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Assessing the Environmental Impact of Demountable Space-Dividing Walls: A Scenario Analysis Approach in a Semi-Detached Case Study Dwelling

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Abstract: The transition towards sustainable construction is crucial, and demountable building elements are frequently advocated for achieving this goal. While these elements offer relocatability during refurbishments, their adoption may increase initial environmental impact due to higher material use and steel connections. To address this, a quantitative assessment of demountable building elements in refurbishment scenarios at the building level is needed, filling a gap in the existing literature. This study bridges the gap by comparing the total environmental impact of demountable and traditional space-dividing walls in refurbishment scenarios for a semi-detached dwelling. Using a life cycle assessment, seven space-dividing wall types, including metal studs, wood structures, and masonry walls, are evaluated under four refurbishment scenarios spanning a 60-year building lifespan. The results reveal that traditional metal stud walls have a lower environmental impact in scenarios with limited refurbishments. In contrast, demountable walls become more environmentally beneficial only when refurbishing at least 60% of the wall area with three or more refurbishments. This conclusion was further validated through sensitivity analysis on the refurbishment rate, refurbished area, and impact assessment method. In this study, the assumed environmental benefits of demountable walls are challenged, providing a robust evaluation in a specific building typology and offering insights for policymakers and industry professionals on the environmental implications of incorporating demountable building elements.

Keywords: circularity; demountable building elements; quantitative assessment; Life Cycle Analysis; scenario analysis; space-dividing walls; environmental impact; sensitivity analysis

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1. Introduction

'There is no planet B' [1]. The rising needs and demands of more than 7.9 billion people have transformed land and water use significantly, generated unprecedented levels of pollution, and affected biodiversity. Currently, the environmental crisis is a hot topic, both literally and figuratively. The building sector exerts a colossal impact on the environment through its current linear construction model, encompassing the 'take-make-use-dispose' approach for buildings and building products. In Europe, the construction sector is responsible for 40 percent of the energy consumption, 36 percent of the emissions of greenhouse gasses, 40 percent of the extracted raw materials, and 65 percent of the waste streams [2–4]. To mitigate this impact, it is crucial to develop a more sustainable built environment with enhanced resource efficiency, reduced waste generation, and lower carbon emissions.

A frequently advocated strategy for facilitating this transition involves embracing the concept of circular construction [5]. The circular economy is defined as 'a regenerative system, in which the resource input and waste, emission, and energy leakage are minimized, according to three strategies: closing, narrowing, or slowing material and energy loops' [6]. In closing loops, the aim is to reuse or recycle materials at the end of their life. Narrowing loops means reducing resource use. Slowing loops involves extending the lifespan of building elements and introducing flexibility and reversibility [7]. To slow the material loop within circular strategies, flexible building element designs can be opted for. These designs allow for easy adaptation, incorporating demountable building elements that can be repurposed. This approach helps avoid premature building (element) demolitions due to static, single-use designs [8]. Indoor spaces in buildings frequently undergo refurbishments to meet users' needs, such as merging distinct rooms to form larger, open areas. This underscores the significant potential for repurposing space-dividing walls during building refurbishments [8,9].

It is essential to quantitatively assess the demountable building strategy's efficacy in achieving this transition, given its prominence in the current academic literature and building sector policy documents [9]. While enhancing the flexibility of building components holds great potential, it does not automatically guarantee environmental benefits. Embracing demountable building principles often involves increased material usage, with many reversible connections relying on steel. This has the potential to increase the initial environmental impact [10–12]. However, by considering the entire life cycle, the environmental impact of demountable building elements may decrease compared to their traditional counterparts. Additional refurbishments in a building's life cycle contribute significantly to its overall environmental impact, as traditional elements are often demolished and replaced. The potential for lasting environmental benefits lies in the use of demountable building elements, which can be easily disassembled and reconstructed. Consequently, it is crucial to assess potential refurbishment scenarios during the building's life cycle [8,12]. Comprehensive research on the long-term environmental advantages of demountable building elements is essential to showcase their role in advancing sustainability in the building industry.

The assessment of the environmental impact of demountable building elements in the literature is still limited [13]. Previous studies have recognized the Life Cycle Analysis (LCA) framework as an important methodology for this assessment [14]. LCA is an assessment tool in which environmental impacts are connected to the relevant inputs and outputs of a product system, including raw materials, energy and water usage, emissions to the air, land, and water, waste, co-products, and other releases [15]. Nonetheless, this methodology is primarily oriented towards a linear approach, wherein the benefits of material reuse and recycling lie beyond the system boundaries of LCA, as outlined by standards NBN EN 15804 and 15978 [16,17]. In response, several methodological papers have emerged to incorporate these aspects into the LCA methodology [8,12,13,18,19]. However, only a handful of case studies have effectively employed these developed frameworks to assess the impact of demountable building elements [8,9,20]. There are few LCA studies that compare the environmental impact of demountable and traditional building elements, but these often rely on hypothetical case studies at the element level, with theoretical scenarios regarding reuse considered [8,9,20].

The work of Vandenbroucke presents an LCA framework comparing the environmental impact of traditional and demountable building elements [20]. This analysis is conducted at the element level (for 1 m^2) for different types of walls, floors, and ceilings, considering assumed theoretical refurbishment rates. The research results indicate that demountable walls have a greater potential for a lower environmental impact compared to traditional walls, especially in scenarios involving refurbishments [20]. The potential environmental impact savings of demountable partition walls are also explored in Buyle's study [9]. This theoretical study considers various end-of-life scenarios for interior walls, recycling, reuse, and incineration, at the element level. The evaluated demountable partition walls demonstrated a lower or at least similar environmental impact compared to traditional walls. However, the paper emphasized that results at the element level may not be generalized and should be applied to real case studies and different building types for informed decision-making [9]. In response to this, Rajagoplan's study modeled and assessed refurbishment scenarios for the Retrofit Lab in Brussels [8]. Using these scenarios, they identified interior walls in the floorplan with high (every year), medium (every 10 years), and low (every 15 years) refurbishment rates. Subsequently, they compared the environmental impact of each wall at the element level for the three refurbishment rates and selected the wall with the lowest environmental impact. In all three scenarios, the demountable wall yielded the lowest impact [8].

Quantitative research on the environmental impact of applied demountable solutions at the building level, considering refurbishment scenarios, remains scarce. Advancing sustainability in the construction industry necessitates comprehensive research on the environmental implications of integrating demountable building elements into specific building typologies. In this paper, a critical gap is addressed by quantitatively assessing the environmental impact of demountable building solutions in real refurbishment scenarios, a domain underexplored in the current literature.

Diverging from previous studies focused solely on element-level analysis, this study pioneers a quantitative assessment of demountable interior walls within a specific building typology—the semi-detached house, constructed with circular design principles. Original construction plans are utilized to evaluate the environmental impact of space-dividing walls with predefined refurbishment scenarios reflecting refurbishment activities over the case study house's lifespan. By comparing the environmental impact at both element and building levels, this study provides practical insights into the environmental impact of building elements and materials over the building's lifetime. The inclusion of sensitivity analysis on diverse impact assessment methods, refurbishment area, and refurbishment rate enhances the results, offering robust and applicable findings. This contributes to a more nuanced understanding of the environmental (dis)advantages associated with demountable building solutions, providing valuable insights for adopting such solutions in buildings.

2. Materials and Methods

2.1. Research Steps

This case study evaluated the environmental impact of adopting demountable interior walls compared to traditional partition walls at both the element and building levels within an existing semi-detached dwelling. This study is comprised of three sequential research steps, outlined in Figure 1.

In the first step, a pilot dwelling with a geometric profile representative of typical residential structures in Flanders was examined for the incorporation of circular strategies. Building plans and sections were thoroughly analyzed to assess adaptability for future alterations. Subsequently, an analysis of commonly used traditional and demountable walls in the Belgian construction sector was conducted to identify the most applicable wall types.

Moving to the second step, the interior wall types and refurbishment scenarios in the pilot dwelling were defined. Seven possible options, including metal studs, wood structures, and masonry walls, were identified from the analysis in the first step. The examination of the pilot dwelling's built-up emphasizes its potential for accommodating refurbishments, leading to the presentation of four refurbishment scenarios. These scenarios, grounded in shifts in owners' functional requirements, were applied to the model house, necessitating adjustments to the floorplan.

The third step involved analyzing the environmental impact and performing a sensitivity analysis, using LCA at both the element, and building scenario levels. At the element level, the examination involved assessing the production, construction, replacement, and end-of-life impact of a 1 m^2 interior wall. The focus was on identifying the most environmentally beneficial wall and analyzing specific materials with the most significant environmental impact. This approach provides a comprehensive understanding of the walls and the reasons for their environmental impact.

Subsequently, these results were extrapolated to the building scenario level by multiplying them with the refurbished area and rates of the refurbishment scenarios, integrating the impact of refurbishments into these calculations. This assessment aids in pinpointing the interior wall with the lowest environmental impact for refurbishment scenarios, offering insights into whether demountable walls genuinely provide advantages in these contexts. Finally, a sensitivity analysis explored the reliability and robustness of the results by considering the refurbished area, refurbishment frequency, and impact analysis methodology.

