FACULTY OF ENGINEERING
AND ARCHITECTURE

Can circular building solutions provide a positive impact? Determining the environmental and financial impact of internal walls.

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Student number: 01706349

Supervisor: Prof. dr. ir. arch. Marijke Steeman
Counsellor: Lisa Van Gulck

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in de ingenieurswetenschappen: architectuur

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Preface

Topics such as material depletion, the growing garbage mountains and the effects of air, water, and soil pollution are indispensable in our current society. One of the main contributors to these environmental issues is the building sector. Therefore, it is important that we, as future engineer-architects, endeavor for a shift from the traditional to a more sustainable building industry. Currently, different sustainable building strategies are being studied and developed for practical use. One of the strategies is the use of circular building elements. In this master's thesis, I was given the opportunity to research this topic. I hope that the results of this master's thesis can contribute to the shift to a more sustainable building sector in the future.

First and foremost, I would like to thank my research supervisor, dr. ir.-arch Marijke Steeman, to stir up my interest in sustainable building techniques and Life Cycle Analysis during her college classes and to allow me to extend this knowledge in this master's thesis. In my future career, I will expand my knowledge about this topic and strive for a more sustainable building industry. Thanks for the guidance and support during last year.
I would like to extend my sincere thanks to my counselor, drs. ir-arch Lisa Van Gulck. She was always there for me whenever I ran into a trouble spot or had a question about my research. Additionally, she consistently allowed this master's thesis to be my own work but was there to guide me in the right direction whenever she thought I needed it. Thanks for all the valuable assistance and insights leading to this final result.

Then, I would like to express my deepest appreciation to architect and project manager Gwen Verlinden. Her passion and belief in a circular and sustainable building industry are endless. Although, her passion goes further than just a belief. She tries to contribute to the sustainable shift in Belgium by participating in research projects such as 'Circular Building, Affordable Housing'. Thank you, Gwen, for all your enthusiasm and valuable

discussions about my research and to expand my knowledge about circular building strategies with the CBBW project in Berchem. But most of all, for giving me the opportunity to present my research together with your project in Ghent and Hasselt. I hope that our paths will cross again in the future.
Also special thanks to Xavier Huyghe from JUUNOO for the interview, all the received information and the quick responses to all my questions about JUUNOO.

Furthermore, I would like to express my endless gratitude to my dearest partner and friend, Jarne Verhaeghe. He listened endless hours to my enthusiasm and struggles about my research topic. He has been my support and refuge when I lost courage in my research. He was the first one who saw my results and with whom I discussed them. His critical view, his feedback on my research, and our endless discussions, widened my view on this topic and brought my master dissertation effectively to a higher level. Thanks, Jarne, for being such a lovely person and to make my life much easier with your support!

Of course, I would also like to thank my parents for their constant support throughout my five years at the University of Ghent, especially during this crowning achievement of my studies. I will never truly be able to express my sincere appreciation to both of them. They have inspired me to continue to strive to become the best version of myself every day and to pursue my dreams. A special thanks to my father for proofreading my master's thesis. It is not obvious to proofread a master thesis on a topic where you don't have expertise in. Last but not least, I must also thank my friend, Arne Decadt. His door was always open when I had problems with my software packages, such as Excel and the text editor Overleaf. Thank you for the support, Arne! With this, I'm immortalizing our agreement.

Thank you very much to everyone, and also to you reader. I hope that this master's thesis provides you new insights.

Jade Claes, 3 June 2022

Admission to use

Jade Claes, 3 June 2022

Can circular building solutions provide a positive impact? Determining the environmental and financial impact of internal walls.

by

Jade Claes

Master's dissertation submitted on 3 June 2022

Supervisor: Prof. dr. ir.arch. Marijke Steeman

Counsellor: Lisa Van Gulck

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Summary

The construction industry puts an enormous pressure on the environment. The transition towards a circular economy (CE) is essential to reduce emissions, resource consumption, and waste generation. Nevertheless, an insufficient number of quantitative studies currently exists to prove the potential 'positive' environmental effect and cost of circular building elements. Furthermore a consistent and governmental recognised CE-assessment framework is also non-existent. Therefore, this study proposes the R-LCA method, based on the Life Cycle Analysis framework in the European standard NBN EN 15804(2019). In this method, the reuse benefits of the circular building elements within the same building are evaluated by adding a refurbishment module to this standard. Supplementary, the R-LCC method is proposed for the financial assessment. The suggested CE-framework is then applied to the case house of 'Circular Building, Affordable Housing' in Berchem to compare the environmental impact and financial cost of the circular JUUNOO walls to the traditional wall assemblies considering future refurbishment scenarios. The analysis shows that the circular JUUNOO walls have in general a slightly lower financial cost and environmental impact than the traditional walls when refurbishment scenarios take place. However, the traditional metal stud wall is a better environmental alternative in the situation without refurbishments. In other words, the added value of using circular instead of traditional building elements is influenced by the refurbishment frequency, the refurbished wall surface, and the assumptions in both methods. The case study shows that the proposed CE-framework can be used to compare the results of circular with traditional building elements with the chosen material properties for any assumed future refurbishment scenario.

Keywords

Circular building elements, circularity metrics, LCA & LCC, JUUNOO walls

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Abstract— **The construction industry puts an enormous pressure on the environment. The transition towards a circular economy (CE) is essential to reduce emissions, resource consumption, and waste generation. Nevertheless, an insufficient number of quantitative studies currently exists to prove the potential 'positive' environmental effect and cost of circular building elements. Furthermore a consistent and governmental recognised CE-assessment framework is also non-existent. Therefore, this study proposes the R-LCA method, based on the Life Cycle Analysis framework in the European standard NBN EN 15804(2019). In this method, the reuse benefits of the circular building elements within the same building are evaluated by adding a refurbishment module to this standard. Supplementary, the R-LCC method is proposed for the financial assessment. The suggested CE-framework is then applied to the case house of 'Circular Building, Affordable Housing' in Berchem to compare the environmental impact and financial cost of the circular JUUNOO walls to the traditional wall assemblies considering future refurbishment scenarios. The analysis shows that the circular JUUNOO walls have in general a slightly lower financial cost and environmental impact than the traditional walls when refurbishment scenarios take place. However, the traditional metal stud wall is a better environmental alternative in the situation without refurbishments. In other words, the added value of using circular instead of traditional building elements is influenced by the refurbishment frequency, the refurbished wall surface, and the assumptions in both methods. The case study shows that the proposed CE-framework can be used to compare the results of circular with traditional building elements with the chosen material properties for any assumed future refurbishment scenario.**

Keywords—**Circular building elements, circularity metrics, LCA & LCC, JUUNOO walls**

I. Introduction

Currently, the building sector is responsible for 40 percent of the energy consumption, 36 percent for the emissions of greenhouse gasses, 40 percent for the extracted raw materials, and 60 percent for the waste streams in Europe [3] [7] [10]. To reduce the negative impact of the construction industry on the natural environment, it is necessary to develop a more sustainable built environment with higher resource efficiency, less waste generation, and lower carbon emissions. One strategy is to shift from a linear to a circular building practice with the focus on the reuse of building materials and elements [11]. The long-term improvement in environmental impact by using circular instead of traditional building elements should be researched to stimulate and accelerate this shift in the current society [19]. Additionally, the financial aspect regarding the adoption of circular building elements may not be disregarded [14].

An insufficient number of quantitative studies currently exists to prove the potential 'positive' environmental effect and cost of circular building elements [6]. Furthermore, to prove the benefits of the reuse potential of building elements in the same building, clear decision support to assess the total environmental performance and financial cost is required. However, the literature lacks a consistent and governmental recognized method to credit the reuse potential [12]. Previous studies identified the Life Cycle Analysis (LCA) framework as an important methodology for the assessment of the environmental performance of a circular building element [16] [17]. Additionally, the Life Cycle Costing (LCC) framework, using the same assumptions and boundary conditions as the LCA framework, can be used to assess the total cost. Nevertheless, the current European standards NBN EN 15804(2019) and 159785(2011) for the LCA of building products focus on assessing the impact of a product system for a single life cycle, from raw material acquisition through production, use, and end-of-life processes [9]. As a result, questions arise about how to use this framework to model and calculate the impact of reusable building elements over multiple life cycles [12]. The end-of-life stage for reusable building elements is by nature a multi-output process: it delivers the waste management of a product, but also creates the new reused product. According to the cut-off allocation approach used in the European standards, the reuse benefits fall outside the system boundaries. This is known as a methodological issue in the conventional LCA framework for assessing circularity [4].

The European standard NBN EN 15804(2019) proposes to quantify the reuse benefits at the end of the systems lifespan in module D [5]. However, the method described in the standard is not easy to interpret and leaves room for multiple hypotheses and scenarios. Additionally, the determination of the end-of-waste stage of building products is debatable and the functional equivalence is not easy to define by the uncertainty of reuse scenarios [22]. Furthermore, a CE-assessment tool is investigated to asses the circular benefits and burdens of reusable building elements during the life cycle of the building. Therefore, the objective of this paper is twofold. In the first part, a consistent and simplified CE-assessment framework is developed, based on the conventional LCA and LCC method, to compare the environmental impact and financial cost of circular to traditional building elements during a buildings lifespan.

Afterward, the developed framework is applied to compare the environmental impact and financial cost of the circular JUUNOO walls with frequently used interior walls in the Belgian construction industry considering future refurbishment scenarios. The analysis is performed on the case study house of the 'Circular Building, Affordable Housing' project in Berchem.

II. The CE-assessment framework

The following CE-assessment framework is proposed to compare the environmental performance and financial cost of circular to traditional building elements during the building's lifespan. Within this framework, the environmental impact is evaluated using the developed R-LCA method and the financial cost using the R-LCC method during buildings lifespan.

A. The R-LCA methodology

The developed R-LCA methodology, based on the traditional LCA framework of European standard NBN EN 15804(2019), is a cradle-to-grave LCA. It includes the impact of the production and construction stage (module A), the use stage (module B), and the end-of-life stage (module C) of the building. In this method, the environmental benefits and burdens of using circular instead of traditional building elements during the building's life span are assessed in multiple building element use cycles within the same life cycle of the building. With this approach, the complex and uncertain allocation procedures of the end-of-life impact of reusable building elements over multiple life cycles can be avoided. The environmental impact of the reuse of building elements during the buildings life span is accounted for in the additional module B5 'refurbishments' in the use stage. The module 'refurbishments' take the environmental impact of a building elements transformation during buildings service life into account. In a refurbishment, the (de)construction impact and the material losses are included in module B5 for the reusable building products, while for the traditional building products also the production and end-of-life impact are included, as illustrated in figure 1. Therefore, with each transformation, the reusability potential of the building elements needs to be checked with the following criteria for reversible building elements [15]. The connections between the components need to be reversible. The building element must be reusable in the same application. The technical component's service life needs to be longer than 10 years. The remaining component's service life needs to be longer than half of the initial technical service life of the component.

For traditional building products, the implementation of the refurbishment module influences the other use phase modules, namely the maintenance and the replacement module. Similarly to the reduction of the number of maintenance scenarios with the number of replacements when modeling the building element's life cycle, the number of refurbishments is subtracted from the number of replacements [20]. In contrast, the number of replacements for reusable building products is not influenced by the number of refurbishments. Furthermore, in the R-LCA framework, the impact of the use, repair, operational energy, and water use processes are not included in the use stage. The reparation impact of building elements is not modeled due to the lack of reliable information for this module. The other modules are excluded because the impact is assumed to be the same for the traditional and circular building elements. After the building's service life, the building products are assumed to be disposed, incinerated, or recycled. The cut-off approach is used to allocate the recycling benefits and burdens. This approach avoids the uncertainty in predicting the future of end-of-life scenarios, but slightly underestimates the benefits of CE practices [12].

B. The R-LCC methodology

The Life Cycle Costing framework, proposed in the international standard ISO 15868 (2011), is similarly structured as the LCA framework. It is nowadays often used for the assessment of the life cycle cost of a specific building product and the framework used in this research [2].

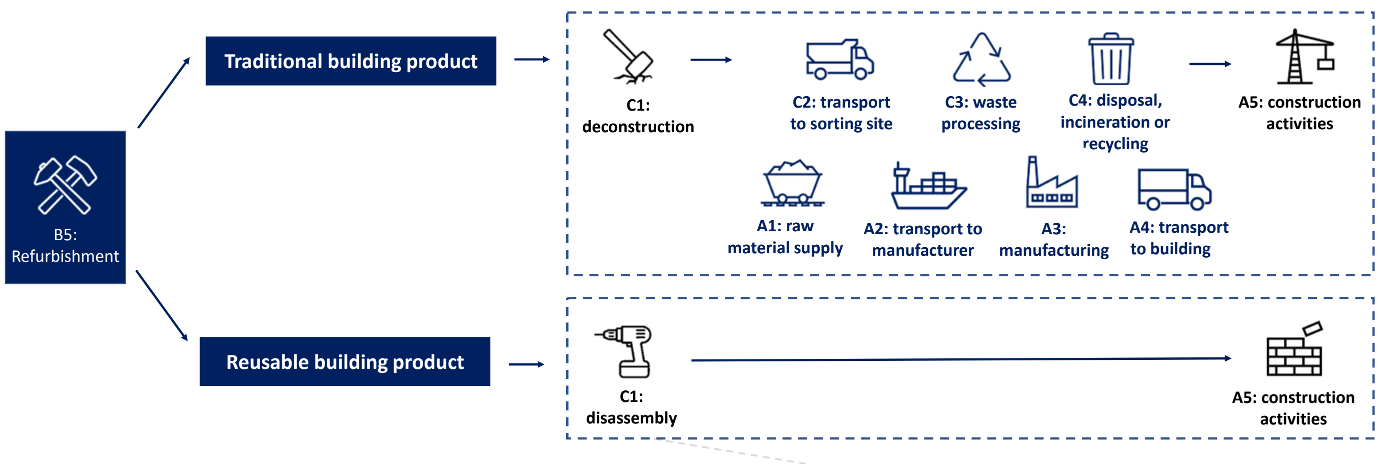

Fig. 1. The implemented module B5 'refurbishments' with the assessed impact modules for reusable and traditional building elements.

To compare the financial and environmental results, the same boundary conditions need to be applied to both frameworks. This means that the LCA and LCC analysis should have the same functional unit, the same building's technical service life, and the same system boundaries, as represented in table 1.

R-LCA method	**R-LCC method**
Initial impact	Initial cost
- Exploitation and production materials	- Materials
- Transport to site	- Transport to site
- Construction	- Labor (construction)
Use/periodic impact	Use/periodic cost
- Refurbishments	- Refurbishments
- Replacements	- Replacements
- Maintenance	- Maintenance
End-of-life impact	End-of-life cost
- Deconstruction	- Labor (deconstruction)
- Transport to end-of-life treatment	- Transport to end-of-life treatment
- End-of-life treatment	- Container

Table 1. System boundaries of the R-LCA and the R-LCC method

The Net-Present Value (NPV) methodology is used within the LCC framework. With this frequently used method, the current value of all the future cash flows generated in the building can be determined, including the initial investment cost [14]. The NPV is the sum of the initial investment costs and the discounted future costs occurring over the lifespan of the building [1]. The selection of the discount rate, determining the present value of future cash, has a major impact on the results of the R-LCC study and is assumed to be between zero and three percent [21] [13]. Nevertheless, the material and labor prices do not change at the same rate as the general discounting rate. To take this into account, a growth rate based on the ABEX index or economic reports has to be defined to reflect the different evolution in material and labor prices [1] [14].

III. Case study: CBBW project in Berchem

A. Research and methodology

The proposed CE-framework is applied to compare the environmental impact and financial cost of the circular JUUNOO walls to frequently used interior walls in the Belgian construction industry in the context of the case house of the 'Circular Building, Affordable Housing' (CBBW) project in Berchem. With these results, the most environmentally and financially beneficial interior wall is determined for future refurbishment scenarios in the case house. The seven investigated interior walls were the JUUNOO walls with plasterboard and MDF (paint), the wetwalls with ceramic and sand-lime building blocks, and the drywalls with wooden framework and traditional metal studs, as illustrated in figure 2.

In the CE-framework, a building's service life of 60 years is assumed corresponding to the mean lifespan of a building in the Belgian context [1]. The R-LCA study on the environmental impact is conducted with the Ecoinvent v3.8 database with the ReCiPe 2016 hierarchist impact method in the software package SimaPro. The environmental impact of the interior walls will be expressed in a single environmental score to make them comparable with the LCC results. Furthermore, the costs in the R-LCC method are inventoried with the ASPEN price data set (2019), in combination with specific financial data from JUUNOO and the container firm Maes, and are multiplied by the Value Added Tax. Then, the costs are actualized by the following economic parameters: a discount rate of 1.5 percent and a growth rate for labour cost of 2.3 percent and material cost of 1.6 percent [21] [18].

First, an analysis of the total environmental impact and financial cost on the element level is performed for the seven interior walls to investigate the influence of the refurbishment rate on the results. The functional unit is assumed to be 1 m^2 of interior wall surface and the refurbishment frequency ranges from zero to three refurbishments. Then the environmental and financial results of the walls are weighted against each other in a multi-objective Pareto front analysis. The set of walls that is optimal for at least one criteria is visualised on the so-called Pareto fronts. Thereafter, these results are extrapolated to the scenario level to determine the most environmental and financial beneficial wall for future refurbishment scenarios in the case study house. Each refurbishment scenario is modelled corresponding to the scenario planning method using an illustrative narrative where the functional needs of the couple, living in the original case house, change or where the household expands, resulting in a transformation of the building. Four different scenarios can be differentiated, namely a 'couple with kids' (one family and household activities) scenario, 'couple with doctor's office' (one family and working activities), 'co-housing' (two families and household activities) and a 'couple with needy elderly' (two families and caring activities) scenario, described in appendix A. The four modelled scenarios have different refurbishment rates and transformed interior wall surfaces to investigate the influence of these parameters on the results. The original interior wall surface of the case house is 66 m^2. For scenarios 1 and 2, three refurbishments take place with a refurbished wall surface of respectively 18 and 49 m^2, while for scenarios 3 and 4, two refurbishments with a refurbished wall surface of respectively 60 and 20 m^2 take place. The impact on scenario level is determined by multiplying the interior wall surface with the results per m^2 on the element level.

B. Results on element level

A multi-objective Pareto Front analysis is used to compare the total environmental impact to the total financial cost of the investigated interior walls for four refurbishment frequencies on element level in figure 3.

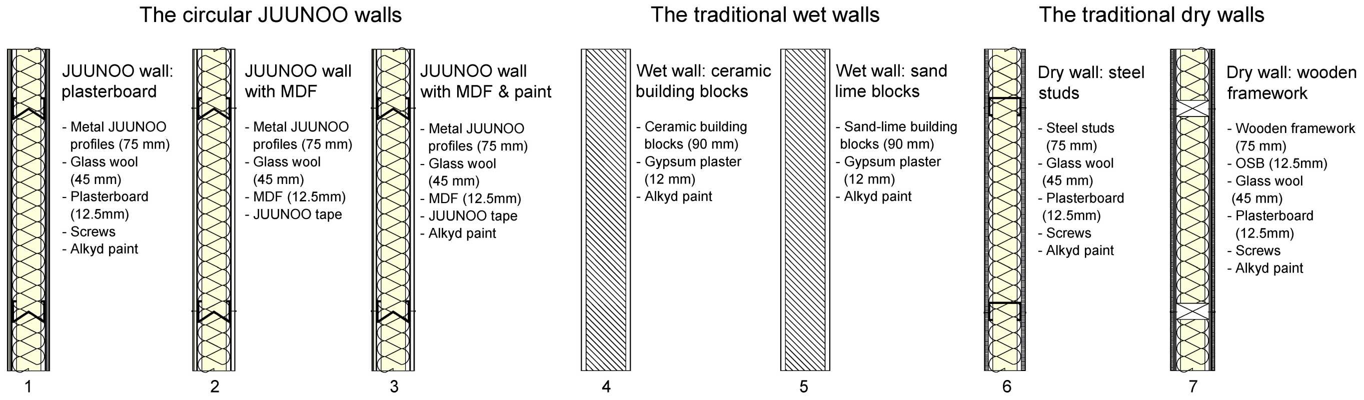

Fig. 2. The seven investigated interior walls in the case house in Berchem.

Figure 3 demonstrates that without refurbishments, the JUUNOO wall with MDF is the most beneficial wall financially, while the traditional wall with metal studs is the most beneficial wall environmentally. While a refurbishment takes place, the JUUNOO wall with MDF has the lowest financial cost, but the JUUNOO wall with plasterboard has the lowest environmental impact during buildings lifespan.

The relative shift between the total environmental impact of the traditional drywall with metal studs and the circular JUUNOO wall with plasterboard is due to the thickness and the reuse potential of the JUUNOO profiles. The production impact of the traditional metal studs is lower because the C-profiles are thinner. Therefore, the fragile C-profiles cannot be reused by a refurbishment. Furthermore, the JUUNOO walls with MDF and plasterboard have a lower financial cost than the traditional drywall with metal studs with each refurbishment frequency. However, the material cost of the traditional metal studs is cheaper. This can be explained by the high labor costs in Belgium and the faster (de)construction time of the JUUNOO walls by the more user-friendly JUUNOO construction system. The JUUNOO wall with MDF is cheaper than the JUUNOO wall with plasterboard because it is not painted. Although, not each building owner loves a wooden finish and prefers paint as finishing material in their house. In this case, the JUUNOO wall with plasterboard is the best financial alternative, followed by the traditional drywall with metal studs. In contrast to the lower financial cost, the JUUNOO wall with MDF has a higher total environmental impact than the JUUNOO wall with plasterboard, due to high temperatures and pressures by the production process of MDF [8].

The figure also illustrates that for different refurbishment frequencies the environmental profits and financial gains grow for the circular JUUNOO walls by an increasing number of refurbishments. By comparing the JUUNOO wall with plasterboard to the traditional metal stud wall, the relative difference in environmental impact mounts from 5 percent for one refurbishment to 30 percent for three refurbishments, while the relative difference in financial costs increases from 10 to 20 percent.

C. Results on scenario level

Figure 4 compares the total environmental impact with the total financial cost of the interior walls by using Pareto Fronts for the four refurbishment scenarios. In this comparison, the most beneficial wall for future refurbishment scenarios can be determined for the CBBW project. The JUNOO wall with MDF has the lowest financial cost for each scenario. Additionally, the best financial painted alternative is the JUUNOO wall with plasterboard, closely followed by the drywall with metal studs. The JUUNOO wall with plasterboard is also the environmentally most beneficial wall, except in the fourth scenario. In this scenario, the traditional drywall with metal studs has a slightly lower environmental impact than the JUUNOO wall due to the very low refurbishment frequency and transformed wall surface during the building's lifespan.

The proportions between the financial and environmental results of the circular and traditional interior walls for the different refurbishment scenarios illustrate that the profits in environmental performance and financial cost of the circular JUUNOO walls increase with more transformed wall surface and a higher refurbishment frequency. Nevertheless, the four assumed refurbishment scenarios in the case house have a relatively small refurbishment frequency and transformed interior wall surface in comparison to the original interior wall surface. Consequently, small gains of around 2 to 6 percent are made in environmental impact and financial cost by using the circular JUUNOO wall with plasterboard instead of the traditional drywall with metal studs. Additionally, when no or very small refurbishments take place, the drywall with metal studs has a slightly lower environmental impact than the JUUNOO walls. Consequently, the drywall with metal studs is proposed as the most beneficial wall when no refurbishments take place. In all the other cases, the JUUNOO wall with plasterboard is suggested.

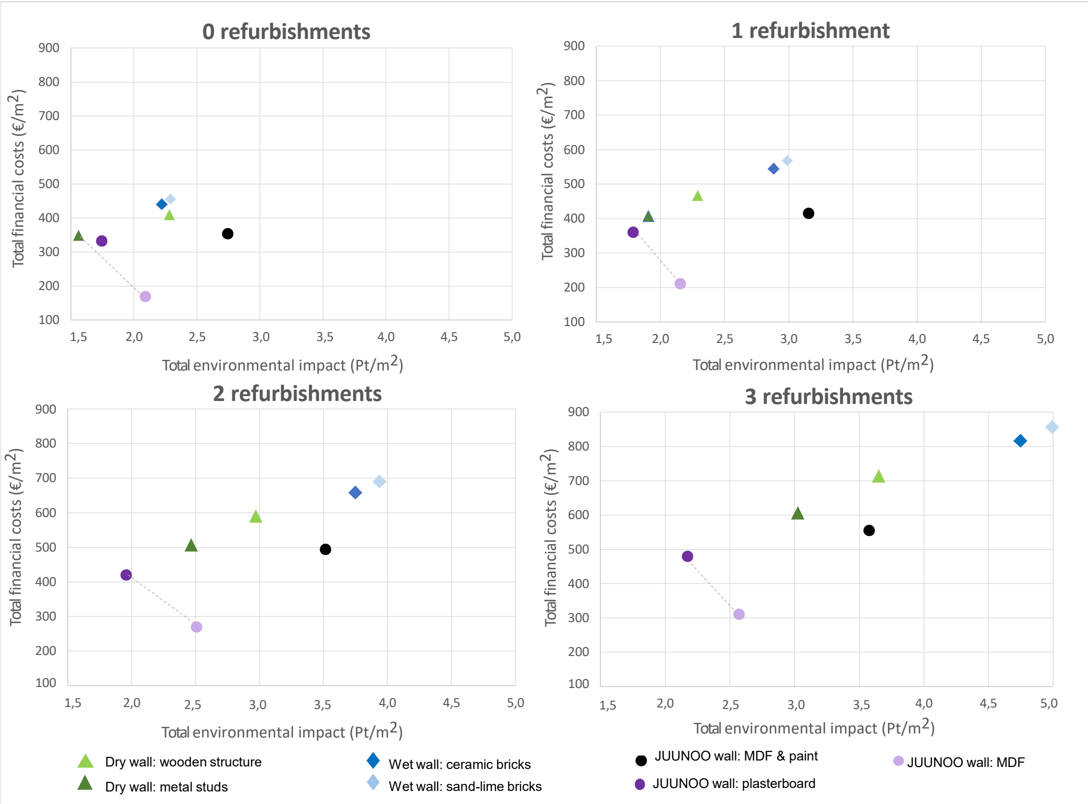

Fig. 3. Comparing the total environmental impact with the total cost of the interior walls using Pareto fronts (dashed lines) for four refurbishment frequencies on element level.

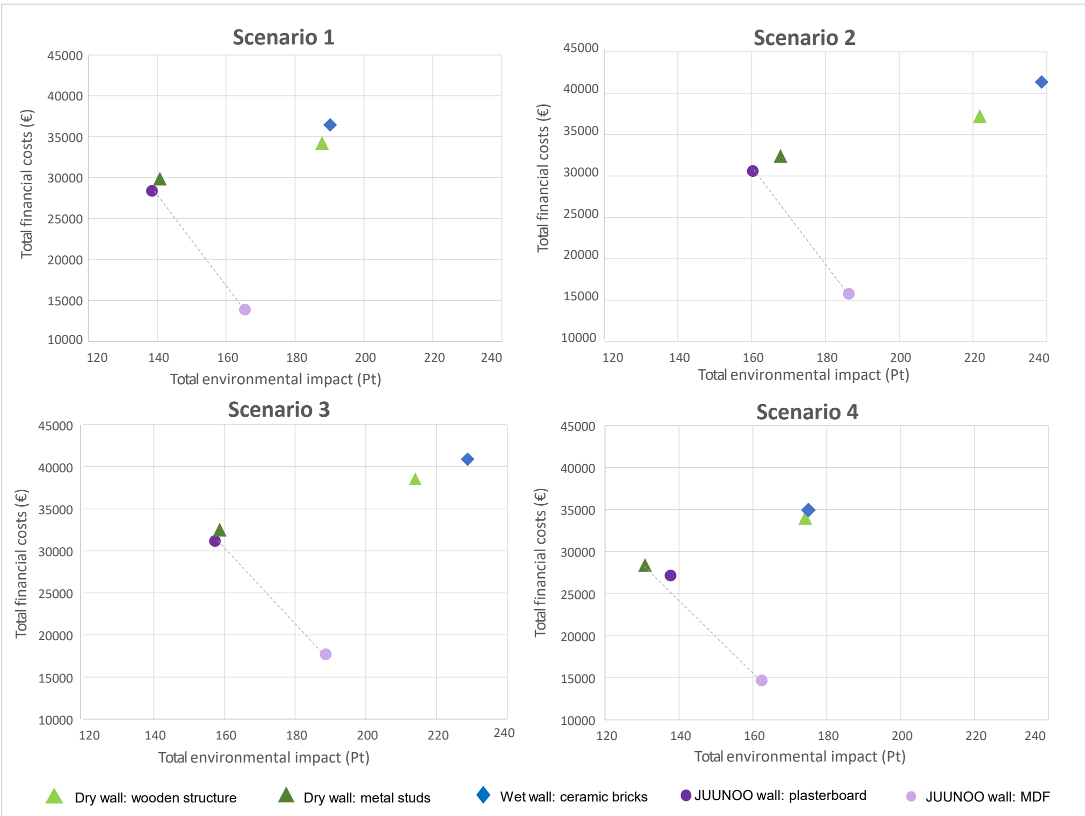

Fig. 4. Comparing the total environmental impact with the total cost of the interior walls using Pareto fronts (dashed lines) for four refurbishment scenarios in the case house in Berchem.

D. Sensitivity analysis

Sensitivity analysis is performed on the technical service life of the building products, the chosen material processes in the databases, the labor cost, the economic parameters, and the refurbishment frequency. Thereby, the influence of the many assumptions in the CE-framework and the robustness of the results is investigated. The performed sensitivity analysis illustrates that the assumptions have a big influence on the absolute environmental impact and financial cost of the interior walls. However, only the relative order and proportions between the results of the seven wall assemblies play a role in this study. The assumptions made on a specific wall assembly, namely the material properties, also have an influence on the relative proportions between the results of the interior walls. A main contributor is the assumed technical service life for the building products. By prolonging the technical service life of MDF from 30 to 60 years, the JUUNOO wall with MDF becomes a better environmental alternative than the JUUNOO wall with plasterboard. Additionally, the environmental impact of the drywall with wooden structure becomes smaller than the JUUNOO wall with MDF by prolonging the technical service life of OSB from 30 to 60 years. Therefore, it is important to take the assumptions on a specific wall assembly into mind by analyzing the results of the case study.

IV. Conclusion

The goal of this paper was twofold. First, due to the lack of a unified and governmental recognised decision tool for evaluating the reuse potential of circular building elements and the many uncertain reuse scenarios in the same building, the CE-assessment framework was proposed. In the CE-assessment framework, the developed R-LCA method was used for the assessment of the environmental performance and the R-LCC method for the evaluation of the financial cost. The environmental and financial results were compared in a multi-objective Pareto Front analysis. Thereafter, the developed CE-framework was applied to compare circular JUUNOO walls with traditional interior walls for future refurbishment scenarios in the case house of the CBBW project in Berchem. Little to no gains were found by using the circular JUUNOO walls compared to the traditional walls in the case house for future refurbishment scenarios. This raises the question whether traditional terraced houses are effectively good potential candidates for the use of the circular JUUNOO interior walls by the small number of refurbishments and transformed interior wall surfaces during the building's lifespan. Lastly, the sensitivity analysis on the results of the case study shows that the proposed CE-framework can be used to compare the financial cost and environmental impact of circular with traditional building elements with the chosen material properties for any assumed future refurbishment scenario.

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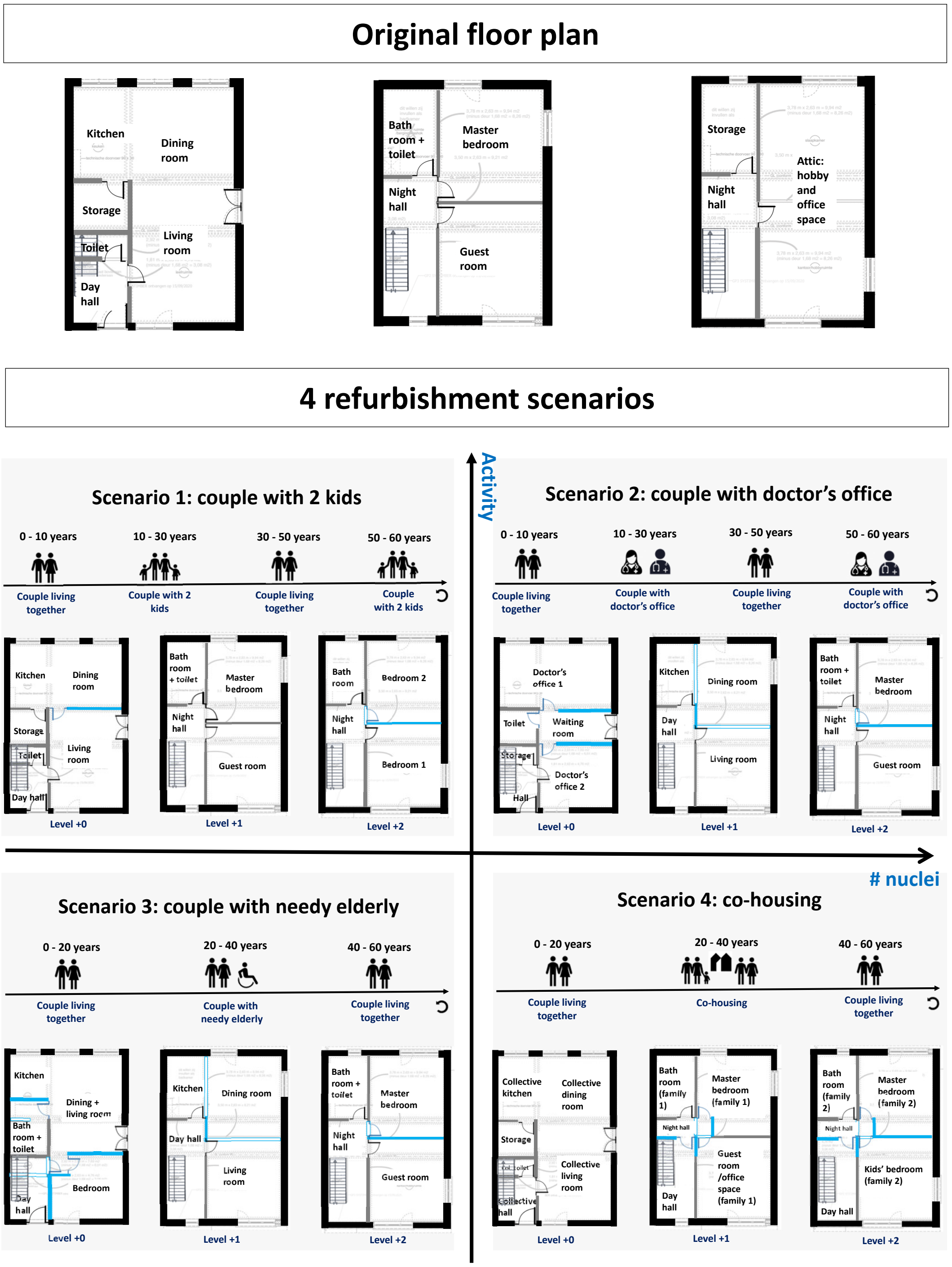
V. Appendix A

The original floor plan of the case house and the four refurbishment scenarios.



Hebben circulaire bouwoplossingen een positieve impact? Bepaling van de milieu en financiële impact van circulaire binnenwanden.

