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Article

Multi-Criteria Decision Analysis Using Life Cycle Assessment and Life Cycle Costing in Circular Building Design: A Case Study for Wall Partitioning Systems in the Circular Retrofit Lab

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Abstract: The Circular Economy (CE) paradigm has been gaining momentum. However, the tools and methods used to design, measure and implement circularity are not immediately suitable for decision making and practice by key stakeholders. This article details a qualitative and a quantitative method to evaluate characteristics such as circularity, adaptability and reuse of building elements amongst others in order to provide decision-makers, such as building clients, architects, investors and policy makers, an objective way to assess the benefits and constraints of circular buildings and elements. The study implements the method in the case study, the Circular Retrofit Lab in Belgium, and uses a multi-criteria decision approach to evaluate qualitative parameters and life cycle assessment and life cycle costing to quantitatively evaluate the circular solutions proposed in this study. As such, the paper shows how a multi-criteria decision approach can be applied to evaluate circular building solutions in the context of practical architectural projects, in this case assessing the suitability of three interior wall systems for applications with different turnover rates. The study shows that the overall performance of the evaluated wall systems varies largely from one expected user scenario to the other.

Keywords: circular building design; reversibility; multi-criteria decision analysis; LCA; LCC; circular retrofit lab; decision-making; PEF; cumulative graphs

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1. Introduction

Building materials generate environmental impacts at various life cycle stages: during the manufacturing of building materials and products, the construction phase, use and maintenance of the building and the disposal or demolition phase. The Circular Economy (CE) paradigm has been gaining momentum and has been characterized as an economy that is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times. Therefore it distinguishes between technical and biological cycles [1]. In the construction sector, a significant emitter of greenhouse gases and producer of huge amounts of waste, the CE concept is relatively new.

The building and construction sector generates about one third of all waste in the European Union [2]. On member state level, similar figures are observed, e.g., 36.7% in Belgium, 41.6% in the Netherlands and 41.5% in the UK (based on weight) [3–5]. Although other sectors may have a different level of importance, construction and demolition waste still has a dominant share of the yearly total waste production. Most stony C–D waste, such as concrete and masonry, in countries such as Belgium, the Netherlands, UK, Germany, Austria and Poland is downcycled as secondary granulates for building and road foundation or reused as reclaimed clay bricks and tiles [6]. It is challenging to design buildings that last for 50–100 years in such a way that the materials can be applied for high quality recycling and reuse. Buildings are often prematurely demolished well before their lifetime because they are designed in a static manner with only one end use in mind. In order to avoid this, buildings should be designed to be easily adapted or disassembled with elements that can be reused or reconfigured in the same or different location.

Efforts to increase sustainability in the building sector need to broaden scope beyond impacts associated to building energy consumption and also focus on other impact categories in the building life cycle assessment (LCA) studies [7]. There is a need to optimize the building performance beyond primary energy consumption by investigating the entire life cycle [7–11]. Design for Change (DfC) has an important role in reducing the environmental impact of the construction industry. This anticipatory method helps manage the constantly adapting needs and demands of society by adopting sustainable construction practices such as reducing pollution and less material intensive construction. Additionally, this concept lends itself to disassemble and recycle—or, even reuse—building elements, thus closing material loops [12].

Current European standards for LCA of buildings and building products do not enable the assessment of materials or elements taking into account multiple life cycles. EN15798 [13] applies potential credits of reuse to outside the system boundary (cf. Module D [13]) and the Product Environmental Footprint (PEF) method [14] applies a generic system expansion approach for all industrial sectors including the construction sector, that does not allow for modeling multiple life cycles (e.g., PEF [14]). There are issues with deciding on end-of-life calculations, end-of-waste of various materials [15] and available life cycle assessment tools do not have a straightforward way for extending lifetime of buildings and building elements e.g., Belgian TOTEM, a life cycle assessment tool used to facilitate LCA in architectural practice [16]. A common representation of impacts in LCA is the bar graphs that represent total impacts per impact category per functional unit. Such bar graphs representing total impacts per module per impact category do not provide useful information for decision maker, especially when reuse of components is involved, since the reuse burdens and credits are allocated outside the system boundary (e.g., Module D in EN15978 [13]). Whereas, when using the PEF method, the net benefits or burdens are readily visible at the module level.

The modeling of service life of a building taking into account all future functions before final decommissioning is a complicated endeavor and requires integrated scenario planning approaches with LCA methods [17]. There is literature available to address the adaptability of building structures but it stresses the lack of evaluation methods available to measure concepts such as adaptability and flexibility in buildings [18,19]. This is an important concept as building designers are always challenged to create solutions to use resources in an efficient manner. Reducing the complexity of the connections in a building system facilitates an easy and quick assembly. Additionally, it also allows key stakeholders to participate in the assembly, maintenance, reconfiguration and deconstruction of the structure [20]. Apart from benefits during the construction phase, it is important to assess transformable structures on their material and cost effectiveness.

Future refurbishments of a building have significant environmental impact and also contribute to long term savings due to reuse of building elements [21]. The return of investment aspect is an interesting aspect for the decision maker and new concepts are required to assist the decision maker in making complicated choices with regards to reversible design principles, and life cycle environmental and cost impacts. The investment cost of circular construction is generally high, which makes the industry reluctant to invest in circular solutions. For example, Doodeman [22] shows that the construction cost of a house built in the Netherlands according to circular principles goes up by EUR 10,000 [23].

Circular construction is more expensive due to use of alternative products that might replace generic steel and concrete and higher labor costs due to alternative or innovative construction techniques [24]. However, when selecting materials in the building design, the initial costs should be balanced against the expected costs savings during the future use stage and end-of-life stage of the building. Therefore life cycle costing (LCC) is an important method in evaluating the costs of different circular scenarios over all life cycle phases [25]. Circular design and construction deliver direct economic benefits such as lower operational and maintenance costs, slower depreciation, higher asset value and increases the industry's competitiveness by avoiding shortages of resources and unstable prices [26,27]. Designing for disassembly and reuse offers a unique solution for the construction sector [28].

The objective of this paper is to use a multi-criteria assessment method to evaluate circular building solutions in order to provide decision-makers, such as building clients, architects, investors and policy makers, an objective way to assess the benefits and constraints of circular buildings and elements. This paper details an assessment method in which both inherent qualities (e.g., reversibility, ease and speed of disassembly) as well as quantifiable environmental and financial performances are taken into consideration in the decision-making process. The described method has been developed based on insights of several concrete case studies within the innovation and action project 'Building as Material Banks' [29]. The application of this method to a particular case study will be highlighted in this paper. The novelty of this work lies in the inclusion of multiple qualitative and quantitative aspects for evaluating circular building and elements through a multi-criteria decision framework. To the best of our knowledge, this decision-making framework has not been applied to circular building solutions and elements.

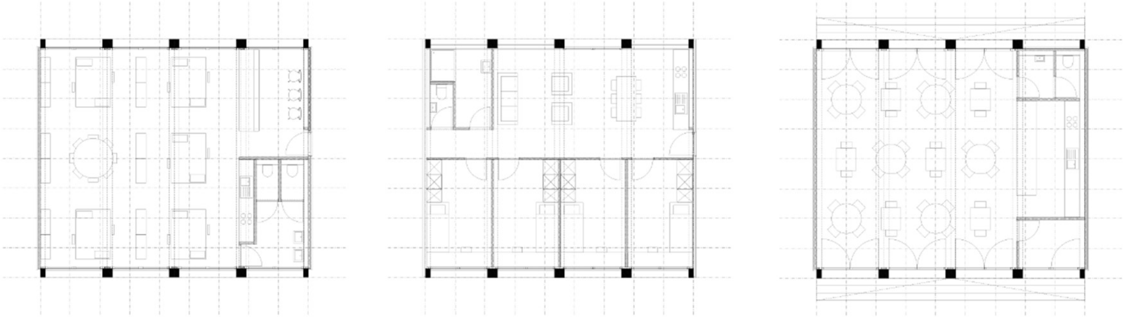
The next section describes the case study used for modeling in detail, followed by the qualitative and quantitative methods used and the results obtained. The last section provides a conclusion formulated based on the analysis.