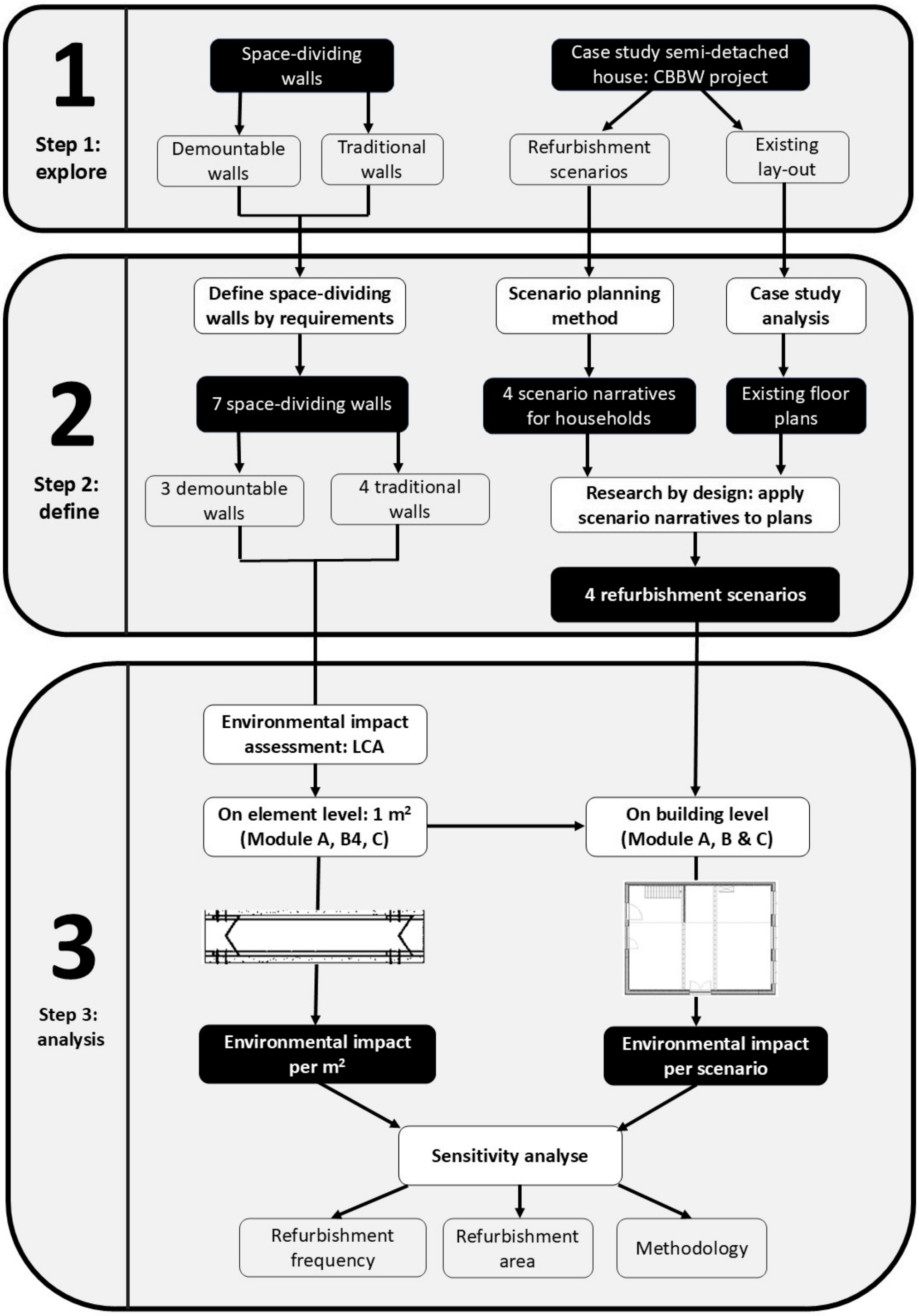

Figure 1. Schematic representation of the research steps.

2.2. Case Study Dwelling

In this study, the focus was on a single-family house in Berchem, designed by Mike-ViktorViktor architects and TEKEN architecture, with construction managed by BOUD, Systimber, and Itho Daalderop. This house is part of the 'Circular Building Affordable Housing' project, a two-year initiative funded by the Flemish government through the Circular Flanders Initiative [21]. This project aims to implement adaptive design and construction strategies in a pilot dwelling, creating affordable circular architecture for individuals in the Flemish housing market.

Constructed between 2021 and 2022, the dwelling has an eight by six-meter footprint and comprises three levels with a total height of nine meters. The design incorporated various circular principles, emphasizing demountability and flexibility. Notably, the façade used demountable bricks, load-bearing interior walls utilized demountable solid wood construction, and space-dividing walls were made from demountable metal stud partitions. The structural support centered around a load-bearing technical core and facades, providing maximum flexibility for interior walls. The adaptable open-plan layout, as depicted in Figure 2, and reversible connection techniques were designed to facilitate future refurbishment and reorganization scenarios [21].

Figure 2. Single-family dwelling: Photo (**a**), section (**b**), floorplan +0 (**c**), and floorplan +1/+2 (**d**).

2.3. Interior Wall Systems

In this study, seven interior wall systems were considered, detailed in Table 1 and illustrated in Figure 3. All walls complied with the technical specifications of non-load bearing, acoustic partition walls, achieving a sound performance rating of at least 43 dB, per the Belgian standard NBN S 01-400-1 for enhanced acoustic comfort in dwellings [22].

Table 1. Overview of wall assemblies' composition. Blue marked materials indicate demountable elements.

Wall Type	Substructure	Finishing Panel	Insulation	Paint
Demountable wall: Metal stud with Plasterboard (CIR_MS_PLA)	2 × Demountable metal stud (75 mm) 8 × Screws (25 mm)	2 × Gypsum plasterboard (12.5 mm)	Glass wool (60 mm)	2 × Acrylic paint (0.01 mm)
Demountable wall: Metal stud wall with MDF (CIR_MS_MDF)	2 × Demountable metal stud (75 mm) 4 × Tape (0.25 mm)	2 × MDF finish (8 mm)	Glass wool (60 mm)	2 × Acrylic paint (0.01 mm)
Traditional wall: Metal studs (TRA_MS)	2 × Metal Stud (75 mm) 8 × Screws (25 mm)	2 × Gypsum plasterboard (12.5 mm)	Glass wool (60 mm)	2 × Acrylic paint (0.01 mm)
Demountable wall: LVL structure (CIR_LVL)	2 × LVL structure (80 mm) 24 × Screws (35 mm)	4 × Gypsum plasterboard (12.5 mm)	Glass wool (60 mm)	2 × Acrylic paint (0.01 mm)
Traditional wall: Wooden structure (TRA_WOOD)	2 × Hardwood structure (75 mm) 24 × Screws (35 mm)	4 × Gypsum plasterboard (12.5 mm)	Glass wool (60 mm)	2 × Acrylic paint (0.01 mm)
Wet wall: Ceramic bricks (TRA_CER)	Ceramic hollow bricks (88 mm) Cement mortar	2 × Plaster (12.5 mm)	/	2 × Acrylic paint (0.01 mm)
Wet wall: Aerated concrete (TRA_AER)	Aerated concrete (100 mm) Adhesive mortar	2 × Plaster (12.5 mm)	/	2 × Acrylic paint (0.01 mm)

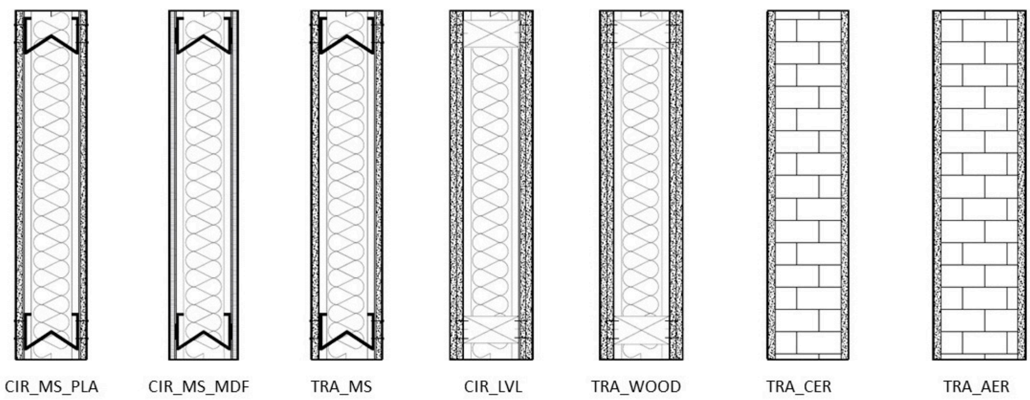

Figure 3. Section of the seven investigated wall assemblies.