Jade Claes

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Samenvatting — **De hedendaagse bouwsector oefent een grote druk uit op het milieu. Daardoor is de transitie naar een circulaire bouwpraktijk noodzakelijk voor het reduceren van de uitstoot, het grondstoffenverbruik en de afvalproductie. Er is echter onvoldoende kwantitatief onderzoek om het potentiële gunstige milieueffect en de besparing in kosten van circulaire bouwelementen aan te tonen. Verder ontbreekt er ook een consistente en door de overheid erkende circulaire kwantificatietool. Daarom is in deze studie de R-LCA methode ontwikkeld, gebaseerd op het traditionele levenscyclusanalyse kader beschreven in de Europese norm NBN EN 15804(2019). Bij deze methode wordt het hergebruikspotentieel van circulaire bouwelementen in eenzelfde gebouw geëvalueerd door de module 'verbouwingen' in dit kader toe te passen. Aanvullend wordt de R-LCC methode gehanteerd om de kosten te begroten. Vervolgens is de voorgestelde circulaire kwantificatietool gebruikt om de milieu-impact en kosten van de circulaire JUUNOO wanden te vergelijken met traditionele binnenwanden voor toekomstige verbouwingsscenario's in de case woning van het 'Circulair Bouwen, Betaalbaar Wonen' project in Berchem. De analyse toont aan dat de circulaire JUUNOO wanden in het algemeen een iets lagere kost en milieu-impact hebben dan de traditionele wanden wanneer verbouwingen plaatsvinden. Echter is de traditionele droogbouw wand met staalprofielen een beter alternatief voor de milieu-impact wanneer geen verbouwingen plaatsvinden. Dat betekent dat de meerwaarde bij het gebruik van circulaire in plaats van traditionele bouwelementen beïnvloed wordt door de verbouwingsfrequentie, het verbouwde binnenmuuroppervlak en de veronderstellingen in beide methodes. Daarbij toont de case studie aan dat de voorgestelde circulaire kwantificatietool geschikt is om de impact en kosten van circulaire met traditionele bouwelementen te vergelijken voor bepaalde materiaaleigenschappen bij elk vooropgesteld verbouwingsscenario.**

Kernwoorden— **Circulaire bouwelementen, circulaire kwantificatiemethodes, LCA & LCC, JUUNOO wanden**

I. Introductie

De bouwsector is verantwoordelijk voor 60 percent van de afvalstromen, 36 percent van de uitstoot van broeikasgassen en 40 percent van de extractie van grondstoffen in Europa [3] [7] [10]. Om de negatieve impact van de bouwsector op het milieu te reduceren, is het noodzakelijk om over te gaan naar een meer duurzame manier van bouwen met een efficiënter gebruik van grondstoffen, minder afvalproductie en een lagere uitstoot van broeikasgassen. Een mogelijke strategie is de transitie van een lineaire naar een circulaire bouwpraktijk met een focus op het hergebruik van bouwmaterialen en elementen [11]. De baten in milieu-impact op lange termijn bij het gebruik van circulaire in plaats van traditionele bouwelementen moeten verder worden aangetoond om de circulaire transitie in de hedendaagse maatschappij te stimuleren [19]. Daarbij mag het financiële kostenplaatje van circulaire bouwelementen niet uit het oog worden verloren [14].

Er zijn momenteel onvoldoende kwantitatieve studies om het potentiële gunstige milieueffect en de besparing in kosten van circulaire bouwelementen aan te tonen [6]. Om de voordelen van het hergebruikspotentieel van bouwelementen in eenzelfde gebouw te beoordelen, is er een duidelijk kader nodig om de milieuprestaties en kosten te evalueren. Er ontbreekt echter een consistente en door de overheid erkende methode om het hergebruikspotentieel te kwantificeren [12]. Eerdere studies identificeerden het levenscyclus analyse (LCA) kader als een belangrijke methode om de milieuprestaties van circulaire bouwelementen te meten [16] [17]. Daarbij kan het levenscyclus kosten (LCC) kader, met dezelfde veronderstellingen en randvoorwaarden, gebruikt worden om de totale kosten te evalueren. Desalniettemin zijn de huidige Europese normen NBN EN 15804(2019) en 159785(2011) voor de LCA van bouwproducten gericht op het beoordelen van de milieu-impact van een productsysteem voor één enkele levenscyclus, gaande van het ontginnen van grondstoffen tot de productie ervan, het gebruik en de eindelevensduur verwerkingsprocessen [9]. Daarbij rijzen vragen op hoe in dit conventioneel LCA kader de impact van herbruikbare bouwelementen over meerdere levenscycli kan worden gemodelleerd en gekwantificeerd [12]. De eindelevensduur fase van circulaire bouwelementen is van nature een multi-output proces: het omvat het afvalbeheer van het product, maar creëert ook het nieuwe hergebruikte deel van het product. Volgens de cut-off allocatiemethode die in de Europese LCA normen wordt gehanteerd, vallen de hergebruiksvoordelen buiten de systeemgrenzen van de levenscyclus. Dit is dan ook gekend als een methodologische probleem in het conventionele LCA kader om hergebruik te beoordelen [4].

De Europese norm NBN EN 15804(2019) stelt voor om de hergebruiksvoordelen buiten de systeemgrenzen te kwantificeren in module D [5]. De methode beschreven in de norm is echter niet eenvoudig te interpreteren en laat daarbij ruimte voor meerdere hypotheses en scenario's. Bovendien is de keuze van de eindelevensduur behandeling van bouwproducten discutabel en de definiëring van de functionele herbruikbaarheid van het element niet eenvoudig door de onzekerheid van de hergebruiksscenario's [22]. Verder wordt ook een circulair evaluatiekader gezocht om de milieugebonden en financiële voor- en nadelen gedurende de hele levenscyclus van het gebouw te beoordelen. Het doel van deze paper is dan ook tweeledig. In het eerste deel wordt een consistente circulaire beoordelingsmethode ontwikkeld, gebaseerd op de conventionele LCA en LCC kaders, om de milieu-impact en kost van circulaire en traditionele bouwelementen te vergelijken tijdens de levensduur van het gebouw. Daarna wordt deze kwantificatietool toegepast om de milieu-impact en kost van circulaire JUUNOO wanden te vergelijken met die van vaak gebruikte binnenwanden in de Belgische bouwsector, rekening houdend met toekomstige verbouwingscenario's. Deze analyse wordt concreet uitgewerkt op de case woning van het project 'Circulair Bouwen, Betaalbaar Wonen' in Berchem.

II. Circulaire kwantificatietool

In deze sectie wordt een beoordelingskader voorgesteld om de milieu-impact en kost van circulaire met traditionele bouwelementen te vergelijken tijdens de levensduur van een gebouw. Binnen dit kader wordt de milieu-impact geëvalueerd door de ontwikkelde R-LCA methode en de financiële kost beoordeeld door de R-LCC methode.

A. R-LCA methode

De ontwikkelde R-LCA methode, gebaseerd op het conventionele LCA kader beschreven in de Europese norm NBN EN 15804(2019), is een cradle-to-grave LCA. Het kwantificeert de impact van de productie en constructie fase (module A), de gebruiksfase (module B) en de eindelevensduur fase (module C). In deze methode worden de milieubaten en -lasten bij het gebruik van circulaire in plaats van traditionele bouwelementen gedurende de levensduur van het gebouw gekwantificeerd in meerdere gebruikscycli van bouwelementen binnen dezelfde levenscyclus van het gebouw. Met deze benadering kan de complexiteit en onzekerheid van de allocatieprocedures over meerdere levenscycli worden vermeden. De milieu-impact van het hergebruik van bouwelementen tijdens de levensduur van het gebouw wordt geëvalueerd in de geïmplementeerde module B5 'verbouwingen' in de gebruiksfase. De module 'verbouwingen' brengt de milieu-impact van de transformaties van een bouwelement in rekening tijdens de levensduur van het gebouw. Bij een verbouwing worden voor de herbruikbare bouwproducten de (de)constructie-impact en materiaalverliezen gekwantificeerd in module B5, terwijl voor de traditionele bouwproducten ook de productie- en eindelevensduurimpact wordt beoordeeld, zoals voorgesteld in figuur 1. Aansluitend moet bij elke verbouwing het hergebruikspotentieel van de bouwproducten beoordeeld worden met de hieropvolgende criteria voor reversibele bouwcomponenten [15]. De verbindingen tussen de componenten moeten omkeerbaar zijn. Het bouwelement moet herbruikbaar zijn in dezelfde toepassing. De technische levensduur van de bouwcomponent moet langer zijn dan 10 jaar. De resterende technische levensduur van de bouwcomponent moet langer zijn dan de helft van de initiële technische levensduur.

Voor traditionele bouwproducten heeft de toevoeging van de verbouwingsmodule echter invloed op de andere modules in de gebruiksfase, namelijk de onderhoud- en vervangingsmodule. Naar analogie met de vermindering van het aantal onderhoudsscenario's met het aantal vervangingen bij het modelleren van de levenscyclus van het traditioneel bouwelement, wordt het aantal verbouwingen afgetrokken van het aantal vervangingen [20]. Bij circulaire bouwelementen daarentegen wordt het aantal vervangingen niet beïnvloed door het aantal verbouwingen. Verder wordt de impact van de gebruiks-, reparatie-, operationele energie- en waterverbruiksprocessen niet gekwantificeerd in de gebruiksfase. De reparatie-impact is niet geëvalueerd wegens het gebrek aan betrouwbare informatie over deze module. De andere modules zijn niet beoordeeld omdat de impact wordt verondersteld gelijk te zijn voor de traditionele en circulaire bouwelementen. Op het einde van de levensduur van het gebouw gaat de methode ervan uit dat de bouwproducten worden gestort, verbrand of gerecycleerd. De cut-off procedure wordt gebruikt om de voordelen en lasten van het recycleren toe te wijzen aan de verschillende levenscycli. Deze benadering vermijdt het onzekere voorspellen van toekomstige eindelevensduurscenario's, maar onderschat lichtjes de voordelen van circulaire bouwelementen [12].

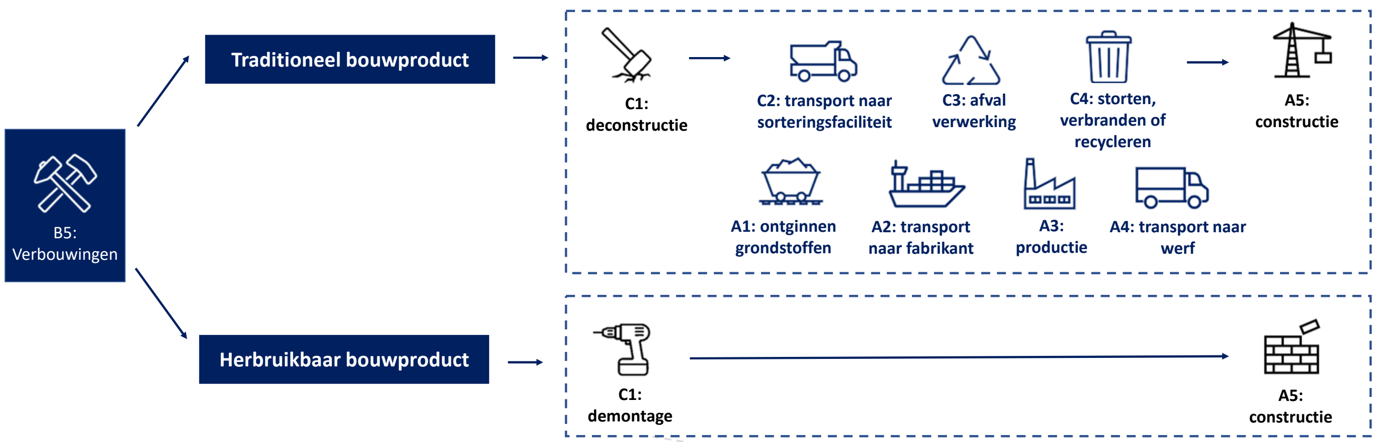

Fig. 1. De geïmplementeerde module B5 'verbouwingen' met de geëvalueerde impact modules voor circulaire en traditionele gebouwelementen.

B. R-LCC methode

Het evaluatiekader voor de levenscycluskosten (LCC), voorgesteld in de internationale norm ISO 15868(2011), is gelijkaardig gestructureerd als het LCA-kader. Het wordt tegenwoordig vaak gebruikt voor de beoordeling van de levenscycluskosten van een specifiek bouwproduct en is ook het kader gebruikt voor dit onderzoek [2]. Om de financiële en milieuprestatie resultaten te kunnen vergelijken, moeten dezelfde randvoorwaarden worden gehanteerd voor beide kaders, namelijk dezelfde functionele eenheid, technische levensduur van het gebouw en systeemgrenzen, zoals weergegeven in tabel 1.

R-LCA methode	**R-LCC methode**
Initiële impact - Materialen - Transport naar de site - Constructie	Initiële kost - Materialen - Transport naar de site - Arbeid (constructie)
Gebruik/periodieke impact - Verbouwingen - Vervangingen - Onderhoud	Gebruik/periodieke kost - Verbouwingen - Vervangingen - Onderhoud
Eindelevensduur impact - Deconstructie - Transport naar de eindelevensduur behandeling - Eindelevensduur behandeling	Eindelevensduur kost - Arbeid (deconstructie) - Transport naar de eindelevensduur behandeling - Container

Table 1. Systeemgrenzen van de R-LCA en de R-LCC methode.

De Net-Present Value (NPV) methode is toegepast binnen het conventionele LCC kader. Met deze veelgebruikte methode kan de huidige waarde van alle toekomstige kosten in het gebouw worden bepaald, inclusief de initiële investeringskost [14]. De NPV is de som van de investeringskosten en verdisconteerde toekomstige kosten gedurende de levensduur van het gebouw [1]. De selectie van de discontovoet, die de huidige waarde van toekomstige kosten bepaalt, heeft een grote invloed op de resultaten van het LCC-onderzoek. Deze wordt verondersteld tussen 0 en 3 percent te liggen [21] [13]. Echter veranderen de materiaal- en arbeidskosten niet aan hetzelfde tempo als de algemene discontovoet. Om dit in rekening te brengen wordt een aangroeivoet op basis van de ABEX-index of economische rapporten gedefinieerd om de verschillende evolutie van materiaal- en arbeidsprijzen in rekening te brengen [1] [14].

III. Case studie: CBBW project in Berchem

A. Onderzoek en methodologie

De ontwikkelde circulaire kwantificatietool is gebruikt om de milieu-impact en kosten van de circulaire JUUNOO wanden te vergelijken met vaak gebruikte binnenwanden in de Belgische bouwsector in de case woning van het 'Circulair Bouwen, Betaalbaar Wonen' project in Berchem. Hiermee wordt de binnenmuur met de laagste kost en milieuimpact gezocht voor toekomstige verbouwingsscenario's in het CBBW-project. De zeven onderzochte binnenwanden, voorgesteld in figuur 2, zijn de JUUNOO wanden met gipskarton en MDF (verf), de natbouw wanden met keramische snelbouwsteen en kalkzandsteen, en de droogbouw wanden met houten draagstructuur en staalprofielen.

In het evaluatiekader wordt uitgegaan van een technische levensduur van 60 jaar voor de woning, gebasseerd op de gemiddelde levensduur van Belgische gebouwen [1]. In de R-LCA methode wordt de milieu-impact van de bouwproducten bepaald door de Ecoinvent v3.8 databank met de ReCiPe 2016 hierarchist impact methode in het softwarepakket SimaPro. De milieu-impact van de binnenmuren wordt uitgedrukt in één milieuscore om ze vergelijkbaar te maken met de LCC-resultaten. Verder worden de kosten in de LCC-methode opgebouwd uit de ASPEN prijzen dataset (2019), in combinatie met specifieke financiële gegevens van JUUNOO en het containerbedrijf Maes, en vermenigvuldigd met de BTW-waarde. Vervolgens worden de kosten geactualiseerd met de volgende economische parameters: een discontovoet van 1,5%, een aangroeivoet voor arbeidskosten van 2,3% en voor materiaalkosten van 1,6% [21] [18].

Eerst worden de totale milieu-impact en kosten op element-niveau bepaald voor de zeven binnenwanden om de invloed van de verbouwingsfrequentie op de resultaten te onderzoeken. De functionele eenheid is 1 m^2 en de verbouwingsfrequentie reikt van nul tot drie verbouwingen. Dan worden de milieuprestatie en financiële resultaten vergeleken met elkaar in een multi-dimensionele Pareto fronten analyse. De groep wanden die optimaal is voor minstens één criteria wordt voorgesteld op de zogenoemde Pareto fronten. Daarna worden deze resultaten uitgebreid naar scenario-niveau om de meest milieuvriendelijke en financieel voordelige wand te bepalen voor toekomstige verbouwingsscenarios in de CBBW woning. Elk verbouwingscenario wordt gemodelleerd volgens de scenarioplanning methode met behulp van een gebruiksverhaal. In dit verhaal veranderen de functionele behoeften van een samenwonend koppel dat verblijft in de oorspronkelijke woning of breidt hun huishouden uit, waardoor de woning moet worden aangepast. Vier scenarios zijn gemodelleerd in bijlage A, namelijk het scenario 'koppel met 2 kinderen' (één gezin met huishoudelijke activiteiten), 'koppel met doktersspraktijk' (één gezin met werkactiviteiten), 'koppel met zorgbehoevende oudere' (twee gezinnen en zorgactiviteiten) en 'co-housing' (twee gezinnen en huishoudelijke activiteiten). De vier gemodelleerde scenario's hebben verschillende verbouwingsfrequenties en verbouwde binnenwandoppervlaktes om de invloed van deze parameters op de resultaten te onderzoeken. De oorspronkelijke binnenmuuroppervlakte in de case woning is 66 m^2. In scenario 1 en 2 vinden drie verbouwingen plaats met een verbouwingsoppervlakte van respectievelijk 18 en 49 m^2, terwijl in scenario 3 en 4 twee verbouwingen plaatsvinden met een verbouwingsoppervlakte van 60 en 20 m^2. De impact op scenario-niveau wordt bepaald door het binnenmuuroppervlak te vermenigvuldigen met de resultaten voor 1 m^2 op element-niveau.

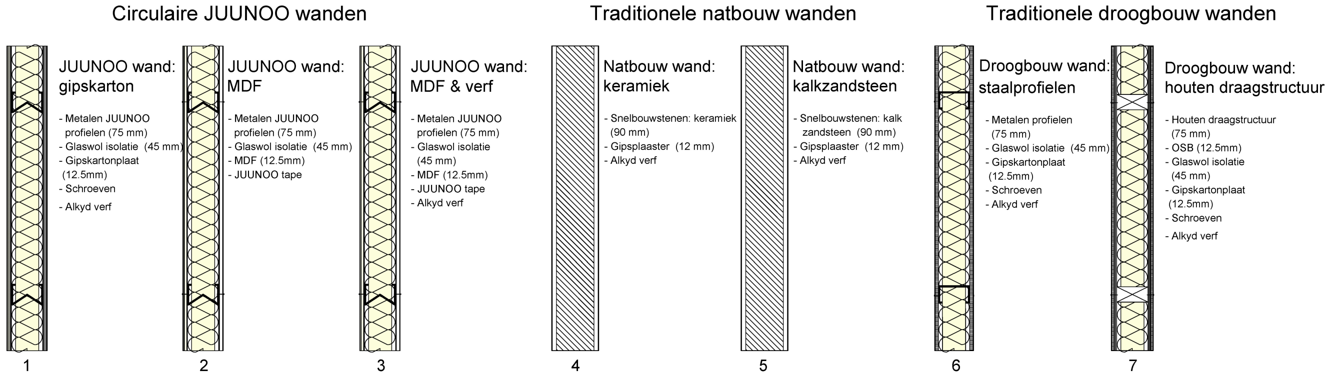

Fig. 2. De zeven onderzochte binnenwanden in de case woning in Berchem.

B. Resultaten op element-niveau

Een multi-dimensionele Pareto fronten analyse wordt gehanteerd om de totale milieu-impact samen met de kosten van de onderzochte binnenwanden te vergelijken voor vier verbouwingsfrequenties op element-niveau in figuur 3. Figuur 3 toont aan dat zonder verbouwingen de JUUNOO wand met MDF de financieel meest voordelige binnenwand is, terwijl de traditionele droogbouw wand met staalprofielen de laagste milieu-impact heeft. Wanneer verbouwingen plaatsvinden, heeft de JUUNOO wand met MDF nog altijd de laagste kosten, maar heeft de JUUNOO wand met gipskarton een betere milieuscore dan de droogbouw wand met staalprofielen.

De relatieve verschuiving in rangorde voor totale milieuimpact van de traditionele droogbouw wand met staalprofielen en de circulaire JUUNOO wand is te verklaren door de dikte en het hergebruikspotentieel van de JUUNOO-profielen. De productie-impact van de traditionele staalprofielen is lager omdat de C-profielen dunner zijn. Maar daardoor kunnen de fragiele C-profielen niet hergebruikt worden bij een verbouwing. Verder hebben de JUUNOO wanden met gipskarton en MDF een lagere kost dan de traditionele droogbouw met staalprofielen bij elke verbouwingsfrequentie, zelfs al zijn de materiaalkosten van de traditionele staalprofielen goedkoper. Dit komt door de hoge arbeidskosten in België en de kortere (de)constructie tijd van JUUNOO wanden bij het gebruiksvriendelijke JUUNOO bouwsysteem. De JUUNOO wand met MDF is goedkoper dan de JUUNOO wand met gipskarton omdat deze niet geverfd is. Niet elke gebouweigenaar verkiest echter een houten afwerking en verf krijgt dan de voorkeur voor hun woning. In dat geval is de JUUNOO wand met gipskarton het financieel beste alternatief, gevolgd door de traditionele droogbouw wand met staalprofielen. In tegenstelling tot de lagere financiële kost, heeft de JUUNOO want met MDF een hogere milieukost dan de JUUNOO wand met gipskarton, vanwege het productieproces van MDF met hoge drukken en temperaturen [8].

De figuur toont ook aan dat voor verschillende verbouwingsfrequenties de milieu-impact en financiële voordelen verbeteren voor de circulaire binnenwanden bij een toenemend aantal verbouwingen. Tussen de JUUNOO wand met gipskarton en de traditionele droogbouw wand met staalprofielen neemt het relatieve verschil in totale milieuimpact toe van 5 percent bij één verbouwing naar 30 percent bij drie verbouwingen, terwijl het relatieve verschil in financiële kosten oploopt van 10 tot 20 percent.

C. Resultaten op scenario-niveau

Figuur 4 vergelijkt de totale milieu-impact samen met de totale kost van de onderzochte binnenmuren voor de vier gemodelleerde verbouwingsscenario's, zodat de meest voordelige binnenwand voor toekomstige scenario's kan worden bepaald voor de CBBW woning. De JUUNOO wand met MDF heeft de laagste financiële kost voor elk scenario. Daarnaast is het financieel best geschilderde alternatief de JUUNOO wand met gipskarton, op de voet gevolgd door de droogbouw wand met staalprofielen. De JUUNOO wand met gipskarton heeft de laagste milieu-impact, behalve voor het vierde scenario. In dit scenario heeft de traditionele droogbouw wand met staalprofielen een iets lagere milieuimpact dan de JUUNOO wand met gipskarton omwille van de zeer lage verbouwingsfrequentie en verbouwde binnenwandoppervlakte tijdens de levensduur van het gebouw.

De relatieve verhoudingen tussen de resultaten van de circulaire en traditionele binnenwanden voor de verschillende verbouwingsscenario's tonen aan dat de winst in kosten en milieu-impact van de JUUNOO wanden groeit met het aantal verbouwingen en de toenemende verbouwingsoppervlakte. De vier gemodelleerde verbouwingscenario's hebben echter een relatief kleine verbouwingsfrequentie en verbouwde binnenwandoppervlakte in vergelijking met het de oppervlakte van de oorspronkelijke binnenwanden. Bijgevolg worden beperkte winsten van 2 tot 6 percent in milieu-impact en financiële kosten gerealiseerd bij het gebruik van de JUUNOO wand in plaats van de traditionele droogbouw wand met stalen profielen. Bovendien heeft de traditionele droogbouw wand met staalprofielen een kleinere milieu-impact dan de JUUNOO wanden, wanneer er geen of zeer kleine verbouwingen plaatsvinden. Daarom wordt de droogbouw wand met staalprofielen voorgesteld als de meest voordelige binnenwand zonder verbouwingen. In alle andere gevallen is de JUUNOO wand met gipskarton de meest voordelige wand voor de case woning in Berchem.

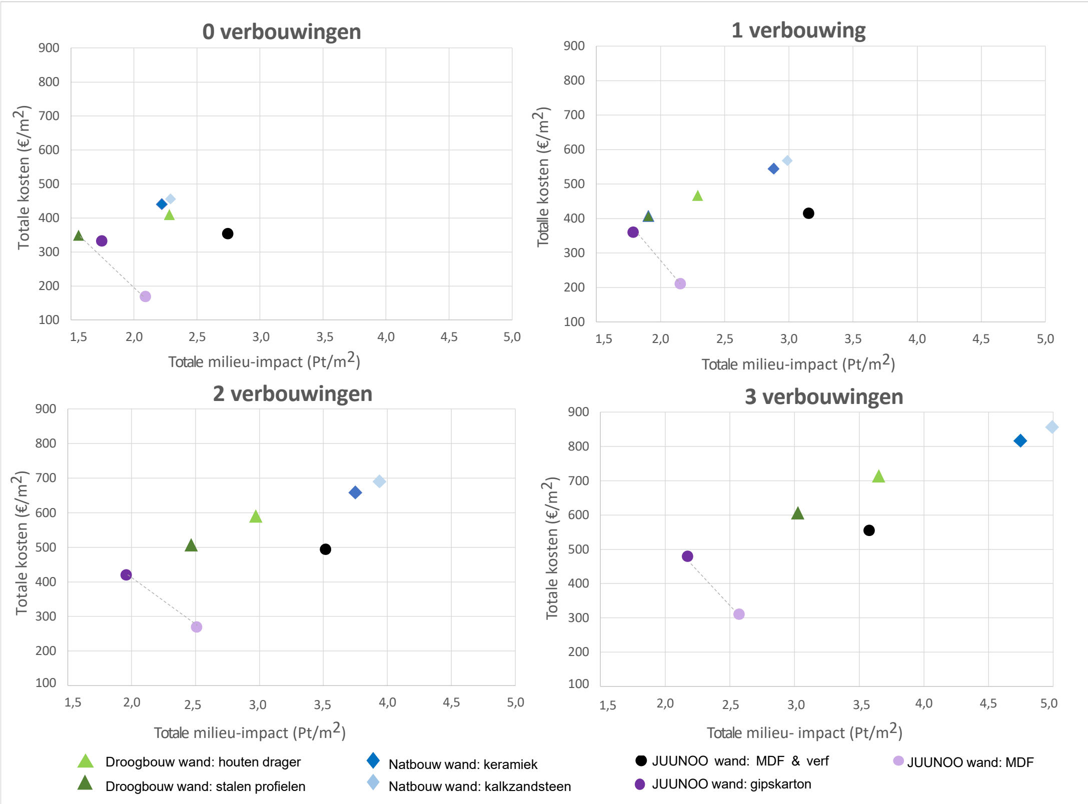

Fig. 3. Vergelijken van de totale kost samen met de totale milieu-impact van de binnenwanden met behulp van Pareto fronten (stippelijnen) voor de vier verbouwingsfrequenties op element niveau.

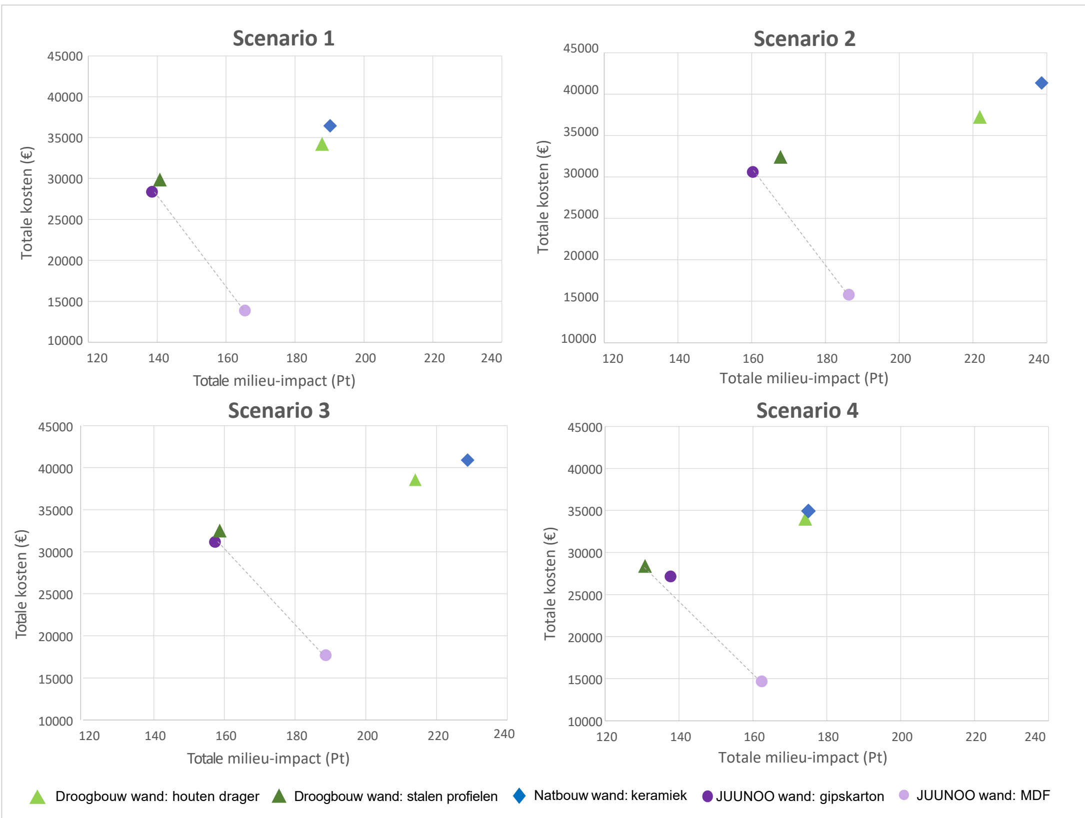

Fig. 4. Vergelijken van de totale kost samen met de totale milieu-impact van de binnenwanden met behulp van Pareto fronten (stippelijnen) voor de vier verbouwingscenario's in de case woning in Berchem.

D. *Gevoeligheidsanalyse*

Een gevoeligheidsanalyse is uitgevoerd op de technische levensduur, de gekozen materiaalprocessen, de arbeidskosten, de economische parameters en de verbouwingsfrequentie. Daarmee wordt de robuustheid van de resultaten en de invloed van de vele aannames in de methodes onderzocht. De gevoeligheidsanalyse toont aan dat de aannames in de methodes een grote invloed hebben op de absolute waarden van de milieu-impact en financiële kosten van de binnenmuren. In dit onderzoek speelt echter enkel de relatieve verhoudingen tussen de resultaten van de binnenwanden een rol. De veronderstellingen voor de materiaaleigenschappen van een specifieke binnenwand beïnvloeden eveneens de relatieve verhoudingen tussen de resultaten van de binnenwanden. De vooropgestelde technische levensduur van bouwproducten heeft hierop een grote impact. Door de technische levensduur van MDF te verlengen van 30 naar 60 jaar, wordt de JUUNOO wand met MDF een beter milieuvriendelijk alternatief dan de JUUNOO wand met gipskarton. Anderzijds wordt de milieu-impact van de droogbouw wand met houten structuur kleiner dan de JUUNOO wand met MDF door de technische levensduur van OSB te verlengen van 30 naar 60 jaar. Daarom is het belangrijk om rekening te houden met de aannames van een specifieke wandconstructie bij het analyseren van de resultaten van de case study.

IV. Conclusie

Het doel van deze paper was tweeledig. Wegens het gebrek aan een consistent en door de overheid erkend circulair evaluatiekader om het hergebruikpotentieel van circulaire bouwelementen in eenzelfde gebouw te evalueren, werd een circulaire kwantificatie tool voorgesteld. In dit beoordelingskader werd de R-LCA methode ontwikkeld voor de kwantificatie van de milieu-impact en de R-LCC methode voor de begroting van de kosten. De milieu-impact en financiële kosten werden dan samen vergeleken in een multi-objectieve Pareto Fronten analyse. Daarna werd deze circulaire kwantificatietool gehanteerd om de milieu-impact en kost van circulaire JUUNOO wanden te vergelijken met traditionele binnenwanden voor toekomstige verbouwingsscenario's in de case woning. Er werden weinig winsten gemaakt door JUUNOO wanden te gebruiken in plaats van de traditionele droogbouw wand met staalprofielen bij de vooropgestelde verbouwingsscenario's. In het licht van deze resultaten rijst de vraag of rijhuizen goede potentiële kandidaten zijn voor het gebruik van circulaire JUUNOO wanden omwille van het beperkt aantal verbouwingen en verbouwd binnenmuuroppervlak tijdens de levensduur van het gebouw. Ten slotte tonen de resultaten van de gevoeligheidsanalyse van de case studie aan dat de voorgestelde circulaire kwantificatietool gehanteerd kan worden om de financiële kosten en milieu-impact voor vooropgestelde verbouwingsscenario's te vergelijken van circulaire met traditionele bouwelementen op basis van de gekozen materiaaleigenschappen.

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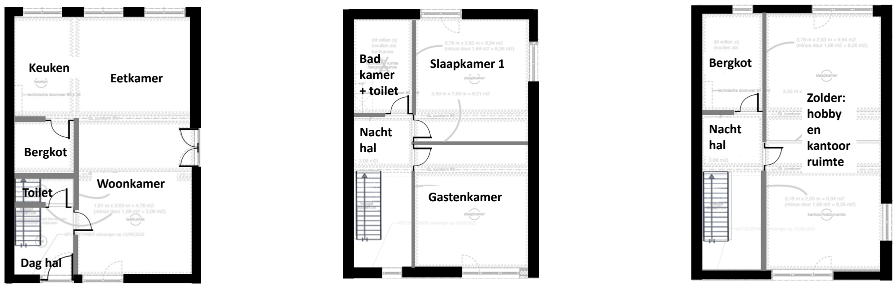
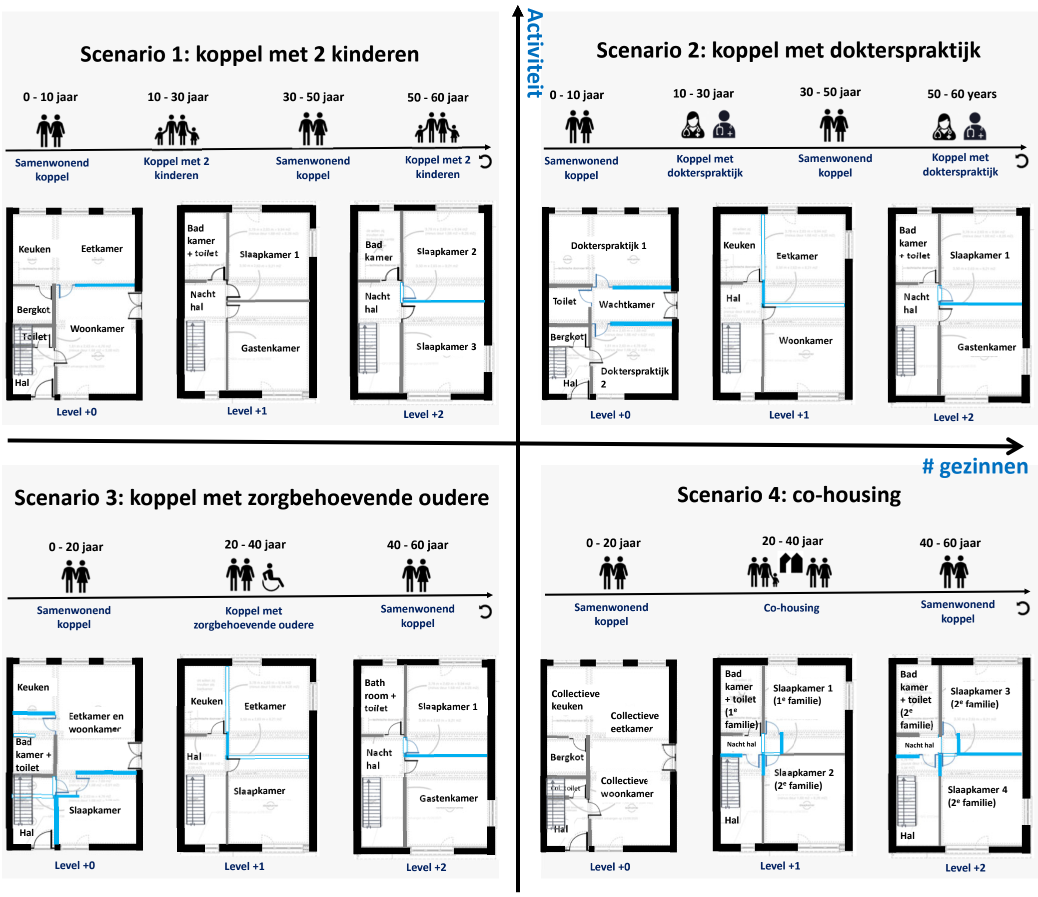
V. Bijlage A

De originele grondplannen van de case woning en de vier verbouwingsscenario's.

Originele grondplannen



De 4 verbouwingsscenario's



Contents

Used abbreviations

BCI	Building Circularity Index
CBBW	Circular Building Affordable Housing (Circulair Bouwen, Betaalbaar Wonen)
CE	Circular Economy
CE-LCA	Life Cycle Analysis of the Circular Economy
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Analysis
LFI	Linear Flow Index
MCI	Material Circularity Index
MDF	Medium Density Fiberboard
MFA	Multi Flow Analysis
MSW	Municipal Solid Waste
NPV	Net Present Value
OSB	Oriented Strand Board
OVAM	Public Waste Agency of Flanders (Openbare Vlaamse Afvalstoffenmaatschappij)
PCI	Product Circularity Index
PEF	Product Environmental Footprint

R-LCA	Life Cycle Analysis of reuse scenarios
R-LCC	Life Cycle Costing of reuse scenarios
SCI	System Circularity Index
SL	Service Life
UN	United Nations
VAT	Value Added Tax
VRE	Value-based Resource Efficiency

Chapter 1

Introduction

1.1 Context

1.1.1 Environmental challenges

'There is no planet B' (Berners-Lee, 2019). 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. Humanity is consuming more resources than the earth can regenerate and the ecological footprint of the world population increases dramatically (Barn, 2017). The actual topics such as climate change, the depletion of resources, and the growing garbage mountains, are indispensable in our current society.