2. Materials and Methods

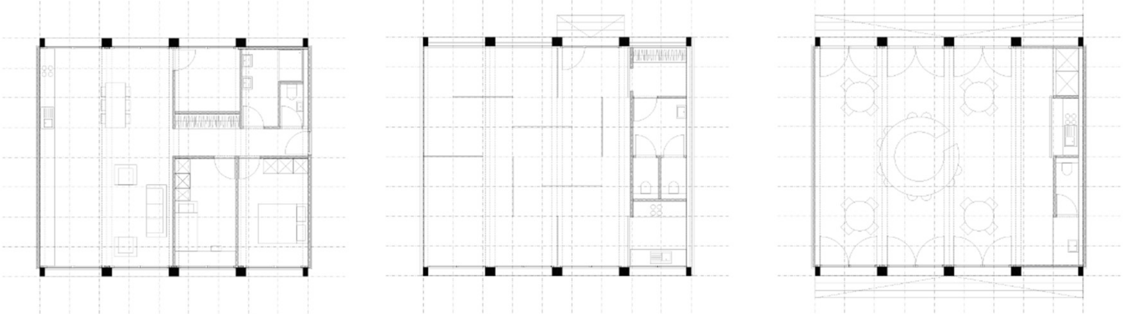
2.1. Case Study Design and Scenario Planning

The study presented in this paper focuses on the Circular Retrofit Lab (CRL) case. This is a pilot project for circular refurbishment of eight former student housing modules on the campus of the Vrije Universiteit Brussel (Belgium). The project aimed to practically implement design for change principles and more specifically aspects of reversible design [12]. Using reversible connections and an adaptable plan lay-out are meant to facilitate future maintenance, renovation and reorganization. Therefore, it implemented lifecycle thinking early in the design process. An exercise in scenario planning led to a wide range of potential plan layouts, considering different future functions for the project. Figure 1 shows plan variations for student housing, office and lab spaces, workshops and even a restaurant. While the project was eventually designed and constructed to house a dissemination and co-working space, the development of an adaptable plan and use of reversible building solutions allow to implement transformation scenarios more easily in the future. Planned as a short-term redevelopment, the future reconversion of the top floor into guest apartments was included more specifically in the refurbishment project of the Circular Retrofit Lab.

Figure 2 shows the Circular Retrofit Lab's exterior and interior after its refurbishment. One of the main challenges in the project was the selection of appropriate building solutions. The research and design team therefore worked closely with industrial stakeholders, exploring reversible solutions on the market but also supporting the redevelopment or prototyping of new and highly innovative products and systems. Where the design and construction of the project mainly focused on the practical implementation of such reversible systems, a large part of the research went into establishing an assessment method for their evaluation. This paper elaborates on the assessment of interior wall systems. As a pilot project, the CRL was designed to illustrate different solutions for different types of walls, based on a set of wall type scenarios.



Administration office Updated student housing Bistro / restaurant



Apartment type 2/3 Exhibition space Information office

Figure 1. A series of scenarios shows potential future uses and corresponding plan layouts for the Circular Retrofit Lab project.

Figure 2. The Circular Retrofit Lab is a set of refurbished student housing modules, currently housing a dissemination space and offices.

2.2. *Defining Interior Wall Type Scenarios*

To integrate aspects of circular design and Design for Change in the assessment, it was important to translate the design of the CRL and the exploratory scenario planning into specific transformation scenarios for the different building elements, in this case the interior walls. Table 1 shows three wall type scenarios: a quickly changing interior wall, a technical interior wall and a dwelling-dividing interior wall. Figure 3 shows how each wall type figures into the general spatial layout of the CRL. Each wall type is characterized by an expected turnover rate, defining the pace with which transformations such as relocations or adaptations occur. Wall type scenario 1 comprises the most dynamic walls. They are part of the dissemination space and are expected to change regularly following changes in the spatial layout for temporary exhibitions and events. They have a yearly turnover rate. Wall type scenario 2 regards the technical walls, whose main function is to close off but also keep accessible the different building techniques. As such, they are not expected to be moved or replaced regularly but do need to be uncovered or dismantled when technical updates, maintenance or replacements take place. Their turnover rate is 10 years. Wall type scenario 3 finally covers the dividing wall that will be added to split up the top floor into two guest apartments. Its expected transformations include removal and relocation due to functional changes, with a turnover rate of 15 years.

Table 1. Three wall type scenarios distinguish between different turnover rates for different interior walls.

Wall Type Scenario	Turnover Rate (Years)	Description
Scenario 1: quickly changing interior wall	1	Walls and wall segments in the central space of the dissemination room (exhibition walls, presentation walls . . .)
Scenario 2: technical interior wall	10	False walls to cover technical systems (water, heating, electricity and ventilation)
Scenario 3: dwelling-dividing interior wall	15	Central wall or walls to split up the open space into individual housing units

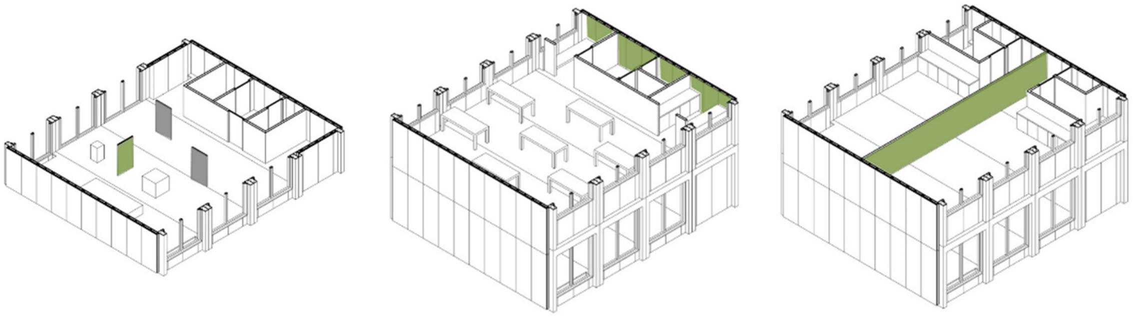


Figure 3. Each wall type performs a different function in the spatial organization of the CRL project. Scenario 1 refers to the quickly changing interior wall, Scenario 2 refers to technical interior wall and Scenario 3 refers to the dwelling-dividing interior wall.

2.3. Selecting Interior Wall Systems

This study includes three different wall systems, as presented in Table 2 and Figure 4. They were selected through market research, based on their apparent potential in Design for Change (DfC) applications. Reversible assembly was one of the main parameters in this, along with the basic functional requirements for interior walls. Additionally important was the active involvement of the manufacturers, as improvements were made to the systems along the way. The three systems represent very different approaches towards DfC and interior wall materialization. System 1 consists of a wooden frame with gypsum fiberboard. Prefabricated floor-to-ceiling modules are positioned between wooden beams on the floor and ceiling. The resulting interlocking eliminates the need for additional fasteners such as screws, bolts or glue. System 2 is a solid wooden wall. It consists of vertical beam elements that are connected through steel spacers, thus generating a discretized CLT panel. System 3 consists of a steel frame topped with wooden panels. The steel bars are connected using clamps. The wooden panels can be attached to the frame with hooks, bolts or screws. Throughout the study, the wall systems are compared to a standard baseline solution: a drywall system with steel frame.

Table 2. The study includes three interior wall systems, compared to a baseline solution.

Wall System	Substructure	Connections	Finishing
System 1: wooden frame with gypsum fiberboard	Prefabricated wooden frame	Screws	Gypsum fiberboard, paint
System 2: massive wood	Solid wooden beams	EPDM, L-connectors, steel connector bolts	Varnish
System 3: steel frame with wooden panels	Steel frame	Clamps, hooks, bolts, screws	Plywood panels, varnish
Baseline: gypsum cardboard with metal stud	Steel frame	Screw, plaster joining	Plasterboard, paint

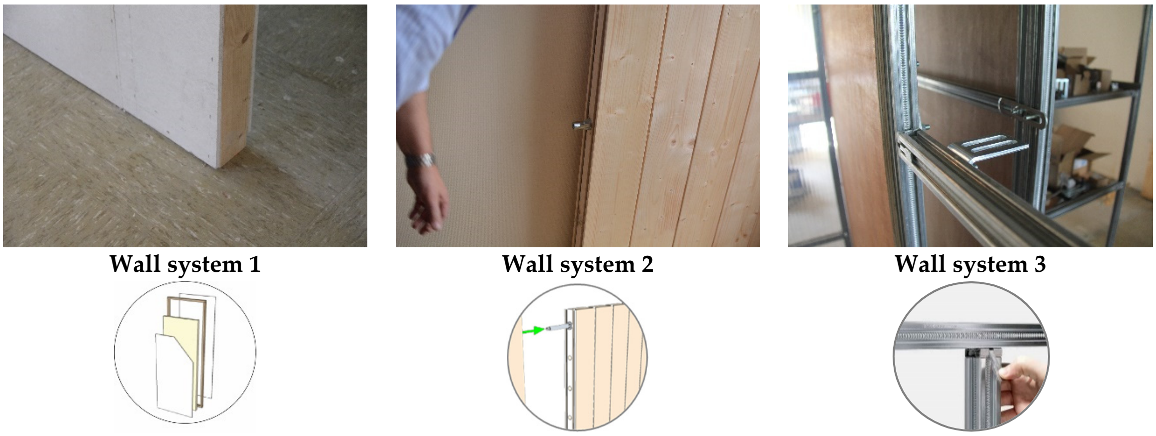

Wall system 1 **Wall system 2** **Wall system 3**

Figure 4. Each interior wall system has a different materialization and assembly method.

2.4. Multi-Criteria Decision Analysis

Decision making is tough if a well-structured logical structure is not available for design and use of various elements where multiple criteria are available. A multi-criteria decision-making analysis (MCDA) method is a tool used to select the best compromising solution or solutions from a list of several potential alternatives by taking into consideration a set of criteria [30–32]. The method is used to solve complex problems by analyzing multiple criteria simultaneously based on both quantitative and qualitative information [33]. Additionally, MCDA enables to consider the preferences of the different actors in the decision-making process [34]. MCDA frameworks have been applied to various applications, eg to evaluate pavement conditions, trenches and remediation methods [35–37].