The four traditional wall types were identified based on a study of commonly used interior walls in the Belgian construction sector [23]. These included dry walls with wooden or metal stud structures and masonry walls constructed using aerated concrete or hollow ceramic building blocks, categorized as 'traditional' due to the inability to reuse their materials. The analysis also encompassed three demountable interior walls. Two were demountable metal stud walls: one used in the case study house with a demountable medium-density fiberboard (MDF) finish, and the second featuring a gypsum plasterboard finish. Additionally, a third demountable wall, common in wood skeleton construction, featured a laminated veneer lumber (LVL) structure with a gypsum plasterboard finish. These circular walls allow for the reuse of studs/beams, circular tape, glass wool, and MDF finish.

2.4. Refurbishment Scenarios

The case study dwelling featured an open floor plan, offering flexibility for diverse space layouts. Currently owned by a couple, the initial interior wall positions were customized to meet their specific requirements.

To anticipate potential future refurbishment scenarios, identifying the key drivers for refurbishments in residential building projects is crucial. These drivers are influenced by foreseeable trends, like the aging population, and less predictable factors related to individual preferences and socio-economic conditions [24]. In the context of the Flemish housing market, essential drivers encompass changes in household numbers and evolving functional demands [25]. Categorizing these drivers on a matrix axis, in this study, four distinct future refurbishment scenarios were identified, as illustrated in Figure 4.

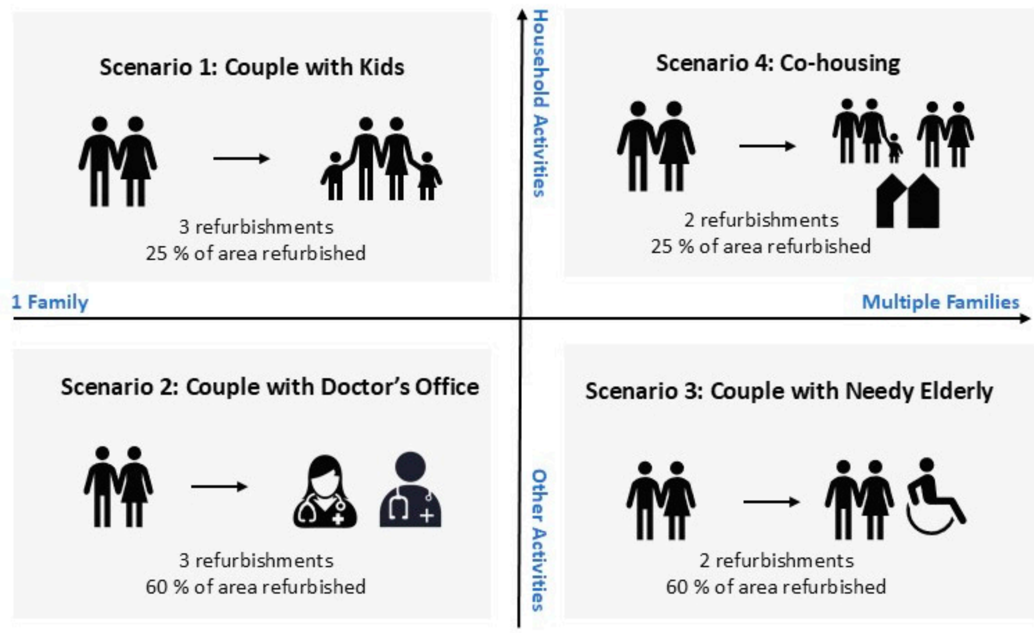

Figure 4. The two drivers for future change plotted against each other, as a basis for the development of four scenario narratives, based on the matrix of Cambier.

In each scenario, a couple residing in the original case study house experiences changing functional needs or household expansion, leading to necessary refurbishments in their residence. The four identified scenarios are as follows: 'Couple with Kids'; 'Couple with Doctor's Office'; 'Co-housing'; and 'Couple with Needy Elderly'. Each scenario unfolds over a 60-year timeline, aligning with the assumed service life of the dwelling and representing the average lifespan of residential buildings [26–28].

Across these scenarios, a series of refurbishments occurs, each involving the relocation of interior walls. The selection of these specific scenarios is thoughtfully justified, addressing both minor and major refurbishments while also considering the number of refurbishments, as depicted in Figure 5. The relocated walls in the case study house are illustrated in Figure 6. Importantly, in this study, there is an exclusive focus on assessing the environmental impact of interior wall relocation, excluding secondary effects such as the movement of the kitchen and floor-to-ceiling connections from the scope of analysis.

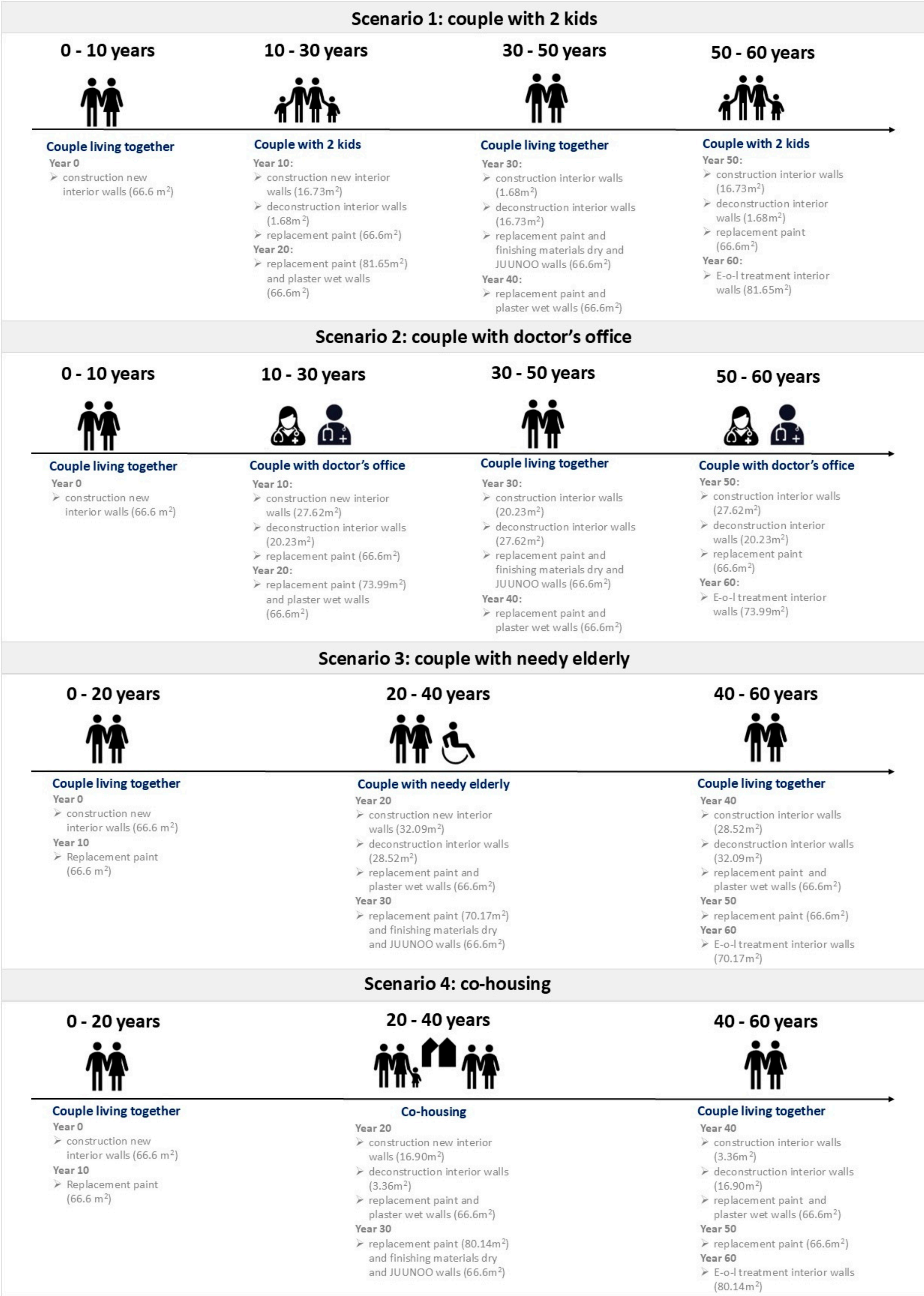

Figure 5. Timeline for the four different scenarios, showing when which material is (de)constructed, replaced, or refurbished.