The current world population reaches 7.9 billion people. The upward trend in the population size, as illustrated in figure 1.1, is expected to continue according to the United Nations report: it will reach 8.5 billion in 2030, 9.8 billion in 2050, and 12.2 billion in 2100 (UNEP, 2021). Accordingly, the world economy is expected to be four times larger by 2050 than today with a demand for more energy and natural resources, growing waste production, and a corresponding pollution degree (OECD, 2012).

The overpopulation and the associated environmental impact resulted in the agreement between 195 countries, signed at the United Nations Climate Change Conference in Paris in 2015, to keep global warming ideally below 1.5°C but at least below 2°C. However, the Emission Gap Report 2021 demonstrated that the world is on track for a global temperature rise of 2.7°C by the end of this century. To achieve the ambitious goal of the Paris agreement, the annual greenhouse gas emissions need to be halved in the next eight years (UNEP, 2021).

Other current environmental challenges are the depletion of resources and the growing waste mountains. Nowadays, the world population produces 2.01 billion tons of solid waste. The dramatic increase in waste production is expected to continue reaching 3.40 billion tons of waste annually in 2050 (Kaza et al., 2018). In addition, the extraction of material resources reached 88.6 billion tonnes in 2017 and is trending towards the double by 2050, as shown in figure 1.1 (Barn, 2017).

The report of the club of Rome warned that if the present growth trends continue unchanged, the limits of the growth of this planet will be reached within the next hundred years. Industrial growth will deplete the world's minerals and bathe the world's biosphere in fatal levels of pollution (Meadows et al., 1972). Nowadays, the environment is a hot topic in Europe, literally and figuratively. 94% of the Europeans state that the environment is important for them (European Commission, 2019). The transformation to a more sustainable society will be one of the most important challenges of this century.

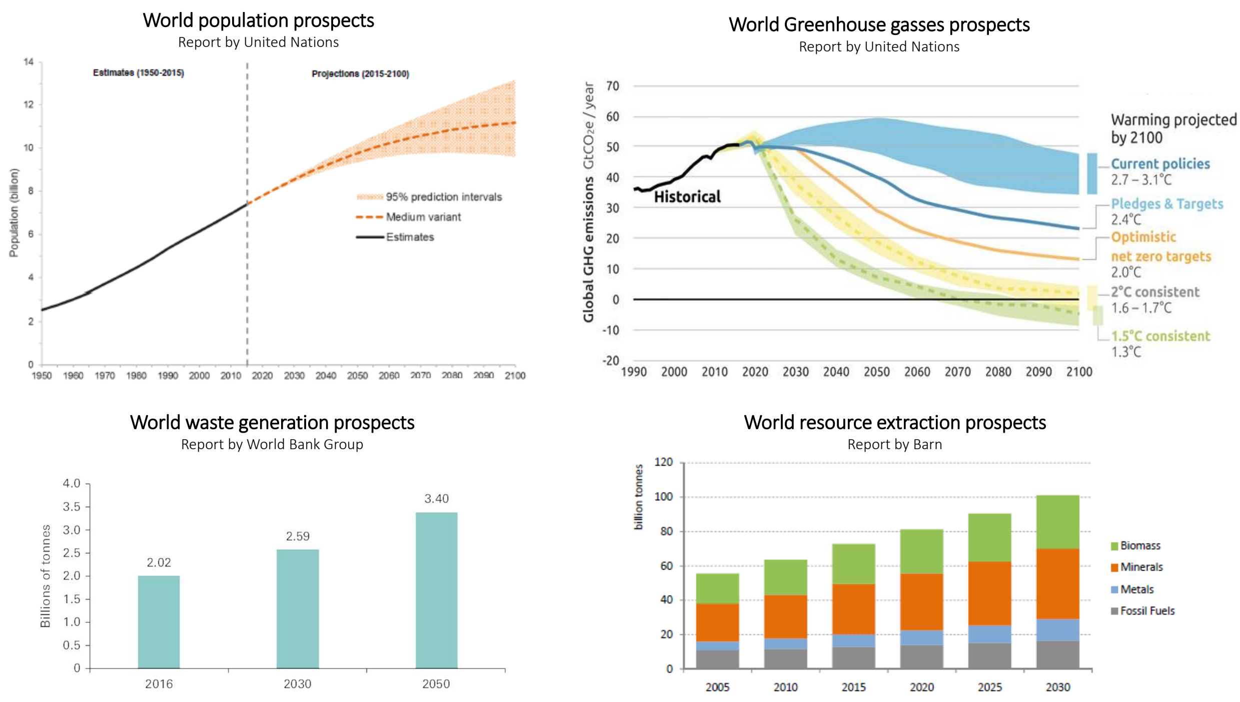


Figure 1.1: The current and future environmental challenges, based on Barn's report (2017), Kaza's report (2018) and the United Nations report (2021).

1.1.2 From a linear to a circular building industry

The building sector plays a vital role in decreasing the environmental impact. Currently, the building industry is responsible for 40 percent of the European energy consumption, 60 percent of the waste streams, 36 percent of the emission of greenhouse gasses, and 40 percent of the extracted raw materials in Europe (European Commission, 2020; Kaza et al., 2018; Barn, 2017).

One of the main reasons for this large environmental impact by the construction sector is the use of a linear economic model based on a “take, make, use and dispose of” principle. The linear construction economy starts with the extraction of raw materials, which are then processed to become construction materials. Then these materials are transported to the construction site, where they are assembled such that they can not be deconstructed. At the end of the buildings’ lifespan, the materials are demolished and landfilled or incinerated (Benachio et al., 2020). Therefore it is urgent to develop a more sustainable built environment with higher resource efficiency, less waste generation, and lower carbon emissions.

The circular economy (CE) is a potential solution for lowering the environmental impact of the building industry (Lei et al., 2021). It enables economic growth without an ever-increasing pressure on the environment (Pomponi & Moncaster, 2017). There is a wide range of definitions for CE in the literature, which all mention reusing, reducing, and recycling activities (Kirchherr et al., 2017). Geissdoerfer (2017) provides an example of such a definition: ‘the circular economy is a regenerative system, in which the resource input and waste, emission, and energy leakage are minimized, done by three strategies: closing, narrowing, or slowing material and energy loops’. Integrating these CE principles into the building industry will require fundamental changes in the way of designing, the development of new business models, and rethinking of the current supply chains (Bocken et al., 2016; Minunno et al., 2018).

In the current traditional mindset, the idea prevails that circular construction is more expensive than traditional construction, mostly because the initial investment costs of circular building elements can be higher. It has been proven that it is possible to earn back the initial higher investment costs with profits during the prolonged life cycle of the element (Paduart, 2012; Hart et al., 2019). Also, the initial environmental impact of circular construction methods can be higher. Reversible connections are mostly made of steel and additional independent material layers are needed. By taking into account the whole life cycle, the environmental impact can decrease in comparison to traditional building methods (Paduart, 2012). Yet, to prove these long-term returns, quantitative assessment methods are needed (Hossain & Ng, 2018).

Currently, there is no government-recognized framework to assess the environmental impact and financial cost of circular building elements during their service life. Furthermore, in the literature, there is a huge variety of quantitative circularity assessment methods focusing on different criteria. Of these methods, Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) prove potential for CE assessment with certain adoptions in their methodological framework (van Stijn et al., 2021; De Wolf et al., 2020; Pomponi & Moncaster, 2017; Buyle et al., 2019; Lei et al., 2021; Corona et al., 2019; Rajagopalan et al., 2021).

1.2 The objectives and research questions

In literature, the circular construction industry is seen as an important strategy to reduce the environmental impact of the building sector (Lei et al., 2021). In practice however, it is still in its infancy. Building clients are not implementing the circular building principles on a large scale because of some barriers: the many-sided and fragmented information network of circular strategies, the current potentially higher investment costs of circular building materials and elements, a limited number of case studies that prove the long-term financial and environmental returns, and the lack of a consistent framework to assess the financial and environmental impact during the life cycle of circular building elements (Hossain & Ng, 2018; Kirchherr et al., 2017; Hart et al., 2019; Romnée & Vrijders, 2018).

This research addresses and attempts to alleviate these barriers. Consequently, the objectives of this research are multi-layered. Nevertheless, the main objective is to develop a quantitative methodology, based on the existing LCA framework, to assess the environmental impact of a reusable building element during the building's service life. Additionally, a methodology, based on the LCC framework, is investigated to quantify the financial life cycle costs. Thereafter, both methodologies are applied to the case study of 'Circular Building, Affordable Housing' in Berchem to compare the environmental impact and financial costs of traditional wall assemblies to circular wall assemblies.

The master dissertation consists of two parts, answering the two main research questions. The research question of the first part (chapters 1 to 5) is 'How do current LCA and LCC methods need to be adapted to be able to determine the environmental and financial impact of a circular building element during the building's life span?'. The second main research question, 'In which refurbishment scenario is it beneficial in terms of environmental impact and financial cost to use circular interior walls in the residential project in Berchem?', is answered in the second part (chapter 6). To elaborate upon these two main research questions, a set of sub-questions are developed and answered in each chapter.

- Chapter 1 'Introduction': Why is the circular building economy a hot topic nowadays, but not implemented on large scale in the building industry?
- Chapter 2 'The circular building industry': What is the definition of the circular economy and what is the difference with the traditional linear economy in the building industry? What are typical theoretical and practical strategies in the circular building industry?
- Chapter 3 'Assessing the circular building industry': Are there currently assessment frameworks to map the environmental and additional financial benefits of circular building elements during the building's lifetime?
- Chapter 4 'Life Cycle Analysis meets the circular economy': Can we use the conventional LCA assessment framework to map the environmental benefits over the whole life cycle of a circular building element? Which assumptions and transformations are required in the traditional LCA assessment framework for implementing these CE strategies?
- Chapter 5 'Life Cycle Costing meets the circular economy': Is there an assessment framework to map the financial benefits over the whole life cycle of a circular building element? Which assumptions and transformations are required in the traditional LCC assessment framework for implementing these CE strategies?
- Chapter 6 'Evaluation of the case study in Berchem': Have the circular JUUNOO interior walls a lower initial and/or total environmental impact and financial cost in comparison with traditional walls in the residential project in Mechelen? In which refurbishment scenarios is it beneficial in terms of environmental impact and financial cost to use circular interior walls in the residential project in Berchem?

Chapter 2

The circular building industry

The first hurdles towards the large-scale implementation of circular building principles are the many-faceted and fragmented information network, and the wide variety of definitions that engage in different aspects of circularity (Kirchherr et al., 2017; Romnée & Vrijders, 2018). Therefore, the following chapter sketches a global overview of the circular building industry. First, the definitions of sustainable development and the circular building economy are stated. Then, the adjusted definition for reusable building elements will be discussed. Finally, a number of theoretical and practical circular design strategies serve as illustrations to concretize the definition.

2.1 Adoption of circularity in the building industry

2.1.1 Sustainable development in the construction sector

As discussed in the introduction section, a more sustainable development of the construction sector is needed to combat the current global environmental challenges (Kaza et al., 2018; Barn, 2017). A first definition of sustainable development is formulated by the UN Commission of Environment and Development in the Brundtland report in 1987 as 'the development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland, 1987). This definition promotes a holistic sustainability approach based on three pillars: people (social development), planet (environmental issues), and profit (economic growth) (Elkington, 2008).

The definition of sustainable development in the Brundtland report can be interpreted in the construction industry as 'the development of building strategies and techniques to meet the needs of current clients, in such a way that future generations can still build without hampering, due to the scarcity of raw materials and energy sources'. The three pillars of sustainability can have their counterpart in the building industry. The social aspect can be addressed by building aesthetics, comfort, and safety, while the environmental impact is covered by the use of eco-friendly building materials, fuel-efficient transport, and green energy. The economical aspects are associated with longevity, flexibility, and profitability (Vlaamse Overheid, 2019).

In the last decades, lowering the environmental impact of buildings received increasing attention from researchers, policy-makers, and companies (Buyle et al., 2019). However, the focus is often limited to reducing energy consumption and minimizing carbon emissions, without considering the burden-shift between different kinds of environmental impact (Pomponi & Moncaster, 2017). For instance, increasing the thickness of an insulation layer in a wall assembly reduces the energy consumption but increases the amount of material used. Therefore, it is important to consider the total impact over the complete life cycle of the materials (Rajagopalan et al., 2021). Nowadays, the concept of life cycle thinking is gaining more importance in the construction industry. Significant environmental impacts are directly related to waste generation from refurbishment, demolition, and construction. These can be avoided by applying the circular economy strategy to buildings (Hossain & Ng, 2018).

2.1.2 Definition of the circular building industry

For the development of a sustainable building environment, a paradigm shift from the linear "take, make, use, and dispose of" approach to the circular "reduce, recycle, reuse" model is required, as visualized in figure 2.1 (Kirchherr et al., 2017). In this research, the circular economy is defined as 'a regenerative system, in which the resource input and waste, emission, and energy leakage are minimized' (Geissdoerfer et al., 2017). This can be accomplished by three strategies: closing, narrowing, or slowing the material and energy loops. In closing loops, the main goal is to recycle the materials at their end of life. Slowing loops focus on prolonging the use of building elements, extending their life spans, and introducing multiple life cycles by flexibility and reversibility. Finally, narrowing the loops is achieved by a reduction of resource use (Bocken et al., 2016).

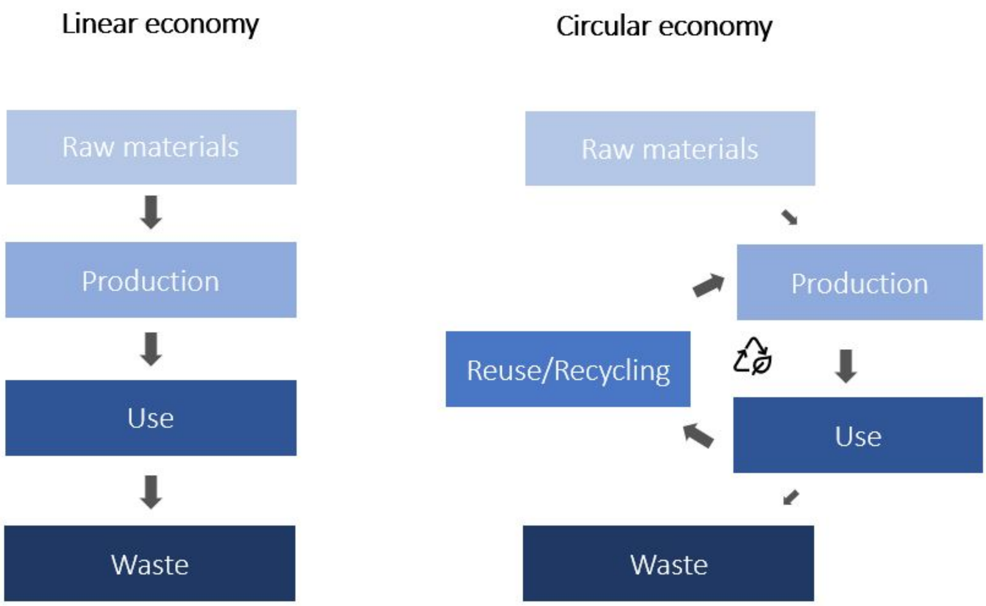


Figure 2.1: The linear versus the circular economy

The material life cycle can be divided into technical and biological cycles. In the biological cycle, renewable bio-based materials are returned to Earth at the end of their life cycle, through processes like composting and anaerobic digestion. Meanwhile, in the technical life cycle, the life cycles of the manufactured materials are prolonged by circular strategies such as repair, remanufacturing, and recycling (Macarthur Foundation, 2016). In this research, the focus lies on slowing the loops, addressing the technical life cycles of building elements.

2.1.3 A conceptual framework for the circular building industry

There are three main strategies to implement the circular economy in the building industry. The first strategy is urban mining based on the reuse of resources from existing buildings. The second strategy is the realization of more transformable buildings by reversible building elements and flexible building lay-outs. The final strategy is the development of new business models aiming to create added value during the whole life span of the building (Beauclerque, 2020). This research focuses on the development and assessment of transformable buildings.

To conceptualize the idea of circularity in the building industry, Vermeulen (2019) developed the 10R-framework. It is a detailed version of the waste hierarchy of Lansink, which clarified how waste should be used and disposed of in multiple life cycles. The ten strategies are hierarchically ordered, R0 being the highest and R9 the lowest level of circularity. They are represented in figure 2.2 (Vermeulen et al., 2019).

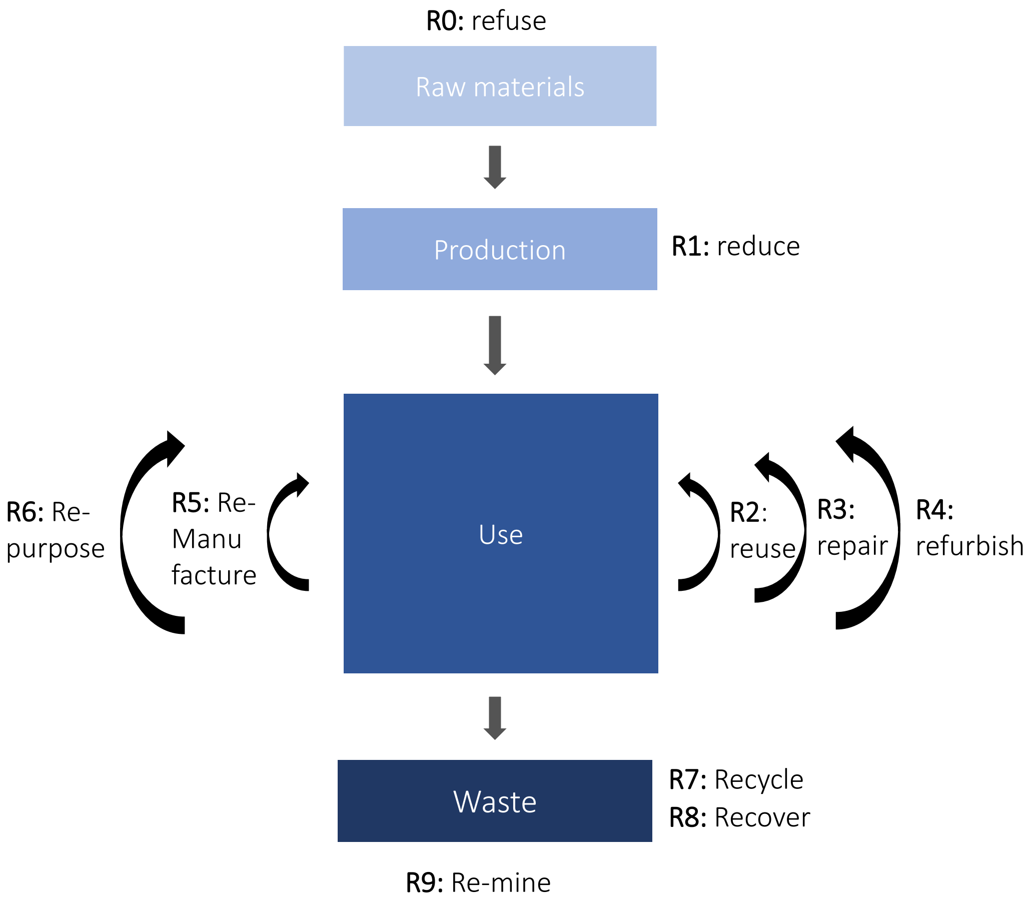


Figure 2.2: A visual representation of the CE conceptual framework, based on the theory of Vermeulen (2019)

The ten conceptual strategies can be categorized by three different goals: smarter product use and manufacture (R0 and R1), extended lifespan of building products (R2, R3, R4, R5, and R6), and the useful application of materials (R7, R8, and R9) (Vermeulen et al., 2019).

2.2 Design guidelines for circular buildings

For the adoption of the circular philosophy in the building practice, need for design guidelines exists. Many different circular strategies are developed in the CE literature but are not always accessible for architects, clients, builders, and contractors (Benachio et al., 2020; Vandenbroucke, 2016). The following practical framework, based on the circular design principles of OVAM (2015) and the leaflets of Vandenbroucke (2016), clarifies twelve design principles to strive for a more sustainable and circular construction industry.

In the practical framework shown in figure 2.3, two levels are distinguished: the building and the element level. Each level is partitioned in three sub-levels: components, interfaces, and composition. The subcategory ‘components’ represents the smallest elements of the assembly. Next, ‘interfaces’ revolves around the interaction between the different components, while ‘composition’ contains strategies about their composition. The twelve design principles are arranged in the framework.

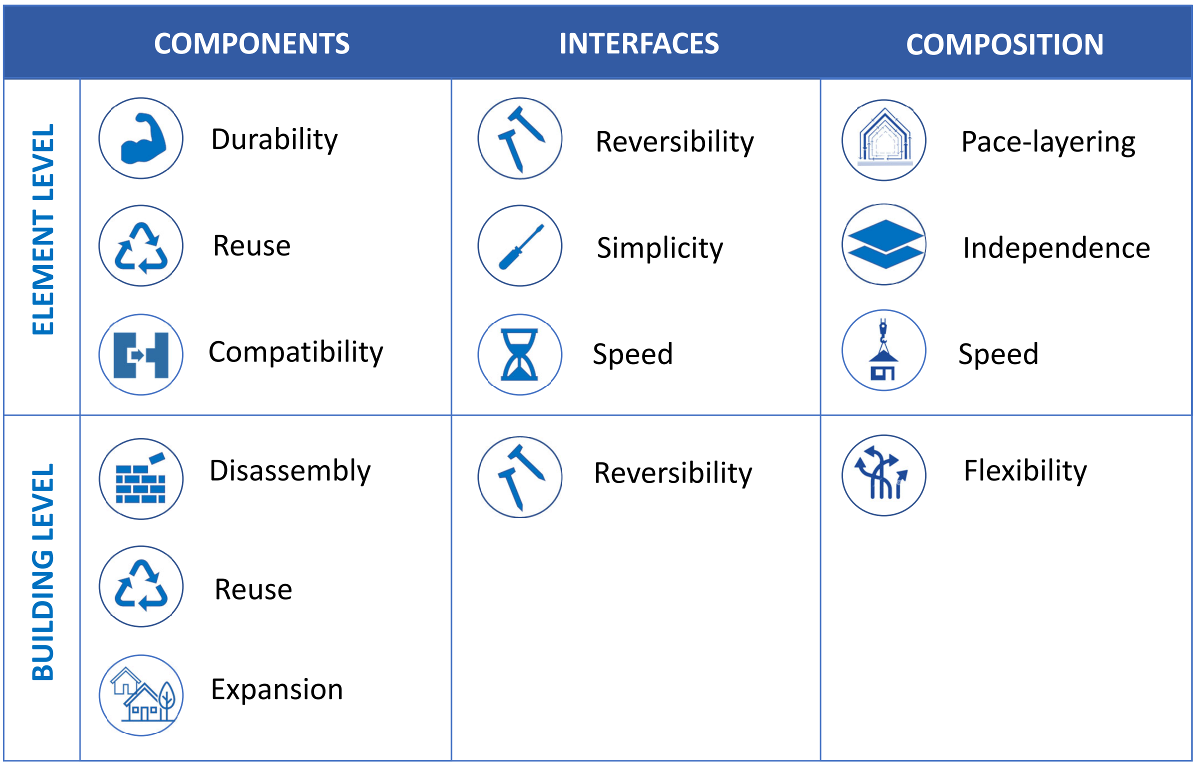


Figure 2.3: Practical design principles for implementing circularity in the building sector, based on the circular design principles of OVAM (2015) and Vandenbroucke (2016).

2.2.1 Components

There are three practical objectives on the element level for components: durability, reuse, and compatibility. Durability means choosing materials with a long lifespan and a good resistance against damage and wear. Some examples are masonry, ceramics, and cellular glass (Pater & Cristea, 2016). The second objective is reuse, promoted by second-hand material databases, such as 'Rotor DC' and 'Proremat' in Belgium. By using standard elements, better interchangeability within and between different building systems is possible, stimulating reuse (Beauclerque, 2020). Compatibility is achieved by following a dimensional standard, such as the Belgian modular sizing system of OpenStructures, illustrated in figure 2.4.

On the building level, there are also three goals: disassembly, reuse, and expansion. Disassembly is a principle where building elements are used in such a way that they can be easily removed without any damage. An example is the timber construction method with tongue and groove joints of Lignature (OVAM, 2015). Another guideline is expansion. A change in function or volume of a building may require a change in technical requirements, such as a sufficient bearing capacity and adequate technical installations, and in functional requirements, such as the layout of spaces (Beauclerque, 2020). To account for probable function changes during designing, the bearing construction can be over-dimensioned and the storey height can be larger modeled (Romnée & Vrijders, 2018).

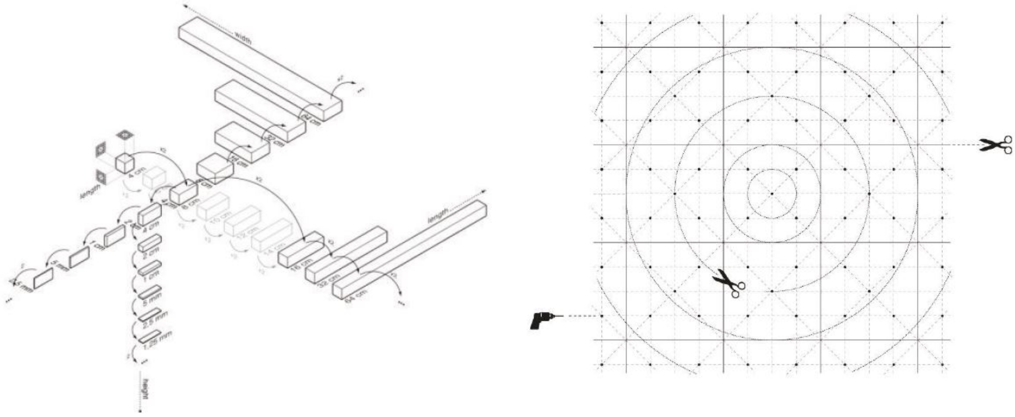


Figure 2.4: The modular sizing system of OpenStructures (2014), based on fractals

2.2.2 Interfaces

There are three guidelines for interfaces between components: reversibility, simplicity, and speed. The reuse of elements is dependent upon the reversibility of the connections between the different components (Romnée & Vrijders, 2018). Good reversible connections are bolts, screws, and Velcro straps, while irreversible connections are glue, welding, and mortar (Paduart, 2012). The guideline of simplicity emphasizes the use of simple, commonly used connection methods, such as screws and nails (Vandenbroucke, 2016). The speed of the (dis)assembly is influenced by the number of fixings and the visual, physical, and ergonomic accessibility of joints. The principle 'speed' is illustrated in figure 2.5 (Paduart et al., 2013).

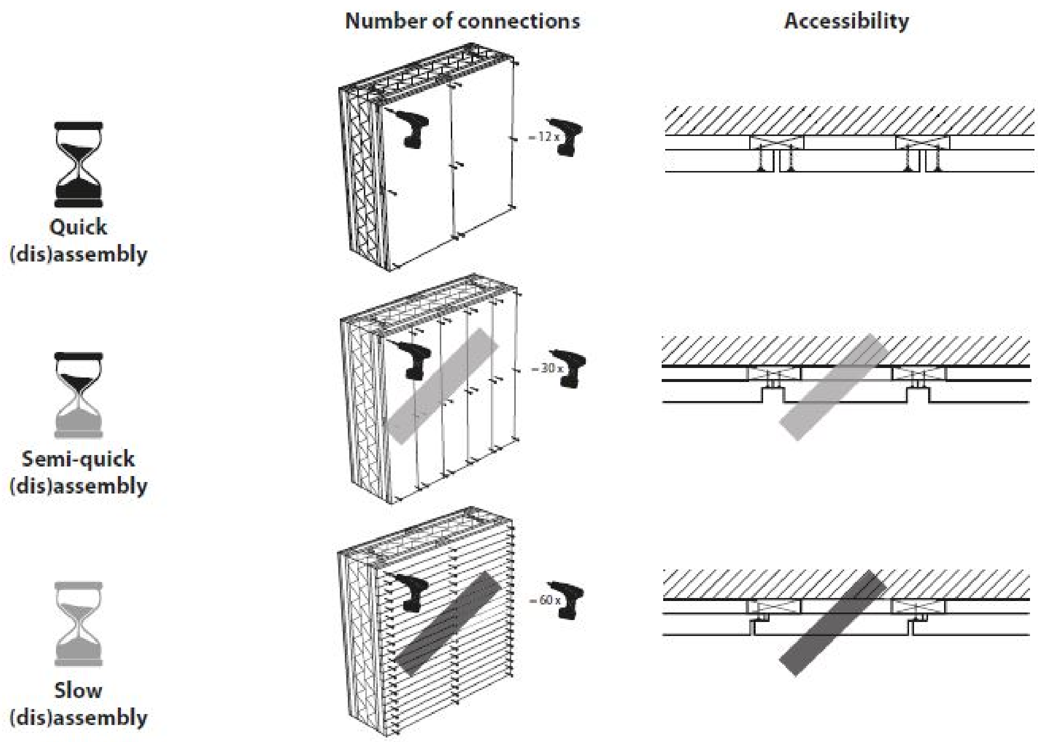


Figure 2.5: The influence of the accessibility and the number of connections on the speed of (dis)assembly, based on Vandenbrouckes leaflets (2017)

2.2.3 Composition

For the aspect composition, four guidelines are important: independence, pace-layering, prefabrication, and flexibility. Independence revolves around the possibility to remove a building component without removing adjacent components (Vandenbroucke, 2016). Pace-layering is based on the principle of organizing the different components of the building element into different layers according to their technical and functional lifespan (Romnée & Vrijders, 2018). The technical lifespan is defined as the maximum period in which a component can physically carry out its function (van Stijn et al., 2021). The functional life span of a building element is influenced by regulations and the change in the user's needs (Brandt, 1995). Figure 2.6 illustrates the gradation in pace-layering, ranging from a total integration to a total separation of the various layers.

Another guideline is the prefabrication of building elements. Prefabricated building elements are assemblies manufactured offsite, generally in a factory, and then transported to construction sites for incorporation into the building. This strategy is used to gain more quality control, reduction of construction waste, and increased building speed in the construction process (OVAM, 2015). In the last guideline, 'flexibility' plays a major role in the easy adaptation of the building to respond to all the needs of various uses during its lifetime (Romnée & Vrijders, 2018). An example strategy to realize flexibility in buildings is the use of open floor plans.

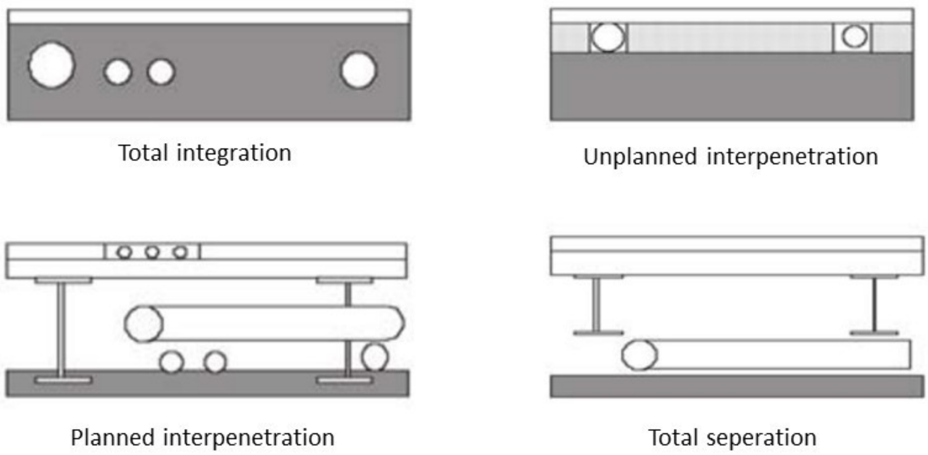


Figure 2.6: The graduation in pace-layering, based on the figures of Durmisevic (2006).

Chapter 3

Assessing the circular building industry

Another obstacle for the implementation of the circular building industry is the lack of a governmental recognized assessment framework to quantify the impact and benefits of circular building materials and elements during a building's lifespan (Lei et al., 2021). Therefore, the following chapter gives a global overview of regularly used assessment methods in literature. At the end, an assessment method that can be used with or without appropriate modifications for the evaluation of reusable building elements during the building's life span is discussed.

3.1 Introduction

In the previous chapter, the circular economy (CE) is defined as 'a regenerative system, in which the resource input and waste, emission, and energy leakage are minimized' (Geissdoerfer et al., 2017). This definition connects circularity with sustainability and serves as a benchmark for exploring CE-assessment methods to quantify circular building elements. At this moment, a huge amount of circular assessment methods of different dimensions and levels can be found in the CE literature (Lei et al., 2021; Corona et al., 2019; De Wolf et al., 2020; Hossain & Ng, 2018; Pomponi & Moncaster, 2017; Ghisellini et al., 2016).

The most frequently assessed CE dimensions are the economic, environmental, behavioral, societal, technological, and governmental ones. Furthermore, the assessment methods can be partitioned into three levels for the construction industry: the micro-level (buildings and infrastructure), the meso-level (districts), and the macro-level (cities, regions or nations). The micro-level can be divided into three sub-levels: the material, the component, and the system-level (Ghisellini et al., 2016). In this research, the focus lies on the micro-level and the economic and environmental dimensions of the circular building industry.

In the following section, a general overview of CE assessment methodologies is given. This list is not exhaustive and only discusses the most frequently used methods in the current CE literature and practice. The different assessment methods address three main categories: circularity indicators, sustainability indicators, and sustainability frameworks, as illustrated in figure 3.1 (Lei et al., 2021; Corona et al., 2019). The indicators focus on a single aspect of circularity or sustainability. The circularity indicators concentrate on the fraction of waste being recycled or reused, while the sustainability indicators zoom in on a specific environmental effect of a circular strategy, such as the depletion of resources or the emission of greenhouse gasses. In contrast to the indicators, the sustainability frameworks focus on mapping various environmental effects of the circular building elements in relation to each other (Lei et al., 2021).

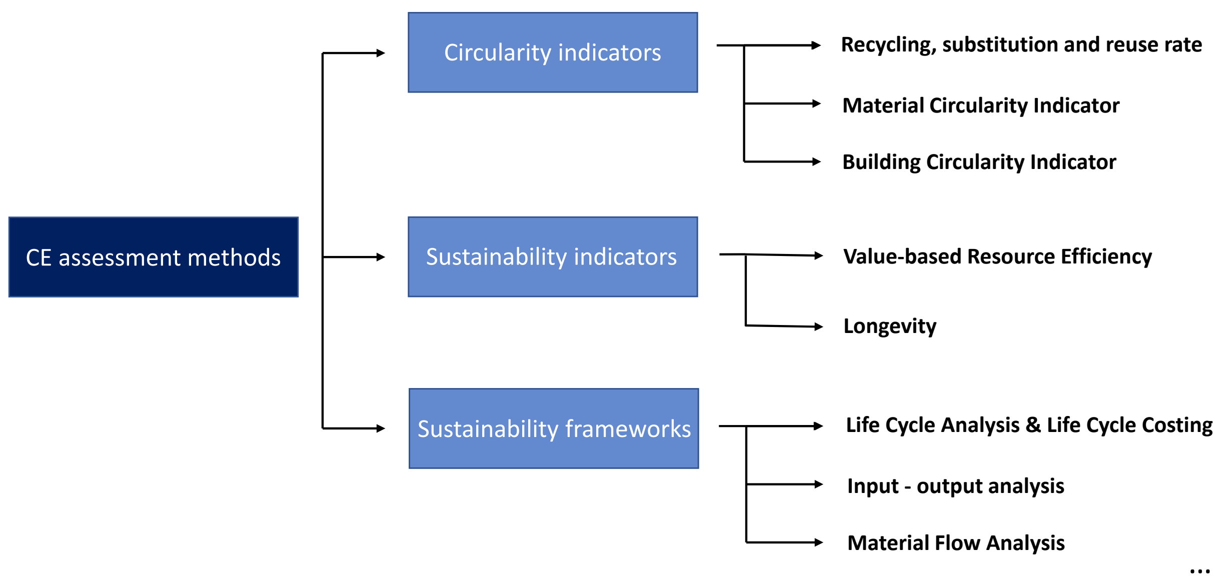


Figure 3.1: Schematic of the current frequent used CE assessment methods in the building industry

3.2 Circularity indicators

Circularity indicators measure the intrinsic circularity degree, such as the amount of recirculated materials in a product, represented by a value between 0 and 100 percent. A limited number of circularity indicators are used in the current building industry, namely the recycling rate, the substitution rate, and the reuse rate. These indicators cover a specific scope. In contrast, other indicators address a broader context of the reuse and recycling activities, but lack corresponding practices, such as the Material Circularity Index and the Building Circularity Index (Macarthur Foundation, 2016; Lei et al., 2021). The definitions and formulas of the different circularity indicators can be found below.