This paper shows how a multi-criteria decision approach can be applied to evaluate circular building solutions in the context of practical architectural projects, in this case assessing the suitability of three interior wall systems for applications with different turnover rates. In this study, the MCDA framework studied has a hierarchical structure of criteria and indicators applied to all solutions. The solutions are evaluated using weighting, scoring, and ranking for the qualitative part [32,38]. The solutions that scored highly are then evaluated using quantitative methods such as LCA and LCC to evaluate environmental and financial impacts. The alternatives in this study are the three wall systems and one baseline solution that were presented in Figure 4. The set of criteria is presented in this section together with a set of weights for each of the wall type scenarios that were previously presented in Table 1. Scoring the wall systems results in an evaluation matrix, ranking them based on their suitability for each wall type scenario. The next sections will detail the qualitative and quantitative assessments adopted for this study.

2.4.1. Qualitative Assessment

Aspects of circular design and Design for Change (DfC) are generally not included in the selection of building products or solutions. Yet, they can greatly impact the potential for reuse and selective dismantling and thus decrease the lifecycle impact of buildings and building materials. Moreover, the resulting ease of maintenance, reorganization and future refurbishment can improve user comfort. The presented approach therefore includes a qualitative assessment of the interior wall systems to evaluate their fitness for the different wall type scenarios and to allow selecting the most suited solutions for the quantitative assessment. The research and design team therefore established a list of qualitative criteria, as presented in Table 3. Different project stakeholders as well as the manufacturers of the selected wall systems were involved in the definition of these criteria through co-creative sessions. The assessment focuses on a limited set of criteria and indicators, most relevant for the case of the Circular Retrofit Lab. All systems are commercially available and are suited for interior wall applications. The study focuses on aspects of reversible design to assess their fitness with regards to the developed scenarios and corresponding turnover rates. Additionally, the project stakeholders pointed to the quality of the finishing and the acoustic performance as essential criteria for the wall system selection. The environmental and financial impact were not weighted in this qualitative assessment, as they are part of the subsequent quantitative part of the study.

Table 3. The qualitative criteria consist of a reversibility, finishing and acoustical comfort criterion, each with different indicators.

	Qualitative Criteria	Description
1	Reversibility criterion	The degree in which the system's assembly can be reversed and adapted to future needs
1.1	Reversible connections	The ability to demount the system without damaging the components
1.2	Speed of assembly and disassembly	The overall speed of both the assembly and disassembly process
1.3	Reuse of materials or components	The ability to reuse the materials and components after disassembly (durable, not easily damaged, . . .)
1.4	Accessible and adjustable integration of technical systems	The ability to access technical systems (cables, ducts, . . .) for maintenance, replacement or adjustment
1.5	Independency of the composing building components	The ability to remove, replace or adapt individual components within the system without compromising adjacent ones
1.6	Kit-of-parts standardization	The use of a compatible system of components that can be reconfigured into different assemblies
2	Finishing criterion	The quality of the system's finishing layer
2.1	Visual aspect of the finishing	Aesthetic aspects of the finished wall system (visibility of connections, seams . . .)
3	Acoustical comfort criterion	The acoustical comfort the system provides
3.1	Acoustical performance	High (>57 dB), medium (57 dB > x > 51 dB) or low (<51 dB) acoustical performance

The qualitative evaluation of the wall systems was based on three elements: (i) the available technical information, (ii) discussions with the manufacturers and (iii) a series of practical workshops. During these workshops the different wall systems were mounted in an experimental test space, by professional assemblers delegated by the manufacturers but also students without prior knowledge of the systems. These workshops allowed testing the assembly process as well as the dismantling, reuse and reconfiguration.

Table 4 shows a weighing grid with three sets of weights, one for each wall type scenario. It incorporates the requirements of the different scenarios and thus represents the importance of the different criteria and indicators. Scenario 1 requires high levels of reversibility due to its short turnover rate. Yet, the integration of technical systems or acoustical comfort is less relevant in its function as a moveable dissemination wall. Scenario 2 requires reversibility in terms of access and integration of technical systems. Scenario 3 has the longest turnover rate. As a dividing wall acoustics are much more important, while the speed of assembly or standardization are less important. The circular construction experts of the Circular Retrofit Lab team at VUB Architectural Engineering weighed the criteria and scored the wall system based on the available documentation and the practical experience from the workshops. Multiplying weights and scores resulted in a ranking of the systems for each wall type scenario. This ranking supported the selection of potential wall systems for the quantitative assessment.

Table 4. Weights (expressed in percentages) represent the importance of the different qualitative criteria for the three wall type scenarios.

	Qualitative Criteria	**Scenario 1 (Quickly Changing Interior Wall)**	**Scenario 2 (Technical Interior Wall)**	**Scenario 3 (Dwelling Dividing Interior Wall)**
1	Reversibility criterion	65%	70%	45%
1.1	Reversible connections	15%	10%	10%
1.2	Speed of assembly and disassembly	12%	8%	5%
1.3	Reuse of materials or components	12%	8%	8%
1.4	Accessible and adjustable integration of technical systems	2%	20%	8%
1.5	Independency of the composing building components	12%	18%	8%
1.6	Kit-of-parts standardization	12%	6%	6%
2	Finishing criterion	25%	15%	25%
2.1	Visual aspect of the finishing	25%	15%	25%
3	Acoustical comfort criterion	10%	15%	30%
3.1	Acoustical performance	10%	15%	30%
	TOTAL	100%	100%	100%

2.4.2. Quantitative Assessment-LCA and LCC for CRL Solutions

A quantitative approach was also used to evaluate the wall types selected from the qualitative MCDA approach. The methods, LCA and LCC were utilized to evaluate the environmental and financial performance of the wall types. The following section details the methods used for the LCA and the LCC evaluation.

LCA Modeling Approach

The Circular Building Life Cycle Assessment (CBLCA) is a combination of two established LCA methods: the standard, EN 15978—Sustainability of Construction Works: Assessment of Environmental Performance of Buildings [39] and the Product Environmental Footprint (PEF) method developed by the European Commission [40]. A Belgian LCA method provides the background scenarios for the life cycle phases. The public waste agency of the Flemish region along with its counterpart within the Brussels-Capital Region and the Walloon region, developed a Belgian methodology to assess the environmental performance of buildings and building elements called the MMG LCA method, Environmental Performance of Materials used in Building Elements (in Dutch: Milieugerelateerde Materiaalimpact van Gebouwelementen, MMG) [41]. This method is aligned with the European EN 15978 standard [39] but does not incorporate certain modules (e.g., B5 'refurbishment') in its calculation.

The European Commission built the PEF method and the Organizational Environmental Footprint (OEF) method as part of the "Building a Single Market for Green Products" communication [42]. The PEF method builds upon existing LCA methods with the aim to harmonize them. The PEF method applies two methods to deal with multi-functionality in recycling, re-use and energy recovery situations [14]. The PEF method puts forward an End-of-Life (EoL) solution called a parametrized shared burden approach [X-(X-1)] known as the Circular Footprint Formula (CFF) [40]. The EN15978 standard also has two EoL solutions: a recycled content approach accounting for the A, B and C modules and an end-of-life recycling approach considering Module D where all benefits and burdens are accounted for in this module [39]. The basic formulas used to calculate the life cycle impacts for the CFF and the EN15978 and the adapted formulas for application in CRL are shown in the Annex A. The table in Annex A highlights the differences in modeling approach related to the CFF and the EN15978 method. Impacts related to recycling, reuse and recovery processes—as well as avoided impacts related to substitution of primary resources (products or elements)—are considered, but differently for both methods. Using the CFF within the PEF method, the impacts of the processes such as recycling and reuse are allocated to the modules where the processes occur. For example, the process impacts due to the use of a partitioning solution and the substitution benefits due to a reversible design are modeled in the production module by accounting for the impacts and benefits separately. However, in the EN15978 approach, the net benefits/impacts are all allocated to a Module D (outside of the system). The impacts and benefits of reversible design leading to reduced material use and disposal are not allocated to the respective modules. The formulas used to calculate using EN15978 and the PEF method are shown in Appendix A.

As the CRL is a Belgian pilot, typical Belgian scenarios related to transport of materials and product, as well as business-as-usual End-of-Life (EoL) scenarios as applied in the MMG method have been applied to this case study. The CBLCA methodology uses the two methods (EN15978 and the PEF method) detailed above to evaluate the environmental sustainability of a building. However, there are benefits and drawbacks to using the two methods. The strengths and weakness of the EoL approaches of the EN15978 and PEF methods are presented in Table 5. The CFF parametrized approach presents an opportunity to stimulate building design, management of building during use and waste management for circular solutions. The CFF accounts for the number of recycling cycles and is capable of allocating burdens and benefits of a repeatedly recycled material in multiple product systems [43]. This attribute is particularly valuable when dealing with reversible solutions as this study does. Hence moving forward, only results using the PEF method will be shown in the next section.

Table 5. Strength and weakness of End-of-Life (EoL) approaches used in the EN15978 and the PEF methods.