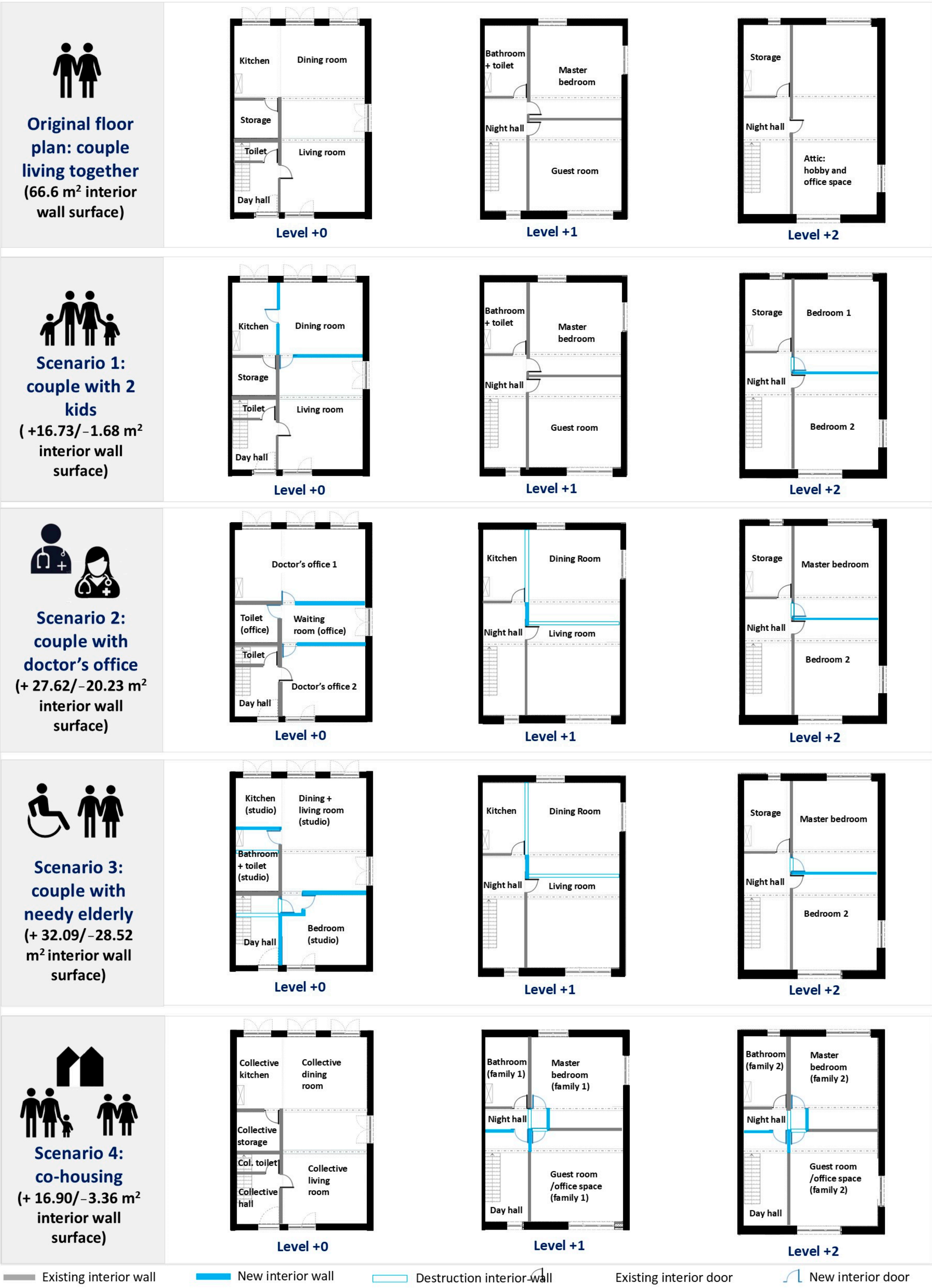

Figure 6. Overview of the original floorplan and the floorplans of the four refurbishment scenarios with the relocated walls. The original floorplan transforms during the first refurbishment to that of the specific refurbishment scenario, then reverts to the original layout during the second refurbishment, and so forth.

2.4.1. Scenario 1—Couple with Kids

In this typical Belgian household narrative, the number of household members changes, but the activity remains the same. A couple living together for a decade decides to raise one to two children, prompting refurbishment for additional rooms. Two bedrooms are added in the attic, and a dividing wall is introduced between the kitchen and living room. After 20 years, as the kids move out, the two bedrooms are recombined into a hobby space in the attic, and the ground floor transforms into an open kitchen. In the subsequent two decades, with the house too large for the elderly couple, they decided to sell it to another family with kids.

2.4.2. Scenario 2—Couple with Doctor's Office

In scenario 2, the primary use of the property shifts from exclusive residential to include professional functions, while the number of household members remains the same. A couple living together for a decade decides to establish a medical practice. This leads to the conversion of the ground level into a dedicated office, with the open-plan kitchen and living room relocated to the first floor. Two bedrooms and a bathroom have been added to the second level. After 20 years, upon the couple's retirement, the property reverts to its original layout. Subsequently, the couple vacates the residence, selling it to another self-employed individual.

2.4.3. Scenario 3—Couple with Needy Elderly

The case study house transforms into a multi-generational kangaroo dwelling after 20 years, as the couple welcomes an elderly family member in need to live with them. To accommodate the increased household size and additional caregiving responsibilities, the house undergoes several changes. The ground level is converted into a wheelchair-accessible studio, equipped with a kitchen, living room, bedroom, bathroom, and toilet. To ensure privacy, a separate entrance is incorporated. The original open kitchen and living room are relocated to the first level, along with two additional bedrooms and a bathroom to meet the expanded household's needs. Unfortunately, after two decades, the elderly family member passes away, prompting a restoration of the house to its original layout.

2.4.4. Scenario 4—Co-Housing

In scenario 4, after 20 years, the couple decides to live with another family. While the residential activity remains consistent, adjustments are required in the house's floor plan. The ground floor is transformed into a shared kitchen and living room, with each floor's rooms becoming private units for each family. Additional entrance halls and doors are added to ensure privacy. After two decades, one family moves out, and the house is restored to its original layout. The scenarios exhibit variations in the number and extent of refurbishments.

Scenarios 1 and 2 undergo three refurbishments, while Scenarios 3 and 4 experience two. Additionally, Scenarios 1 and 4 entail minor refurbishments, relocating 25% of interior walls, while Scenarios 2 and 3 involve more substantial changes, with 60% of interior walls being relocated.

2.5. Quantitative Assessment—LCA Method

To assess the environmental impact of building elements, prior research highlights the importance of using the LCA framework, grounded in European standards NBN EN 15804 and 15978 [14,16,17]. This framework calculates the environmental impact of a building element by assessing the environmental effect of processes and materials used during production and construction (module A), use (module B), and end-of-life stage (module C) [15]. According to the cut-off allocation approach in the European standards, recycling and reuse benefits and burdens are beyond the defined system boundaries of LCA [14].

In response, various methodological papers seek to integrate reuse benefits and drawbacks into the LCA framework. A common approach is to quantify these effects throughout the life cycle [12,20,26,29]. Similarly, in this study, the environmental impact of reuse within module B5 'refurbishments' in the LCA framework over the building's lifespan is evaluated. This module accounts for refurbishment impact, considering the demolition and replacement impact for a traditional element, while a demountable element only considers disassembling and reassembling. Refer to Figure 7 for a detailed representation of the life cycle stages assessed in the evaluation.

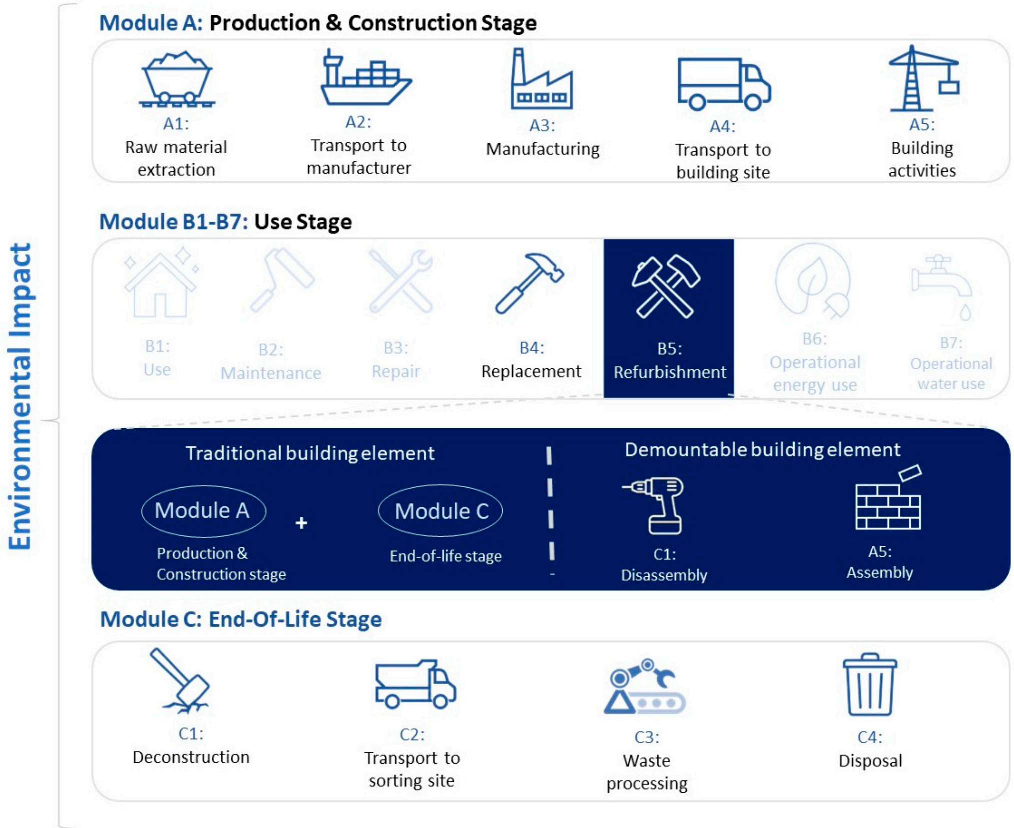

Figure 7. Included stages for assessing the environmental impact of demountable and traditional building elements.