3.2.1 Recycling rate, substitution rate and reuse rate

The recycling rate is the fraction of wasted materials reprocessed at the end of their life stage. The percentage of recycled or composted municipal solid waste (MSW) is calculated by the following formula (SWRA, 2016; Lei et al., 2021):

$$RecR[\%] = \frac{m_{MSW,recycled/composted}}{m_{MSW,landfilled/incinerated/recycled/composted}} \times 100 \tag{3.1}$$

with:

- $m_{MSW,recycled/composted}$ = mass of the recycled and composted municipal solid waste [tons]
- $m_{MSW,landfilled/incinerated/recycled/composted}$ = mass of the recycled, landfilled, incinerated and composted municipal solid waste [tons]

The second circularity indicator used in practice is **the reuse rate**. This rate is the percentage of reused wasted materials at the end of their life stage, calculated by the following formula (Lei et al., 2021):

$$ReuseR[\%] = \frac{m_{MSW,reused}}{m_{MSW,landfilled/incinerated/reused}} \times 100 \tag{3.2}$$

with:

- $m_{MSW,reused}$ = mass of the reused municipal solid waste [tons]
- $m_{MSW,reused/incinerated/landfilled}$ = mass of the landfilled, incinerated and reused municipal solid waste [tons]

The last circularity indicator '**the substitution rate**' directs attention to the product stage, where primary materials are replaced by recycled or reused materials, and is calculated by the following formula (Lei et al., 2021):

$$SubsR[\%] = \frac{m_{primarymaterials,reused/recycled}}{m_{primarymaterials,new/reused/recycled}} \times 100 \tag{3.3}$$

with:

- $m_{primarymaterials,reused/recycled}$ = mass of the reused and recycled primary materials [tons]
- $m_{primarymaterials,reused/recycled/new}$ = mass of the reused, new and recycled primary materials [tons]

3.2.2 Material Circularity Indicator

The Material Circularity Indicator (MCI) measures the restorative fraction of the material flows of a product. The MCI is described as 'an indicator which measures the extent to which linear flow has been minimized and the restorative flow maximized for its component material, and how long and intensively it is used compared to a similar industry-average product' (Macarthur Foundation, 2016).

The MCI formula 3.4 contains various product characteristics: the mass of the finished product M, the mass of the virgin material V, the unrecoverable waste W, expressed in kg, and the utility factor χ, described by the lifetime and the intensity of the product use.

$$MCI = 1 - LFI \times F(\chi) \tag{3.4}$$

The LFI is the Linear Flow Index, calculated by

$$LFI = \frac{V + W}{M} \tag{3.5}$$

The F(χ) is the function of the utility factor, calculated by

$$F(\chi) = \frac{0,9}{\chi} \tag{3.6}$$

However, the MCI is a mass weighting method. This means that the material with the most mass will dominate the results. In addition, due to the uncertainties of end-of-life material treatments, the output of the unrecoverable waste is hard to define. Furthermore, the accuracy is limited when evaluating complex building systems (Verberne, 2016; Macarthur Foundation, 2016).

3.2.3 Building Circularity Indicator

The Building Circularity Indicator (BCI) measures the restorative fraction of the material flows in a building. It combines the results of the Material Circularity Indicator, the Product Circularity Indicator, and the System Circularity Indicator in consecutive steps (Macarthur Foundation, 2016).

The Product Circularity Indicator (PCI) merges the MCI of all the different materials, including the interfaces and connections between them. The PCI is calculated by the summation of each material in the product, multiplied by 17 different disassembly factors F_i ranging from 0 (no reversibility) to 1 (completely reversible), as shown in the following formula:

$$PCI = \frac{1}{F_d} \sum_{i=1}^{n} MCI \times F_i \quad with \quad F_d = \sum_{i=1}^{n} F_i \tag{3.7}$$

The System Circularity Indicator (SCI) measures the circularity of the products in a system. The SCI is calculated by the summation of each product, multiplied by the factors W_j. The factors W_j take the different lifetimes of the different products, based on Brandt's shearing layers concept, and the weight of sales revenues of the product into account, by the following formula:

$$SCI = \frac{1}{W_s} \sum_{j=1}^{n} PCI \times W_j \quad with \quad W_s = \sum_{j=1}^{n} W_j \tag{3.8}$$

The Building Circularity Indicator (BCI) assesses the different systems as a complete assembly, for example a building, by multiplying them with factors LK_k. These factors take the system dependencies and the system importance into account. The BCI is calculated by following formula (Verberne, 2016):

$$BCI = \frac{1}{LK} \sum_{k=1}^{n} SCI \times LK_k \quad with \quad LK = \sum_{k=1}^{n} LK_k \tag{3.9}$$

As such, it is a mass weighting method, because it is an extension of the MCI, taking the connections, interfaces, product lifetimes, weight of sales revenues, and system dependencies into account with certain subjective factors (Macarthur Foundation, 2016).

3.3 Sustainability indicators

The current sustainability indicators and frameworks are used to quantify the environmental, social and economic impact in society. As mentioned in the introduction, sustainability indicators are used to measure the effect of a circular strategy on a specific impact category, like the emission of carbon gasses. Two frequently used indicators ‘material longevity’ and ‘Value-based Resource efficiency’ are described below (Corona et al., 2019).

3.3.1 Value-based Resource Efficiency

The Value-based Resource Efficiency (VRE) is a mass-based sustainability indicator, aligned with environmental, economic, and social policies. It measures resource efficiency and circularity, by linking those to the market value of natural resources. The VRE formula 3.10 contains the output value of a product Y, the volume of natural resources X_i, and the weight factors w_i. The weight factors represent the environmental and societal impact and relate to the market prices.

$$VRE[\%] = \frac{Y}{\sum_{i=1}^{n} w_i X_i} \tag{3.10}$$

The output value Y is measured by the value added to the product after manufacturing and is based on market prices. It is equal to the difference between the total product’s value and the input values of the materials, energy, and services, as shown in the following formula (Di Maio et al., 2017):

$$Y[€] = Output_{Total} - Input_{Material} - Input_{Energy} - Input_{services} \tag{3.11}$$

3.3.2 Longevity

Longevity can be defined as ‘the length of time for which a material is retained in a product system.’ It depends on the initial, refurbished, and recycled lifetime of the building product. The first is associated with the lifetime of use as a new product, the second with the reused and refurbished lifetime, and the last with the recycling and returning rate to a construct for another new product. The formula can be stated as (Franklin-Johnson et al., 2016):

$$Longevity[Months] = T_{Initial} + T_{Refurbishment} + T_{Recycled} \tag{3.12}$$

3.4 Sustainability frameworks

Sustainability frameworks assess the value or burden created by implementing circular building strategies. They take into account a broader scope of impact categories to avoid burden-shifting between the different kinds of impact. The three often used frameworks in literature: Life Cycle Analysis (LCA) and/or Life Cycle Costing (LCC), material Flow Analysis (MFA), and Input-Output Analysis, are described below (Lei et al., 2021).

3.4.1 Input-Output Analysis

Input-Output Analysis or inter-industry analysis is an important branch in current economics. The original goal was to develop a quantification tool to assess the economic interdependence between different sectors within a regional, national, and international economy (Miernyk, 1966). However, it is often used to analyze the environmental and socio-economic impact associated with the activities of the different sectors (Corona et al., 2019). Then, the Input-Output Analysis is done by mapping the flows and goods, and the associated pollution, raw material use, and costs, between the different sectors. It is a top-down approach that assesses the whole elements, and not the individual components. As such, it is mostly used to compensate for the shortcomings in process and material information in other sustainability frameworks (Corona et al., 2019).

3.4.2 Life Cycle Analysis & Life Cycle Costing

In the past decades, Life Cycle Analysis (LCA) is used for the evaluation of the inputs, outputs and potential impact of a product system throughout its life cycle (Lei et al., 2021; ISO 14040, 2006). Different indicators to assess the environmental impact are implemented to avoid the risk of environmental burden-shifting between different impact categories, such as global warming, depletion of resources and ozone depletion (Pomponi & Moncaster, 2017; Jannsens, 2013). Therefore, the sustainability assessment framework is based on the modeling of cause-effect relationships in the environment induced by resource extraction, pollution, and emissions (Hellweg & Milà i Canals, 2014). The LCA framework, based on the international standards IS0 14040 and ISO 14044, contains four steps, which are illustrated in figure 3.2 and further discussed in chapter 4.

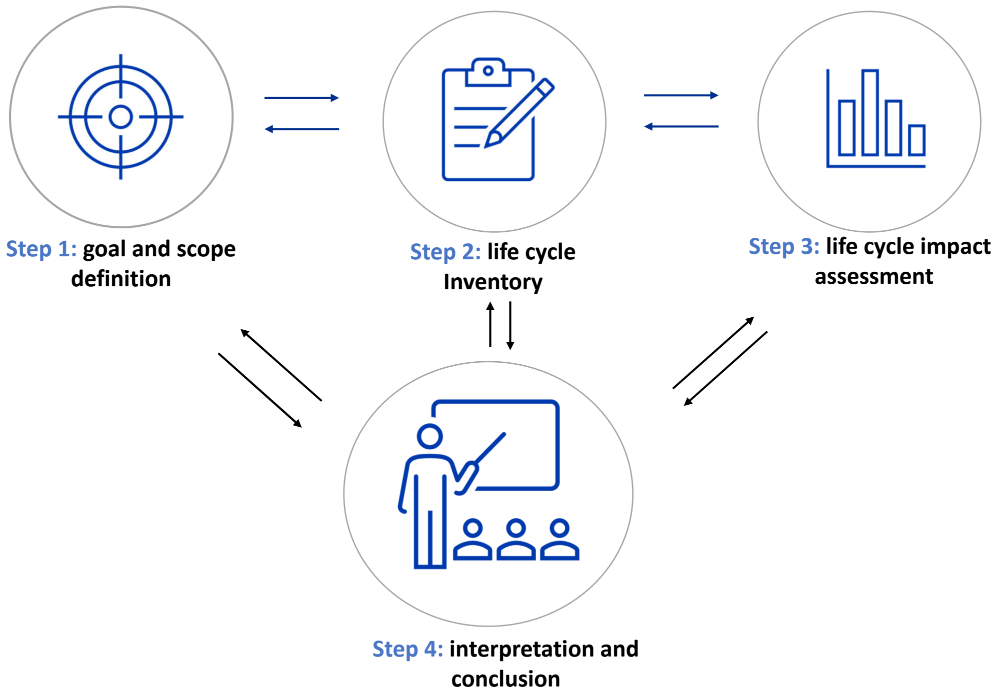


Figure 3.2: The four steps of the LCA framework, based on ISO 14040 and 14044.

The results of the environmental impact, determined by the LCA framework, can be supplemented with the financial costs, calculated with the Life Cycle Costing (LCC) framework. Nowadays, it is a popular method for evaluating the economic sustainability based on the life cycle of a product or process (Balanay & Halog, 2019). This quantification method adds up all the financial costs associated with the asset, starting from its initial cost to its end of life cost (Waldo, 2016). The LCC framework aligns with the framework of the LCA analysis and is further discussed in chapter 5.

3.4.3 Material Flow Analysis

To provide product information regarding resource use and losses of materials in the environment, Material Flow Analysis (MFA) is widely applied (Laner & Rechberger, 2016). It is a bottom-up evaluation method to analyze the stocks and flows of materials or energy and to estimate the environmental load, with specific space and time constraints (Farjana & Li, 2021). The physical flows of materials or energy in and out a given system, expressed in physical units, and the material transactions among actors within the system, are mapped, monitored, and analyzed at different scale-levels according to the goal of the study (Graedel, 2019; Ohnishi et al., 2017).

The assessment method estimates and adjusts mass balances, based on the fundamental principle of mass conservation (Farjana & Li, 2021). The basic idea is that raw materials, water, and air are extracted from the natural system as inputs, then transformed into manufactured products, and finally re-transferred to the natural system as waste and emissions (OECD, 2012). The MFA assessment is done in four steps, as shown in figure 3.3 (Laner & Rechberger, 2016).

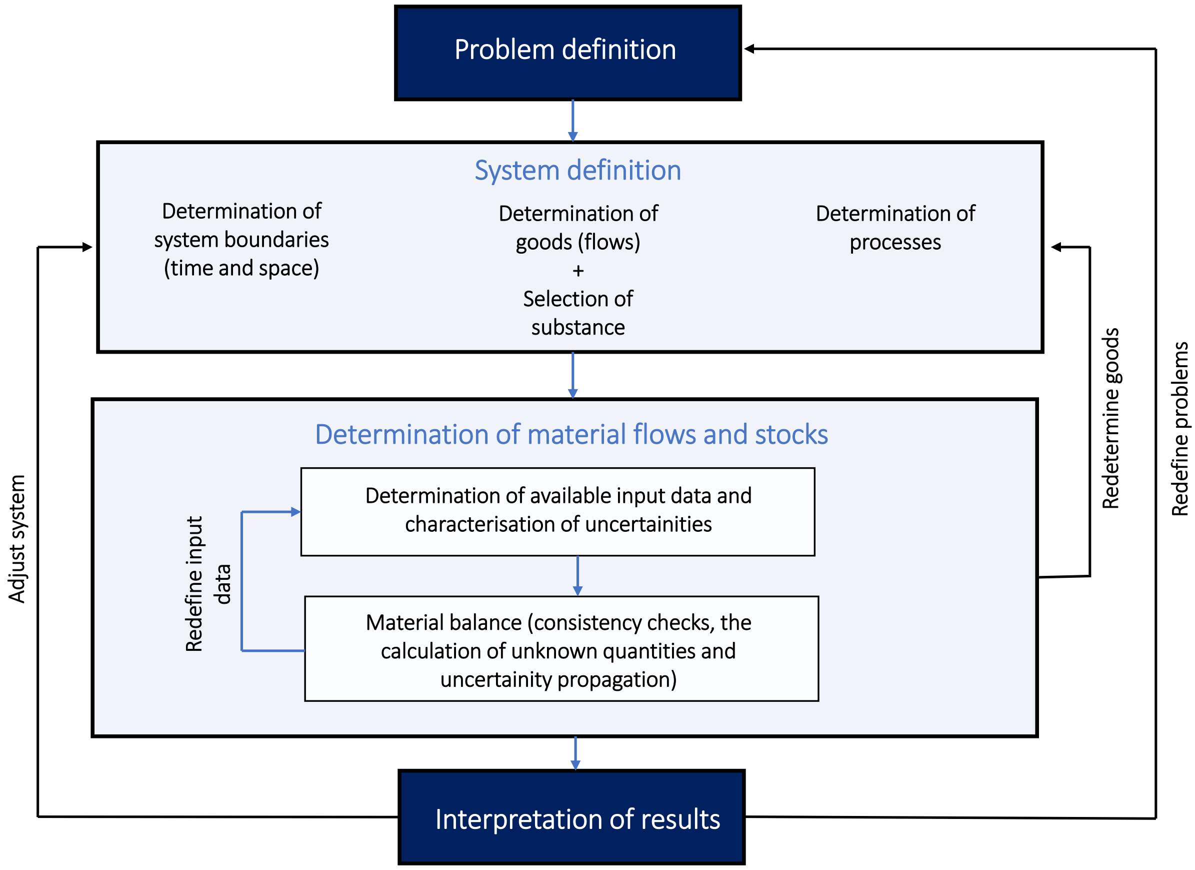


Figure 3.3: The four steps of the MFA methodology, based on the theory of Brunner and Rechberger (2004).

3.5 Discussion

A quantitative assessment methodology for the evaluation of the overall environmental impact and financial cost of circular building elements is explored. For that purpose, circularity indicators, which measure the intrinsic degree of circularity or the recycling potential, are not appropriate. The sustainability indicators assess the environmental impact for a single impact category, which can cause environmental burden-shifting (Pomponi & Moncaster, 2017). Therefore, a sustainability framework assessing multiple impact categories, such as the depletion of resources and the emissions of greenhouses gasses, is proposed for the assessment of circular building elements during building's lifespan.

Input-Output analysis is based on national static values, which lack detail for single products and processes (Corona et al., 2019). Consequently, MFA and LCA are most frequently used to assess the benefits of the CE in the building industry (van Stijn et al., 2021). However, due to the use of material masses in MFA, information is missing on the corresponding environmental impact (Laner & Rechberger, 2016; Lei et al., 2021). MFA is a valuable tool for waste and resource management, since it is suitable for studying the route of materials flowing into recycling sites and stocks in space and time (Withanage & Habib, 2021). On the other hand, LCA tries to consider all the relevant flows of materials and energy associated with the provisioning of the function of the product. There, cause-effect relationships are used to determine the relative contribution of the flows to the different environmental impact categories (Haupt et al., 2018). Additionally, the LCC framework, using the same assumptions and system boundaries as the LCA framework, can be used to assess the total financial costs.

For those reasons, the LCA and LCC framework are chosen as a base to consequently develop an assessment framework to evaluate the environmental impact and financial cost of reusable building elements during a buildings' lifespan.

Chapter 4

Life Cycle Analysis meets the circular economy

Life Cycle Analysis (LCA) has the potential to rate the environmental impact of circular building elements, as discussed in the previous chapter. However, there are no current recognized European and international LCA standards to evaluate the circular construction industry (van Stijn et al., 2021). In the following chapter, the limitations of the conventional LCA methodology and the adaptions in the framework to evaluate circularity are discussed. Also, different circular LCA frameworks in the literature are reviewed. Finally, an own developed method based on the conventional LCA framework is proposed for the assessment of reusable building elements during the building's life span.

4.1 From a conventional to a circular LCA

The conventional LCA methodology, according to the international standards ISO 14040 and ISO 14044, and the European standard NBN EN 15804, focuses on estimating the impact of a product system for a single life cycle. In the circular construction industry however, especially in the case of reuse strategies, materials and building elements potentially go through multiple use cycles within the building's life cycle. Therefore, the assumptions in certain stages in the conventional LCA framework need to be adapted (ISO 14040, 2006; Lei et al., 2021). In the following section, the conventional LCA framework and the modified stages, as represented in figure 4.1, are discussed. Thereafter, the challenges of implementing the CE in the conventional LCA framework are highlighted.

Figure 4.1: The assumptions of the coloured stages: service life, system boundaries, specific and generic data collection, and allocation, need to be modified for the integration of CE in the conventional LCA framework.

4.1.1 Step 1: goal and scope definition

In the step 'goal and scope definition', the intended use and subject need to be defined, determing the level of detail and the system boundaries of the study (Allacker, 2010). The different steps to complete this goal and scope definition are described below.

Goal definition

Initially, the application, the reason, the research question, and the intended target audience of the study have to be described to define the scope of the study (ISO 14044, 2006; Desmyter, 2001). The goal of this research is to elaborate a framework to prove the environmental and financial benefits of using reusable instead of traditional building elements during the building's life span. The target audience is the building industry.

Scope definition

In the subsequent step, it is important to describe the system boundaries by methodological choices, assumptions, and limitations as described in the section below. LCA is an iterative process, implying that it starts with a set of choices and requirements, but may be adapted later when more information becomes available (Allacker, 2010).

The main elements to establish are **the functional unit** and **the reference flow**. The functional unit unambiguously specifies the function, the properties and/or technical performances and serves as a reference unit to compare the environmental impact of materials, building components, and buildings (Jannsens, 2013; Allacker et al., 2018). For instance, the functional unit for the comparison of two different paint systems can be defined as the unit surface protected for ten years. Next, the reference flow is the quantified amount of input and output flows of materials and energy that are necessary for the element or building to deliver the performance and function, described by the functional unit (ISO 14044, 2006).

Besides the definition of the functional unit, the provided **service life** of building(elements) also plays an important role (Jannsens, 2013). The service life is determined by the technical, economical, and/or functional life span. The technical lifespan is the maximum period during which a component can physically handle its function, while the economic lifespan is the period where the benefits outweigh the costs of a building. For the evaluation of the reuse potential of circular building elements by means of the conventional LCA method, the functional life span needs to be included into the framework. The functional life span is influenced by changes in the users' needs and regulations. By analyzing the interplay of the different life spans, the overall service life can be determined (Brandt, 1995; van Stijn et al., 2021).

Moreover, the service life can be decided on three levels: the building level, the building layer level, and the component and material level, as shown in figure 4.2. The smallest units of a building, the materials, each have an economic and technical service life. Then, the materials are combined into building elements interacting dynamically in space and time (Pomponi & Moncaster, 2017). The service life of these building elements is often determined by the economic and technical life span of the materials and joining techniques. However, the functional service life may also play an important role in the determination of the life span of a building element (van Stijn et al., 2021; Brandt, 1995). It is often disregarded because it contains an inherent uncertainty of the change in needs by the various users during the long life span of the building. Nevertheless, it is important to take into account future refurbishment scenarios in the estimation of the environmental impact of circular building elements. This is indispensable to determine the real and long-term savings due to the reuse of the elements (Pomponi & Moncaster, 2017).

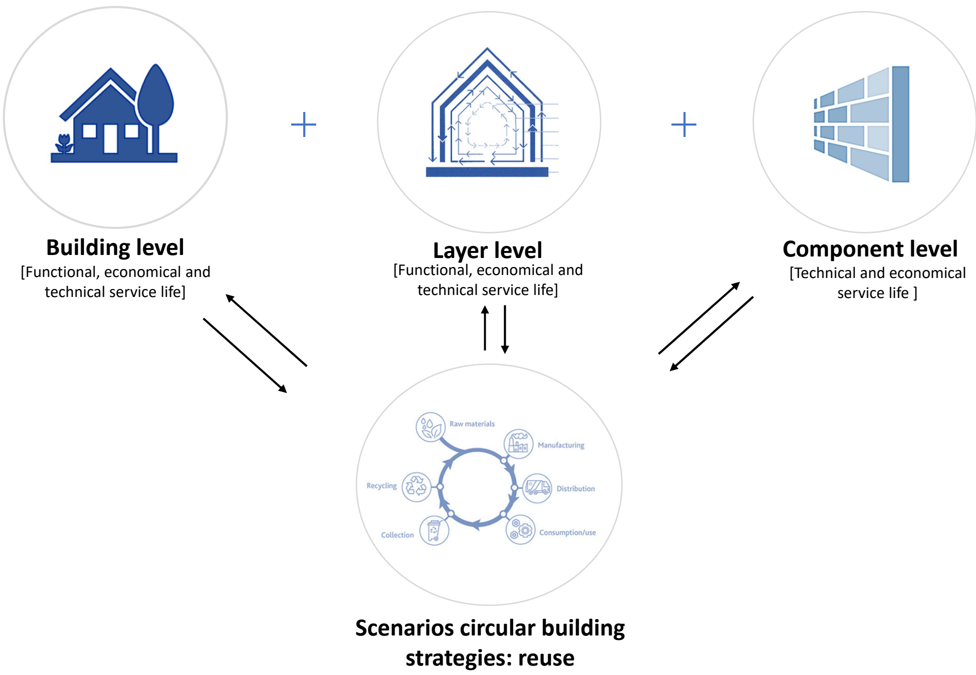


Figure 4.2: The service life can be determined on three levels in the LCA framework.

For the scope definition, **the system boundaries** of the building element's life cycle need to be delineated. The European standards NBN EN 15804 and NBN EN 15978 segregated the life cycle of a product system into different modules with specific boundaries. Figure 4.3 represents the defined activities and processes for each life cycle stage. Additionally, the current European standard NBN EN 15804 (2019) distinguishes three types of LCA dependent on the included modules in the framework. The 'cradle-to-gate LCA' assesses only the production stage (module A1-A3), while the 'cradle-to-gate with options' LCA evaluates the production and end-of-life stage (modules A and C). The 'cradle-to-grave' LCA accounts for all the life cycle stages (modules A, B, and C).
In Europe, it is required to perform an LCA from cradle-to-grave on building element and building level. However, for the assessment of the benefits of the circular building industry, a cradle-to-cradle approach (modules A, B, C, and D) is recommended in the literature. It incorporates the benefits and loads of reuse, recycling, and recovery activities beyond the system boundaries by means of module D and creates a cyclic life cycle assessment (Lei et al., 2021).

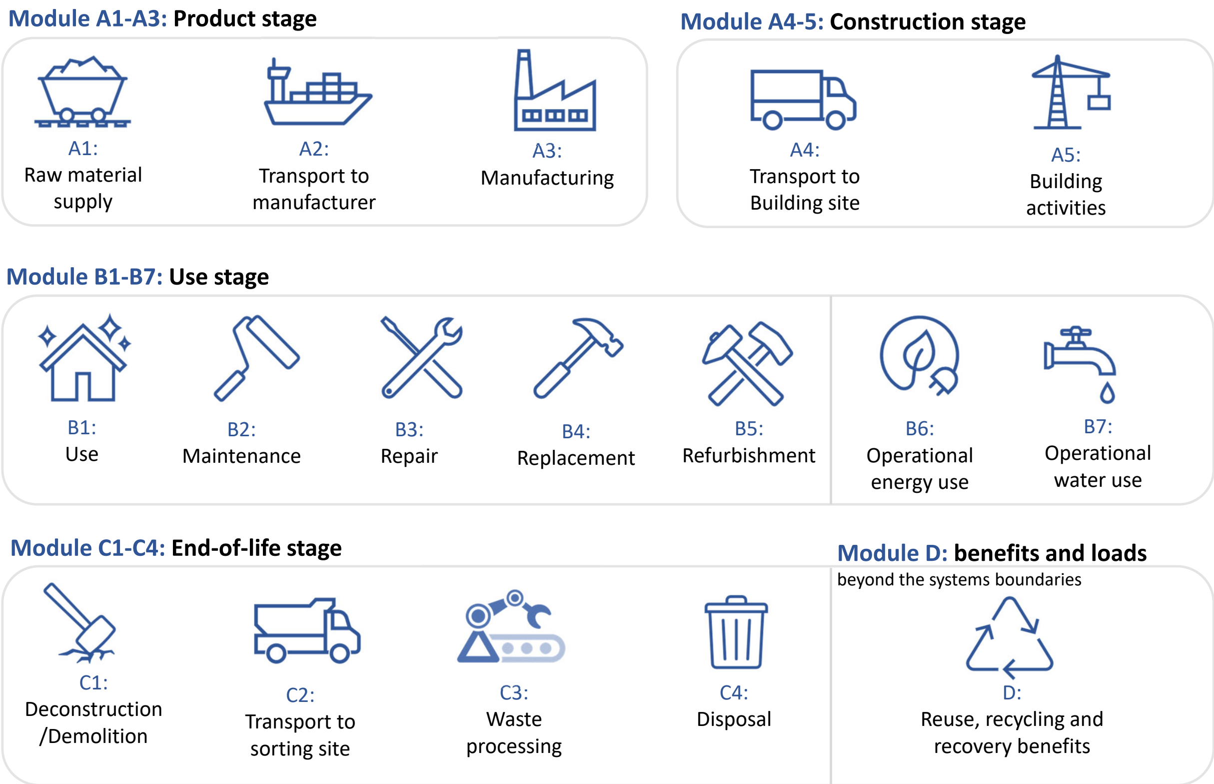


Figure 4.3: Graphical representation of the different stages of the product systems life cycle

Methodology

Finally, the methodology must be defined. Therefore, the impact assessment method and the used sources and databases addressing the data requirements should be selected. The data requirements play a major role in the completeness, precision, and representativeness of the LCA results (Allacker, 2010). Two types of data can be used: specific and generic data. Generic data can be retrieved from databases, such as the Ecoinvent v3.8 database, GaBi database, and the IVAM database, while specific data needs to be collected by manufacturers (Jannsens, 2013).

A commonly used database for generic data in Belgium is the Ecoinvent v3.8 database (Debacker et al., 2012). The Ecoinvent v3.8 database covers environmental data for more than 10.000 processes, including a large number of processes for building materials and products. The data mainly represents Western Europe, especially Switzerland and Germany. Nevertheless, it contains several specific Belgian processes, such as the Belgian electricity mix. Additionally, the generic data can be customized to the Belgian context by the transparent and flexible underlying framework of the processes (Allacker et al., 2018; Goedkoop et al., 2019).

Also the impact assessment method has to be chosen, which is linked to the environmental indicators. Examples are the ReCiPe method, the CML 2002, and the Ecoindicator 99 (Jannsens, 2013). Nevertheless, the ReCiPe method is recommended by the ILCD manual (2010) when using several environmental indicators. With this method, the environmental impact can be determined on three levels: by the individual indicators, by three intermediate indicators (damage according to ecosystems, human health, and availability of raw materials), and by one aggregated score.

4.1.2 Step 2: life cycle inventory

The life cycle inventory (LCI) is the most labor-intensive step in the LCA framework (Allacker, 2010). In this step, the specific and generic data are collected. The data collection includes the inventory of all the net and gross amounts of materials and products and the corresponding environmental impact. Thereafter, the data requires calculations and conversions to relate them to the reference flow of the functional unit (ISO 14044, 2006; van Stijn et al., 2021).

For the assessment of reusable building elements in the same building, all the (re)used materials should be inventoried during the building's life span (van Stijn et al., 2021). This means that the input and output processes of a building before and after a refurbishment should also be collected, together with the disposed of, recycled, incinerated, and/or reused materials (Obrecht et al., 2021). This data can be gathered by process-based, economic input-output, or hybrid analysis. The process-based analysis is a bottom-up data collection of the environmental impact by considering each process of a product, while the input-output analysis is in contrast a top-down data collection method. This method deals with the upstream and downstream material flows between different economic sectors, as discussed in the previous chapter. The hybrid analysis combines both methods. The most used analysis method for current CE-LCA applications is process-based data collection. Nevertheless, the lack of end-of-life LCI data is a critical issue in this method (Lei et al., 2021). This obstacle can be overcome by hybrid analysis or building material passports and BIM models, which are out of the scope of this study (van Stijn et al., 2021).

Allocation

The product system's life cycle is separated into life cycle stages, as shown in figure 4.3, and the input and output processes need to be distributed across these different stages (Jannsens, 2013). When the unit processes are shared among different product systems, these need to be properly allocated by specific allocation procedures. The steps to identify the kind of allocation procedure are described by the European standard ISO 14044 (2006):

- Step 1: when possible, avoid allocation by dividing the unit process into two or more sub-processes or by expanding the product system to include the additional functions.
- Step 2: when allocation can not be avoided, the data of the systems should be partitioned between the products along with their underlying physical relationships.
- Step 3: when underlying physical relationships are not possible, the data should be partitioned between the products along with other relationships, such as the economic value.

However, this procedure is insufficiently accurate for different products with different functions and use cycles, which is a methodological issue in the conventional LCA (Corona et al., 2019). In the first use cycle, the products are manufactured from raw resources. After that, an unknown number of consecutive intermediate cycles follow, where the material is reused or recycled. In the last use cycle, the product is landfilled, incinerated or recycled (De Wolf et al., 2020).

There are three generic allocation modeling approaches for assessing circular building scenarios, illustrated in figure 4.4 and described below.

- The cut-off approach (100:0)
  In the cut-off approach, the environmental impact of each stage is counted within the cycle they occur (De Wolf et al., 2020). Accordingly, all the impact of the production phase is allocated to the first use stage. The impact of the collection and preparation for recycling and reuse, or/and burdens at the end of the cycle are allocated to the subsequent use stage (Obrecht et al., 2021). The adoption of the cut-off approach avoids the uncertainty in predicting the future of end-of-life scenarios (Lei et al., 2021).

- The substitution approach (0:100)
  In the substitution approach, the recycling benefits and burdens are attributed to the product that provides the recycled materials (Lei et al., 2021). As a consequence, the environmental impact is allocated to the use cycle of the primary product. (Corona et al., 2019). The soft spot of this approach is the forecast of future recycling and reuse scenarios. It is hard to predict these scenarios, because of the relatively long service life of building materials and components (De Wolf et al., 2020).

- The distributed approach
  In the distributed approach, the burdens and credits are shared between the primary and recycled, recovered or reused products (Corona et al., 2019). There are different kinds of distributed approaches (Lei et al., 2021; Obrecht et al., 2021; De Wolf et al., 2020):

  - PAS-2050: the production and end-of-life impact are equally distributed over all the use cycles.
  - Circular Footprint formula: the burdens of the production and demolition stages are allocated to the first and last use cycle, while the benefits of reuse are shared between intermediate use cycles.
  - The linear degressive method: the building impact is allocated to the different use cycles of the building in a linearly degressive manner.
  - SIA 2032: the burdens of product and end-of-life stages are distributed over the different use cycles, based on the ratio of the actually used and expected life span.

The estimation of the number of life cycles in future recycling and reuse scenarios renders the distributed approach complicated. However, this approach is usually mentioned in the literature of CE assessment, because it promotes multi-cycle design. Less production and recycling burdens are attributed to each life cycle when the total number of life cycles increases (Lei et al., 2021).

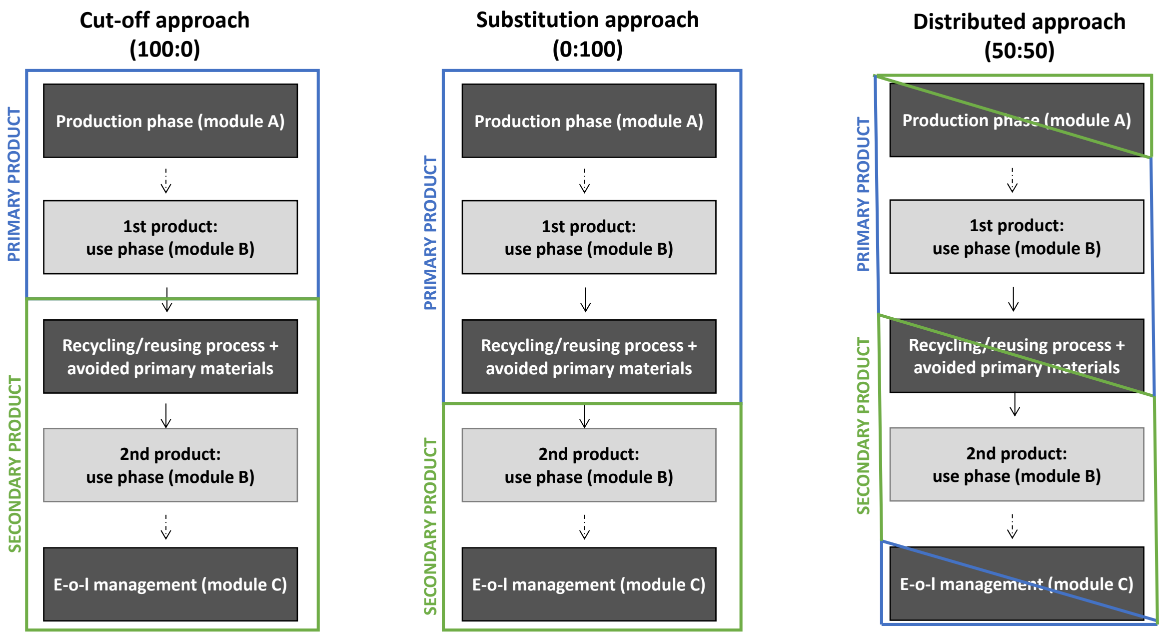


Figure 4.4: Schematic of the three types of allocation methods: the cut-off, the substitution and the distributed approach.

In the current circular LCA literature, two detailed frameworks are proposed: the EN 15978 method, on the building level, and the Product Environmental Footprint (PEF) method, on the product level. These methods quantify the impact related to recycling, reuse, and recovery processes, as well as the avoided impact due to the substitution of primary resources, products, or elements (Rajagopalan et al., 2021; De Wolf et al., 2020). The EN 15978 method is an end-of-life modeling method, containing the life cycle stages A, B, C, and D. Module D is introduced to quantify the reuse and recycling benefits beyond the system boundaries. The PEF-method captures the waste flows and the material recirculation benefits at each life cycle phase of the built environment as a real-time end-of-life modeling method (Lei et al., 2021).

All the discussed allocation methodologies and modeling approaches distribute the environmental burdens and benefits of recycled and reused materials over multiple life cycles. However, each framework leads to different results and focuses on different CE strategies (Lei et al., 2021). For instance, the cut-off method encourages the use of existing secondary materials and components, while the substitution approach promotes the downstream design. It is important to take this into account when choosing an allocation method for a study.