Approach	Strengths	Weaknesses
Recycled content approach (EN15978)	Valid for all EoL scenarios Stimulates a good waste management: "polluter (of today) pays" principle > waste management oriented	Benefits/impacts related to future recycling/reuse/energy recovery are not taken into account: does not stimulate future circularity End-of-Waste status is difficult to define
End of life recycling (EN15978)	Stimulates design for reversibility and good building management: "rewards future benefits" Future benefits/impacts are clearly communicated in a separate module D	Not valid for open-loop recycling Does not stimulate current circularity (i.e., recycled content) Module D is not useful when communicating multiple EoL cycles in buildings End-of-Waste status is difficult to define
Shared burden approach (PEF method)	Valid for all EoL scenarios Stimulates (equally fixed) future and current circularity	LCI modeling of virtual virgin and recycled/reuse processes are required
Parametrized end of life approach (PEF method)	Valid for all EoL scenarios Stimulates (parameterized) future and current circularity.	LCI modeling of virtual virgin and recycled/reuse processes are required Provided allocation values ("A factors") do not represent "reuse" market; if unknown we recommend A = 0.5 for reuse scenarios

LCC Modeling Approach

The life cycle cost calculation follows the principles of ISO 15686-5: 2017 Buildings and Constructed Assets—Service life planning—Part 5 life cycle costing [44]. This standard sets out the basic methodology and provides general guiding principles, instructions and definitions for life cycle costing. The scope of costs included in the life cycle costing analysis are construction, operation, maintenance and end-of-life costs. The ISO standard is applicable at all levels from portfolios of buildings down to component assessments. The life cycle cost calculations for the CRL follow the same modular approach as the EN 15978 standard for environmental performance assessments of buildings.

For the LCC calculations, a discount rate of 4% is applied to discount future costs to a common basis for the year 2018. The average inflation is assumed to be 2% and constant over the lifetime of the building. The use phase includes multiple maintenance, repair and replacement cycles—and accordingly multiple production and EoL processes—to understand the cost implications of the partitioning solutions under consideration [44].

3. Results

3.1. Application of Qualitative Assessment to CRL

3.1.1. Workshops and Evaluation

Figure 5 shows some of the outcomes of the workshops as well as some of the practical issues that were raised. Aside from informing the quantitative assessment, these workshops provided insights for the optimization of the wall systems and their connections. For this reason, manufacturers were involved and improved prototypes were implemented along the way.

Table 6 contains the scoring of the systems for the indicators of the previously defined criteria, quantifying whether the systems acquired a positive (1), neutral (0.5) or negative (0) evaluation from the experts. Each of the three proposed systems scores high on reversibility. Yet, the more massive and modular systems (System 1 and 2) are less independent (different modules are coupled in a fixed series), cannot as easily be reconfigured as a kit-of-parts system and are less versatile in the integration of technical systems. The steel kit-of-parts system (System 3) performs better for these criteria but has issues with acoustical performance due to the seams. Moreover, the visibility of the connections has a strong impact on aesthetics.

Table 6. The indicators for the three main criteria were scored based on a positive (1), neutral (0.5) and negative (0) evaluation.

	Qualitative Criteria	**System 1 Wood + Fiberboard**	**System 2 Massive Wood**	**System 3 Steel + Wood**	**Baseline Metal + Gypsum**
1	Reversibility criterion				
1.1	Reversible connections	1	1	1	0
1.2	Speed of assembly and disassembly	1	1	0.5	0.5
1.3	Reuse of materials or components	0.5	1	1	0
1.4	Accessible and adjustable integration of technical systems	0.5	0.5	1	0
1.5	Independency of the composing building components	0	0	1	0
1.6	Kit-of-parts standardization	0	0.5	1	0.5
2	Finishing criterion				
2.1	Visual aspect of the finishing	1	1	0.5	1
3	Acoustical comfort criterion				
3.1	Acoustical performance	1	1	0.5	1

3.1.2. Ranking of the Wall Systems

Multiplying the scores (Table 6) with the different sets of weights (Table 4) led to a series of three evaluation matrices, one for each wall type scenario (Tables 7–9). This allows ranking the wall systems. Due to their more reversible character the selected wall systems are consistently ranked higher than the business-as-usual baseline solution. Yet, the evaluation grids also show considerable differences between the systems themselves.

Wall system 1 - wood + fibreboard

Wall system 2 - massive wood

Wall system 3 - steel + wood

Figure 5. The systems were tested during three (student) workshops.

The ranking of the systems informed the selection of potential systems for each scenario in the following quantitative part, as presented in Table 7. Only systems with a total weighted score of at least 70% were considered in the next part of the study. Evidently, the baseline was considered for each scenario.

Table 7. Ranking of the wall systems using the weights for scenario 1—quickly changing interior wall.

	Qualitative Criteria	System 1 Wood + Fiberboard	System 2 Massive Wood	System 3 Steel + Wood	Baseline Metal + Gypsum
1	Reversibility criterion	34%	46%	59%	12%
1.1	Reversible connections	15%	15%	15%	0%
1.2	Speed of assembly and disassembly	12%	12%	6%	6%
1.3	Reuse of materials or components	6%	12%	12%	0%
1.4	Accessible and adjustable integration of technical systems	1%	1%	2%	0%
1.5	Independency of the composing building components	0%	0%	12%	0%
1.6	Kit-of-parts standardization	0%	6%	12%	6%
2	Finishing criterion	25%	25%	12.5%	25%
2.1	Visual aspect of the finishing	25%	25%	12.5%	25%
3	Acoustical comfort criterion	10%	10%	5%	10%
3.1	Acoustical performance	10%	10%	5%	10%
	TOTAL	69%	81%	76.5%	47%

Table 8. Ranking of the wall systems using the weights for scenario 2—technical interior wall.

	Qualitative Criteria	System 1 Wood + Fiberboard	System 2 Massive Wood	System 3 Steel + Wood	Baseline Metal + Gypsum
1	Reversibility criterion	32%	39%	66%	7%
1.1	Reversible connections	10%	10%	10%	0%
1.2	Speed of assembly and disassembly	8%	8%	4%	4%
1.3	Reuse of materials or components	4%	8%	8%	0%
1.4	Accessible and adjustable integration of technical systems	10%	10%	20%	0%
1.5	Independency of the composing building components	0%	0%	18%	0%
1.6	Kit-of-parts standardization	0%	3%	6%	3%
2	Finishing criterion	15%	15%	7.5%	15%
2.1	Visual aspect of the finishing	15%	15%	7.5%	15%
3	Acoustical comfort criterion	15%	15%	7.5%	15%
3.1	Acoustical performance	15%	15%	7.5%	15%
	TOTAL	62%	69%	81%	37%

Table 9. Ranking of the wall systems using the weights for scenario 3—dwelling dividing interior wall.

	Qualitative Criteria	System 1 Wood + Fiberboard	System 2 Massive Wood	System 3 Steel + Wood	Baseline Metal + Gypsum
1	Reversibility criterion	23%	30%	42.5%	5.5%
1.1	Reversible connections	10%	10%	10%	0%
1.2	Speed of assembly and disassembly	5%	5%	2.5%	2.5%
1.3	Reuse of materials or components	4%	8%	8%	0%
1.4	Accessible and adjustable integration of technical systems	4%	4%	8%	0%
1.5	Independency of the composing building components	0%	0%	8%	0%
1.6	Kit-of-parts standardization	0%	3%	6%	3%
2	Finishing criterion	25%	25%	12.5%	25%
2.1	Visual aspect of the finishing	25%	25%	12,5%	25%
3	Acoustical comfort criterion	30%	30%	15%	30%
3.1	Acoustical performance	30%	30%	15%	30%
	TOTAL	78%	85%	70%	60.5%

3.2. *Application of LCA and LCC to CRL Solutions*

The solutions shown in Table 10 were included in the evaluation using LCA and LCC methods described in Section 2.4.2. The following section details the results obtained using the quantitative approach. The environmental and financial performances of the baseline solution (gypsum cardboard with metal stud) and second and third systems (i.e., massive wood solution and steel frame with wooden panels, respectively) were compared for the quickly changing interior wall scenario. In the technical interior wall scenarios only the baseline gypsum cardboard with metal stud solution and the steel frame with wooden panels are considered. For the dwelling dividing interior wall scenario (Scenario 3), all wall options are taken into account.

Table 10. The ranking of the systems supported the selection of the wall systems for the different scenarios in the quantitative assessment. The selected wall systems and scenarios evaluated for the LCA and LCC study are shown in this table.

	System 1 **Wood + Fiberboard**	**System 2** **Massive Wood**	**System 3** **Steel + Wood**	**Baseline** **Metal + Gypsum**
Scenario 1: quickly changing interior wall		X	X	X
Scenario 2: technical interior wall			X	X
Scenario 3: dwelling-dividing interior wall	X	X	X	X

3.2.1. Cumulative Environmental Impacts

To conduct this study, an inventory was provided by the authors working on the CRL for all the transformation scenarios and the partitioning solutions. This inventory was used to obtain the necessary data to perform LCA on the various scenarios using the EN15978 and the PEF method. The results were calculated using the CBLCA methodology described in Section 2.4.2 but only the PEF method was utilized for the results. This is due to the choice of visual representation selected for the results.