The evaluation did not consider the impact of usage, maintenance, repair, operational energy use, and operational water use. The reparation and maintenance impact of building elements was not modeled due to a lack of reliable information for this module and its minimal contribution to the total environmental impact. Other modules were excluded based on the assumption that the impact was the same for both traditional and demountable building elements. The biogenic carbon impact of wood was also not considered. Furthermore, assumptions regarding the assessed stages, including material losses (5%), average end-of-life scenarios (incineration, recycling, or disposal), and average transport scenarios, were derived from the Belgian MMG methodology [30]. For a detailed understanding of all assumptions, please refer to the Supplementary Materials. The Supplementary Materials include material properties in Table S1, assumptions for Module A outlined in Table S2, and assumptions for Module C presented in Table S3.

A point-based single environmental score, calculated with the ReCiPe 2016 methodology and the Ecoinvent v3.8 database, was used to compare the environmental impact of the walls. Endpoint indicators in LCA offer several advantages, accurately reflecting the consequences on human health, natural resources, and biodiversity. They are easily understandable and comparable, and they take into account interactions and trade-offs between different environmental impact categories. However, a notable limitation arises from the inherent subjective weighting process, where weights are subjectively assigned to various environmental effects [31]. To address this, the sensitivity analysis utilized alternative impact assessment methods to showcase result robustness.

2.5.1. Element Level

In the first step, the environmental impact of interior walls was compared at the element level, using the functional unit of a 1 m^2 non-bearing space-dividing wall with an average sound insulation of 43 dB, over a 60-year period. Refurbishments at the element level were not taken into account. However, it is acknowledged that some materials in the wall may have a shorter service life than the study period, possibly requiring replacement during the building element's lifetime. To determine the functional lifespan of a material, the guidance document on product lifespans from Straub (SBR) was utilized [32]. If a material's lifespan was exceeded during the building element's lifetime, the framework incorporated the impact of periodic replacement. The number of replacements is determined using the formula provided by Vandenbroucke [20], as follows:

$$N_{rep} = \frac{T_{building}}{T_{tech,element}} - 1 - N_{re}$$

with:

$T_{building}$ = the lifespan of the building [years];
$T_{tech,element}$ = the technical lifespan of the building element [years];
N_{ref} = the number of refurbishments during the building life span [−], when reusable material = 0;
N_{rep} = the number of replacements during the building life span [−].

2.5.2. Building Level

In the next step, the results at the element level for 1 m^2 were extrapolated to the scenario level to identify the most environmentally beneficial wall for future refurbishment scenarios in the case study dwelling. The scenario-level impact was calculated by multiplying the interior wall surface with the results per m^2 at the element level and incorporating the refurbishment impact. The refurbished area and refurbishment rate were determined based on the four predefined refurbishment scenarios.

Demountability in refurbishment scenarios is assumed under the following conditions [29]:

- Connections between the building components must be reversible.
- The building component must be reusable in the same application.
- The technical lifespan of the building component must exceed 10 years.
- The remaining lifespan of the component after the intervention must be more than half of the initial technical lifespan of the product.

For demountable building elements, only the effects of assembly and disassembly are considered during refurbishment. In contrast, for traditional elements, the production, construction, and end-of-life impact are considered during refurbishment, as illustrated in Figure 7. If there is an insufficient number of demountable walls during a refurbishment, the addition of extra walls includes production and construction impact. In case of an excess of interior walls, they are temporarily stored in the dwelling until the end of their lifespan, when the end-of-life impact is considered.

2.6. Sensitivity Analysis

In this study, a sensitivity analysis was conducted on the refurbishment rate, refurbished area, and the impact assessment method. The purpose was to assess how changes in assumptions may impact results, enhancing the reliability of the research. The first part of the sensitivity analysis focused on the refurbishment rate and the proportion of the refurbished area relative to the total interior wall area. This is crucial as the environmental impact is initially calculated for the four proposed refurbishment scenarios, identifying the wall with the lowest environmental impact for each scenario. Parametrizing these variables allows us to determine the most beneficial wall for a broader range of scenarios, helping understand conditions where the demountable wall outperforms the traditional wall. Within the sensitivity analysis, the number of refurbishments varied from one to five. Each refurbishment involved either the construction or deconstruction of traditional interior walls or the assembly or disassembly of demountable interior walls. The cycle began with the construction of new interior walls in the first refurbishment, followed by their demolition or disassembly in the next. Moving on to the third refurbishment, the cycle was repeated with the construction or assembly of these walls, and this pattern continued for each subsequent refurbishment. The refurbished wall ratio ranged from 0 to 100%, incrementing in steps of 10%.

The second part of the sensitivity analysis assessed the influence of choosing different impact assessment methodologies on the results. Single-point environmental scores for interior walls are typically derived through a subjective weighting process, assigning weights to various environmental effects within a specific impact assessment methodology. In this analysis, diverse impact assessment methodologies with different weightings were explored and how the choice of a calculation method impacts the results was examined. For cross-methodology comparison, relative outcomes were used. These outcomes were calculated by determining the environmental scores for each wall within an impact assessment methodology, then dividing each methodology-specific outcome by the wall with the lowest methodology-specific score. Consequently, for every impact assessment methodology in the sensitivity analysis, the wall with the lowest impact has a value of 1, while all other walls will have a value higher than 1.

The chosen impact assessment method, ReCiPe 2016, was compared with three other endpoint methods to explore the impact of endpoint weightings on results. The selected endpoint methods were Ecological Scarcity 2021, Environmental Footprint 3.1, and World+ v1.47. Ecological Scarcity 2021 and Environmental Footprint 3.1 are European endpoint methods. The former assesses environmental impact based on pollutant emissions, resource consumption, and waste generation in burden points, aligning with the sustainability themes investigated [33]. The latter, the Environmental Footprint 3.1, shares identical impact categories with ReCiPe but employs different weightings. Developed by the European Commission, it is used for calculating the environmental impact of products and organizations [34]. The third method, the World+ v1.47, consistently evaluates regional life cycle emission inventories within the global economic context and features similar impact categories to ReCiPe [35].

Next, the same analysis was conducted for three midpoint indicators of ReCiPe 2016. This specific sensitivity analysis concentrates on individual environmental issues to avoid subjective weightings in the results. The chosen indicators were Climate Change, Ecotoxicity, and Mineral Resource Scarcity. These specific indicators were selected as the primary focus was on addressing the impact of climate change (CO_2 emissions), soil and water contamination (from landfills and chemical substances), and the scarcity of mineral resources—core challenges targeted by material reuse initiatives.

3. Results

3.1. Element Level

The environmental impact of the seven walls is initially examined at the element level, incorporating production and construction impact (module A), replacement impact (module B4), and end-of-life impact (module C). A stacked bar plot is used to represent the environmental impact of each wall, providing an easily interpretable comparison of different variables. The environmental impact is quantified in pt/m^2. Figure 8 shows the environmental impact of the walls across various life cycle stages, distinguishing between initial impact and total life cycle impact. Figure 9 breaks down the total environmental impact score of the wall into its different material layers, pinpointing the material types with the most significant impact.

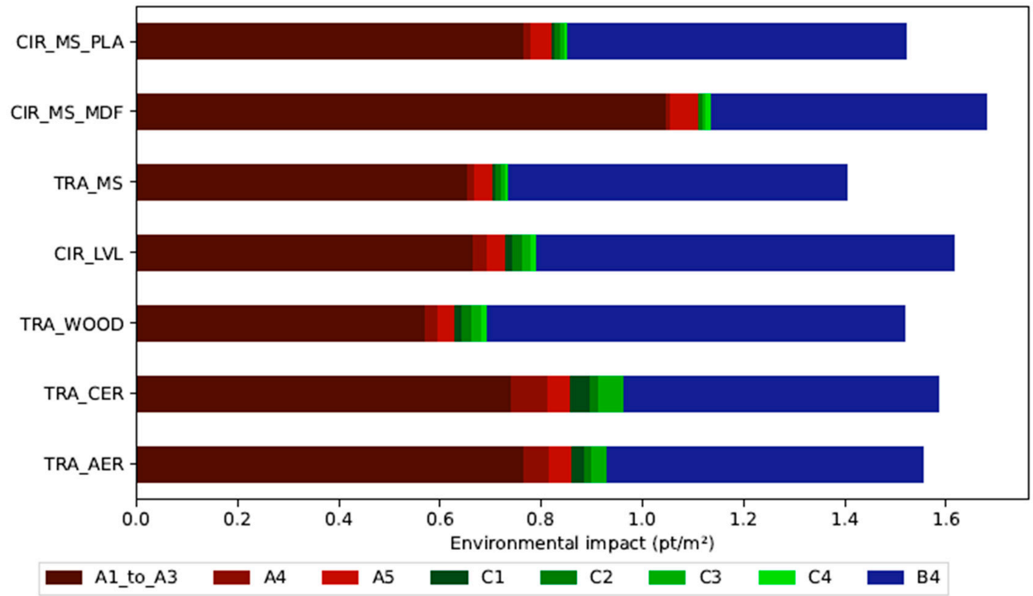

Figure 8. Bar plot depicting the environmental impact of the seven walls, subdivided by the impact of different life cycle stages.