4.1.3 Step 3: life cycle impact assessment

The purpose of Life Cycle Impact Assessment (LCIA) is to interpret the inventoried data of the LCI-phase and to evaluate the potential contribution to the environmental impact. This is accomplished by defining environmental impact categories and additional indicators (Jannsens, 2013). Thereafter, the inventoried data is classified and characterized. The outcome is an environmental profile of a specific building product. These are the mandatory steps of the LCIA, while normalization, grouping, and weighting are optional steps (ISO 14044, 2006). The different stages are further described in the section below.

Environmental impact categories and indicators

In the first stage of the LCIA, the various environmental impact categories and indicators are identified, such as global warming and the depletion of resources (Allacker, 2010). These are mainly the consequence of certain emissions to earth, air, and water, the extraction of raw materials, and the land and water use (Jannsens, 2013). The international standards ISO 14040 and 14044 do not impose environmental impact categories and indicators but describe the criteria. Meanwhile, the European norms NBN EN 15804 and 15978 propose categories and indicators which can be used in an LCA for a building element or building. These indicators fall within two subcategories: CEN-indicators, which describe actual environmental issues, and CEN+-indicators, which describe inventoried data like raw material use and waste categories. The various indicators are illustrated in figure 4.5 (NBN-EN15978, 2012).

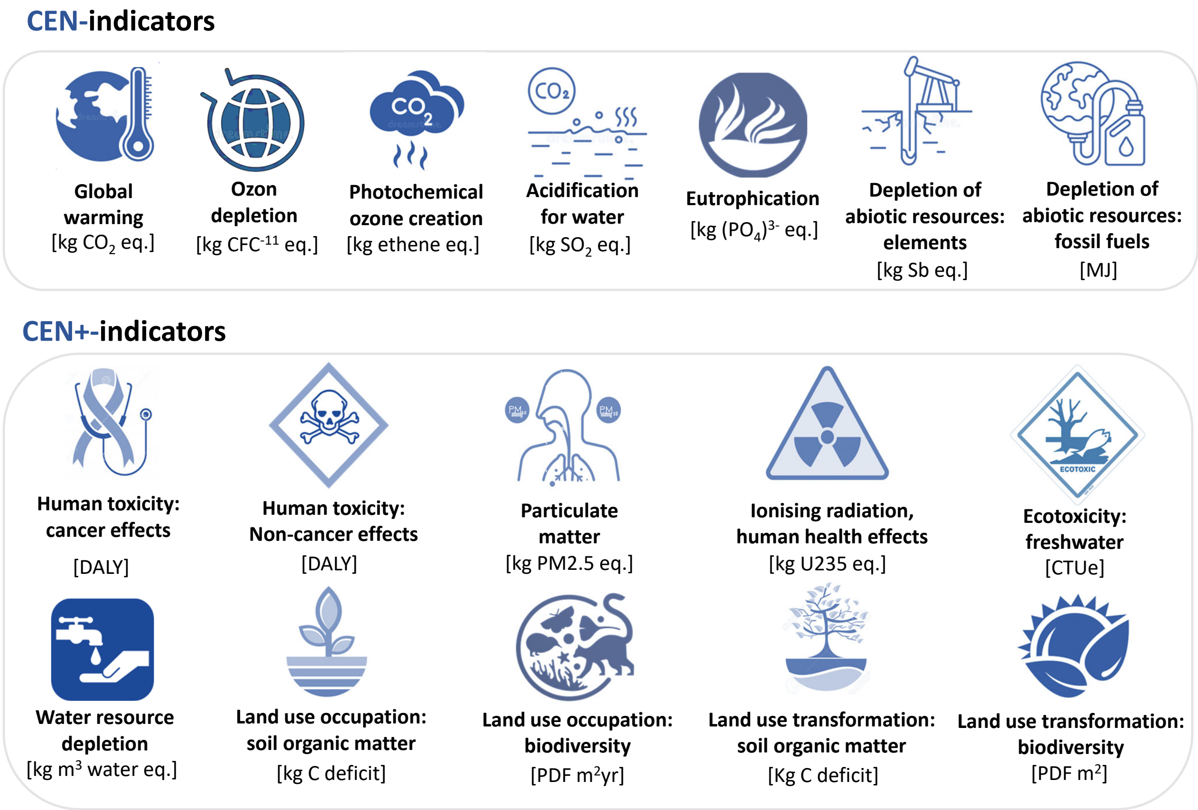


Figure 4.5: Scheme of the CEN and CEN+ indicators, proposed in the NBN EN 15804, with their basic unit.

Classification and characterisation

In the **classification phase**, the inventoried data is grouped under one or more impact indicators. For instance, carbon dioxide is grouped under the environmental indicator global warming (Allacker, 2010). Thereafter, the data is characterized. This means that the contribution of the input and output processes is expressed in terms of a common denominator or reference unit. The reference units of the CEN and CEN+-indicators are shown in figure 4.5 (Jannsens, 2013).

In practice, the conversion of the data towards a reference unit is done by **characterization factors**. These factors are linked to the chosen impact assessment method. An example is given for the environmental impact indicator of global warming. All the greenhouse gasses, which contribute to global warming, should be expressed in the reference unit kg CO_2-equivalents. The factor for converting CH_4-gasses is 25 in the ReCiPe method (Allacker et al., 2018).

Then, all the different converted contributions are summated to an environmental impact score for each indicator. The combination of the results of the various individual environmental indicators leads to an environmental profile of the considered product (Jannsens, 2013).

Normalisation, grouping, and weighting

The results of the different impact indicators are difficult to compare because they have different reference units. Therefore, the environmental impact of the indicators is compared to a reference system in the **normalization phase** (ISO 14044, 2006). The average yearly impact of a European citizen is often used as a reference basis. The results of the different indicators are expressed as a percentage of these reference values. Those percentages make it possible to compare environmental impacts of different categories to each other (Allacker, 2010).

Still, the multitude of individual impact scores for the various indicators makes it difficult to evaluate the environmental impact of the different products. When two products are compared based on the results of one individual indicator, there is a risk of burden-shifting from one environmental category to another. Therefore, the optional steps '**grouping and weighting**' are introduced to consolidate the individual impact scores of the various indicators to an aggregated environmental score (Debacker et al., 2012).

In the 'grouping' step, the different impact categories are partitioned into different groups on a nominal basis (for example global and local) or by proposed hierarchies (low, medium, and high priority). In the 'weighting' step, the normalized and grouped results are multiplied by certain weighting factors, whose value is based on judgments of individuals or companies, and summated to an aggregated score (Jannsens, 2013). Examples of often used weighting factors are the prevention and damage costs. The damage costs estimate the demand function upon the environmental quality, while the prevention costs measure the loss in welfare by potential environmental effects (Allacker et al., 2018). This weighting step is by consequence subjective, due to the dependency on value judgments and interests of the performer. The various sets of weighting methods produce different results, which means that these should be well clarified in the LCA study (Allacker, 2010).

4.1.4 Step 4: the interpretation of the results

In the last step of the LCA framework the obtained results, being the environmental profiles and/or aggregated scores, have to be interpreted with the research question and proposed goal of the study in mind, so that conclusions and recommendations can be established (Debacker et al., 2012). This interpretation step is executed in three stages: the identification of the significant points, the verification in terms of the completeness, sensitivity, and coherence of the data, and the making of the report with conclusions and recommendations (ISO 14044, 2006). It is important that the context of the study, namely the assumptions, limitations, and boundaries, is reflected in the environmental results of the Life Cycle Analysis (Jannsens, 2013).

4.1.5 Challenges quantifying circularity with LCA

In literature, the Life Cycle Assessment of circular building strategies is considered to be still in its infancy (De Wolf et al., 2020). At the moment, there are some inherent restrictions in the CE-LCA framework. First, the main problem is the lack of site-specific end-of-life data possibly hampering the assessment of the potential of circular building elements. However, this problem can be tackled by material passports and BIM models of buildings, and a hybrid life cycle data inventory (van Stijn et al., 2021). Then, there is a lack of time-related considerations. Internal and external temporal factors, such as the degradation of reused or recycled materials, have significant impacts on the service life of the building products (Lei et al., 2021). The dynamic LCA, taking the degradation of materials into account, is not in the scope of this study.

Another problem is the inconsistency in the determination of the system boundaries. The system boundaries have to be consistent in the end-of-life modeling across the whole life cycle. However, there is a variety of life cycle impact allocation methods to attribute the benefits of reuse and recycling to the different life cycles, each resulting in different LCA results. The inconsistent system boundaries and lack of normalized allocation methods can make it difficult to compare the results of different circular LCA studies with each other.

4.2 Case studies for the LCA of circularity

Certain stages of the conventional LCA framework have to be modified for the assessment of circular building strategies. Therefore, different assumptions and procedures have to be chosen in the modified stages to reach the goal of the research. In this research, a LCA framework to quantify reusable building elements during the service life of the building is explored. To that end, an overview of current case studies of circular LCA is given in table 4.1. This table discusses the subject and the assumptions made regarding the service life, system boundaries, data collection, and allocation procedure for the different studies.

The case studies from Rajagopalan (2021), van Stijn (2021), and Eberhardt (2019) take the benefits of recycling, reuse, and energy recovery after a product's service life into account with module D. Additionally, the distributed approach is used to allocate the environmental impact over the multiple life cycles. Nevertheless, it is difficult to estimate the number of building element life cycles (Lei et al., 2021). Also, the determination of the end-of-waste stage of building products is debatable and the functional equivalence is not easy to define considering the uncertainty of recycling and reuse scenarios. Strong insights into the production and recycling processes of materials are necessary to apply this methodology. Furthermore, the results are not always easy to interpret and leave room for multiple scenarios and hypotheses (Wastiels et al., 2013). Consequently, this approach is not a consistent and simplified assessment framework for the evaluation of reusable building elements during the buildings lifespan.

Another approach is to quantify the benefits and burdens of recycling and reuse in multiple-use stages within the same life cycle. The LCA framework of Buyle (2019) evaluates the environmental impact of interior wall systems over multiple use stages but ignores the impacts of the production and end-of-life phase. Also, Paduart used this approach for the assessment of the impact of circular building elements. However, the demolition impact of the circular building elements is ignored. She assumes that the demolition impact for circular and traditional building elements is the same at the end of their life cycle (Paduart, 2012; Paduart et al., 2013). In this study however, a methodology to assess the environmental benefits and burdens related to reusable building elements during their **whole life cycle** is needed, comparing traditional with circular building elements. For this reason is in the following section the **R-LCA framework** developed based on the LCA framework of the European standard NBN EN 15804. The R-LCA framework quantifies the benefits and burdens from reuse during buildings lifespan within the module B5 'refurbishments'.

Case studies for the CE-LCA						
Case study	**Author**	**Subject**	**Service life (SL)**	**System boundary**	**data collection**	**allocation**
Case study: the circular design of the Mahatma Gandhi district in Mechelen	(Paduart et al., 2013)	The social houses of the Mahatma Gandhi district on building element, building and district level	Building SL: 60 year and building element SL: 10 and 15 years for non-bearing interior walls, and 20 and 30 years for facades	Modules A, B, and C	Specific data of manufacturers and general data of the Ecoinvent v3.8 database	Cut-off approach
A case study for wall partitioning systems in the Circular Retrofit Lab	(Rajagopalan et al., 2021)	The Retrofit Lab on building element level: the wall systems	Building SL: 60 years and building element SL: 1 year for quickly changing interior walls, 10 year for technical interior walls and 15 years for dwelling-dividing interior walls	Module A, B, C, and D	General data of the Ecoinvent v3.8 database	PEF method with the distributed approach: circular footprint formula
A Circular Economy Life Cycle Assessment model for building components: a study for BAU kitchens	(van Stijn et al., 2021)	The comparison of the Business-as-usual kitchen (BAU-Ki), reclaim kitchen (R-Ki), and the circular kitchen (CI-Ki) on building element and part level	Building element SL: 80 years and building part SL for example infill panels: 20 years (BAU-Ki), 10 years (R-Ki) and 20 to 40 years (CI-Ki)	Module A, B, C, and D	Specific data of manufacturers and general data of the Ecoinvent v3.8 database	Distributed approach: the PAS-2050 approach and the linear degressive method
A case study in Belgian context: the comparison of internal wall assemblies	(Buyle et al., 2019)	The comparison of different interior wall assemblies on building element level	Building SL: 60 years and building element SL: 15 years	Module B (only B3, B4, and B5)	Specific data of marginal suppliers and general data of the Ecoinvent v3.8 database for background processes	Cut-off approach
The LCA of a Danish office building designed for disassembly	(Eberhardt, Birgisdóttir, & Birkved, 2019)	A Danish office building on building element and building level	Building SL: 50 and 80 years, and the building structural elements are assumed to be used in one or two future subsequent product systems	Module A, B, C, and D	Project-specific data of construction companies and general data of the Ecoinvent v3.8 database for the background processes	The expansion EN 15978 method with a combination of the distributed and substitution approach, depending on the reusability and recyclability of the materials

Table 4.1: Overview of the subjects and the assumptions for the modified modules in the different CE-LCA case studies of Paduart (2013), Rajagoplan (2021), van Stijn (2021), Buyle (2019), and Eberhardt (2019).

4.3 The developed R-LCA framework

As discussed in the previous sections, a circular LCA framework is needed to compare the total environmental impact of reusable building elements with traditional building elements during buildings lifespan. Therefore in this study, the developed R-LCA framework is proposed, based on the conventional LCA framework according to the European standard NBN EN 15804. The modifications made to the conventional framework are described below.

Service life

It is difficult to predict the service life of a building, even though it has a big influence on the results of a LCA study (Paduart et al., 2013). However, in the current literature, one often assumes a building's service life of 60 years. This is the mean life span of a building in the Belgian context (Allacker, 2010). The life span of a building element is affected by the technical, economic, and functional service life. The technical and economic service life can be found in service life catalogs, such as the 'Service life of building products' list of SBR, a Belgian research institute (Haas et al., 2011). The technical life span depends on the flexibility and the periodic adaptations of the building. For the determination of the functional service life, certain refurbishment scenarios have to be assumed during the building's lifespan.

Allocation procedure

The benefits of the reused and recycled building elements in new building systems fall outside the system boundaries of the traditional LCA framework proposed by the European LCA standards NBN EN 15804 and 15978. Consequently, these are usually not taken into account in current LCA studies (Pomponi & Moncaster, 2017). Nevertheless, reusable building elements provide the opportunity to be disassembled and reused in the same building in different refurbishments, while traditional walls must be demolished and reconstructed with new materials.

In this study, the impact of the refurbishments of reused and traditional building elements are assessed in different use cycles within the same life cycle. As such, the complicated distributed allocation method of the reuse benefits outside the system boundaries can be avoided. Furthermore, the cut-off allocation method, also used in the traditional LCA framework, is chosen to assess the e-o-l impact of building products at the end of the building's life span. By using this allocation method, the environmental impact of each life cycle is counted within the life cycle they occur, so the uncertainty of future e-o-l scenarios can be avoided. However, the recycling and reusing benefits of the building element after the building's life cycle will be slightly underestimated.

System boundaries

The R-LCA methodology is a cradle-to-grave LCA. The environmental impacts of the production and construction stage, use stage, and end-of-life stage are evaluated, as represented in figure 4.6. For the assessment of the environmental impact of the building elements used in multiple use cycles in the same building, module 'B5: refurbishments' is taken into account. The impact addressed by this module is dependent on the reuse potential of the building product by a refurbishment. By traditional building products, the impact of the end-of-life treatment of the destroyed building element and the production and construction phase of the new element need to be accounted for. In the case of the reusable building products, only the impact from assembly, material losses, and disassembly have to be evaluated. Therefore, after each refurbishment, the reuse potential needs to be checked with the predefined criteria for reversible building components by Paduart (2013):

- The connections between the building components need to be reversible.
- The building component must be reusable in the same application.
- The technical and economical component's service life needs to be longer than 10 years.
- The remaining component's service life needs to be longer than half of the initial technical service life of the component.

The degradation of the quality of the reused building components in the different use cycles is out of the scope of this research and is not taken into account. Then, the impact of module B5 is multiplied by the number of refurbishment scenarios during the lifespan of the building. Furthermore, in the R-LCA framework is not counted for the impact of the use, repair, operational energy, and water use modules in the use stage. The reparation impact of building elements is not modeled due to the lack of reliable information for this module. The other modules are excluded because those are assumed to be equal for the traditional and circular building elements in the same building.

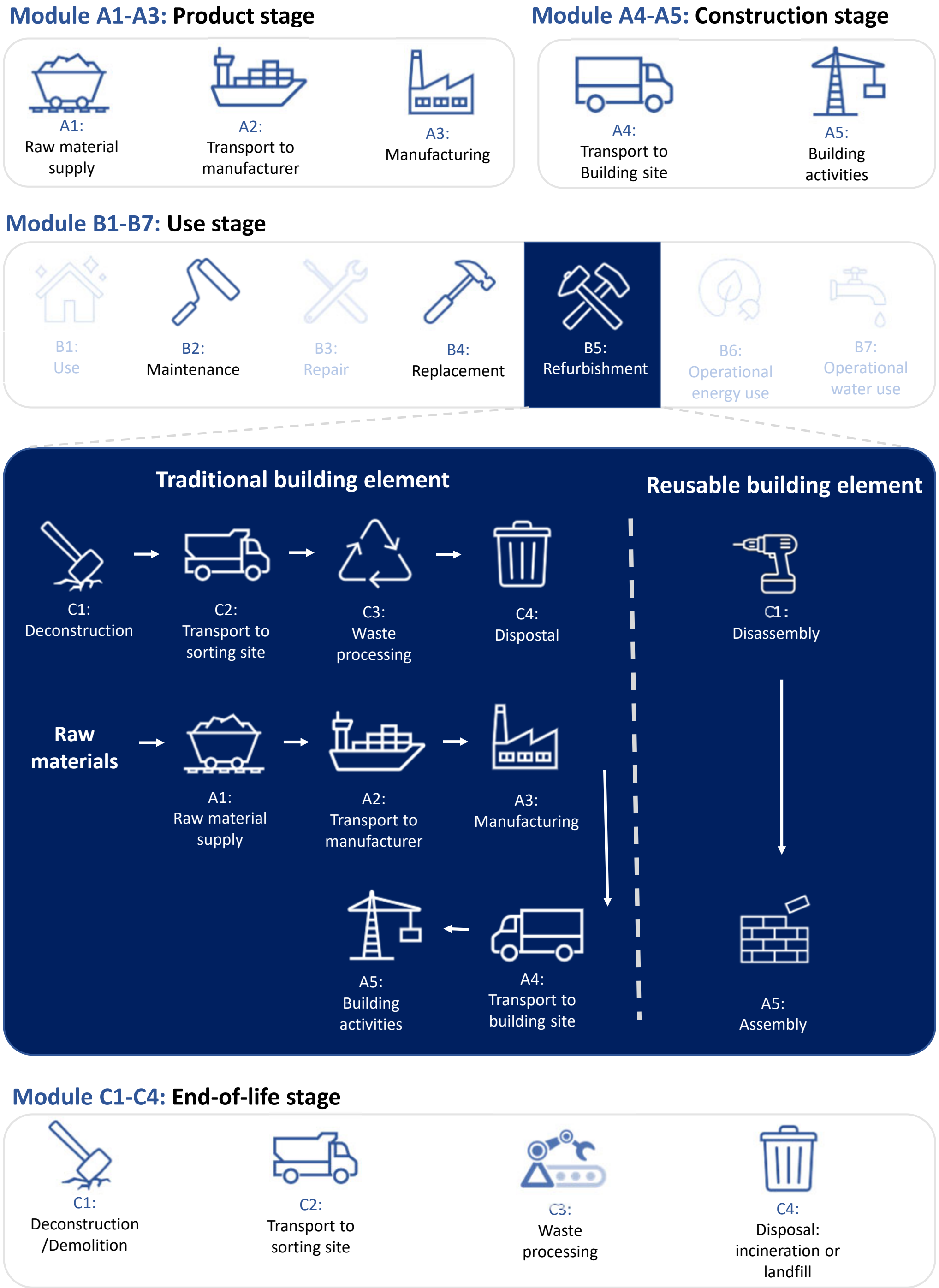


Figure 4.6: The systems life cycle stages of the developed R-LCA framework with the implemented coloured module B5 'refurbishment'. The greyed out modules are not implemented in this framework.

Data collection

In the Life Cycle Inventory step, all the input and output flows during the life cycle stages of the product's system are collected within the predefined system boundaries. This is done using chosen databases and assumed transport, (de)construction, maintenance, replacement, refurbishment, and end-of-life scenarios.

For the assessment of the different use cycles, module B5 'refurbishment' is used. However, the application of this module influences the impact of module B2 'maintenance' and B4 'replacement' by traditional building products. The number of replacements and maintenance scenarios changes, while refurbishments take place during the building's service life. The definition of the refurbishment frequency and the formulas for the replacement and maintenance rate, based on the framework of Vandenbroecke (2016), are described below.

For the definition of the functional life span of a building element, specific refurbishment scenarios in the building will be assumed. These scenarios determine the number of refurbishments in the building. Therewith, the number of replacements of a traditional building product during the life span of a building is calculated by the following formula:

$$N_{B4} = \frac{T_{building}}{T_{tech,element}} - 1 - N_{B5} \tag{4.1}$$

with:
$T_{building}$ = the lifespan of the building $[years]$
$T_{tech,element}$ = the technical lifespan of the building element $[years]$
N_{B5}= the number of refurbishments during building's life span $[-]$
N_{B4}= the number of replacements during building's life span $[-]$

If N_{B4} is an integer, it is equal to the actual number of replacements. If it is not an integer, the result is rounded up when the replacement is necessary for the technical requirements of the elements. The result is only rounded down for aesthetic requirements when the remaining building's life span is less than half the element's service life. Two assumptions are made for the replacement module. If the building product should be replaced, then also all the irreversible connected parent material layers should be replaced. Additionally, each layer would be replaced by an identical one.

Furthermore, the number of maintenance scenarios of the finishing layer during the building's life span is determined by the following formula:

$$N_{B2} = \frac{T_{building}}{f_{maintenance}} - N_{B4} - N_{B5} - 1 \tag{4.2}$$

with:
$T_{building}$ = the lifespan of the building $[years]$
$f_{maintenance}$ = the maintenance frequency $[years]$
N_{B5}= the number of refurbishments during building's life span $[-]$
N_{B4}= the number of replacements during building's life span $[-]$
N_{B4}= the number of maintenance scenarios during building's life span $[-]$

Chapter 5

Life Cycle Costing meets the circular economy

5.1 Introduction

In the previous chapter, a methodological R-LCA framework was developed to validate the long-term environmental benefits of reusable building elements. However, in the current building context, the financial aspects involved with the adaption of circular building elements may not be disregarded (Paduart, 2012). The evaluation of initial investments and life cycle costs play a role in adopting circular building strategies in the Flemish building industry (Mouligneau, 2021).

In the UK Green Council in 2019, most building clients stated that financial concerns form one of the barriers for the implementation of the CE strategies in the construction industry. On account of the utilization of infrequently used building materials and products, and the higher labor costs of alternative and innovative construction techniques, the investment costs resulting from circular building strategies are usually higher than those of traditional building styles (Surgenor et al., 2019). It follows that the return of the investment costs and the avoided environmental impact in the long term are key to the implementation of the circular building industry (Rajagopalan et al., 2021). Circular building strategies can have economic benefits, such as lower maintenance and replacement costs, slower depreciation of material values, a higher asset value, and averting unstable prices due to the depletion of certain resources (EuropeanCommission, 2014). Therefore, an assessment method for the evaluation of the overall financial costs, next to the environmental impact, of the entire building's element lifespan is important (Rajagopalan et al., 2021).

Accordingly, the economic evaluation in this study aims to get an insight into the financial feasibility of reusable building elements during a building's lifespan. To obtain consistent results about the total environmental impact and financial cost of a building element, a framework that aligns with the goal, scope, assumptions, and decisions stated in the R-LCA method is necessary. To this end, the Life Cycle Costing (LCC) framework is chosen as the basis for the assessment of the total financial cost.

5.2 The proposed R-LCC framework

The Life Cycle Costing method can be defined as 'a technique which enables comparative cost assessments to be made over a specified period, taking into account all relevant economic factors in terms of initial and future operational costs', according to the international standard ISO 15686 (2011). This standard outlines the basic methodology and provides general guiding principles, instructions, and definitions for LCC. The LCC framework, which resembles the LCA framework, contains four steps, illustrated in figure 5.1 and described in the following sections.

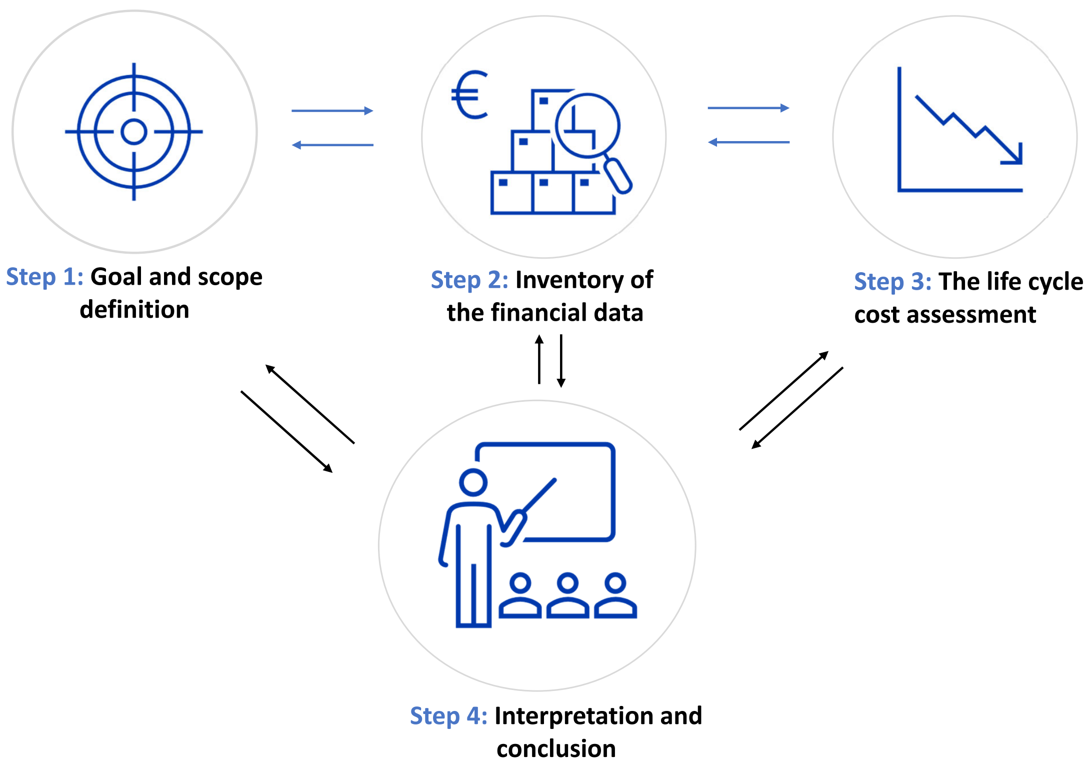


Figure 5.1: The four steps of the LCC framework, based on ISO 15686 (2011)

5.2.1 Step 1: goal and scope definition

The first step 'goal and scope definition' is the same for the LCC and LCA framework (Paduart, 2012). The goal, scope, and used methodology need to be defined for the research, as also stated in paragraph 4.1.1. In the assessment of circular building elements, the financial and environmental results must be compatible. Therefore, the decisions and assumptions made in the R-LCC framework need to be aligned to those of the R-LCA framework. The scope of the financial study includes thereby the production costs (material costs), the construction costs (the transport, equipment, and labor costs), the use costs (maintenance, replacement, and refurbishment costs), and the end-of-life costs (labor, transport, and container costs). Costs related to the designer's fee, operational energy, and technical installations are not considered, because they are assumed to be equal for all the assembly techniques.

5.2.2 Step 2: inventory of the financial data

To compare the financial costs of reusable building elements to traditional building elements, reliable financial data is required. Relevant financial information sources of the Belgian construction industry are the BOUWUNIE database, the ASPEN index, and the UPA-BAU database. The often-used ASPEN index is an extensive Belgian database of average contractor prices, updated every six months. It provides building material costs and (de)construction costs (equipment, labor, and transport) of building parts, expressed in €/m or $€/m^2$. The general data of the databases can be supplemented by specific data of product catalogs and manufacturers (Paduart, 2012).

The required data for the LCC framework can be arranged into four subcategories:

- The material cost of the new, refurbished, or replaced building element.
- The (de)construction cost: the transport cost, equipment cost, and the labor cost of the new, refurbished, or replaced building element.
- The maintenance cost of the building element during the building lifespan
- The end-of-life cost: the container cost and the container transport cost.

After that, the general and specific financial data should be raised by the Value Added Tax (VAT). In the European Union, the VAT is a general, broadly based consumption tax applied to the value added to goods and services. The financial costs of new building components have to be multiplied by the factor of 1.21 (21% VAT), and for the replaced and refurbished elements by 1.06 (6% VAT) (*What is VAT?*, 2018).

5.2.3 Step 3: life cycle cost assessment

There are two assessment approaches, dynamic and static, for the life cycle cost assessment. In the static approach, the financial costs are assessed based on the investment costs without considering the moment they appear. On the other hand, in the dynamic approach, the costs are evaluated in function of the moment of investment by multiplying with a factor, called the discount rate (Thiebat, 2019). The dynamic approach is used, because it is more accurate for the quantification of the financial costs of a reusable building element, due to the currency being more worth today than in the future (Paduart, 2012).

For the conversion of the financial cost at the time of the original investment to the present value, the Net Present Value methodology (NPV) is used. In this method, the total financial costs are determined by the sum of the initial and discounted future costs over the building's life span (Allacker, 2010):

$$LCF = IF + SPV(PF) + SPV(EOL) - RV \tag{5.1}$$

with:

- IF = Initial Financial costs [€]
  The IF costs are related to the materials, construction activities, and transport from the factory to the building site.

- SPV(PF) = Sum of the Present Values of the Periodic Financial costs [€]
  The PF costs are related to the maintenance, replacements, and refurbishments during the building's lifetime.

- SPV(EOL) = Sum of the Present Values of the End-Of-Life costs [€]
  The EOL costs are related to deconstruction activities, transport from site to sorting center, and landfill or incineration activities.

- RV = Residual Value [€]
  No residual financial value at the end of the building's life span is assumed for building materials and elements in this research.

The Present Value (PV) of a future cost is the amount of money that needs to be saved today, to have the funds available for meeting the future cost at the predicted time when it will occur. This can be calculated by the following formulas (Paduart, 2012):

$$PV(C_t) = \frac{C_t}{(1+d)^t} = \frac{C_0 \times (1+i)^t}{(1+d)^t} \tag{5.2}$$

$$PV(C_t) = \frac{C_0 \times (1+i)^t}{(1+d)^t} \tag{5.3}$$

$$PV(C_t) = \frac{C_0 \times (1+g')^t}{(1+d')^t} \tag{5.4}$$

with

- C_t = future cost [€]
- C_0 = cost at present time [€]
- d = nominal discount rate [-]
- d' = real discount rate [-]
- i = inflation rate [-]
- g' = real growth rate [-]
- t = time [year]

The discount rate

The discount rate needs to be specified to determine the Present Value of a future cost. This factor, reflecting the value over time of money, is used to convert cash flows occurring at various times to a common time (ISO 15686, 2011). There are two main types: the nominal and the real discount rate. The real discount rate is not influenced by inflation and deflation. In contrast, the nominal discount rate is influenced by both. Nevertheless, the prediction of inflation and deflation values is difficult in view of the long life span of buildings (Paduart, 2012). Therefore, the use of the real discount rate is recommended in the international standard ISO 15686 (2011). Notice that the selection of the discount rate value has a major impact on the results of the LCC study (Waldo, 2016). The near-present costs become more important with a higher discount rate. In contrast, the distant future costs gain more importance with a lower discount rate (Gluch & Baumann, 2004).

The conversion from the nominal to the real discount rate is calculated using the following formula (Paduart, 2012):

$$d' = \frac{(1+d)}{(1+i)} - 1 \qquad (5.5)$$

with:

- d' = real discount rate [-]
- d = nominal discount rate [-]
- i = inflation rate [-]

The real discount rate is assumed to be between zero and three percent. A static discount rate of zero percent is proposed for sustainability studies (Waldo, 2016). The static approach is argued by Howarth as 'although discounting is appropriate concerning the efficient use of the generation's resources, it is inappropriate when the generation is primarily concerned with redistributing resource rights to future generations' (Howarth & Norgaard, 1992). The upper boundary of three percent is taken from the Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 for the calculation of cost-optimal measurements (NBN-EN16627, 2015).

The growth rate

Building material and labor prices are not increasing at the same pace as the general inflation rate over a certain period. Therefore, a growth rate is applied. This factor reflects the price evolution of specific products and services over time. It is calculated using the difference between the product and service prices and the general inflation rate over the same period (Allacker, 2010; Paduart, 2012).

The value of the nominal growth rate of materials and labor in Belgium can be obtained from economic reports or calculated with the ABEX index (Paduart, 2012). The ABEX index reflects the evolution of average costs in the Belgian building industry for a specific period. It is influenced by the supply and demand of the building market. In times of high demand, the building prices rise and the ABEX-index increases (*ABEX indexen*, 2021).

The conversion from the nominal to the real growth rate is calculated using the following formula (Paduart, 2012):

$$g' = \frac{(1+g)}{(1+i)} - 1 \tag{5.6}$$

with:

- g' = real growth rate
- g = nominal growth rate
- i = inflation rate

5.2.4 Step 4: interpretation and conclusion

The last step 'interpretation and conclusion' is the same for the LCC and LCA framework (Paduart, 2012). First, the significant financial prices of certain stages and/or materials will be identified. Then, the financial study undergoes verification in terms of completeness and coherence of the data. In addition, some sensitivity analysis must be applied to the results because many assumptions are made for the discount rate, the building's lifetime, the building element's turnover rate, and the growth rate, due to their uncertainties. Finally, the results must be compiled into a report with conclusions and recommendations (ISO 15686, 2011).

Chapter 6

Analysis of the interior walls in the case house in Berchem

6.1 Introduction

In the previous chapters, a methodology is developed to evaluate the initial and total environmental impact and financial cost of reusable building elements over the building's lifespan. This method is used in the following study to compare the impact and costs of different wall assemblies in the case study house in Berchem. The study is induced by an interview of Anna Paduart with the Flemish social housing company. The interview demonstrates that there is a demand for flexible non-bearing interior walls as a means to adapt the interior of social houses according to the users' needs (Paduart, 2012).

Therefore, the objective of the study is to identify the financial and environmental most advantageous interior wall for the different refurbishment scenarios in the case house. First, a financial and environmental study on the element level is carried out to compare the total environmental impact and cost of the traditional walls against the circular JUUNOO walls for different refurbishment frequencies. This is followed by a detailed analysis of the contribution of the different life cycle stages and building products to the total result in order to pinpoint the hot spots in the processes and materials. Then the financial and environmental most beneficial wall with regard to a certain refurbishment frequency is determined. Subsequently, the outcomes of the LCA and LCC study on element level are introduced in the analysis on building layer level for certain representative scenarios with the single-family home in Berchem. From these results, the most advantageous wall for the case study house is determined. Afterward, sensitivity analyses are executed on the results.

6.2 The case house and the research

6.2.1 The case house in Berchem

The case study focuses on the single-family home in Berchem, realised by MikeViktorViktor architects, TEKEN architecture, BOUD, Systimber and Itho Daalderop. The case house is part of the bigger project 'Circular Building Affordable Housing (CBBW)'. The main goal of this project consists of bridging the gap between the research and the practice in the circular building industry. Therefore, circular design principles and life cycle thinking are implemented in the case house within the boundaries of the existing Belgian building context, like urban development rules, structural requirements, and the preferences of the client. The use of an adaptable open plan layout, as demonstrated in figure 6.1, and reversible connection techniques are meant to facilitate future renovation, reorganization, and maintenance scenarios (*Circulair Bouwen Betaalbaar Wonen*, 2020).

Figure 6.1: Single-family home in Berchem: photograph, section, facade and floor plans.

6.2.2 The research and the interior wall assemblies

The following study focuses on the non-bearing interior walls in the case house in Berchem. The used interior walls are circular JUUNOO walls with Clicwall panels in medium-density fibreboard (MDF) as finishing material. The environmental performance and financial cost of this reference interior wall will be compared with other circular JUUNOO walls and frequently used interior walls in the Belgian construction industry, such as wet- and drywalls. The investigated interior wall assemblies are represented in table 6.1 and described below. The material thicknesses are based on the standard measurements defined in the ASPEN index (2019) or on technical product sheets (collected in appendix D).