One form of representation of the environmental impacts is through a cumulative graph of impacts at every stage of the entire wall solution lifetime. This form of representation is useful when analyzing various building solutions over long lifetimes and to identify the best solution in the long term. Only impacts related to global warming potential (or climate change) in kgCO_2 eq are shown.

The cumulative graphics for all three scenarios are modeled and shown. For each scenario modeled (quickly changing, technical interior wall, and dwelling dividing interior wall) the analysis was performed using the PEF LCA method. Figures 6–8 represent the environmental impacts per square meter of wall for a lifetime of 60 years of a building.

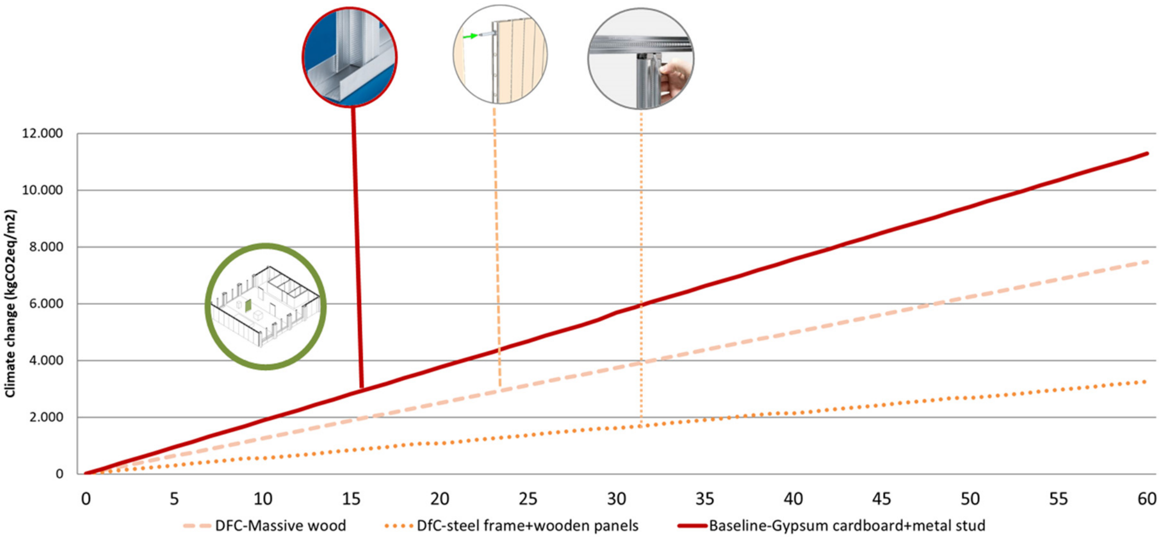


Figure 6. Global warming impacts per m^2 of Scenario 1, the quickly changing interior wall. The baseline gypsum cardboard with metal stud solution is compared with the Design for Change (DfC) solutions steel frame with wooden panels and massive wood. Transformation occurs every year in this scenario.

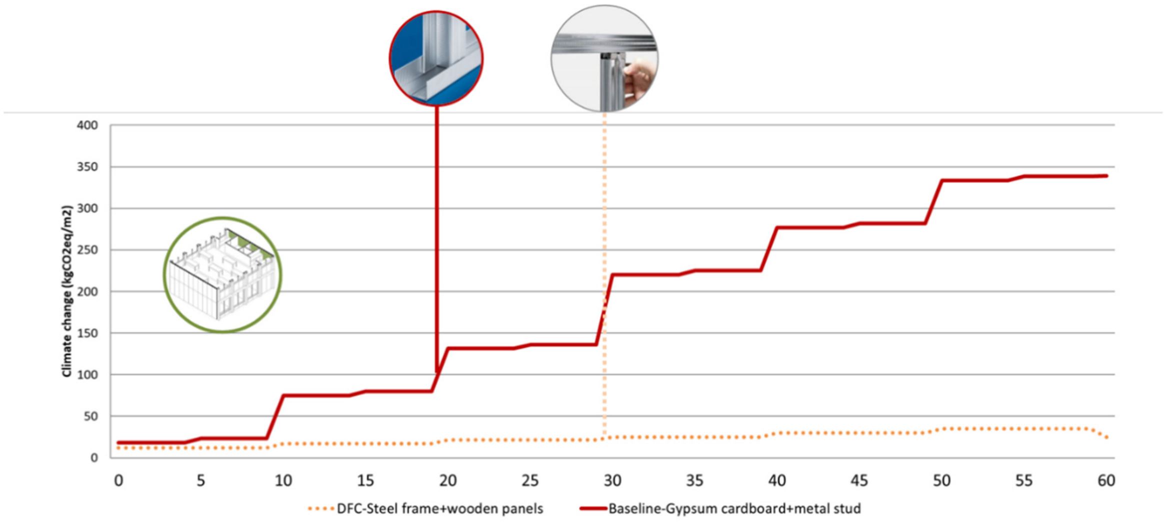


Figure 7. Global warming impacts per m^2 of Scenario 2, the technical interior wall. The baseline gypsum cardboard with metal stud solution is compared with the Design for Change (DfC) solution steel frame with wooden panels. Transformation occurs every 10 years.

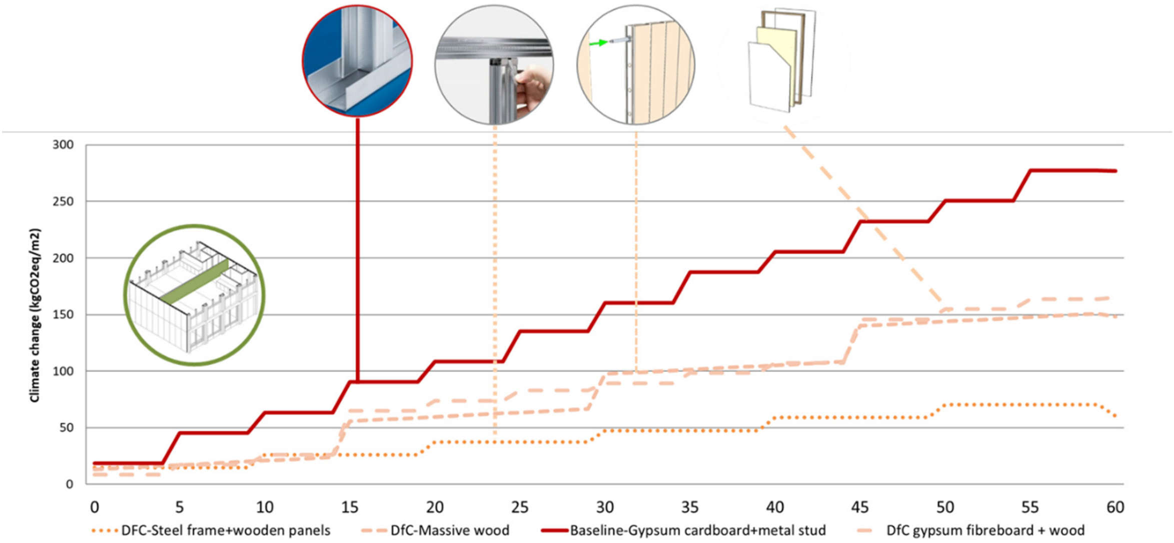


Figure 8. Global warming impacts per m^2 of Scenario 3, the dwelling dividing interior wall. The baseline gypsum cardboard with metal stud solution is compared with the Design for Change (DfC) solutions steel frame with wooden panels, massive wood and gypsum fiberboard with wood. Transformation occurs every 15 years.

For the quickly changing interior wall (Transformation scenario 1 in Figure 6) lower global warming impacts are discerned for all reversible interior wall solutions, compared to the baseline interior wall. For the steel frame and wooden panels solution and for the massive wood solution, impacts are 71% and 34% lower than the baseline, respectively. The steel frame and wooden panels solution is characterized by similar manufacturing environmental impacts in year 0 (14.69 kgCO_2 eq/m^2) compared to the baseline solution (14.60 kgCO_2 eq/m^2), but lower maintenance (every 5 years), replacement (every 30 years) and refurbishment impacts (every year) (3539 kgCO_2 eq/m^2 compared to 11278 kgCO_2 eq/m^2). For the massive wooden wall similar conclusions can be drawn, i.e., similar manufacturing impacts and 33% lower maintenance, replacement and refurbishment impacts. The better life cycle performance of the reversible wall solutions is mainly attributed to lower refurbishment and deconstruction/reassembly impacts, due to their design characteristics and direct reuse of the wall components. After the complete life cycle, it is the steel frame and wooden panels solution that has an overall better performance compared to the massive wood reversible design solution.