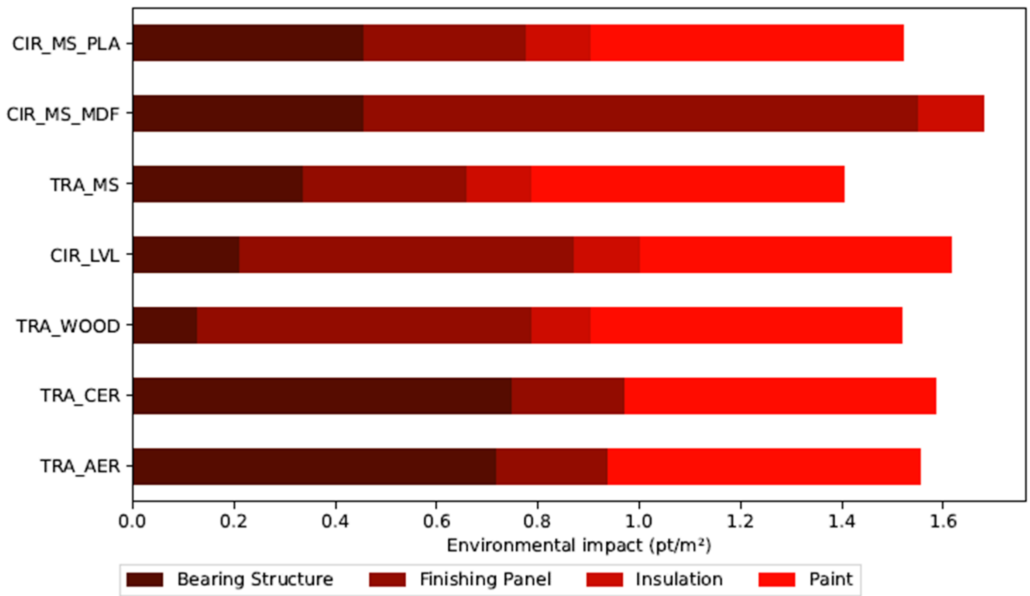

Figure 9. Bar plot depicting the environmental impact of the seven walls, subdivided by the impact of the bearing structure, finishing panel, insulation, and paint.

Figure 8 indicates that traditional drywalls, particularly the TRA_MS and TRA_WOOD walls, have the lowest environmental impact. In contrast, traditional masonry walls (TRA_AER and TRA_CER), the CIR_LVL wall, and the CIR_MS_MDF wall exhibit the highest environmental impact. The figure emphasizes that the overall impact is significantly influenced by the material production phase. Notably, when considering only the initial environmental impact (module A), it is observed that the TRA_WOOD wall has a lower impact than the TRA_MS wall, while the order remains consistent for the other walls.

Besides the significant production impact, replacements also play a crucial role in the results. As noted in Section 2.5, specific materials within a wall may not endure for the full 60 years, requiring replacements over the building's lifetime. The replacement phase (B4) leads to an increase ranging from 40 to 120 percent across all walls when compared to modules A and C. Notably, there is a substantial replacement impact in the wood structure walls, TRA_WOOD, and the CIR_LVL wall. Figure 9 delves into the impact of various materials within the wall to provide a better understanding of these results.

The bearing structure significantly influences the overall results, constituting approximately 25% to 50% of the total impact, except in the case of drywalls with a wooden structure. The low environmental impact of wood, attributed to its biogenic nature, explains this exception. Hence, the initial environmental impact of the TRA_WOOD wall is the lowest for modules A and C. It is noteworthy that the total environmental impact of demountable metal studs exceeds that of traditional metal studs. This is due to the thinner nature of traditional studs, making them fragile and non-reusable. Metal's high environmental impact primarily results from pig iron production in blast furnaces and fossil fuel consumption during the iron ore sintering process [36]. This clarification elucidates the lower environmental impact of the TRA_MS wall in comparison to the CIR_MS_MDF and CIR_MS_PLA walls. The high environmental impact of the traditional masonry walls is attributed to the bearing structure. The structure significantly contributes to the total environmental impact, driven by the intensive ceramic brick baking process at temperatures of around 950 degrees Celsius and the intricate cement production for aerated concrete [37,38].

Finishing materials contribute 20% to 40% to the overall impact, except for the CIR_MS_MDF wall, where it is 60%. The notable impact of MDF arises from its production process, involving high temperatures, pressures, and synthetic resin for wood fiber binding [39]. Intriguingly, plasterboards have double the impact in wood structure walls compared to the metal stud walls, due to the greater number needed to achieve the required sound insulation. Plasterboards' impact results from the production drying process, involving ground gypsum rocks, chemicals, water, and a significant cellulose layer [40]. Due to the production impact of plasterboard and the need for replacement every 30 years, the TRA_MS wall with a single layer of cladding has a reduced overall environmental impact compared to the TRA_WOOD and CIR_LVL walls with double cladding.

Insulation has a limited contribution, approximately 10%, to the final impact. This stems from the production process, which involves melting and fiberizing glass, along with the use of adhesives for curing [41]. In contrast, paint plays a more substantial role, constituting 30% of the impact. Acrylic paint undergoes five replacements, occurring once every 10 years, and its impact results from the use of solvents, additives, hardeners, accelerants, and desiccants during production.

3.2. Scenario Level

To quantify the environmental benefits and burdens of demountable walls, it is important to take various refurbishment scenarios during the life cycle of the building into account. The element-level results are extrapolated across defined scenarios to determine the optimal wall with the lowest environmental impact within the case study dwelling. Figure 10 illustrates these results through a cumulative graph, depicting the impact at each stage of the entire building lifespan, providing valuable insights for assessing different building elements over extended durations.

When analyzing the initial environmental impact in year 0, it becomes clear that the TRA_WOOD wall exhibits the lowest environmental impact, followed by the TRA_MS wall. These findings align with the outcomes observed at the element level. Subsequently, the environmental impact of the walls undergoes a three- to four-fold increase due to replacements and refurbishments during the building's life cycle. Every decade, the impact for each wall rises due to the need for paint replacement, except for the CIR_MS_MDF wall, which does not involve paint. By year 30, a significant increase in environmental impact is noticeable as plasterboard or MDF requires replacement in all walls. It is important to note that the increase in environmental impact for walls with wooden structures is more pronounced compared to those with metal studs, due to the necessity of replacing four plasterboards instead of two.

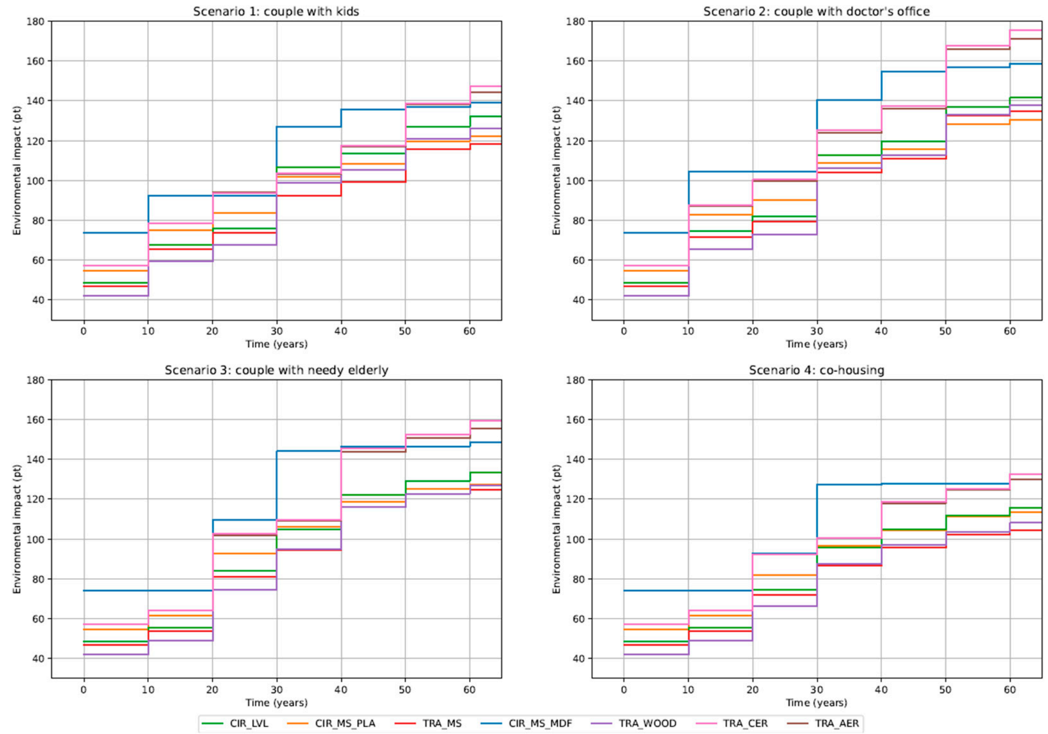

Figure 10. Environmental impact of the seven different wall assemblies for the four different scenarios.