The first interior wall type, the circular JUUNOO wall, is in general composed from JUUNOO profiles, mineral wool insulation, and finishing material. In the study, three different finishing materials are investigated, specifically plasterboard with alkyd paint and medium-density fiberboard (MDF) with or without alkyd paint. The mineral wool insulation, the JUUNOO tape, the JUUNOO profiles, and the MDF have reuse potential. Remark that the MDF can only be reused two times with a residual value of 20 percent. In contrast, the plasterboard has to be replaced at each refurbishment because it is too thin and fragile to demount.
The other two wall types are traditional interior walls. The second wall type, the drywall, can be subdivided into drywalls with traditional metal studs and drywalls with a wooden frame. These walls are built up with a structural framework between which glass wool is placed. Then the finishing material, plasterboard, is screwed onto this structure. Only the insulation material and the wooden structure can be reused after a refurbishment. The thin metal studs are damaged by deconstruction due to their fragility. In contrast, the metal JUUNOO profiles are thicker, which averts this problem and makes them reusable. For the third type, the wetwall, two types of building blocks are frequently used, namely the ceramic and the sand-lime building blocks. It is finished with painted plaster. None of the materials of this wall are reusable.

To answer the main research question 'Have the circular JUUNOO walls a lower initial environmental impact and financial cost in comparison to the traditional walls in the residential project in Berchem?', a study is carried out on the element and scenario level. On the element level, the environmentally and financially most optimal wall assembly for a certain refurbishment rate is determined. Afterward, the study is extrapolated to the scenario level to figure out the most beneficial wall assembly for a predefined scenario in the case house.

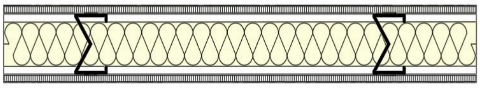
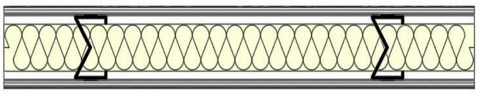
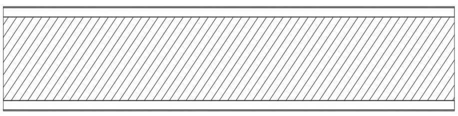
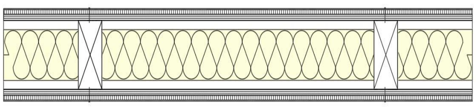
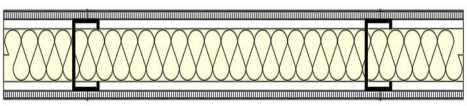
Wall types	Wall assembly
 JUUNOO wall: plasterboard  JUUNOO wall: MDF (+ paint)	JUUNOO wall: plasterboard - Metal JUUNOO profiles: 75 mm - Insulation, glass wool: 45 mm - Plasterboard & screws: 2 x 12.5 mm - Alkyd Paint JUUNOO wall: MDF - Metal JUUNOO profiles & tape: 75 mm - Insulation, glass wool: 45 mm - Clicwall MDF panels & tape: 2 x 12.5 mm - (Alkyd Paint)
 Wetwall	Wetwall: ceramic building blocks - Ceramic building blocks: 90 mm - Gypsum plaster: 2 x 12 mm - Alkyd Paint Wetwall: sand lime bricks - Sand-lime building blocks: 90 mm - Gypsum plaster: 2 x 12 mm - Alkyd Paint
 Drywall: wooden framework  Drywall: metal studs	Drywall: wooden framework - Wooden frame: 75 mm - Insulation, glass wool: 45 mm - OSB board: 2 x 12,5 mm - Plasterboard & screws: 2 x 12.5 mm - Alkyd Paint Drywall: metal stud wall - Metal profiles: 75 mm - Insulation, glass wool: 45 mm - Plasterboard & screws: 2 x 12.5 mm - Alkyd Paint

Table 6.1: The different investigated interior wall assemblies

6.2.3 The used methodology

The environmental performance and financial costs of the reference JUUNOO wall are compared to the other wall assemblies over its whole life cycle. The implemented life cycle processes for this wall are represented in figure 6.3. The developed R-LCA framework (chapter 4) and the R-LCC framework (chapter 5) are utilized for the assessment of the environmental impact and financial costs of the different interior walls. The assumptions made in the frameworks and the used databases are described below. Then the environmental and financial results of the walls are weighted against each other in a multi-objective Pareto front analysis. The set of walls that is optimal for at least one criteria is visualised on the so-called Pareto fronts.

Life Cycle Analysis framework

The environmental impact of the different materials and processes of the interior wall assemblies is determined with the developed R-LCA method and the software SimaPro. In the LCI step, the ecoinvent v3.8 database is used to map the energy and resource impact of the different materials. During the mapping, certain transport, construction, maintenance, and e-o-l scenarios are assumed, as illustrated in figure 6.2. Additionally, it is necessary to estimate the service life of the building products, elements, and the building for the data collection. In this study, the technical and economic service life of building products is given by the 'Service life of building products' list of SBR (2011). The functional service life of building elements is determined by the predefined refurbishment scenarios, on the scenario level, or by the assumed refurbishment rate, on the element level. A building's service life of 60 years is assumed according to the average life span of a building in the Belgian context (Allacker, 2010). Thereafter in the LCIA step, all the different environmental impacts are aggregated into a combined environmental score by the ReCiPe 2016 hierarchist methodology, so that the results of the different walls can be compared with each other in a multi-objective Pareto front analysis. The used processes in SimaPro and the assumptions can be found in appendix A.

Life Cycle Costing framework

The financial costs of the interior walls are assessed with the R-LCC framework, discussed in chapter 5. With this framework, the costs for the materials, labor, transport, and end-of-life treatment are evaluated. The mean cost of the materials and transport is based on the target prices of the ASPEN index 2019, actualized for 2022, in combination with price quotes from JUUNOO walls and product catalogs. Furthermore, average Belgian labor prices for the construction industry, being 35 euros per hour, are assumed (Statbel, 2018).

These are multiplied by the calculation factor of labor, found in the ASPEN index 2019 or given in the interview with Xavier Huyghe from JUUNOO (2022). The end-of-life costs are determined by the container and container transport cost of the Belgian firm Maes (Maes, 2021). The periodical and end-of-life costs are integrated into the financial analysis with their current value through actualization. Specific economic parameters are implemented, namely a real discount rate of 1,5 percent and a real growth rate on labour costs of 2,3 percent and on material costs 1,6 percent (Waldo, 2016) (Statbel, 2021). The used prices and assumptions can be found in appendix B.

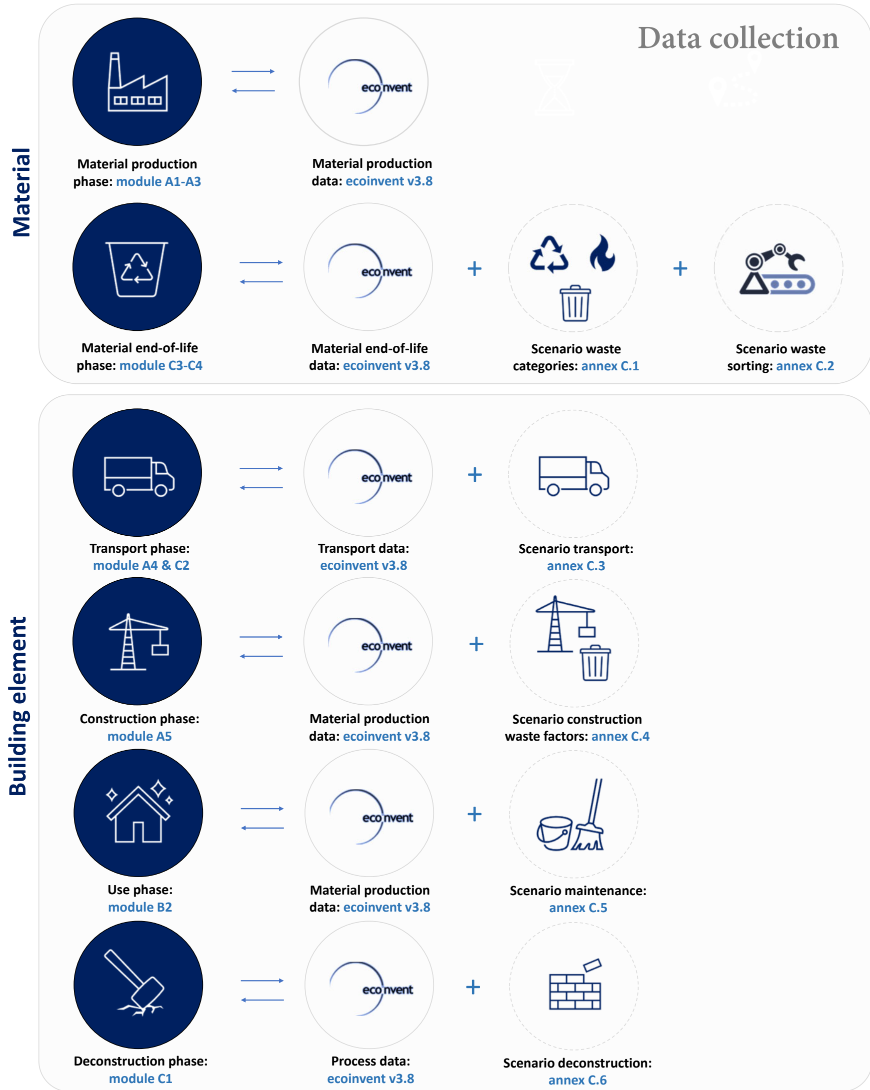


Figure 6.2: The LCI phase: used databases and scenarios in the research

Figure 6.3: The life cycle stages of the reference JUUNOO wall

6.3 Comparison of the interior walls on element level

In this section, the impact and costs of the different wall assemblies represented in table 6.1 are compared on the element level to investigate the influence of the refurbishment rate on the results. This is done with a Life Cycle Analysis to determine the environmental performance and a Life Cycle Costing to determine the financial costs of the interior walls. To guarantee an objective comparison of all the variations, a functional unit of 1 m^2 is assumed. In addition, the main contributing processes and materials of the building elements are explored. Thereafter Pareto fronts are used to determine the most beneficial wall for a certain refurbishment frequency. Lastly, a sensitivity analysis is performed on the refurbishment frequency, service life, chosen material processes, and economical parameters to analyze the robustness of the results.

6.3.1 The results of the Life Cycle Analysis

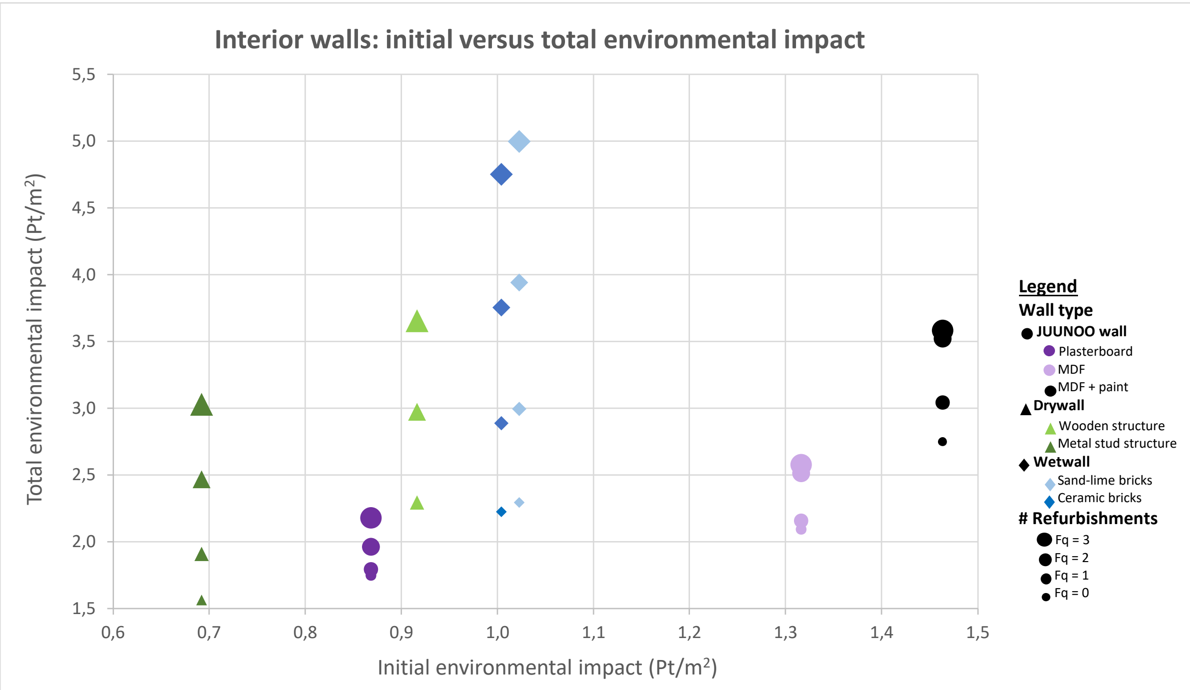


Figure 6.4: Overview of the initial versus the total environmental impact of the different interior walls for four refurbishment frequencies on element level.

Figure 6.4 gives an overview of the initial and the total environmental impact of the different interior wall assemblies for four refurbishment frequencies. The refurbishment frequencies, from one to three refurbishments, are chosen to evaluate the influence of the periodical refurbishments, respectively every 30, 20, and 15 years, on the total environmental impact of the different interior walls. The last refurbishment frequency illustrates the total environmental impact of the interior walls without refurbishments. The assumptions in which year replacements and refurbishments of building products take place at a given refurbishment rate can be found in appendix E.

The figure illustrates that the circular JUUNOO wall with plasterboard has a higher initial environmental impact than the traditional drywall with metal studs. Additionally, all the traditional walls score better on the initial impact than the reference JUUNOO wall with MDF. Remarkably, there is a big gap in the initial impact between the JUUNOO wall with plasterboard and with MDF as finishing material.

Furthermore, the total environmental impact grows with an increasing refurbishment frequency for each interior wall. The proportions between the total environmental impact for the different refurbishment rates are larger for the traditional walls than for the circular JUUNOO walls. Without refurbishments, the environmentally most beneficial wall is the drywall with metal studs, followed by the JUUNOO wall with plasterboard. The JUUNOO wall with MDF (and paint) has the least favorable environmental score. For a non-zero refurbishment frequency, the JUUNOO wall with plasterboard and the wetwalls respectively have the lowest and highest total environmental impact. Note that the reference JUUNOO wall with MDF has a lower impact than the traditional walls after two refurbishments. Another remarkable observation is that the total environmental impact of the drywall with a wooden structure for zero and one refurbishment lie close to each other. This is because the refurbishment is done after 30 years when the replacement of the finishing material and the OSB takes place. For the interpretation of these results, a closer look is taken at the environmental impact over time, per life cycle stage, and per material in the following section.

Environmental impact over time

Figure 6.5 is a cumulative graph, giving an overview of the environmental impact at every life cycle stage of the different wall assemblies during building's service life. Certain trends can be recognized. The charts of the interior walls, except these of the JUUNOO wall with MDF, slightly incline due to the yearly maintenance impact and make a small leap every ten years when replacing the paint layer. After 30 years, the graphs of the JUUNOO and drywalls undergo a big leap. This is caused by the replacement of the finishing materials, namely the plasterboard and MDF. For the same reason, the graphs of the wetwalls make a big leap after 20 and 40 years, when the finishing plaster is replaced.

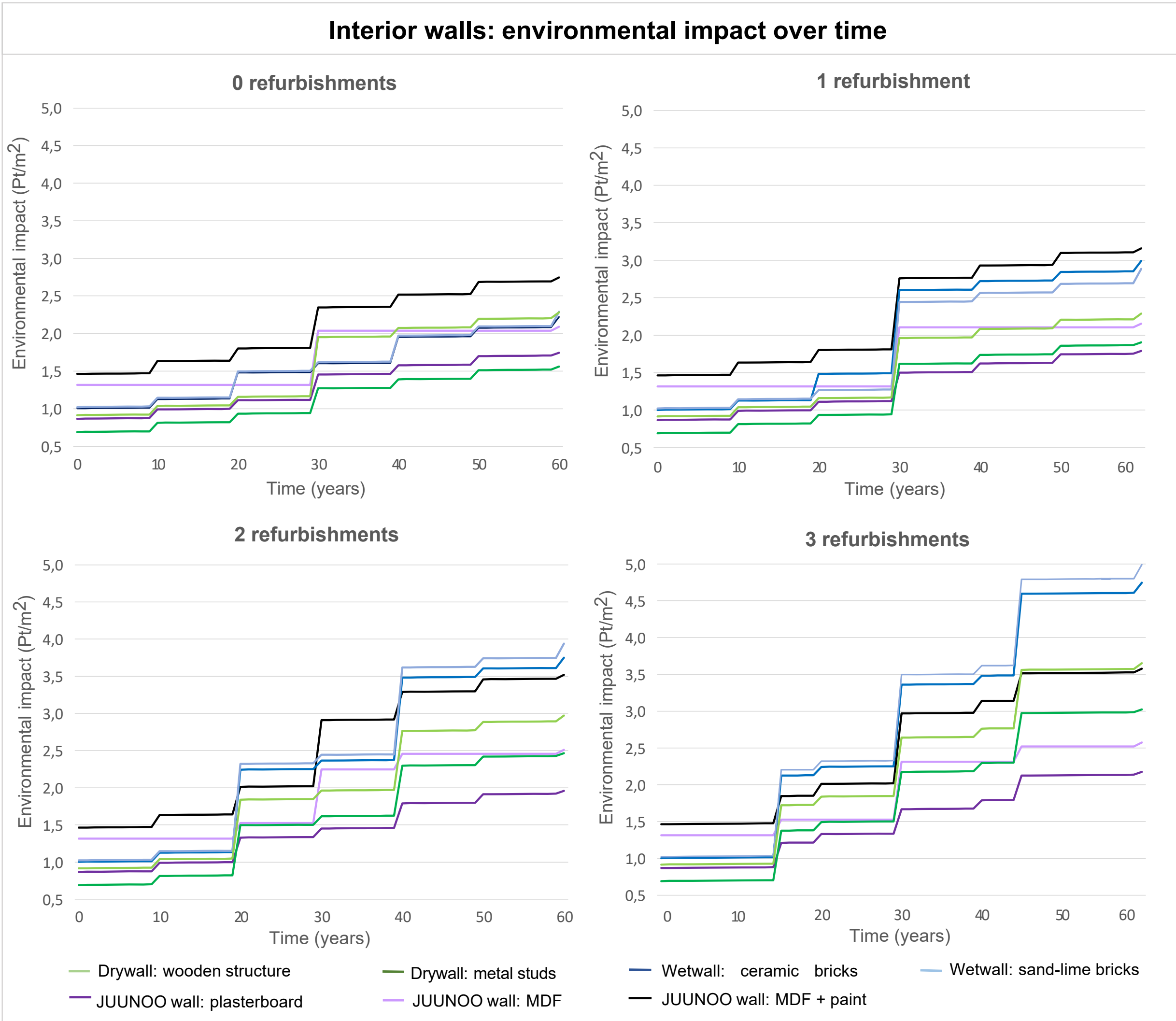


Figure 6.5: Overview of the environmental impact over time for the different interior walls for the four refurbishment frequencies on element level.

Moreover, each refurbishment causes an additional leap in the figure. The jump in the graphs of the traditional walls is bigger than with the circular walls. This is because with each refurbishment of a traditional wall, all the materials must be replaced, while for the circular wall certain materials can be reused. Consequently, more refurbishments make it more appropriate to use circular JUUNOO walls. Note that the proportions between the total environmental impact for the JUUNOO wall with MDF and plasterboard diminishes after two refurbishments. This is due to the reuse potential of the finishing material MDF, while the painted plasterboard should be replaced for each refurbishment.

Environmental impact per material

Figure 6.6 compares the contribution of the different materials to the total environmental impact of the different interior walls for zero and three refurbishments during buildings' service life. The bearing structure has a large influence on the total environmental impact. Without refurbishments, the bearing structure accounts for 20 to 30 percent of the total environmental impact. When there are three refurbishments, the contribution increases for the traditional walls to more than 50 percent but decreases slightly for the circular JUUNOO walls due to the reusable JUUNOO profiles.

Furthermore, it is noteworthy that the traditional drywall with metal studs has a lower initial and total environmental impact without refurbishments in comparison to the circular JUUNOO walls. The traditional metal studs have a lower environmental impact than the JUUNOO profiles because they are thinner. However, the small thickness makes them more fragile and not reusable after a refurbishment. Consequently, the environmental impact of the traditional metal studs is twice the impact of the reusable JUUNOO profiles after three refurbishments. It is also remarkable that the contribution of the bearing structure is the biggest for the drywall with the wooden structure without refurbishments. This is caused by the replacement and production impact of the OSB. The high production impact of OSB is due to the strands, which are mixed with a waterproof resin, and bonded together under high pressure and heat (Benetto et al., 2009). The environmental impact of the bearing structure increases less with the number of refurbishments than the other traditional walls due to the reusable wooden frame.

Besides the bearing structure, the finishing material is also a major contributor to the total environmental impact. On the one hand, without refurbishments, it accounts for 15 to 30 percent of the total environmental impact, except for the JUUNOO walls with MDF for more than 60 percent. The high environmental impact of the MDF is due to the production process. Wood residuals are broken down into wood fibers in a defibrator. Then it is mixed with wax and a resin binder. Afterward, the panels are formed by applying high temperature and pressure (Gul et al., 2017). On the other hand, for three refurbishments, the contribution of the finishing materials to the total environmental impact decreases to approximately 20 percent for traditional walls and increases to 40 percent for the JUUNOO wall with plasterboard and remains the same for the JUUNOO walls with MDF. The increase in the contribution by the JUUNOO wall with plasterboard, while the contribution of the JUUNOO wall with MDF stays the same, can be explained by the reuse potential of the bearing structure and the replaced plasterboard or the reused MDF. Contrary, the decrease in the contribution by the traditional walls is due to the replaced finishing materials and bearing structures.

Note that the contribution of the insulation material to the total environmental impact is rather small. Paint, however, has a large influence on the total environmental impact of the painted interior walls. Without refurbishments, the contribution is around 20 to 30 percent for all the painted interior walls. The absolute environmental impact remains the same for zero and three refurbishments. The reason is that the refurbishments and replacements of paint happen at the same moment during the building's service life. However, the relative contribution of paint decreases to approximately 15 percent for three refurbishments.

Environmental impact per life cycle stage

Figure 6.7 gives an overview of the environmental impact of the production, construction, use, and end-of-life stages, for the different interior walls during the buildings' service life. The production stage causes a large part of the total environmental impact of the different walls. It contributes more than 50 percent for the JUUNOO walls and around 30 to 40 percent for the traditional walls. When the refurbishment frequency increases, the relative contribution of the production phase to the total impact decreases significantly for the traditional walls and slightly in the case of the JUUNOO walls owing to the reuse potential of the JUUNOO profiles. It is also noteworthy that the production impact of the JUUNOO wall with MDF is 20 percent higher than the JUUNOO wall with plasterboard, due to the higher production impact of MDF.

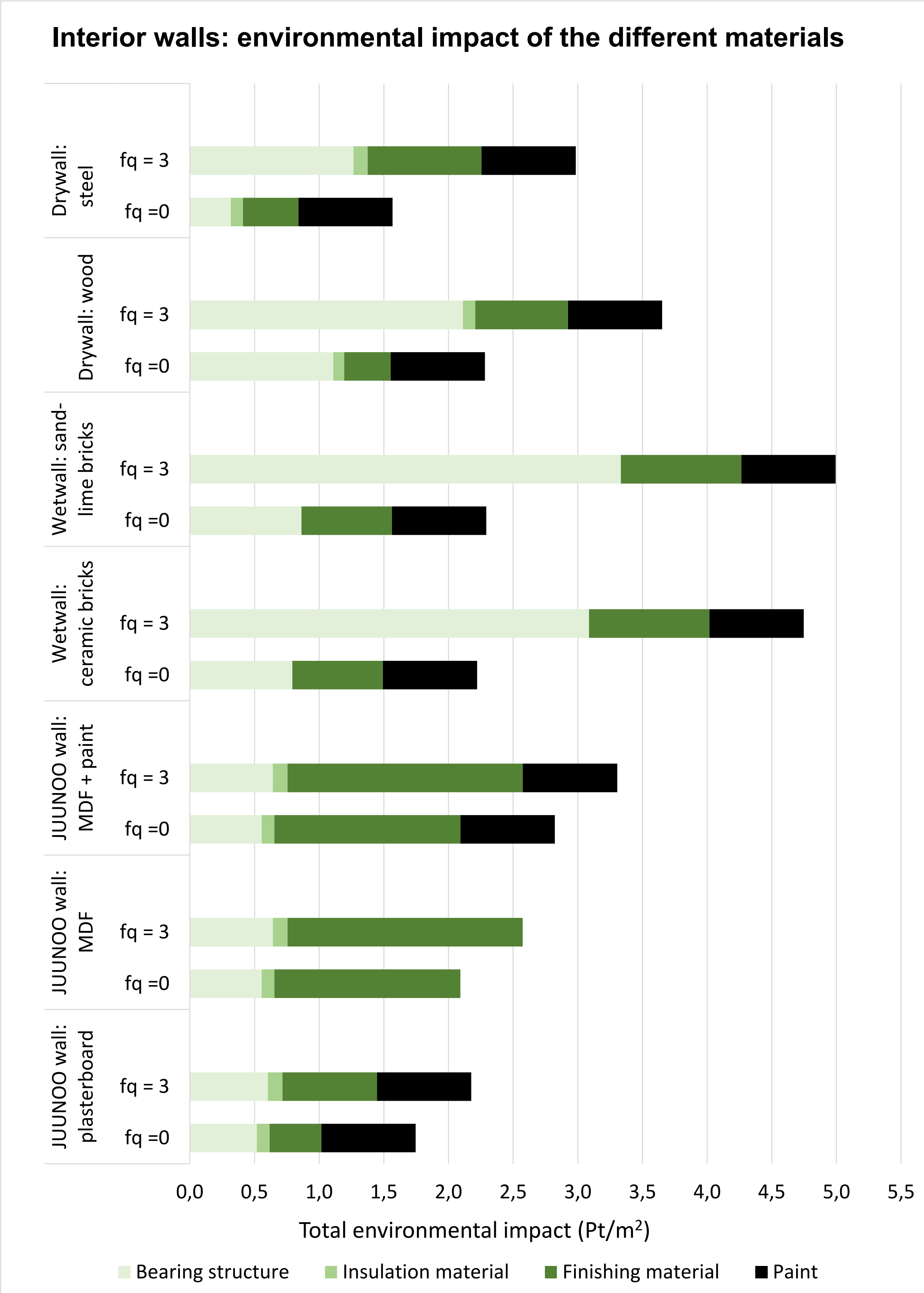


Figure 6.6: Overview of the environmental impact of the different materials for the different interior walls for zero and three refurbishments on element level.

The construction phase has a minor influence on the total environmental impact. The contribution is negligible, except for the wetwalls, whose higher construction impact is caused by the transport of large volumes of heavy building blocks.

The use phase is the main contributor to the total environmental impact. The interior walls, except the JUUNOO walls with MDF, contribute more than 50 percent without refurbishments. The lower contribution of the use phase of the JUUNOO wall with MDF, around 30 percent, is a consequence of the high production impact of the MDF and its reuse potential. Furthermore, the relative contribution of the use phase increases significantly by the traditional walls and only slightly for the circular walls when the number of refurbishments increases. Therefore, a closer look is taken at the contribution of the maintenance, replacement, and refurbishment modules in the use phase. The contribution of the replacement module is the largest, around 50 to 60 percent, for the wetwalls and the drywall with wooden structure. This is caused by the high turn-over rate of the finishing plaster and the high replacement impact of the OSB panel. Additionally, the absolute environmental impact of the replacement module for the traditional walls decreases with an increasing number of refurbishments because the replacement impacts are already partly accounted for in the refurbishment module. Furthermore, the refurbishment impact increases significantly by a higher refurbishment frequency for the traditional walls and slightly for the circular walls, thanks to the reuse potential. The refurbishment impact of the wetwalls and drywall with metal studs triples when there are three refurbishments. The contribution of the maintenance module to the total environmental costs is negligible.

The impact of the end-of-life stage has a limited influence on the total environmental impact. The JUUNOO wall and drywall with metal studs have the smallest e-o-l impact because these walls are dismounted at the end of their service life and the metal profiles are recycled. The e-o-l impact of the drywall with wooden structure is slightly higher due to the incineration of the wooden materials at the end of their lifespan. The wetwalls have the biggest e-o-l impact because of the destructive deconstruction method and the high transport costs of large volumes of heavy building blocks. The stony materials are also recycled at the end of their service life.

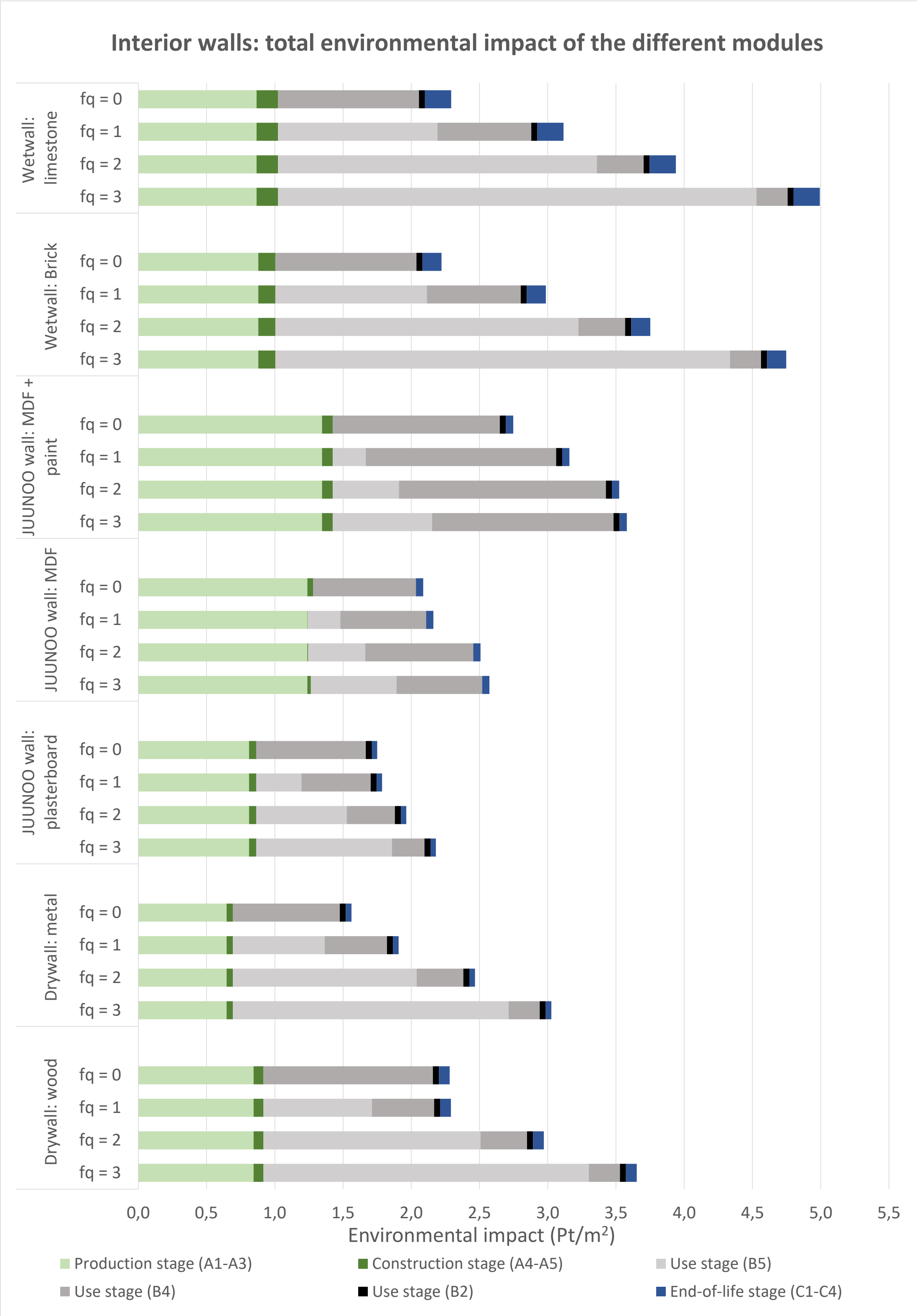


Figure 6.7: Overview of the environmental impact of the different modules of the production, construction, use and end-of-life stage, for the different interior walls for the four refurbishment frequencies on element level.

Sensitivity analysis on the results of the LCA study

A sensitivity analysis is performed to evaluate the influence on the results of certain assumptions and uncertainty factors in the R-LCA framework. In the following study, the influence of the refurbishment frequency on the metal stud walls, the impact of the chosen steel process in SimaPro, and the influence of the assumed technical service life of OSB, MDF, paint, and plaster, on the results is investigated. The sensitivity analysis is represented in the six charts in figure 6.8 and discussed in the section below.

Figure 6.8.a compares the total environmental impact of the drywall with metal studs and the JUUNOO walls with plasterboard and MDF for seven refurbishment frequencies. The total environmental impact is the lowest for the traditional metal stud wall without refurbishments and for the JUUNOO wall with plasterboard for a non-zero refurbishment rate. Nevertheless, the proportion between the total environmental impact of the JUUNOO wall with plasterboard and MDF decreases after two refurbishments, as pointed out by figure 6.5. Figure 6.8.a illustrates that the difference in environmental impact for both walls decreases from two to four refurbishments. However, a significant increase in total environmental impact by the JUUNOO wall with MDF can be noticed for five refurbishments, which results in a remarkable difference in total environmental impact between the JUUNOO walls. This is because the MDF board can be reused two times, while the plasterboard has to be replaced with each refurbishment.

The next figure 6.8.b shows the influence, calculated by the software SimaPro, of the chosen production process of steel on the total environmental impact for the specific cases of the basic oxygen versus the electric steel-making technique. In the electric steel-making process, the electric arc furnace operates as a batch melting production chain delivering batches of molten steel. The basic oxygen steel-making procedure is a process of primary steel production, where carbon-rich molten pig iron is transformed into steel, following the basic oxygen furnace route into the converter, as configured in SimaPro. The total rectangular bars represent the total environmental impact of the interior walls with the traditional basic oxygen process, while the full-colored parts correspond to the walls with the electric steel production process. The extra impact on the total environmental cost of the metal stud walls with the two processes fluctuates around 15 to 20 percent. The ranking in the total environmental impact of the interior walls stays the same, while the proportions change.

The last four graphs (c, d, e, and f) of figure 6.8 represent the sensitivity analysis of the influence of the technical service life of different building products, namely MDF, OSB, paint, and plaster, on the total environmental impact of the interior walls. For the technical lifespan of the finishing materials, assumptions are made based on the SBR list (2011). However, the assumptions are based on the materials of an external facade, which undergo more demanding climate conditions than materials in interior walls.

Figure 6.8.c illustrates the difference in the total environmental impact of the different walls when the technical service life of the OSB is extended from 30 to 60 years, and can be reused two times. The total environmental impact of the walls with OSB, featuring an extended service life of 60 years and reuse potential, is represented by the full-colored part of the rectangular bars. The total bar diagram represents the environmental impact of the walls with the assumed service life of 30 years for the OSB. For a non-zero refurbishment rate, the environmental impact of the drywall with wooden structure becomes smaller than the JUUNOO wall with MDF and metal studs by prolonging the technical service life of OSB from 30 to 60 years. Remark that the difference in total environmental impact for an extended service life becomes larger with more refurbishments. The difference is around 20 percent without refurbishments and 30 percent for two refurbishments. This is by virtue of the reuse potential of OSB which avoids the high replacement impacts of OSB by each refurbishment.

In figure 6.8.d, the total environmental impact of the interior walls is compared for an extended service life of the MDF from 30 to 60 years. Bear in mind that the Clicwall MDF can be reused two times, due to the Uniclic profile system. The total impact of the interior walls with an extended service life is represented by the full-colored part of the bars, while the impact of the walls with the original service life of MDF are illustrated by the total bar diagram. The relative difference in the total impact of the JUUNOO walls with MDF for both service lives fluctuates around 20 to 30 percent. Moreover, the JUUNOO wall with MDF with a service year of 60 years is the environmentally most beneficial wall for each refurbishment frequency.

Similarly, the same kind of graph is used in figure 6.8.e to compare the total environmental impact of the different interior walls, when the technical service life of the paint is extended from 10 to 20 years. The relative difference between the total environmental impact of the interior walls for an extended service life of paint fluctuates between 10 and 20 percent. Note that the traditional drywalls with the extended service life of paint have a lower environmental impact than the JUUNOO wall with MDF up to a refurbishment frequency of two refurbishments, while this is only one refurbishment for the assumed normal service life.