For the technical interior wall (Transformation scenario 2 in Figure 7), similar to the quickly changing scenario, lower global warming impacts are discerned for the reversible interior wall solution, compared to the baseline interior wall. For the steel frame and wooden panels solution, global warming impacts are 90% lower than the baseline. The steel frame and wooden panels solution is characterized by lower manufacturing environmental impacts (12.18 $kgCO_2$ eq/m^2) compared to the baseline solution (18.37 $kgCO_2$ eq/m^2) at year 0, and lower maintenance (every 10 years), replacement (every 30 years) and refurbishment impacts (every 10 years) (35.97 $kgCO_2$ eq/m^2 compared to 371.56 $kgCO_2$ eq/m^2). The dip at the end of the life cycle global warming impact for the reversible design solution is due to the substitution benefits achieved at end of life due to reuse of galvanized steel in screws, nuts and bolts.

For the dwelling-dividing interior wall (Transformation scenario 3 in Figure 8), like previous scenarios, reversible interior wall solutions have lower global warming impacts compared to the baseline interior wall. For the steel frame and wooden panels solution, massive wood solution and gypsum fiberboard and wood solution, global warming impacts are 78%, 48% and 40% lower than the baseline respectively. The reversible interior wall solutions characterized by lower manufacturing environmental impacts (14.69, 13.12 and 8.29 $kgCO_2$ eq/m^2 for steel frame wooden panels, massive wood and gypsum fiberboard and wood solutions respectively) compared to the baseline solution (18.37 $kgCO_2$ eq/m^2) at year 0. The reversible interior wall solutions also have lower maintenance, replacement and refurbishment impacts (70.36 $kgCO_2$ eq/m^2 for steel frame and wooden panel solution, 170.17 $kgCO_2$ eq/m^2 for massive wood solution and 178.91 $kgCO_2$ eq/m^2) compared to 269.67 $kgCO_2$ eq/m^2 for the baseline interior wall solution. The maintenance schedules for the steel frame and wooden panels, massive wood and gypsum fiberboard and wood solutions is 10 years, 5 years and every year respectively versus every year for the baseline solution while the replacement and refurbishment schedules are at 30 years and 15 years respectively for all solutions. Similar to the previous scenario, the steel frame and wooden panels end of life substitution benefits is visible in the dip at the end of the 60-year life cycle.

There is some overlap between the massive wood and the gypsum fiberboard and wood scenario. This is due to the maintenance scenarios of every year for massive timber solution versus every 5 years for gypsum fiberboard and wood scenario. This accompanied with the replacement impacts every 30 years and refurbishment impacts every 15 years causes a few overlaps in global warming impacts. After the complete life cycle, it is the steel frame and wooden panels solution that has an overall better performance compared to the massive wood and gypsum fiberboard and wood reversible design solutions.

3.2.2. Cumulative Financial Impacts

To conduct the life cycle costing calculations, the same transformation scenarios and interior wall solutions were employed as for the environmental assessment (Section 3.2.1). The cumulative graphics for all three scenarios are modeled and shown in Figures 9–11. Financial costs, expressed per square meter of wall for different transformation scenarios, are illustrated as cumulative figures with costs over the whole life cycle of the building for a lifetime of 60 years.

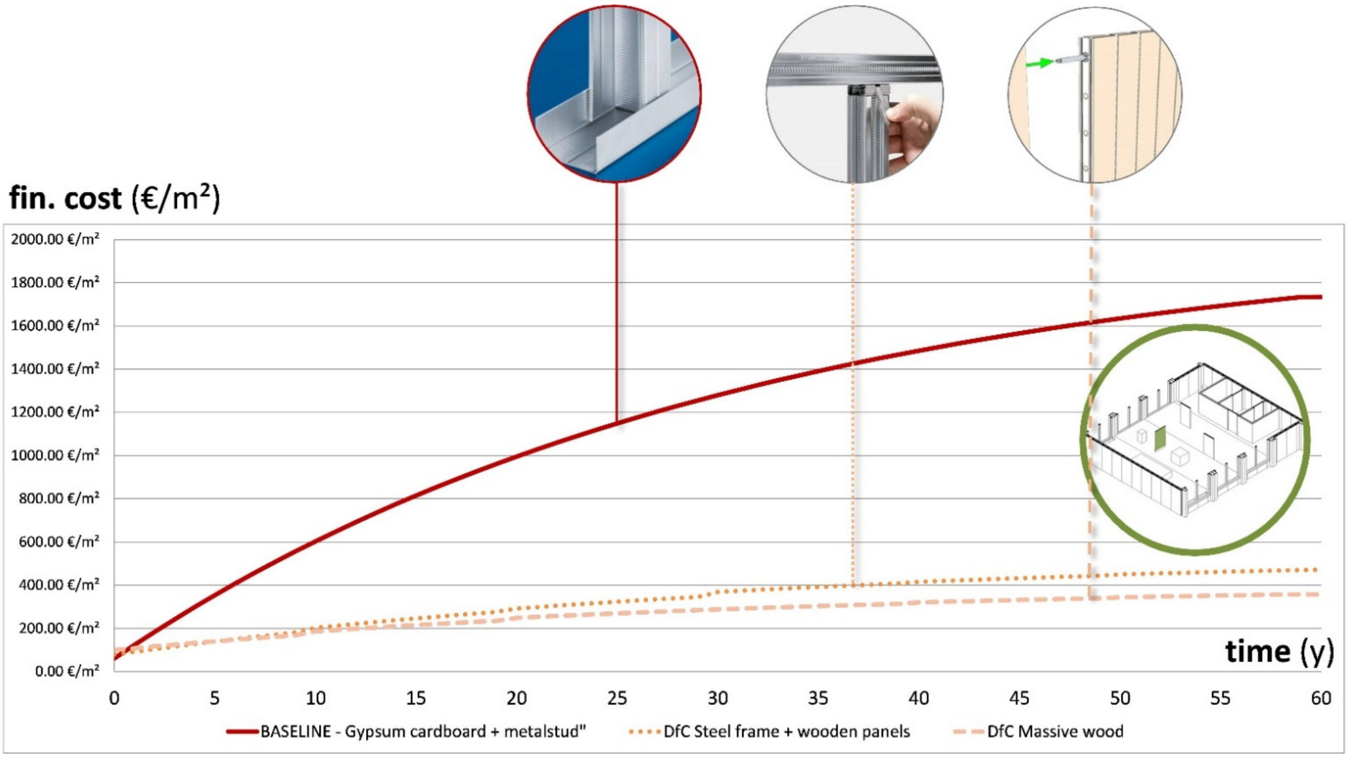


Figure 9. Financial cost per m^2 of Scenario 1, the quickly changing interior wall. The baseline gypsum cardboard with metal stud solution is compared with the Design for Change (DfC) solutions steel frame with wooden panels and massive wood. Transformation occurs every year in this scenario.

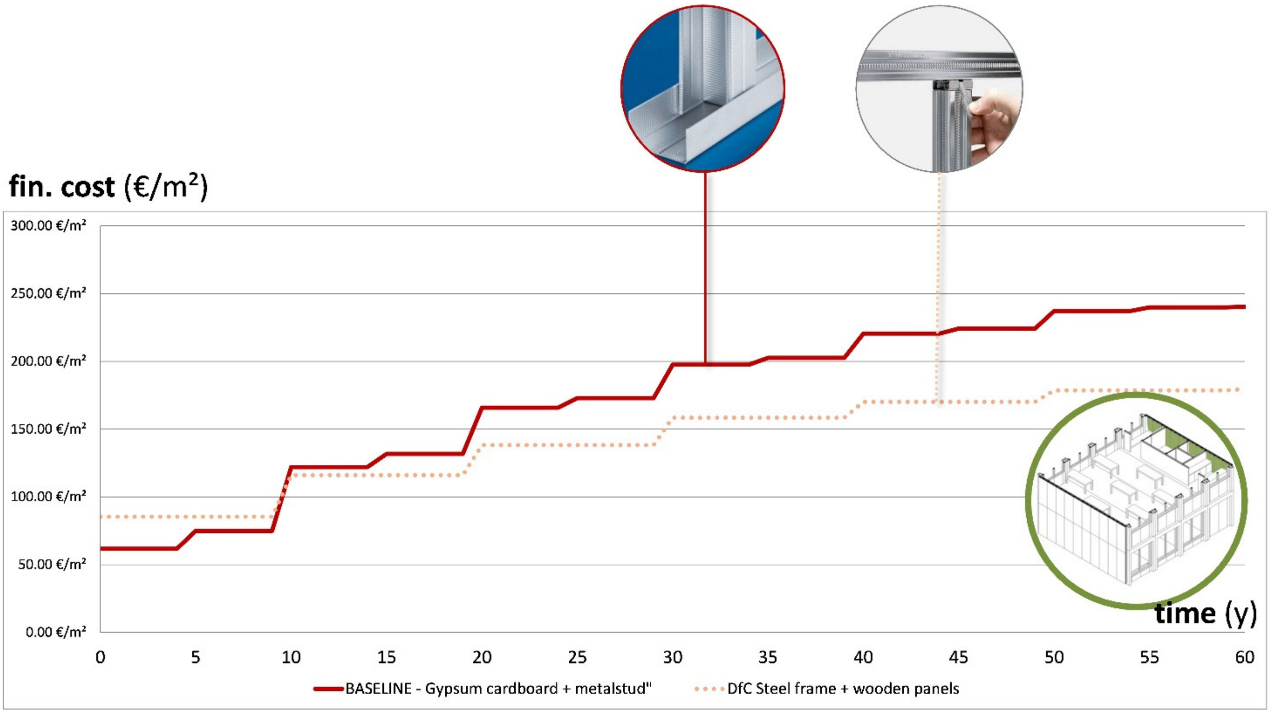


Figure 10. Financial cost per m^2 of Scenario 2, the technical interior wall. The baseline gypsum cardboard with metal stud solution is compared with the Design for Change (DfC) solution steel frame with wooden panels. Transformation occurs every 10 years.