For the masonry walls TRA_AER and TRA_CER, noticeable increases occur at years 20 and 40, coinciding with plaster replacement. Additionally, each refurbishment contributes to an increase in environmental impact. In scenarios 1 and 2, this happens at years 10, 30, and 50, while in scenarios 3 and 4, it occurs at years 20 and 40. This increase is more pronounced for traditional walls, as refurbishments involve replacing all materials, unlike demountable walls, where only plasterboards and screws need replacement.

When evaluating the total environmental impact in scenarios 1 and 4, where a relatively small, refurbished area is involved, the TRA_MS wall again exhibits the lowest environmental impact. This is due to limited refurbishment activities, where the potential benefits of reuse are not fully utilized. As the refurbishment area expands, as in scenario 3, the TRA_MS wall continues to show the lowest environmental impact due to the low refurbishment frequency. In scenario 2, involving a big refurbishment frequency and a large, refurbished area are involved, the CIR_MS_PLA wall has the lowest environmental impact. This is because the demountable profiles in the wall can be reused, offsetting their higher initial impact.

Important to note is that in scenarios 3 and 4, the TRA_WOOD wall has the second-lowest environmental impact, while in scenarios 1 and 2, it is the CIR_MS_PLA wall. The environmental impact of the TRA_WOOD wall is slightly lower than that of the CIR_MS wall when there are no or minimal refurbishments. As more refurbishments take place, the CIR_MS_PLA wall ends up having the lowest impact. It is important to highlight that, in all scenarios, the masonry walls and the CIR_MS_MDF will have the highest total environmental impact.

3.3. Sensitivity Analysis

Applying sensitivity analysis evaluates the robustness of the results and their sensitivity to assumptions. This paragraph explores the influence of the refurbishment rate, refurbishment area, and impact assessment method.

3.3.1. Refurbishment Area and Rate

Section 3.2 focused on determining the interior wall with the lowest environmental impact in various refurbishment scenarios for the case study dwelling. This analysis revealed that demountable walls become more environmentally beneficial with a high ratio of refurbished wall surface area and a high refurbishment rate. To delve deeper into this matter, the subsequent sensitivity analysis parametrizes these two factors to identify the point where traditional walls surpass demountable walls in environmental impact. Using the same assumptions applied at the scenario level, the results are presented in Table 2 in matrix format. The *x*-axis denotes the number of refurbishments (ranging from 0 to 5), while the *y*-axis represents the percentage of walls refurbished (ranging from 0 to 100%). The table highlights the wall type with the lowest environmental impact in each respective scenario.

Table 2. Matrix representing the environmentally most beneficial interior wall, with on the *x*-axis the number of refurbishments and on the *y*-axis the percentage of walls refurbished.

		Refurbishment Rate (-)					
		Fq = 0	**Fq = 1**	**Fq = 2**	**Fq = 3**	**Fq = 4**	**Fq = 5**
Refurbished area (%)	0	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS
	10	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS
	20	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS
	30	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA
	40	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA
	50	TRA_MS	TRA_MS	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA
	60	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA	CIR_MS_PLA	CIR_MS_PLA
	70	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA	CIR_MS_PLA	CIR_MS_MDF
	80	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA	CIR_MS_PLA	CIR_MS_MDF
	90	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA	CIR_MS_PLA	CIR_MS_MDF
	100	TRA_MS	TRA_MS	TRA_MS	CIR_MS_PLA	CIR_MS_PLA	CIR_MS_MDF

The findings indicate that with little refurbishments (0–20% wall area refurbished), the TRA_MS wall exhibits the lowest environmental impact. This is explained by the higher initial environmental impact of demountable metal stud walls due to thicker profiles. For the refurbished area ratios between 30% and 50%, demountable walls, specifically the CIR_MS_PLA wall, demonstrate lower environmental impact after five refurbishments. If fewer refurbishments occur, the TRA_MS wall continues to have the lowest environmental impact. With a refurbishment ratio of 60% or more, demountable walls, especially the CIR_MS_PLA wall, show lower environmental impact after three refurbishments. This is attributed to the reuse potential of demountable profiles. In cases of frequent refurbishments (five or more) over a 60-year building life cycle, the CIR_MS_MDF wall proves to be a sustainable choice. This is because of MDF's reusable nature, despite its higher initial environmental impact, as opposed to the necessity to replace gypsum board in other walls during each refurbishment.

3.3.2. The Impact Assessment Method

In previous sections, the environmental impact of interior walls was assessed using a single endpoint-based environmental score, obtained by weighing various environmental indicators into one score. Although a single score simplifies decision-making, this step is often perceived as subjective. To ensure the robustness of the results, it is essential to compare them with alternative endpoint indicator methods and environmental indicators. The results for alternative impact assessment methods like Ecological Scarcity 2021, Environmental Footprint 3.1, ReCiPe 2016, and World+ are presented in Figure 11. Additionally, Figure 12 displays the results for environmental indicators such as climate change, ecotoxicity, and mineral resource scarcity.

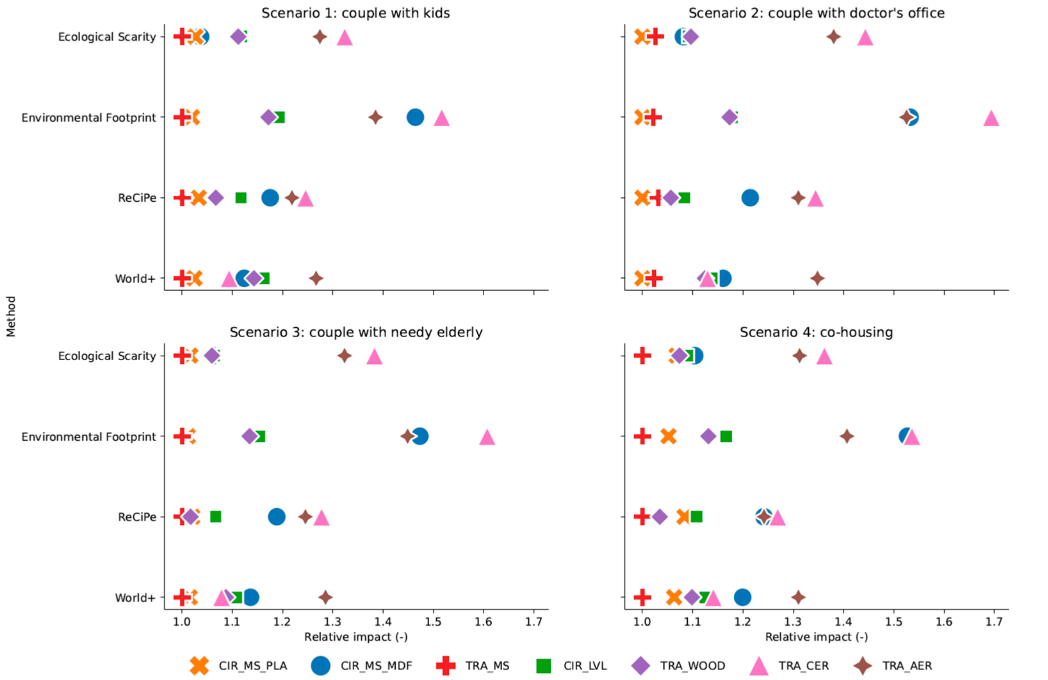

Figure 11. Environmental impact of the different interior wall assemblies for the different scenarios for the various endpoint methods: Ecological Scarcity 2021, Environmental footprint 3.1, ReCiPe 2016, and World+ impact assessment methodology.