In figure 6.8.f, the last sensitivity analysis is performed on the technical service life of the finishing plaster, which is extended from 20 to 30 years. Up to one refurbishment, the relative difference in the total environmental impact of the wetwalls by an extended service life of plaster is around 10 percent. In the case of plaster with a service life of 20 years, the wetwalls have a lower environmental impact than the JUUNOO wall with MDF and the drywall with the wooden structure without refurbishments.

In conclusion, the sensitivity analysis of the technical service life of the finishing materials illustrates that the ranking and relative proportions between the total environmental impact of the interior walls change with another assumed service life of a given building product. In other words, shifts in the assumptions for specific building products have an important influence on the results of the comparative study. Assumptions about general parameters for all the walls have a minor influence on the results.

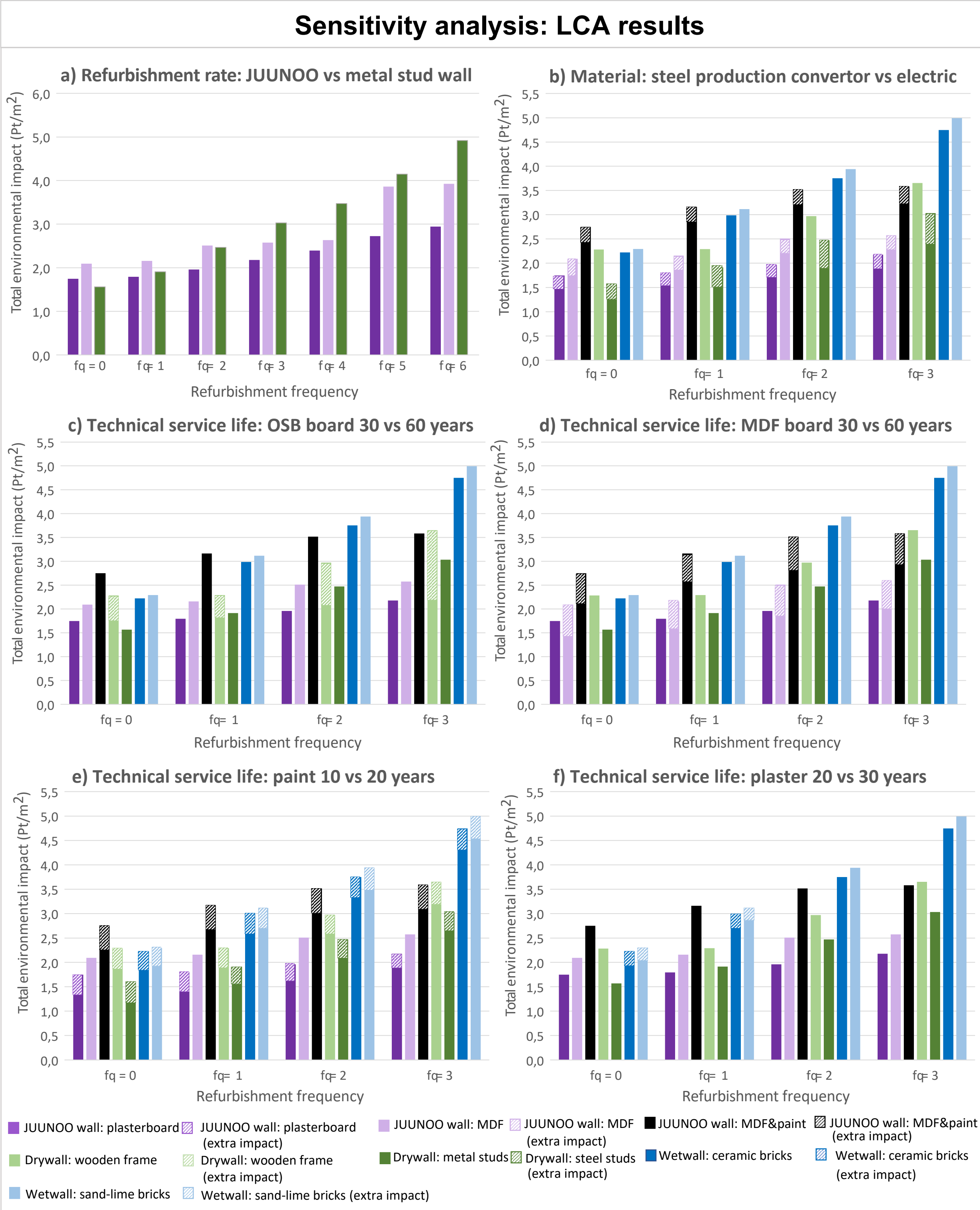


Figure 6.8: Sensitivity analysis on the results of the LCA study, focused on the influence of the refurbishment frequency, the impact of the chosen steel production process, and the influence of the assumed technical service life of the OSB board, MDF, paint and plaster.

6.3.2 The results of the Life Cycle Costing

Figure 6.9 gives an overview of the initial and the total financial costs of the different interior walls for the four refurbishment frequencies. A refurbishment rate from zero to three refurbishments is implemented to compare the total costs of the scenarios with and without periodic refurbishments. The assumptions in which year a replacement and refurbishment of a building element takes place with a given refurbishment rate can be found in appendix E.

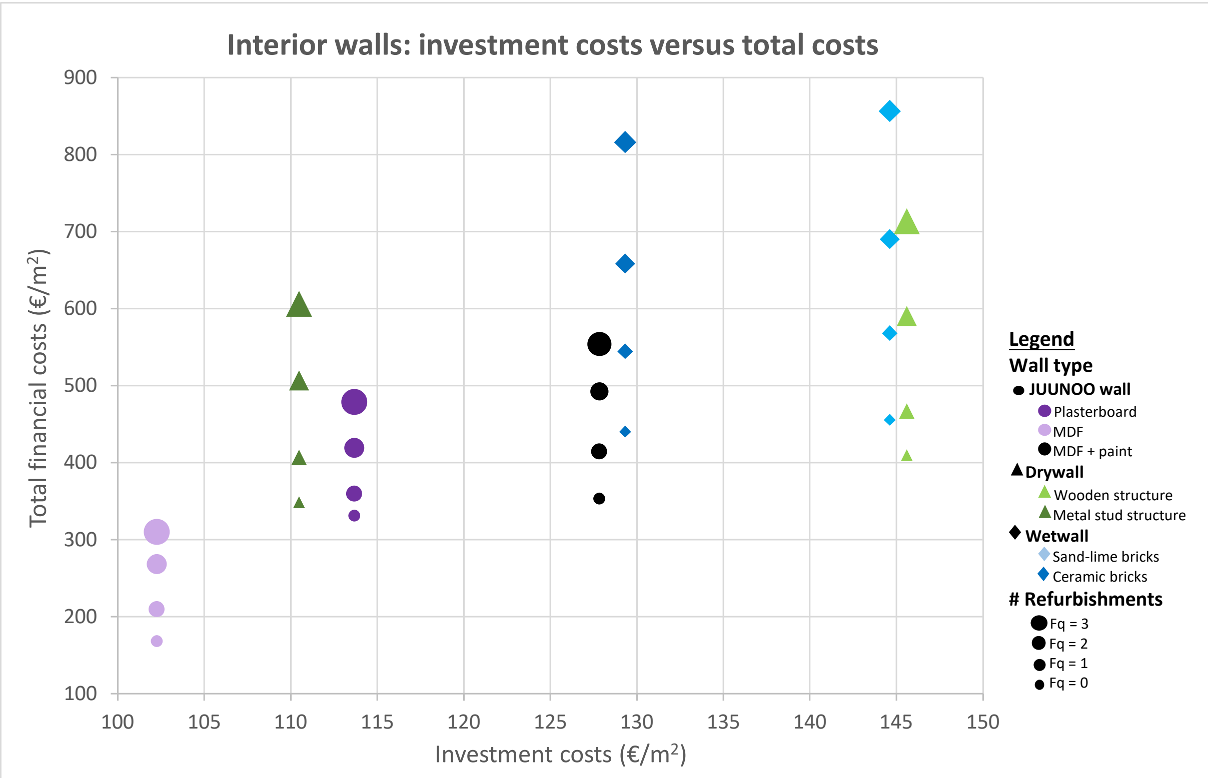


Figure 6.9: Overview of the initial and the total financial costs of the different interior walls for four refurbishment frequencies on element level

The figure clearly illustrates that the investment costs of the reference JUUNOO wall with MDF are the lowest. Thereafter, the traditional drywall with metal studs and the JUUNOO wall with plasterboard have the lowest initial costs. It is remarkabe that all the metal stud walls have lower investment costs than the wooden structure walls and traditional building block walls.

Furthermore, figure 6.9 illustrates that the wall with the lowest total financial costs is also the reference JUUNOO wall with MDF, by virtue of it being not painted. A critical note should be made here. Not all the building owners like wooden finishing and prefer painting as finishing material in their house. Then, the JUUNOO wall with plasterboard is the financially most beneficial solution. The drywall with metal studs is also a good alternative without refurbishments.

Meanwhile, the ratios between the total financial cost of the circular JUUNOO walls and the traditional wetwalls will increase with a higher refurbishment frequency. This means that the use of a circular JUUNOO wall assembly becomes more profitable compared to a traditional wall assembly with an increasing refurbishment rate. Remark that all the circular JUUNOO wall types have a lower total financial cost than the traditional walls after two refurbishments. It is also noteworthy that the financial costs of the drywalls are lower than these of the wetwalls. Therefore, in the following section, a closer look is taken at the financial costs over time, per module and per material, to interpret the results of figure 6.9.

Financial costs over time

In figure 6.10, the financial costs are depicted cumulatively over time to give an overview of the costs of the different interior walls at every stage during the building's service life. The same trends as in figure 6.5 of the environmental impact over time can be recognized.

It is noteworthy that the ranking of the total financial costs of the different interior walls remains the same with each refurbishment frequency. Only the ratios between the total financial costs of the circular and traditional interior walls increase with the number of refurbishments. This is because when refurbishing a circular wall, certain materials can be reused, while for a traditional wall the materials must be replaced. From this, it follows that a higher refurbishment rate makes it more financially interesting to use circular JUUNOO walls. As mentioned in figure 6.9, the JUUNOO wall with MDF has the lowest initial and total financial costs. Figure 6.10 illustrates the reasons, being the lower initial production cost and the avoided replacement cost of paint every ten years. Another remarkable observation is that the production and replacement costs after 30 years are larger for the drywall with wooden frame than for the metal stud walls. This is explained by the higher wood prices nowadays.

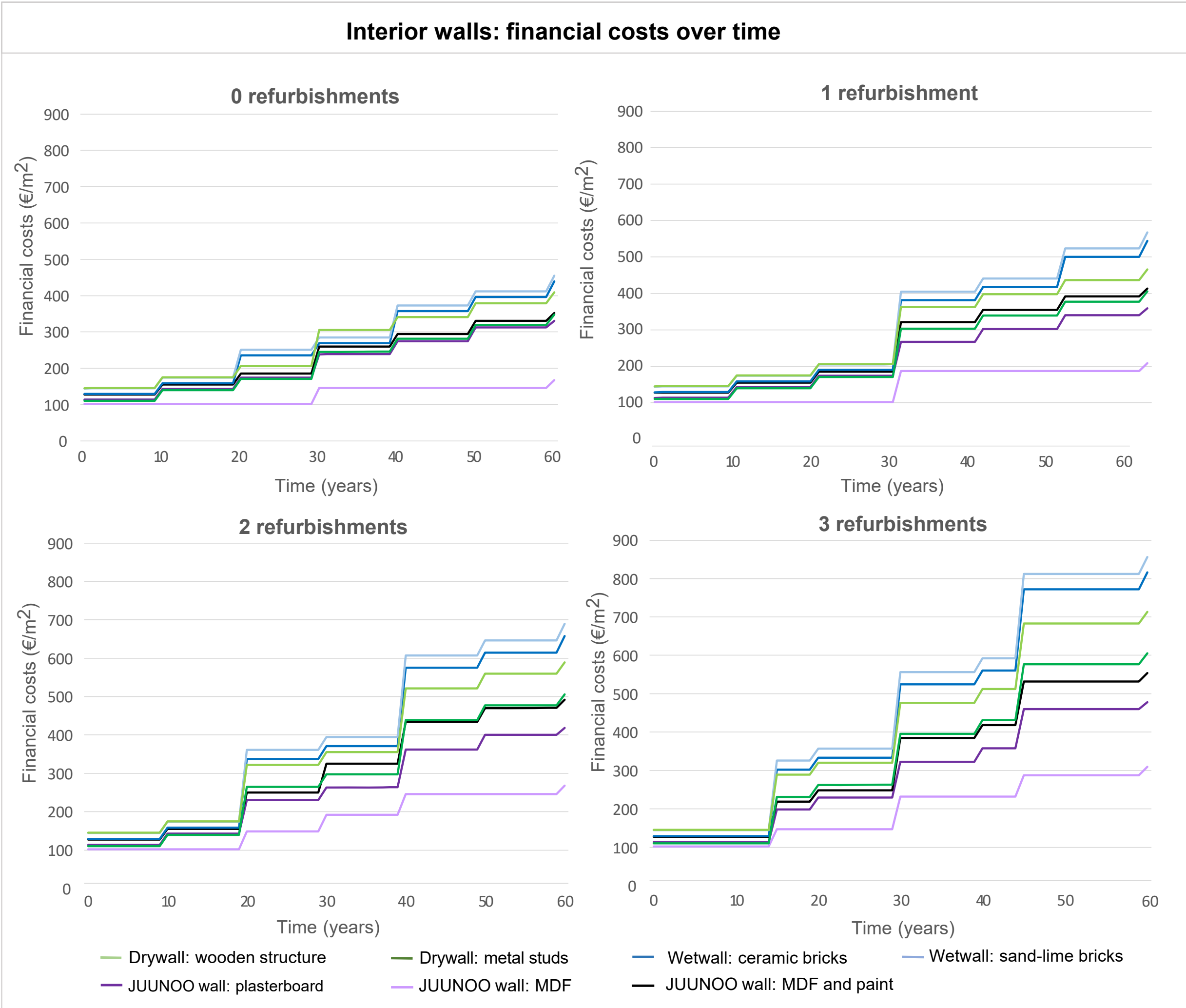


Figure 6.10: Overview of the financial costs over time for the different interior walls for the four refurbishment frequencies on element level.

Financial costs per material

Figure 6.11 illustrates the relative contribution of the different materials on the initial material production cost of the interior walls during building's service life. One of the main contributors is the material cost of the bearing structure. The contribution fluctuates from around 30 percent for the drywalls with metal studs, 50 percent for JUUNOO walls and the drywall with wooden structure, to 65 percent for the wetwalls. The difference in financial costs between the JUUNOO profiles and the traditional metal studs is imputed to the higher material prices of the more advanced JUUNOO profiles. The prices of the wooden structure are also higher than those of the other traditional bearing structures, due to the higher wood prices in comparison with steel and traditional ceramic building blocks. Remark that the ceramic building blocks are cheaper than the limestone blocks because it is a more common construction material in the Belgian construction industry.

Yet another big contributor is the finishing material. The plasterboard of the drywalls and the JUUNOO wall with plasterboard and the MDF of the JUUNOO walls with MDF respectively accounts for 30 and 40 percent to the total costs. However, the finishing plaster of the wetwalls adds a smaller part, around 15 percent, by virtue of the low material costs of plaster. Lastly, paint and the insulation material have a minor impact on the initial material costs, approximately 10 to 20 percent.

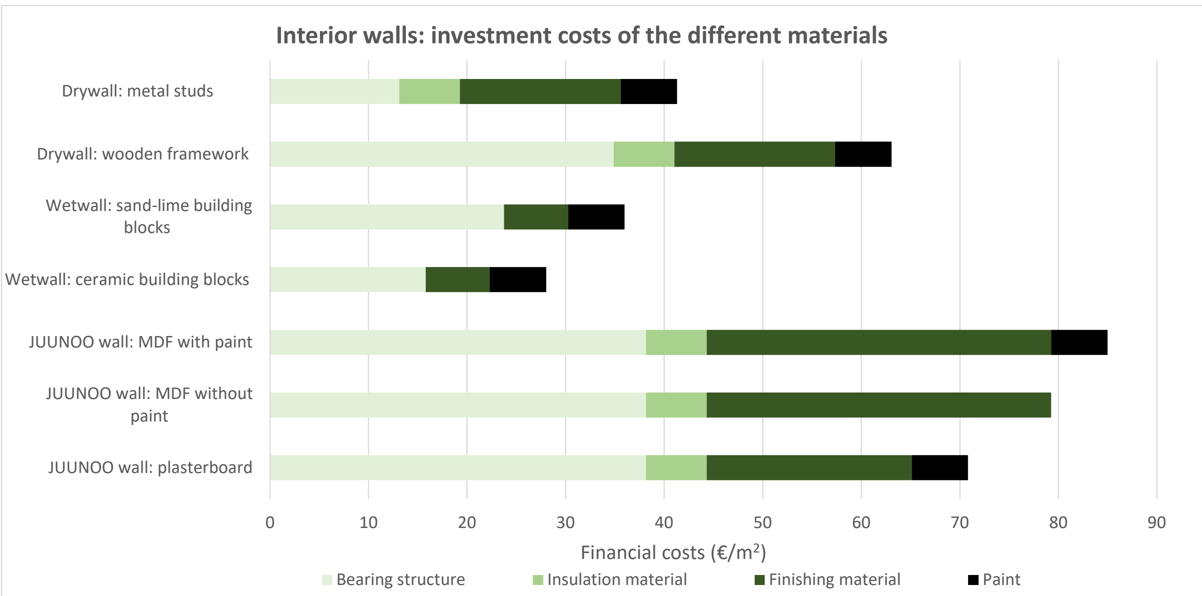


Figure 6.11: Overview of the initial financial costs of the different materials for the different interior walls for zero and three refurbishments on element level.

Financial costs per life cycle module

Figure 6.12 illustrates the contribution of the production, construction, use, and end-of-life stage, to the total financial cost for the four refurbishment frequencies during building's service life. Module A, containing the production and construction stage, has a big influence on the total financial costs, especially without refurbishments. It contributes approximately 35 percent for all the interior walls, except for the JUUNOO wall with MDF where it amounts to 60 percent. The relative contribution of this module decreases significantly for the traditional walls, and slightly for the circular JUUNOO walls with an increasing number of refurbishments.

Furthermore, without refurbishments, the production stage has a small influence, around 10 percent, for the wetwalls and drywalls with metal studs, while the construction phase contributes approximately 20 percent. However, the relative contribution of the production and construction stage of these walls to the total financial cost differs of those to the total environmental impact, as previously discussed in 6.7. Figure 6.7 shows that the influence of the construction phase is rather small for the investigated walls and that the production stage is a main contributor to the total environmental impact. In this case, the higher relative contribution of the construction stage to the total financial costs is due to the high labor costs in Belgium.

Additionally, it is noteworthy that the construction costs for the wetwalls are the highest. This is caused by the very labor-intensive construction process of wetwalls in comparison to the other interior walls. Furthermore, the material cost of the JUUNOO walls is higher than that of the traditional metal stud walls owning to the more advanced layout of the JUUNOO profiles. Nevertheless, the construction costs are much lower. This is achieved by virtue of the more efficient and fast construction of JUUNOO walls. The traditional JUUNOO wall with plasterboard is constructed ten times faster than the traditional wetwall with ceramic building blocks (Huyghe, 2022).

The use stage is the major contributor to the total financial costs. Without refurbishments, it amounts to more than 60 percent of the total financial cost, except for the JUUNOO wall with MDF where it reaches 40 percent. Additionally, the impact of the use stage increases with the number of refurbishments. At three refurbishments, the relative contribution fluctuates around 70 percent, except for the JUUNOO walls with MDF around 55 percent by virtue of the reuse potential of MDF and the omission of paint.

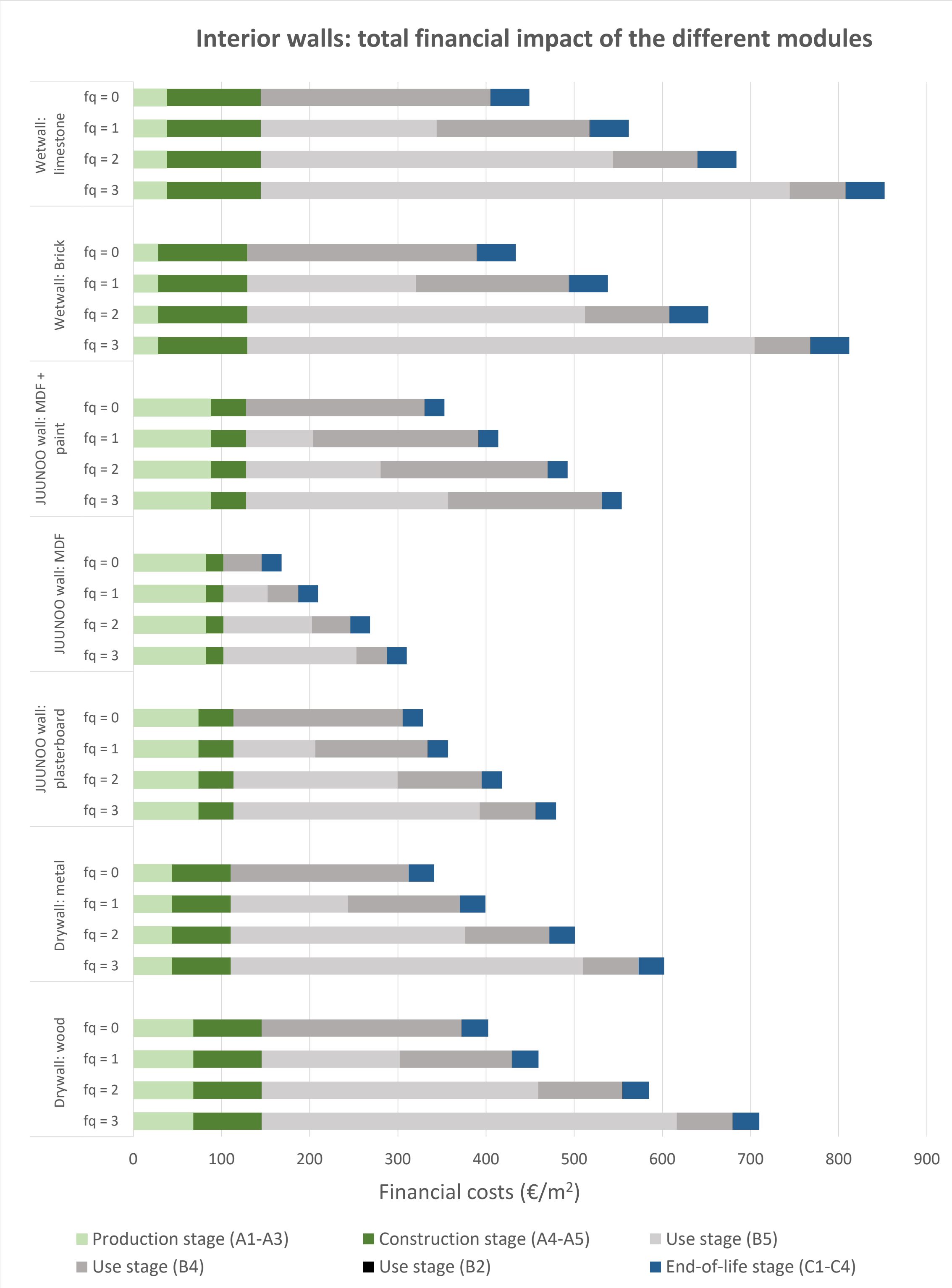


Figure 6.12: Overview of the financial costs of the different modules of the production, construction, use and end-of-life stage, for the different interior walls for the four refurbishment frequencies on element level.

To interpret these results, a closer look is taken at the subcategories of the use stage: refurbishment, replacement, and maintenance costs. The replacement cost is the main contributor to the use stage without refurbishments, but its influence decreases with an increasing number of refurbishments. This is the effect of the growth in refurbishment costs at a higher refurbishment frequency, especially for the traditional walls. But the refurbishment costs of the circular JUUNOO walls also increase, due to the high labor costs for (de)construction of the interior walls and the replacement costs of the plasterboard. The maintenance costs have a negligible impact on the total costs.

The influence of the end-of-life costs on the total financial costs, caused by the labor costs of the deconstruction, the transport costs, and the container costs, are rather minor. The relative contribution amounts to 5 percent for the JUUNOO and drywalls and 10 percent for the wetwalls. The e-o-l costs of the wetwalls are higher because demolishing the wall instead of deconstructing it is a very labor-intensive process. Also, a large volume of stony waste has to be discharged.

Sensitivity analysis on the results of the LCC study

In the following section, a sensitivity analysis is performed to analyze the influence of certain assumptions and uncertainty factors in the LCC framework on the results. Therefore, the contribution of the economic parameters: the discount and growth rate, the impact of the labor costs, and the influence of the assumed technical service life of OSB and paint on the total financial costs are investigated. This sensitivity analysis is represented in the six charts of figure 6.13.

Figure 6.13.a illustrates the influence of the different economical parameters, being the discount and the growth rate, on the total financial costs of the interior walls for three refurbishments. As previously discussed in section 5.2.3, the selection of a suitable discount rate and growth rate is a crucial decision in the dynamic LCC analysis. The real discount rate is assumed to be between 0 and 3 percent in literature, wherefore a discount rate of 1.5 percent is chosen in this research (NBN-EN16627, 2015; Waldo, 2016). Given the uncertainty in the chosen value, the total financial cost calculated by the used discount rate is compared to the total cost assessed with a discount rate of 0 and 3 percent. Thereafter, the total financial costs calculated with the used growth rate for materials of 1.6 percent and labor costs of 2.3 percent, based on the Belgian yearly growth rate of materials and services of 2021, are compared to the total costs recalculated with other growth rates. The

difference in financial costs with the average Belgian growth rate between 2015 and 2019, namely 0.9 percent for material and 1.9 percent for labor costs, the expected growth rate of the Belgian economic prospects 2019-2024 report, namely 1.6 percent for materials and 0.2 percent for labor, and assumed growth rates of 0 and 3 percent are analyzed (Statbel, 2021; Planbureau, 2019).

The influence of the discount rate on the total financial cost is assessed by maintaining the used growth rate for labor and materials and varying the discount rate from 0, 1.5 to 3 percent. Remark that for a low discount rate of 0 percent, the total financial costs of the interior walls are approximately 50 percent higher, while with a higher discount rate of 3 percent, those are 30 to 40 percent lower in comparison to the original total financial costs. This follows from the Present Value formula in chapter 5. When the value of the real growth rate exceeds the real discount rate, the present value of a future cost is higher than the future cost itself, and the other way around. With a total static approach, featuring a discount rate of 0 percent and a growth rate of 0 percent, the total financial costs are assessed based on the initial costs without considering the moment they occur in time. The static total costs turn out 10 to 15 percent lower than the original costs.

Additionally, the influence of the growth rate on the total financial costs is evaluated in figure 6.13.a, by maintaining the used discount rate and varying the growth rate for labor and material costs. By comparing the total financial costs of the interior walls with the used growth rate of 2021 to the costs with the average growth rate between 2015 and 2019, these are increase by 5 to 10 percent. This is caused by the rise in material and labor costs during the Corona crisis. Then, the total costs calculated using the expected growth rate between 2019 and 2024 are 50 percent lower than the reference costs. This is owed to the significantly lower labor cost growth rate, demonstrating that the contribution of the labor costs over time has a major influence on the total financial cost. At last, the reference costs are compared to an average real growth rate of 3 percent, wherefore the financial costs are 35 to 40 percent higher. Conclusively, figure 6.13.a illustrates that the economic parameters have a large influence on the absolute costs and less influence on the relative proportions, and none on the relative ranking in financial costs of the different walls.

As illustrated by figure 6.12, the labor costs are a big contributor to the total financial costs. Therefore, a sensitivity analysis is performed on the labor costs. The total financial cost with the reference labor cost of 35 euros is compared to an average labor cost of 0 and 50 euros per hour (Statbel, 2018; Lauwers, 2022). Figure 6.13.b compares the total financial costs of the interior walls with a reference labor cost of 35 euros, represented by the full-colored parts of the bar diagram, with the total costs of a labor prize of 50 euros per hour. The relative difference in total financial cost fluctuates around 5 to 10 percent. Additionally, the difference in total financial cost increases with the number of refurbishments, as a consequence of the labor costs of (de)construction at a refurbishment. The total financial costs of the traditional walls increase more, namely from 4 to 12 percent, than the costs of the circular JUUNOO walls, namely from 5 to 8 percent. Figure 6.13.c compares the total financial costs of the interior walls with the reference labor cost compared to the case with zero labor costs, represented by the full-colored parts of the bar diagram. The total financial cost decreases by 15 to 20 percent and the same trends as in figure 6.13.b can be observed. Figures 6.13.b and 6.13.c prove that the labor cost only affect the absolute total financial costs and not the relative ranking in total financial costs of the interior walls.

The last two graphs of figure 6.13 represent a sensitivity analysis of the effect of the technical service life of OSB and paint on the total financial cost. In figure 6.13.d, the total financial costs with the reference service life of paint, 10 years, are compared to the costs with its extended service life, 20 years. The full-colored parts of the bars represent the results with the extended service life, while the total bar diagram depicts the results with the reference service life. The difference in total financial costs fluctuates from 10 to 20 percent. This means that paint is an important contributor to the total financial costs. In figure 6.13.e, the influence of the extended service life from 30 to 60 years of the OSB board on the total financial cost is evaluated. Also, the OSB board gains a reuse potential by the extended service life of 60 years. It appears that the financial costs decrease by approximately 10 percent. Figures 6.13.d and 6.13.e demonstrate that the assumed service life of the building products influences the relative proportions between the total financial costs of the interior walls.

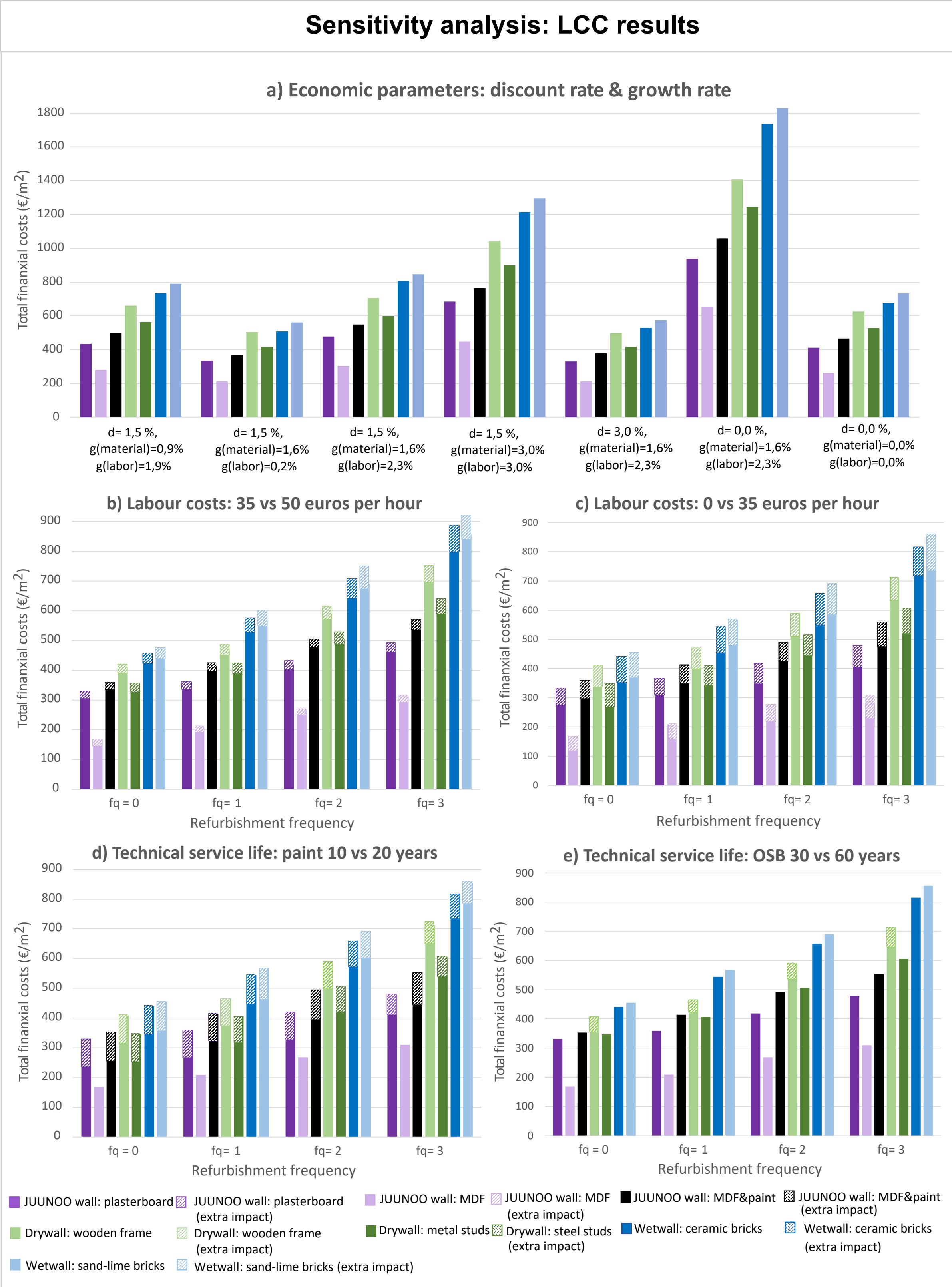


Figure 6.13: Sensitivity analysis on the LCC study, focused on the economic parameters: discount rate and growth rate, labor costs and the chosen technical service life of paint and OSB.

6.3.3 Pareto fronts: the financial vs the environmental results

In the following section, the financial cost is compared to the environmental impact of the different interior walls in a Pareto front analysis. Therewith, the environmentally and financially most beneficial wall can be determined for a certain refurbishment frequency on the element level.

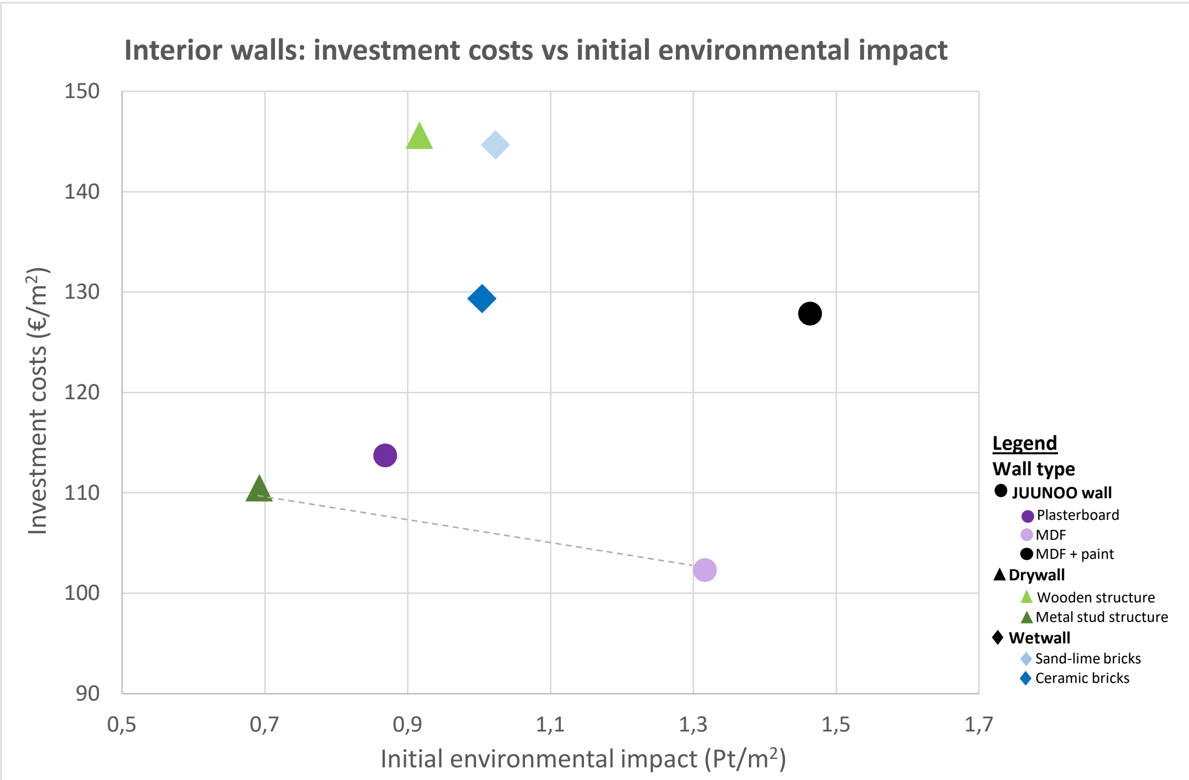


Figure 6.14: Comparing the investment costs with the initial environmental impact of the different interior walls using Pareto fronts (dashed lines) on element level.