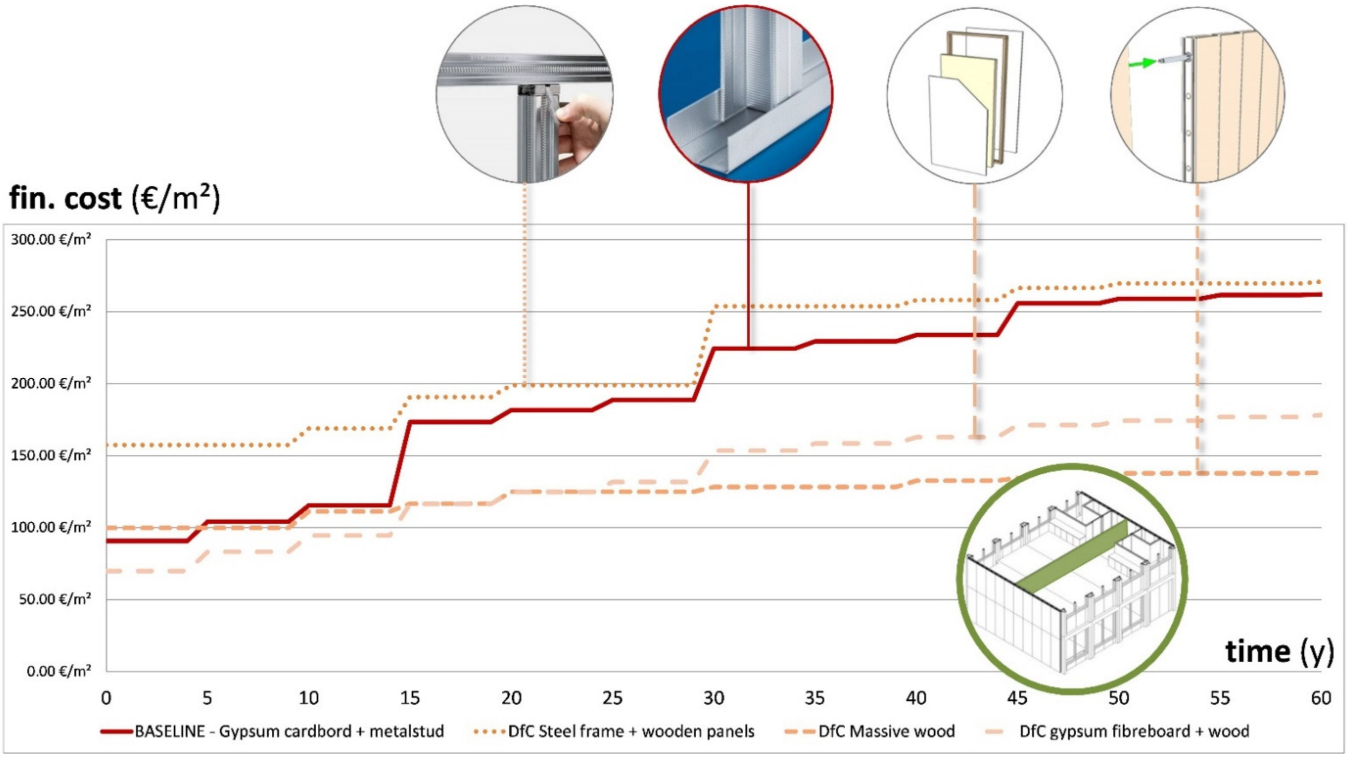


Figure 11. Financial cost per m^2 of Scenario 3, the dwelling-dividing interior wall. The baseline gypsum cardboard with metal stud solution is compared with the Design for Change (DfC) solutions steel frame with wooden panels, massive wood and gypsum fiberboard with wood. Transformation occurs every 15 years.

For the quickly changing interior wall (Transformation scenario 1 in Figure 9) higher initial financial costs (consisting of initial material and installation costs) are discerned for the reversible interior wall solutions, compared to the baseline interior wall (i.e., EUR 61/m^2 for the gypsum cardboard on metal stud solution). For the steel frame and wooden panels solution and for the massive wood solution, total initial costs are 28% and 63% higher than the baseline, respectively. The steel frame and wooden panels solution is characterized by a more than three times higher initial material cost (68 €/m^2) compared to the baseline solution (EUR 21/m^2), but lower installation costs (EUR 10/m^2 compared to EUR 40/m^2). For the massive wooden wall similar conclusions can be drawn, i.e., more than four times higher initial material costs and 83% lower installation costs. Nevertheless, due to the yearly transformations over an expected building life span of 60 years, the preferences are changed based on life cycle costs. After 60 years, the baseline solution will cost 1734 €/m^2, whereas at the end of the building life span the costs of the steel frame and wooden panels solution and massive wooden solution are 73% and 79% lower respectively. The financial investment is returned after the first transformation (i.e., after one year) for both reversible wall solutions. The better life cycle performance of the reversible wall solutions is mainly attributed to lower refurbishment costs and deconstruction or reassembly costs, due to their design characteristics and direct reuse of the wall components. The massive wall solution is also characterized by a lower replacement cost compared to the two other solutions, due to the long technical lifespan of the wall components.

For the technical interior wall (Transformation scenario 2 in Figure 10), similar to the first scenario, the initial financial cost of the baseline scenario (i.e., EUR 62/m^2 for the gypsum cardboard on metal stud) is lower than the initial cost of the selected reversible wall solution (i.e., EUR 85/m^2 for the steel frame with wooden panels). After the complete lifespan of the building, the reversible wall solution has a better life cycle financial performance: the steel frame and wooden panels solution only costs EUR 180/m^2, whereas the baseline costs EUR 240/m^2. This is mainly attributed to the refurbishment costs (i.e., EUR 27/m^2) after each transformation for the demountable wall solution. These costs are 59% lower compared to the baseline, as a result of the design characteristics of the reversible solution and direct reuse of the wooden panels. After the first transformation, i.e., at year 10, the initial investment is recuperated, compared to the baseline solution.

It should be noted that a complete demolition and reinstallation of the gypsum cardboard on metal stud solution is assumed after each transformation, in order to able be to compare both wall solutions in a consistent way on element level (i.e., based on m^2 of wall solution). However, in reality, the gypsum cardboard will only be partly removed to get to technical services and will be fixed afterwards. These actions are very case specific and have to be dealt with on a building level.

For the dwelling-dividing interior wall (Transformation scenario 3 in Figure 11), in contrast to the other two scenarios, one of the reversible building solutions, i.e., the gypsum fiberboard on wooden skeleton solution has the lowest initial financial cost (EUR 70/m^2). This solution is characterized by relatively low material and installation costs, i.e., EUR 43/m^2 and EUR 27/m^2 respectively. For the other two reversible wall solutions, the initial costs are higher (i.e., 74% and 10% higher for the steel frame and wooden panels solution and massive timber solution, respectively), compared to the baseline solution (gypsum cardboard on metal stud): EUR 91/m^2. The life costs of the steel skeleton and wooden panel solution (i.e., EUR 271/m^2) are (slightly) higher than the baseline solution (i.e., EUR 262/m^2). This means that from both initial investment perspective and life cycle perspective, there is no incentive to consider this reversible wall solution for the dwelling application. For the two other reversible wall solutions there is clearly an incentive to use these solutions. The gypsum fiberboard on wooden skeleton has a lower initial cost (see above) and lower life cycle costs, compared to the baseline solution. The massive wood solution is already competitive after year 5, when the baseline solution needs to be repainted. For the wood solution an oil treatment was considered instead of paint. After the first transformation (in year 15) the reversible wall solutions clearly distinguish from the baseline by smaller refurbishment costs, i.e., EUR 36/m^2, EUR 9/m^2 and EUR 36/m^2 for a single transformation, for the steel frame and wooden panel solution, the massive wood solution and gypsum fiberboard on wooden skeleton solution respectively– compared to the baseline solution, i.e., EUR 94/m^2 after each transformation.

4. Discussion

This paper presented a novel two-step approach for the evaluation of building solutions for circular construction projects as well as its application for the assessment of three interior wall systems in the Circular Retrofit Lab case. The approach was based on the development of three future user scenarios for interior walls with different turnover rates. These scenarios were used both to provide the weighting in the qualitative part and to define rates of maintenance, replacement and refurbishment in the quantitative part. Both the qualitative and the quantitative part illustrate, in their own way, the long-term benefits of circular or reversible building design and as such show the relevance of the approach in facilitating more comprehensive decision-making.

