: Supports a CE by converting old materials into usable new products, reducing raw material extraction.
Scenario 1 and 2	Relies on new materials for repairs and replacements, leading to emissions from material production and resource extraction.
Emissions Impact (Scenario 1 and 2)	Emissions due to the production of new replaced materials (B4-B5). Uncertain which materials will be replaced-depending on occupant preferences and the nature of building materials.
Stakeholders	**Homeowners**: Make decisions regarding the replacement, repair, and refurbishment of materials to extend their lifecycle. **Contractors**: Offer consultancy on which materials can be repaired, refurbished, or replaced. They provide technical expertise on how to maintain or upgrade materials to meet modern standards while minimizing waste and emissions. Additionally, they execute repairs and refurbishments to extend the lifespan of materials, contributing to sustainability and efficient resource use. **Deconstruction Specialists:** Provide consultancy on which materials can be salvaged for reuse or remanufacture. They evaluate building elements for potential repurposing, contributing to the circular economy by minimizing waste during demolition and renovation projects. Additionally, they facilitate material recovery at the end of the building's life, ensuring materials are available for reuse or remanufacturing.

3.2.5 End-of-Life Phase

By applying the principles of Repurpose, Recycle, and Recover, construction projects can effectively reduce waste, minimize the demand for new resources, and contribute to a CE. Table 6 summarizes these key principles, their impacts on emissions, and the stakeholders involved in managing materials at the end of their lifecycle.

Table 6: End-of-life strategies and impacts.

Element	Description
Principles	**Repurpose**: Find new uses for building (adaptive reuse) components that are no longer serving their original function, reducing waste. **Recycle**: Process materials into new products to reduce the need for virgin materials. **Recover**: Extract energy or materials from waste to be used in other industries, reducing overall environmental impact.
Impact of Principles	Repurposing extends the life of materials, reducing disposal waste. Recycling reduces the demand for raw materials and conserves resources. Recovery minimizes the environmental footprint by extracting useful energy or materials from waste.
Scenario 1	Focuses on recycling (C2-C4) and energy recovery processes (D module). Wooden materials are firstly incinerated, then used as energy recovery in district heating. While metals are recycled.
Emissions Impact (Scenario 1)	Recycling and energy recovery in Scenario 1 show potential benefits for long-term carbon savings, although it doesn't account for the carbon savings of material reuse.
Scenario 2	Emphasizes the reuse of materials, with some waste processing required for materials such as gypsum, timber, and wood boards.
Emissions Impact (Scenario 2)	Reuse in Scenario 2 reduces the need for new production, contributing to carbon savings.
Stakeholders	**Deconstruction specialists**: Disassemble buildings, recover materials for repurposing, recycling, or energy recovery. **Contractors**: Manage disposal, recycling, or recovery at the end of the lifecycle. **Material banks**: Store and repurpose materials for future use. **Policymakers**: Set standards and offer incentives to support adaptive reuse, recycling, and energy recovery. **Architects and Designers:** Design to adapt existing spaces to new functions and repurpose materials in existing buildings for new design projects.

4 DISCUSSION AND CONCLUSIONS

This study critically evaluated the environmental impacts of materials in building renovation by comparing two scenarios: new materials (Scenario 1) and reused materials (Scenario 2) in a building. The results illustrate the environmental benefits of material reuse, with Scenario 2 demonstrating a significant reduction in GHG emissions, primarily due to the cut-off method applied to reused materials. By incorporating reused materials, Scenario 2 achieved an approximate 94% reduction in GHG emissions compared to Scenario 1, which relies on newly produced materials. This reduction was most evident in the production phase (A1-A3), where new materials, particularly resource-intensive ones contribute substantially to the overall carbon footprint. In contrast, the emissions in Scenario 2 during this phase were zero, as the cut-off method is used.

While the production phase reveals the most significant differences between the two scenarios, other lifecycle stages—A4, A5, B4-B5, and C2-C4 show relatively low GHG emissions. These stages are influenced by various factors, such as transport distances, the choice of waste management practices, and the extent to which materials are replaced or refurbished.

When deciding to use reused materials instead of newly produced ones, several uncertainties arise over the building's lifecycle. For example, the replacement rate is influenced by the nature of materials used (new or reused) during the use phase, as well as by the occupant preferences. Furthermore, transport distances for new materials (Scenario 1) are based on distances by using generic Nordic data. While the transport distance for reused materials is not applied as all materials are derived from the existing building. The construction waste was only calculated for newly produced materials, while for reused materials it remains zero due to utilized materials from the existing building. Thus, prioritizing Scenario 2 over Scenario 1, presents a great potential to prolong the service life of building materials.

The avoided emissions in the D module, accounting for the future recycling, reuse, or energy recovery of materials, further highlight the long-term carbon savings potential of material reuse. For Scenario 1 (new materials), the D module captures the avoided emissions from future material recycling and energy recovery, but these benefits do not exist in Scenario 2, where material reuse has already been credited for the new products.

These findings highlight the importance of strategic material selection of reducing the environmental impact in renovation projects. The choice of materials, whether new or reused, directly influences the GHG emissions associated with a building's lifecycle.

To achieve the full environmental benefits of material reuse, collaborative efforts among stakeholders are essential. The integration of CE principles, such as reuse, repair, and refurbishment, into building renovation requires the active involvement of a diverse group of stakeholders, each with a unique role in influencing material choices and construction practices. Architects and designers, for instance, play a crucial role in specifying and integrating reused materials into building designs, ensuring that the potential environmental benefits of these materials are fully realized. Their decisions during the design phase have a direct impact on the feasibility and effectiveness of material reuse strategies in the construction phase. Furthermore, contractors and deconstruction specialists are vital in sourcing, disassembling, and salvaging materials for reuse, ensuring that valuable materials are not wasted but rather reincorporated into the building cycle. These professionals must also address the technical challenges associated with material reuse, such as ensuring that reused materials meet the required performance standards for safety and durability.

In addition to these industry stakeholders, policymakers play a key role in shaping the broader framework within which material reuse can increase. The development of supportive regulations and financial incentives is essential for encouraging the adoption of reused materials and CE practices across the building sector. Policymakers can foster an environment where the use of reused materials is not only encouraged but made economically viable through incentives such as tax credits, subsidies, or grants. Furthermore, the establishment of regulations that require or incentivize the reuse of materials, as well as the recycling and recovery of materials at the end of their life, will drive the industry towards more sustainable and circular practices. This includes setting standards for material recovery, creating certification systems for reused materials, and promoting the development of material banks to store and track reusable resources.

In conclusion, this study confirms that material reuse is a powerful strategy for reducing the carbon footprint of building renovation projects and advancing the principles of the CE. The integration of reused materials into construction practices offers substantial GHG reductions, particularly in the production phase. However, the potential of material reuse can only be fully realized through collaborative action across all sectors of the building industry, supported by strong policy frameworks that incentivize sustainable practices. By aligning the efforts of architects, designers, contractors, deconstruction specialists, and policymakers, the building industry can significantly contribute to reducing GHG emissions and promoting a more sustainable built environment.

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