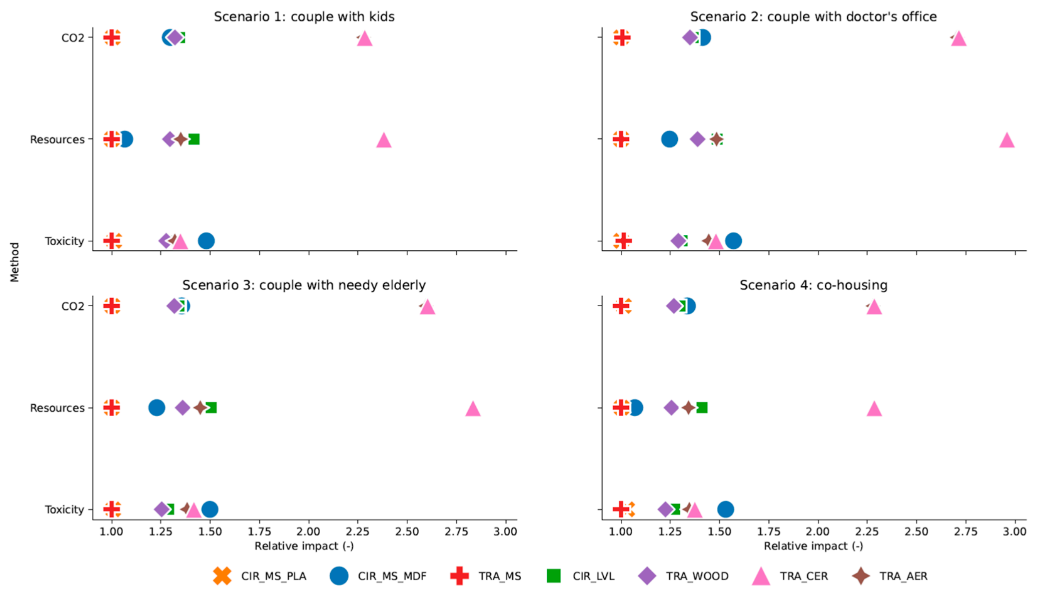

Figure 12. Environmental impact of the different wall assemblies for the various scenarios for three ReCiPe midpoint indicators: climate change (CO_2), ecotoxicity, and mineral resource scarcity.

Figure 11 shows that the environmental impact ranking of walls using ReCiPe 2016 aligns with the results from alternative endpoint methods. In scenarios 1, 3, and 4, the TRA_MS wall consistently has the lowest environmental impact. However, in scenario 2, characterized by a significant refurbished area and refurbishment frequency, the CIR_MS_PLA wall remains prominent with the lowest environmental impact across all assessment methods. Notably, using the ReCiPe 2016 method, the TRA_WOOD wall's environmental impact in scenarios 3 and 4 ranks as the second lowest. However, when considering scores from other impact assessment methodologies, the TRA_WOOD wall only attains average scores. Additionally, there is a consistent trend with masonry walls and the CIR_MS_MDF wall consistently showing the highest environmental impact. This pattern remains, except in the World+ method where the TRA_CER wall scores average, and in the ecological scarcity method where the CIR_MS_MDF wall also scores average. This variation can be attributed to the diverse weighting factors employed in different impact assessment methods.

In Figure 12, similar trends emerge across different scenarios for various ReCiPe Midpoint indicators. Scenarios 1, 3, and 4 indicate the TRA_MS wall has the lowest environmental impact, while in scenario 2, marked by a high refurbished area and rate, the CIR_MS_PLA wall shows the lowest environmental impact. Notably, the CIR_MS_MDF wall, concerning the climate change indicator and mineral resource scarcity, exhibits an average to low environmental impact. However, in terms of toxicity, it records the highest impact due to the elevated toxicity of the synthetic resin used for wood fiber binding. Masonry walls, assessed by each indicator, consistently demonstrate an average to high environmental impact. Both the TRA_WOOD and CIR_LVL walls consistently maintain an average environmental impact score in each assessment method. The slight variation in results can be attributed to each environmental indicator's specific design for assessing a particular environmental feature or category.

4. Discussion

In this study, the aim was to investigate whether demountable walls could offer a more environmentally friendly alternative than traditional interior walls in a case study dwelling. This was examined by studying the total life cycle environmental impact of seven wall assemblies for four predefined refurbishment scenarios in a semi-detached house.

The results indicate that when no refurbishment occurs, the traditional interior wall with metal studs outperforms demountable metal stud walls. This is due to the thinner steel profiles of the traditional wall, consuming less steel, with steel production having a high environmental impact [36]. In the scenarios with small refurbishments and/or low refurbishment frequency, traditional metal stud walls continue to have a lower environmental impact than demountable walls. Notably, the traditional wall with metal studs outperforms those with a wooden structure due to the latter requiring double gypsum boards on both sides for finishing.

In a major refurbishment scenario (about 60% of walls refurbished and more than three refurbishments), the demountable metal stud wall becomes a more environmentally friendly alternative. This is because the slightly thicker profiles of the demountable walls can be reused, while those of the traditional metal stud wall must be replaced. Consequently, it becomes clear that opting for demountable walls is more advantageous under certain circumstances in a semi-detached dwelling. This is further explored in sensitivity analysis, where the refurbishment area and rate are parameterized. It is revealed that at least 60% of the area must be refurbished, with a minimum of three refurbishments during the lifespan of the semi-detached house. Notably, the demountable metal stud wall with MDF finishing becomes more sustainable than the one with plasterboard finish from 70% of refurbished walls and five renovations, as MDF panels can be reused and plasterboard finish does not.

Comparing these results with other studies in the literature, similar findings emerge [8,9,20]. Buyle's assessment of the environmental impact of seven wall assemblies, considering a theoretical refurbishment rate and area, reveals that the traditional metal stud wall has a lower environmental impact in scenarios without refurbishments [9]. However, with three refurbishments and 100% of the walls refurbished, demountable walls begin to exhibit a lower environmental impact [9]. Vandenbroucke's study, which comprehensively evaluates demountable building elements, confirms that frequent refurbishments are essential for the advantageous environmental performance of demountable building elements [20]. Rajagopalan's research findings support this assertion, indicating that demountable walls demonstrate advantages when refurbishing 100% of the walls annually, every 10 years, or every 15 years over the 60-year lifespan of the building [8]. Collectively, these results suggest that regular refurbishments are necessary to achieve a lower environmental impact when using demountable instead of traditional metal stud walls due to the higher initial environmental impact of the latter.

Nevertheless, the results of this work warrant important considerations for further research. It solely focused on the environmental impact of interior walls, neglecting the secondary effects. In the practical (de)construction of traditional interior walls, floor and ceiling finishing restoration is necessary. Conversely, with demountable walls, floor finishing can remain as the profiles are clamped between the ceiling and floor. This implies that the benefits of the demountable walls are slightly higher in practice compared to traditional walls. The study of Ylmen investigates the influence of secondary effects when adding insulation to an external wall [42]. This involves adding extra materials for the floors, walls, ceilings, and roof by widening walls and reinforcing structures, also considering aspects like ventilation and energy consumption. These secondary effects significantly increase the overall environmental impact, contributing to half of the production impact [42]. In this case study, secondary effects are limited to the repair of the floor and ceiling above the replaced interior wall, involving a small amount of materials compared to the large wall areas replaced. While requiring further research, it is expected to make only a modest contribution to overall results.

Additionally, it was assumed that the reusable profiles or beams of demountable walls would be temporarily stored within the house when not in use, with the anticipation of their potential reuse in subsequent refurbishments. The assumption allowed for evaluating the reuse potential of demountable building elements within the same building. Another scenario involves transporting demountable walls to a material depot, introducing considerations for the environmental impact of transport and storage. This could slightly increase the environmental impact of the demountable walls compared to traditional walls and necessitates further investigation. Similarly, the end-of-life impact of materials when the house is demolished, with the potential for reuse and residual value, requires more detailed exploration. Limited data in the literature, often more optimistic from product manufacturers, underscore the need for a realistic assessment.

In this study, the focus was on evaluating the environmental impact of traditional and demountable interior walls in a semi-detached dwelling. To comprehensively assess the environmental impact of demountable and traditional elements in different building types and locations, it is crucial to expand the analysis to include various building typologies in different countries. There is presumed to be significant potential for the use of demountable walls in building typologies such as offices, exhibitions, laboratories, and schools.

5. Conclusions

In this study, the environmental impacts were compared of traditional and demountable interior walls in a semi-detached dwelling over a 60-year lifespan, accounting for various refurbishment scenarios. The results indicate that traditional walls with metal studs exhibit the lowest environmental impact when refurbishments are minimal or non-existent. Demountable walls become environmentally advantageous only under conditions where at least 60% of the total interior wall area is refurbished and a minimum of three refurbishments occur during the building's lifespan.

Given the typically limited frequency and scope of refurbishments in residential buildings, the suitability of demountable walls over traditional walls for reducing environmental impact is questionable in this building typology. However, there is greater potential for their application in building typologies that experience more frequent and substantial refurbishment, such as offices, exhibition spaces, laboratories, and schools.

The scope of this study is limited to assessing the environmental impact of interior walls in a specific residential context. Future research should broaden its scope to include various building typologies and geographic regions. Additionally, subsequent investigations should evaluate secondary impacts, such as the transportation and storage of demountable elements, as well as end-of-life considerations, including material reuse potential following building demolition.

The findings highlight the importance of conducting comprehensive environmental assessments of both demountable and traditional building elements, tailored to specific building types and use cases. In conclusion, this study advocates for a nuanced approach to sustainable construction, offering valuable insights that enable architects, builders, developers, and other industry stakeholders to make informed decisions that contribute to a more sustainable built environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16209126/s1, Table S1: Material Properties; Table S2: Module A assumptions, Production phase: A1–A3, Transport to site: A4, Building activities: A5; Table S3: Module C assumptions, Deconstruction: C1, Transport: C2, Waste Processing: C3, Disposal: C4.

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