While it is already an important step to include aspects of circular design and design for change in the evaluation and selection of building solutions, the qualitative assessment presented in this paper shows the importance of weighting different indicators with respect to the expected use and future use scenarios of the construction elements. After all, circular design encompasses different design aspects and their respective importance varies from case to case. Doing this in a qualitative assessment, as opposed to the quantitative part, moreover allows integrating comfort criteria. As a relatively fast method, this qualitative assessment is well-suited to provide a first selection of the most favorable building solutions.

The quantitative part includes the LCA and LCC of the reversible building solutions. The LCA method adopted uses two different standards, the EN 15978 and the PEF method and modifies it for the CBLCA method. Both the methods, the adapted PEF and the modified EN15978 have strengths and weaknesses. The EN15978 method does not require detailed modeling of the manufacturing phases (A1–A3) and is compatible with existing LCA datasets. It is also valid for all EoL scenarios where the waste management principle of "Polluter Pays" is applied. However, this method does not render itself compatible when circularity is applied as the benefits/impacts related to future recycling or reuse or energy recovery are not taken into account. Additionally, Module D is not useful when a building has multiple EoL cycles and the end-of-waste status is difficult to define and needs to be performed on a case by case basis. Based on these reasons, the PEF method was chosen to evaluate the various circular building wall solutions described in the study. Additionally, this study shows the results using the PEF method in the form of cumulative graphs as the method renders itself easily to highlight the lifetime cumulative environmental impacts. Added the fact that the reversible wall systems have inherent future recycling/reuse benefits, the PEF method was the logical choice for conducting the LCA assessment.

Lower refurbishment costs, together with lower deconstruction and reassembly costs can contribute to a competitive life cycle performance for reversible wall solutions, due to design characteristics and direct reuse of the reversible wall components. Lower replacement costs are also economic benefits of the reversible solutions, due to the long technical lifespan of the wall components. Assumptions on demolition, dismantling and reassembly, reuse and recuperation of components, etc., were made in order to able be to compare baseline and reversible wall solutions in a consistent way on element level, i.e., based on m^2 of wall solution. These assumptions are very case specific and have to be dealt with on a building level.

A comparison of the qualitative and quantitative results show that the various DfC solutions have a lot of benefits compared with the baseline solutions. For example, the massive wood solution used in the quickly changing interior wall and the dwelling dividing interior wall is preferable to other solutions from a qualitative, environmental and financial standpoint. However, the steel frame with wooden panels is not the preferred solution compared with the baseline financially even though it has qualitative and environmental benefits.

One drawback of this approach the authors have noted is that it does not necessarily provide a singular choice at the end of the analysis. This multi criteria decision analysis method would require another weighting of the various solutions after the qualitative and quantitative study has been conducted to arrive at a single preferred solution. The final weighting is not included in this study as it is subjective and dependent on the decision maker's preference of either qualitative or quantitative attributes. This step is considered beyond the scope of this study and thus is not included in the framework described. This study provides a method for evaluating circular building solutions with multiple criteria for selection. The qualitative and quantitative assessments in this study are applicable to circular building solutions beyond the ones presented in this study.

5. Conclusions

Overall, an MCDA approach can help decision-makers to discard certain design options and focus on a restricted number of "high qualitative" options. Furthermore, it helps the designer to improve design solutions. A qualitative selection along with a quantitative LCA and LCC that focusses on cumulative impacts of solutions will provide enough information for a decision maker to facilitate an informed choice. The additional step of weighting the qualitative and quantitative results which have subjective influences on the final choice of reversible solutions are not presented in this study but will be a part of any decision maker's framework when applying the MCDA method presented in this study.

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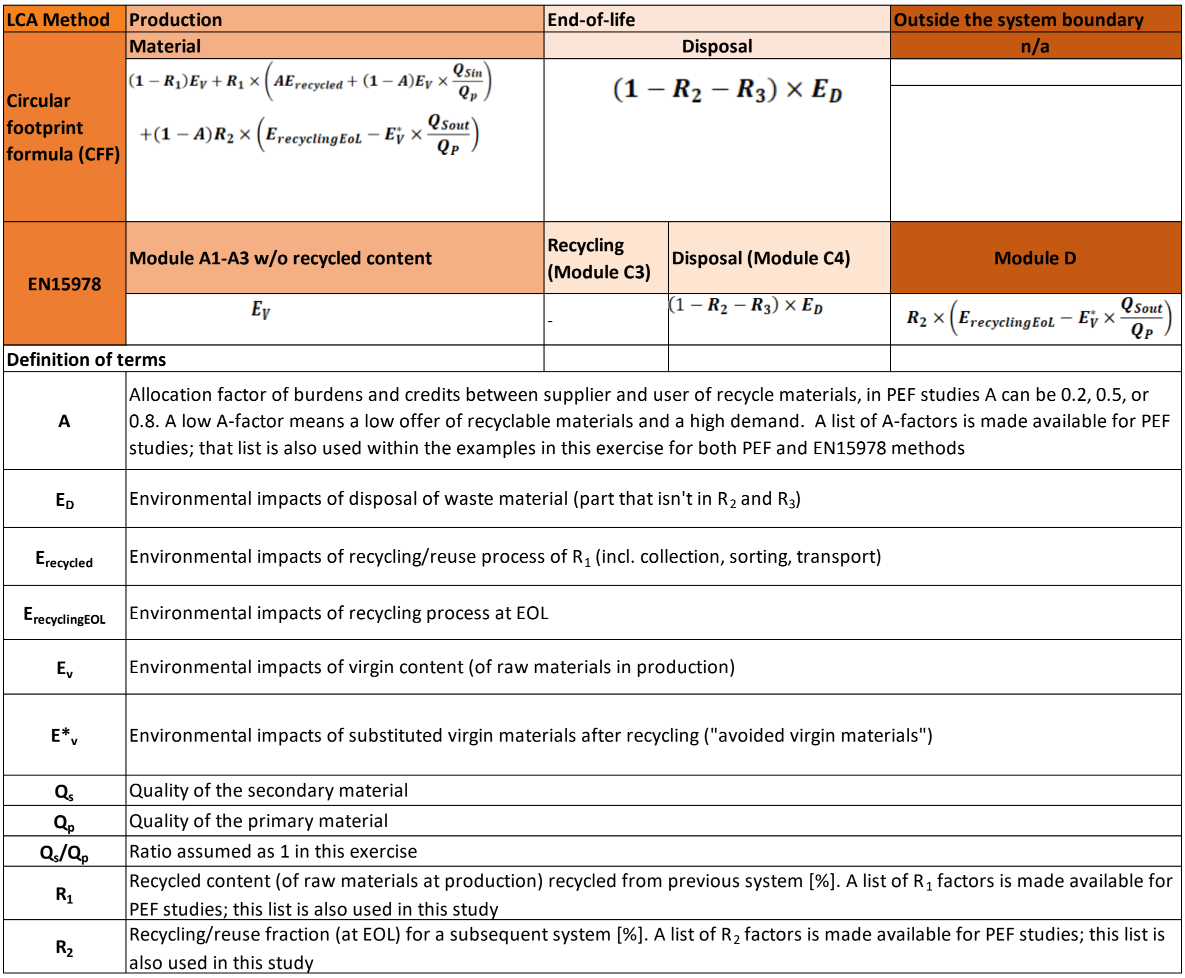
Appendix A

Formulas used for calculating life cycle impacts using the Circular Footprint Formula (CFF) and the EN15978 method for production, end of life and modules outside the system boundary and definition of terms used in the formula. This case study does not have any energy recovery. The formulas related to energy recovery are not included in this table.



LCA Method	Production	End-of-life		Outside the system boundary
	Material	Disposal		n/a
Circular footprint formula (CFF)	$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_p}\right)$ $+(1-A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$	$(1-R_2-R_3)\times E_D$		
EN15978	Module A1-A3 w/o recycled content	Recycling (Module C3)	Disposal (Module C4)	Module D
	E_V	-	$(1-R_2-R_3)\times E_D$	$R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$
Definition of terms				
A	Allocation factor of burdens and credits between supplier and user of recycle materials, in PEF studies A can be 0.2, 0.5, or 0.8. A low A-factor means a low offer of recyclable materials and a high demand. A list of A-factors is made available for PEF studies; that list is also used within the examples in this exercise for both PEF and EN15978 methods			
E_D	Environmental impacts of disposal of waste material (part that isn't in R_2 and R_3)			
$E_{recycled}$	Environmental impacts of recycling/reuse process of R_1 (incl. collection, sorting, transport)			
$E_{recyclingEOL}$	Environmental impacts of recycling process at EOL			
E_v	Environmental impacts of virgin content (of raw materials in production)			
E^*_v	Environmental impacts of substituted virgin materials after recycling ("avoided virgin materials")			
Q_s	Quality of the secondary material			
Q_p	Quality of the primary material			
Q_s/Q_p	Ratio assumed as 1 in this exercise			
R_1	Recycled content (of raw materials at production) recycled from previous system [%]. A list of R_1 factors is made available for PEF studies; this list is also used in this study			
R_2	Recycling/reuse fraction (at EOL) for a subsequent system [%]. A list of R_2 factors is made available for PEF studies; this list is also used in this study			

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