Figure 6.14 compares the initial environmental impact to the initial financial cost of the different wall assemblies using Pareto fronts. Two interior walls are situated on the Pareto front, namely the traditional drywall with metal studs and the reference JUUNOO wall with MDF. The JUUNOO wall with MDF has the lowest investment costs because it is not painted. Painting is a labor-intensive process and the average labor prices in the building sector are high. Additionally, the faster (de)construction process in comparison to traditional walls decreases the investment costs of the JUUNOO walls. In contrast, the JUUNOO walls with MDF induce the highest initial environmental impact because of the high temperature and pressure production process of MDF. The best financial alternative is the drywall with metal studs, which has also the lowest initial environmental impact. The initial environmental impact of the traditional drywall with metal studs is lower than the JUUNOO walls and the drywall with wooden framework, attributable to the lesser thickness of the metal studs on the one side and the high production impact of OSB on the other side. The investment costs of the traditional wetwalls and the drywall with wooden framework are higher than the metal stud walls, due to the labor-intensive construction process and the high wood prices.

Next, figure 6.15 compares the total environmental impact to the total financial costs of the different interior wall assemblies using Pareto fronts for four refurbishment frequencies. Without refurbishments, the circular JUUNOO wall with MDF and the traditional drywall with metal studs are positioned at the Pareto front. However, for a non-zero refurbishment frequency, the JUUNOO wall with MDF and JUUNOO wall with plasterboard lie on the Pareto front.

The JUUNOO wall with MDF has the lowest total financial costs, just as the lowest investment costs. An additional reason for this, besides the faster (de)construction of the JUUNOO wall and the omission of paint, is the reuse potential of the JUUNOO profiles and the MDF. In contrast, the materials of the traditional walls and the plasterboard of the other JUUNOO wall have to be replaced with each refurbishment. However, not all building owners love wooden finishing materials. Therefore, the financially best painted alternative is the JUUNOO wall with plasterboard, closely followed by the traditional drywall with metal studs without refurbishments. Another remarkable observation in the figure are the lower total financial costs of the drywalls in comparison to the wetwalls. This is caused by the more labor-intensive (de)construction process of wetwalls. Furthermore, the total financial costs of all the circular JUUNOO walls are lower than the traditional walls after two refurbishments.

The traditional drywall with metal studs is the most environmentally beneficial wall without refurbishments. It has a lower total environmental impact and a slightly higher financial cost than the JUUNOO wall with plasterboard. This is respectively caused by the lesser thickness of the fragile metal studs and the more labor-intensive (de)construction of the wall. However, as soon as refurbishments take place, the JUUNOO wall with plasterboard has the lowest total environmental impact. The relative shift in the environmental impact of the JUUNOO wall and the traditional metal stud wall is attributable to the reuse potential of the JUUNOO profiles. Keep in mind that the environmental impact of the JUUNOO wall with MDF is higher than the JUUNOO wall with plasterboard, due to the high impact of the high-temperature production process of MDF. The drywalls have a lower total environmental impact than the wetwalls, due to the large volume of building blocks and the high-temperature production process.

Figure 6.15 also illustrates that the total environmental impact and financial costs increase significantly for the traditional walls and slightly for the circular JUUNOO walls by the number of refurbishments. In other words, the profits in environmental impact and the gains in financial costs increase for circular JUUNOO walls with an increasing number of refurbishments. The relative difference in total environmental impact between the JUUNOO wall with plasterboard and the traditional steel stud wall raises from 5 percent for one refurbishment to 30 percent for three refurbishments, and between the JUUNOO wall with plasterboard and the traditional ceramic wetwall from 35 to 55 percent. Furthermore, the relative difference in financial costs between the JUUNOO wall with plasterboard and the traditional metal stud wall increases from 10 to 20 percent. Additionally, the relative difference between the total costs of the JUUNOO wall with plasterboard and the traditional ceramic wetwall increases from 30 to 40 percent. The lesser increase in the difference of the financial costs is due to the high labor costs for construction and deconstruction in comparison with the material costs at refurbishments.

Furthermore, the results are compared to a similar research on element level performed by Paduart, where traditional interior walls were compared to another type of circular walls with massive reusable U-profiles (Paduart, 2012). She also demonstrates that the circular walls have a lower environmental impact and financial cost with a nonzero refurbishment rate and that the environmental and financial gains increase with the number of refurbishments. However, the differences in financial costs between the used circular walls and traditional walls were slightly lower with an increasing number of refurbishments than in the performed research. The larger difference in financial costs between the circular JUUNOO walls and the traditional walls in this study is due to the more user-friendly JUUNOO profiles. The initial material cost is for both types of circular walls higher than for the traditional drywall with metal studs, but the advanced JUUNOO profiles guarantee a faster deconstruction and construction time than the massive reusable U-profiles. Important financial gains can be reaped in labor costs in the building industry.

In conclusion, the traditional drywall with metal studs is proposed as the most environmentally beneficial wall without refurbishments. If refurbishment occurs, the JUUNOO wall with plasterboard is suggested. The reference JUUNOO wall with MDF has the lowest total financial cost, but a slightly higher environmental impact than the proposed walls. Further, it becomes clear in the study on element level that the wetwall with sand-lime building blocks and the JUUNOO wall with MDF and paint have a high environmental impact as well as high financial costs, wherefore these walls are not further researched on building layer level.

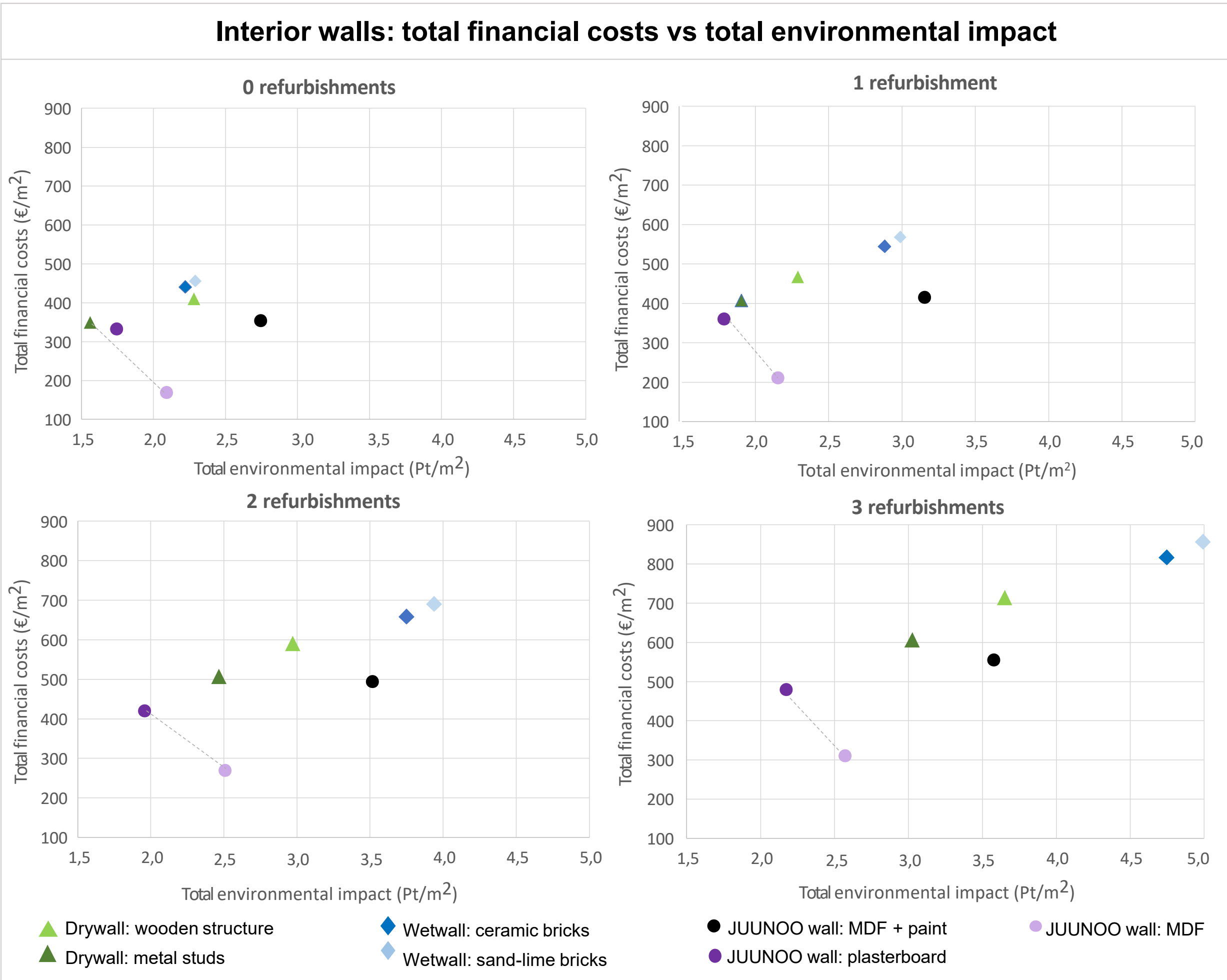


Figure 6.15: Comparing the total environmental impact with the total cost of the interior walls using Pareto fronts (dashed lines) for four refurbishment frequencies on element level.

6.4 Comparison of the interior walls on scenario level

For the determination of the most beneficial interior wall for future refurbishment scenarios in the case study house in Berchem, a scenario planning methodology is used to model them. First, narratives are developed describing how the needs of the users change during the building's lifetime. The narratives are projected on design alternatives of the case house in Berchem, so that future transformations of the floor plans and the refurbishment frequency can be determined. Then, the results of the LCA and LCC studies on the element level are implemented in the analysis on the building layer level for certain representative scenarios. The used scenarios and methodology are more detailed in the following section. Thereafter, the results of the LCA and LCC study on the building layer level are discussed. Finally, Pareto fronts serves to compare the environmental impact to the financial costs of the different walls on building layer level. Therewith, the most beneficial wall for a given refurbishment scenario in the case study house is determined. Additionally, a sensitivity analysis is carried out on the used methodology to evaluate the robustness of the results.

6.4.1 Development of scenarios and the used methodology

Future refurbishment scenarios of the case house are developed by identifying the main drivers for transformations in residential building projects in Belgium. These are influenced by trends that are certain to take place in the future, such as the aging population, and less predictable trends determined by individual preferences and socio-economic circumstances influencing the housing ideal (Friedman, 2002). Drivers relevant for the Flemish households are the number of users, the type of household, the functional requirements of the users, the rapidity and extent of change, and the user's behavior (Cambier et al., 2021).

In this research, the number of nuclei and the functional requirements are selected as the principal drivers for change. These two main drivers are plotted on the axis of a matrix, which is split further into four types of future refurbishment scenarios, as illustrated in figure 6.16 (Cambier et al., 2021). Each scenario is an illustrative narrative where the couple, living in the original case house, goes through a change in functional needs or an expansion of the household, resulting in a transformation of the building. Four different scenarios can be distinguished, specifically the 'couple with kids' (one family and household activities), 'couple with doctor's office' (one family and working activities), 'co-housing' (two families and household activities) and 'couple with needy elderly' (two families and caring activities) scenarios.

Thereafter, the refurbishment scenarios for the four plausible households are put on a timeline, as illustrated in figure 6.18. The period of the analysis is the assumed service life of the case house, being 60 years, and the refurbishment frequency is assumed for each scenario. It varies from two refurbishments, for scenarios 3 and 4, to three refurbishments, for scenarios 1 and 2. Then, the future transformations of the floor plans of the case house according to the scenarios are modelled, as shown in figure 6.17. Take note that different refurbishment frequencies and transformed interior wall surfaces are chosen, to investigate the influence of both parameters on the total environmental impact and total financial cost. A high refurbishment rate is assumed in scenarios 1 and 2, against a lower rate in scenarios 3 and 4. Additionally, a large surface of transformed interior walls is assumed for scenarios 2 and 3, and a lesser surface for scenarios 1 and 4. In the following paragraph, the different scenarios and narratives are explained in more detail.

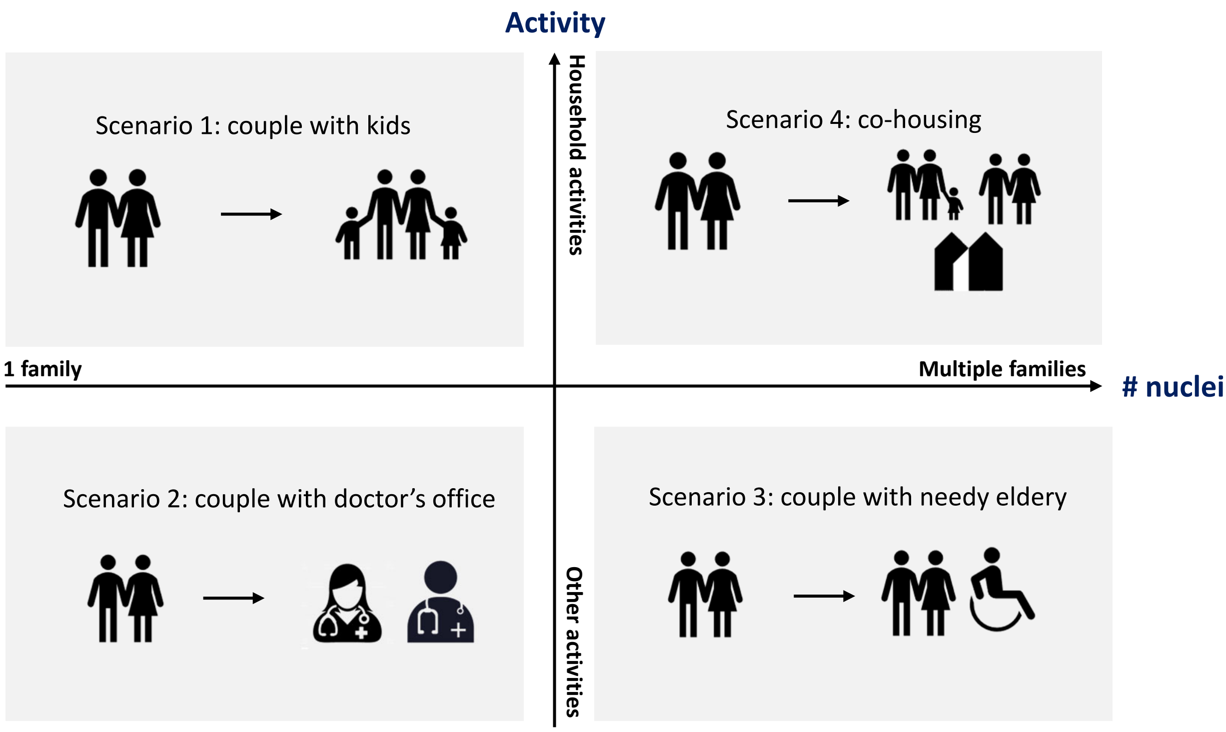


Figure 6.16: The two selected key drivers, namely the number of nuclei and the activity, for future change plotted against each other, as a basis for the development of four scenario narratives, based on the matrix of Cambier (2021).

Scenario 1: couple with kids

The first narrative, the couple with kids, is a conventional development of a household in Belgium. In 2014, 82 percent of the households in Flanders have one or two children (Peters et al., 2014). A couple living together decides after ten years to raise one or two children. Because of the increase in the number of household members, additional rooms need to be created. Two extra bedrooms are constructed in the attic and a dividing wall is built between the kitchen and the living room on the ground floor. After twenty years, the kids have grown up and move out. The two bedrooms are then recombined into an attic and hobby space. The ground floor is reconverted into an open-plan kitchen and living room. Twenty years later, the couple leaves the house and sells it to another family.

Scenario 2: couple with doctor's office

For the second scenario 'the couple with the doctor's office', the activities in the case house in Berchem change from only residential use to the addition of other professional activities, while the household size stays the same. A couple decides after 10 years to start a doctor's surgery. This 'homework' scenario implies a transformation of the ground level to a secluded office space. Therefore, the open-plan kitchen and living room are relocated from the ground floor to the first level. On top of that, two extra bedrooms and a bathroom are constructed on the second floor. After twenty years, the couple retires. Consequently, the case house reconverts to its original form with an open-plan kitchen on the ground level and a large attic as hobby space on the second level. After 20 years, the couple leaves the house and sells it to another self-employed person, who starts a new enterprise.

Scenario 3: couple with needy elderly

The Flemish housing services are searching for affordable housing solutions for needy elderly, aiming to stimulate a more independent living style than in nursing homes ("Ruimte *Vlaanderen Opsplitsen of Zorgwonen*", 2017). The third scenario narrative 'the couple with needy elderly' offers one possible solution for this issue, called a kangaroo dwelling. The case study house becomes a multi-generational dwelling after 20 years, where the couple lives together with a needy elderly under the same roof. With the increase of household members and the additional caring besides residential activities, the case house needs to be adapted. The ground level is converted to a studio for the elderly, with a kitchen, living room, bedroom, bathroom, and toilet. All the rooms of the studio are wheelchair accessible. To guarantee privacy for both parties, a separate entrance to the studio and the house is created. The original open kitchen and living room are relocated from the ground floor to the first level. In addition, two extra bedrooms and a bathroom are constructed on the second level. After 20 years, the elderly moves out, and the house is reconverted to its original configuration.

Scenario 4: co-housing

For the fourth scenario 'the co-housing project', the number of families changes but the residential activity stays the same. Co-housing is a residential living project where several private housing units are merged. It contains a range of private rooms and common spaces, depending on the nature of the project. This way of housing offers an opportunity for social interaction and common activities (Van Looy, 2017). The couple decides to co-house with another family with one child after twenty years. For this manner of living, certain adaptations need to be made to the floor plans of the case house. The ground floor becomes a collective open kitchen and living room, while the rooms of each floor level become the private unit of each family. To guarantee privacy, an additional entrance hall and door per floor level is added for each family. After twenty years, one of the families decides to move out. Then, the case house is reconverted to its original form.

The chosen methodology

By means of the scenario planning method, the floor plans and refurbishment rate of the four predefined refurbishment scenarios are determined. Therewith, the surface of the interior walls built, maintained, replaced, refurbished, and deconstructed is mapped. Additionally, the technical service life of the building elements is defined by the refurbishment frequency. Then, the total financial costs and environmental impact of the four refurbishment scenarios must be assessed. Out of these results, the most beneficial wall for future refurbishment scenarios in the case study house in Berchem can be identified. There are different approaches for extrapolating the financial and environmental results from the element level to the building element level. Therefore in the following section, three approaches are discussed.

The expanded method, used in the case study of the Gandhi district of Paduart (2013), is the most simplified approach. The main focus of Paduart's research lies in determining the most beneficial wall for a certain refurbishment rate in an existing social building block. Therefore, only the financial cost and environmental impact of the transformed walls are mapped. In Paduart's research, the results on element level for 1 m^2 of interior wall surface for three refurbishment rates are multiplied by the transformed interior wall surface to compare the results. For the assessment of the case study, this methodology can provide the basis. However, the environmental impact and costs of the original not-refurbished walls also need to be accounted for. The interior wall surface of the original floor plan must be multiplied by the total environmental impact and financial cost on the element level without refurbishments. In addition, the refurbished wall surface is multiplied by the results on element level for one and two refurbishments, respectively for scenarios 3 &4 and 1 &2.

The second own-developed approach assesses the financial costs and environmental impact of the original floor plan in the same way as in the expanded method, while a more detailed method is used to evaluate the impact and costs for the refurbished walls of the four predefined scenarios. At the first refurbishment, the impact and cost of the newly-built walls are calculated by multiplying the constructed surface with the financial and environmental results of modules A and C on the element level. Next, the impact and cost of the deconstructed walls are evaluated by multiplying the deconstructed wall surface with the results on the element level for the deconstruction module for the reusable materials and the total e-o-l module for the traditional materials. For the subsequent refurbishments, the impact of the deconstructed walls is assessed in the same manner. Additionally, the constructed walls are evaluated by multiplying the constructed wall surface with the results on element level for the construction module for the reusable materials and those for the production and construction module for the other materials. With this approach, the overestimation of the expanded method can be mitigated. For instance, in the first scenario, two refurbishments are fully accounted for with module B in the expanded method, but in reality only one and a half refurbishments take place.

In the previous approaches, the total cost and impact of the walls are calculated by multiplying the environmental and financial results of 1 m^2 interior wall surface with the total wall surface. However, a simplification is made here. The impact of certain finishing materials, like silicon kits and L-profiles, at the connections with other building elements, is neglected. In addition, a specific volume of metal profiles and wooden framework is assumed in 1 m^2 of the interior wall. In the whole interior wall, the amount of steel and wood in the wall may be different. Additional metal studs and wood beams are added in the connections with other building elements and at door openings. Therefore in the detailed method, the financial costs and environmental impact per kg or volume of material are multiplied by the total amount of materials in each wall and the additional impacts and costs of silicon kits, lintels, additional screws and nails, foils, L-profiles, and corner profiles are counted in. However, this technique is very laborious. Therefore, the developed method is proposed for this research. Afterward, a sensitivity analysis is performed on the used methodology.

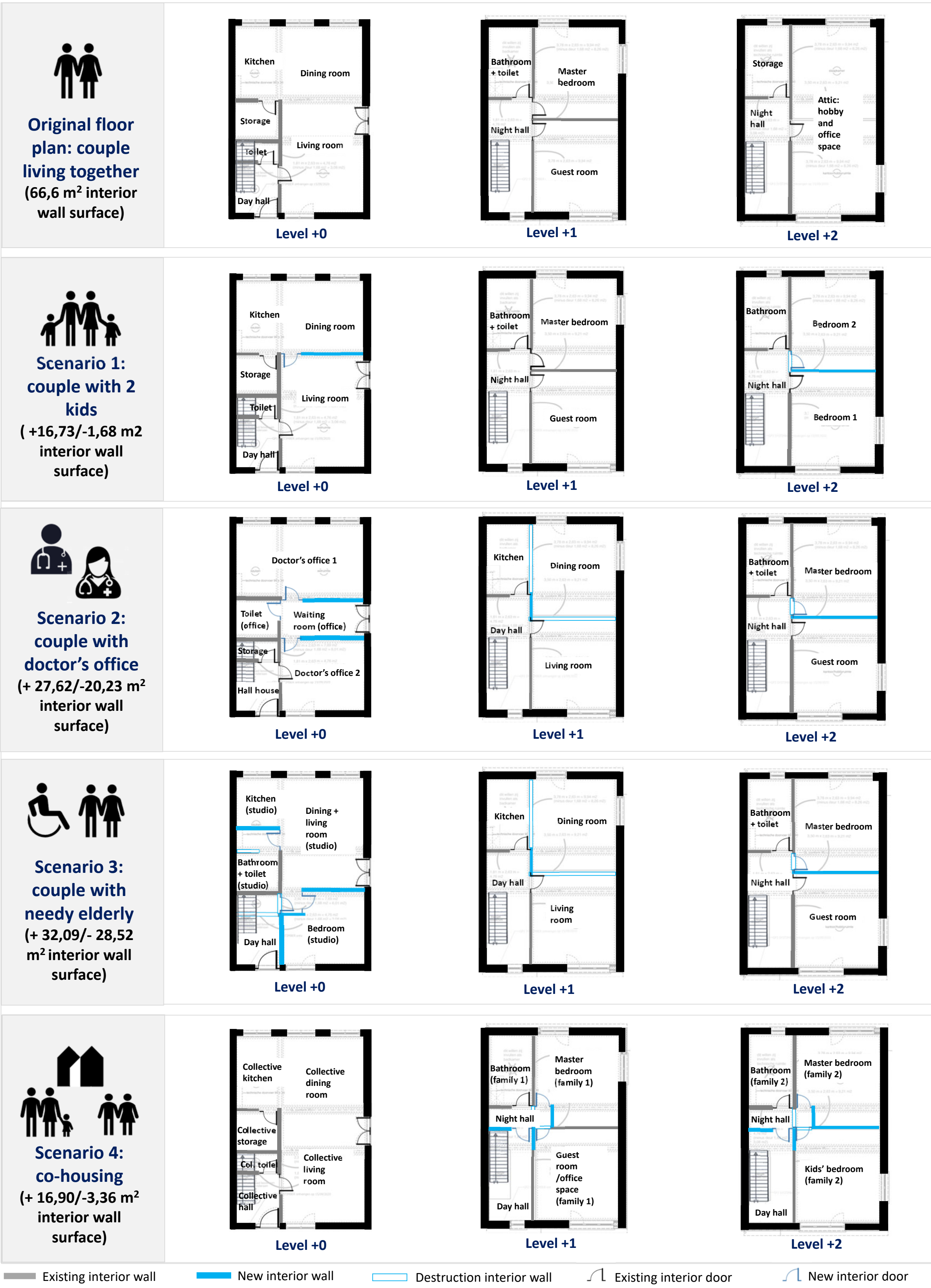


Figure 6.17: Overview of the original floor plan and the floor plans of the four refurbishment scenarios with the transformed walls.

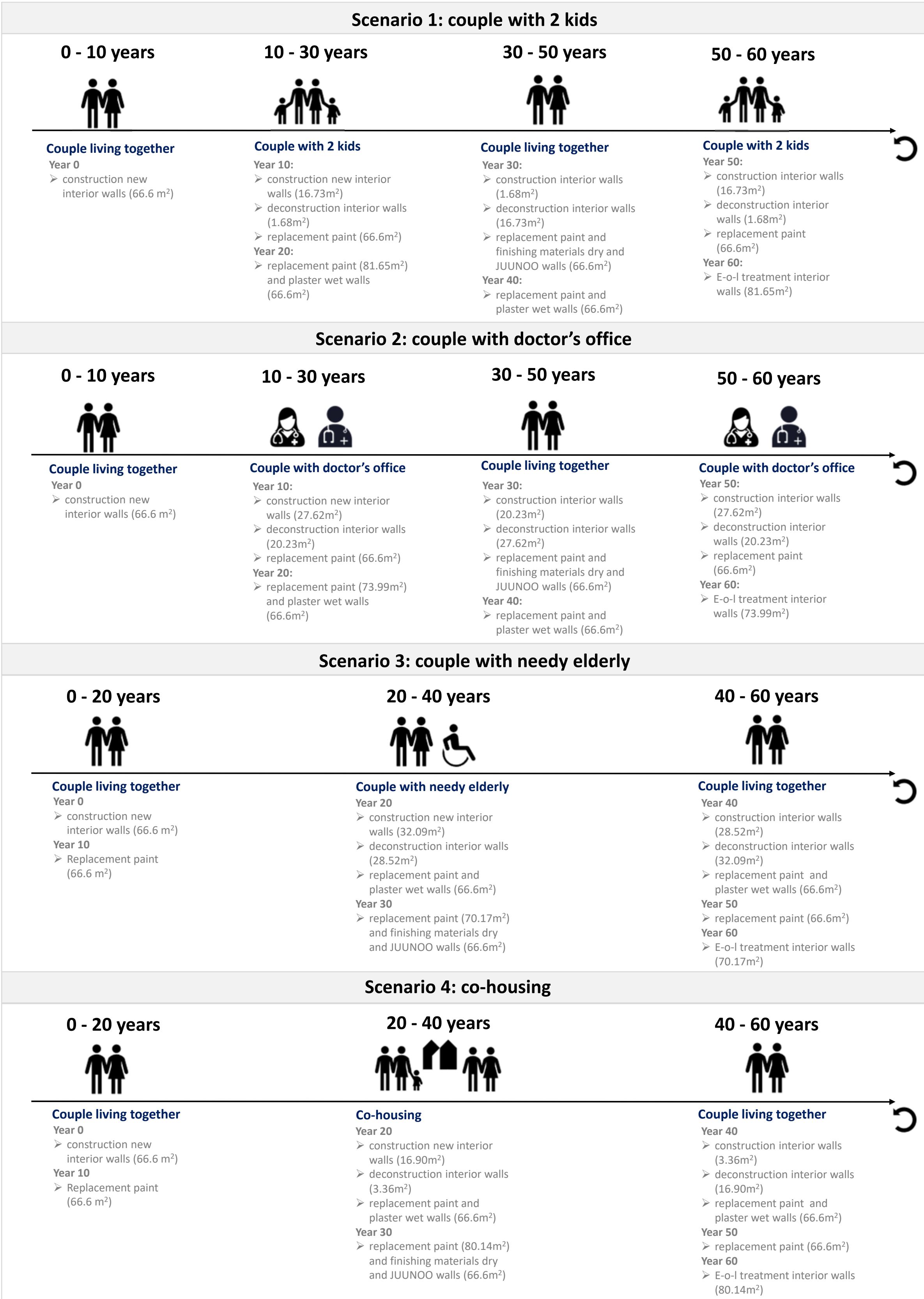


Figure 6.18: Timeline for the four different scenarios, when which material is (de)constructed, replaced or refurbished

6.4.2 The results of the Life Cycle Analysis

First, figure 6.19 compares the environmental impact of the different interior walls over time for the four scenarios: scenario 1 'couple with children', scenario 2 'couple with doctor's practice', scenario 3 'couple with needy elderly', and scenario 4 'co-housing'. The same trends appear as discussed in the environmental impact over time analysis on element level in section 6.3.1. Note that the graphs make an additional leap with each refurbishment. In scenarios 1 and 2, this happens after 10, 30, and 50 years, and in scenarios 3 and 4 after 20 and 40 years. Furthermore, the figure illustrates that the traditional drywall with metal studs has the lowest initial environmental impact, and the JUUNOO wall with MDF has the highest initial environmental impact for the four scenarios, due to the high production impact of MDF.

The total environmental impact of the interior walls is two to three times larger than the initial environmental impact for the four scenarios. For all the scenarios, except scenario 4, the total environmental impact of the JUUNOO wall with plasterboard is the lowest. In contrast, the frequently used wetwall with ceramic building blocks has the highest total environmental impact for all the scenarios. For scenario 4, the drywall with metal studs has the lowest total environmental impact. It is also remarkable that for scenarios 3 and 4, with a low refurbishment frequency, the total environmental impact is respectively lower or slightly higher than the JUUNOO wall with plasterboard. Additionally, the same trends can be observed in scenarios 1 and 4 for a small transformed wall surface. This illustrates that the refurbishment frequency and transformed surface play the main role in the determination of the environmentally most beneficial wall.

Furthermore, the graphs of the environmental impact over time in figure 6.5 on the element level are compared with the graphs in figure 6.19 on the scenario level. By comparing the relative ranking and proportions between the total environmental impact of the walls of scenarios 1 and 2 with those of the graph of two refurbishments on element level, and between the graphs of scenarios 3 and 4 with those of the graph of one refurbishment, it becomes clear that the graphs follow another relative sequence and/or have other relative proportions between the total environmental impact. It seems like the ranking and the relative proportions between the total environmental impact of the scenarios lie between these of zero and one refurbishment. The reason for these results is discussed in figure 6.20 and the following section.

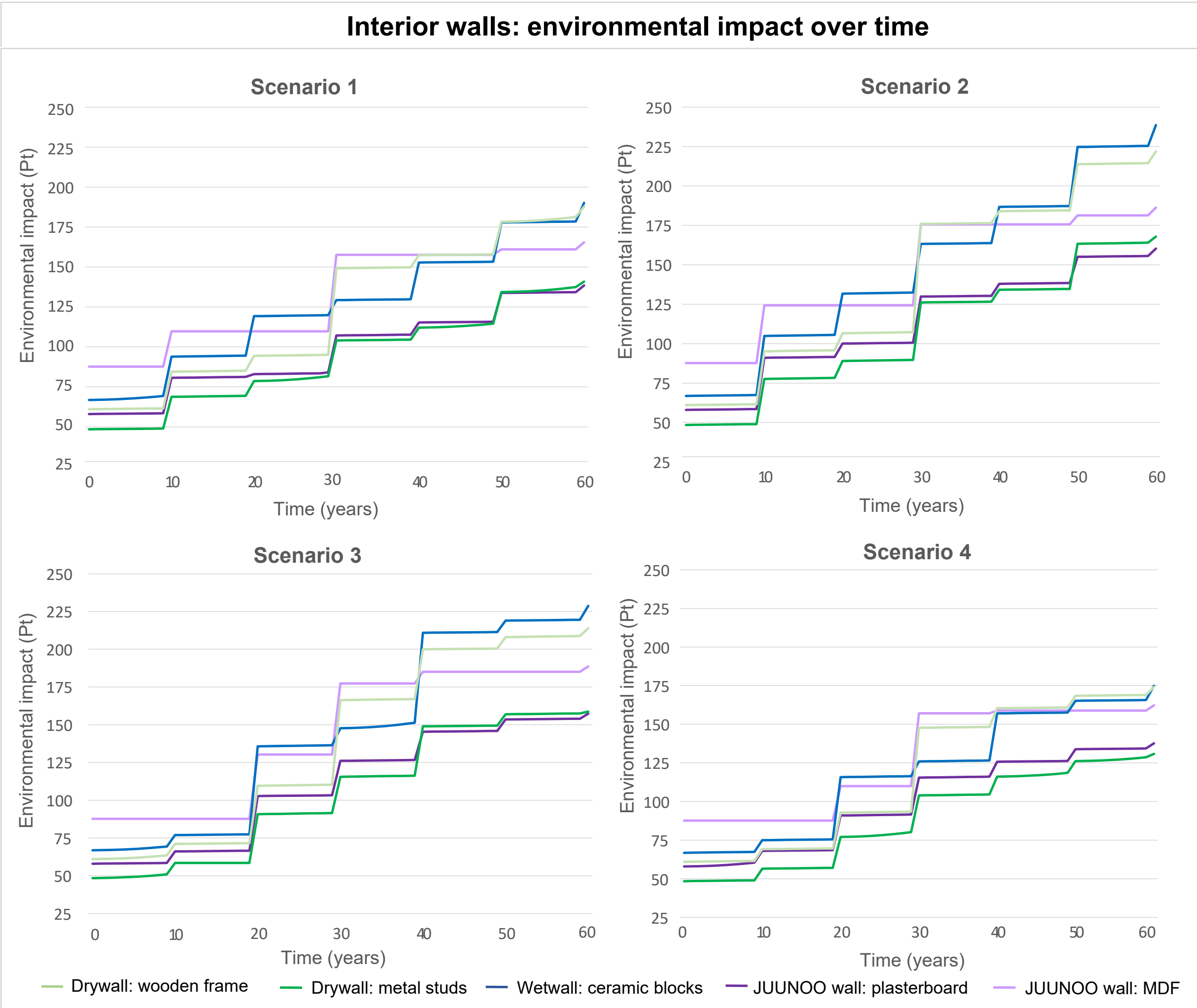


Figure 6.19: Overview of the environmental impact over time for the different interior walls for the four scenarios on scenario level.

Figure 6.20 gives an overview of the environmental impact of the production, construction, use, and end-of-life stage, of the investigated interior walls during buildings' service life for the four scenarios. The production phase has a large influence on the total environmental impact of the four scenarios. It contributes 30 to 40 percent to the total environmental impact of the interior walls, except for the JUUNOO wall with MDF where it rises to 50 percent. The end-of-life phase has a lesser influence on the total impact, fluctuating from 2 to 10 percent. In contrast, the major contributor to the total environmental impact is the use phase, contributing 50 to 70 percent.

A closer look is taken at the contribution of the replacement and refurbishment module in the use phase. The replacement module has a an important influence on the total environmental impact. It contributes 30 to 40 percent, dependent on the contribution of the refurbishment module. Then, the refurbishment module contributes around 25 percent for scenarios 1 and 4, with a low amount of transformed interior wall surface in comparison to scenarios 2 and 3, where the refurbishment module contributes approximately 35 percent. Furthermore, the refurbishment module can be split into two subcategories: new walls and wall transformations. During the first refurbishment, an additional surface of new interior walls is constructed in the case house in Berchem. The total production and e-o-l impact should be counted in for this wall, while for the circular materials in the other refurbishments only the (de)construction impact is accounted for. Module B5 'new wall' contributes to more than 50 percent of the total refurbishment module. Consequently, the relative contribution of module B5 'refurbishments' is rather small in the total environmental impact. This is because a relatively low refurbishment frequency is assumed for the four scenarios in the case study in Berchem.

Additionally, a comparison of the transformed with the newly-built wall surface in the case house in Berchem is carried out. In scenarios 1 and 4 with the small transformed wall surface, approximately 25 percent of the interior walls in the case house are repositioned. In scenarios 2 and 3, 50 percent of the interior walls are replaced. The amount of transformed interior wall surface in comparison with the originally built surface and the small refurbishment frequency explain the relative ranking and the ratio between the total impact of the interior walls in figure 6.20 on scenario level. The amount of interior walls newly built is larger than the amount replaced for the four scenarios with a lower refurbishment rate. It follows that the relative difference between the total environmental impact of the interior walls for the four scenarios lies between zero and one refurbishment on the element level.

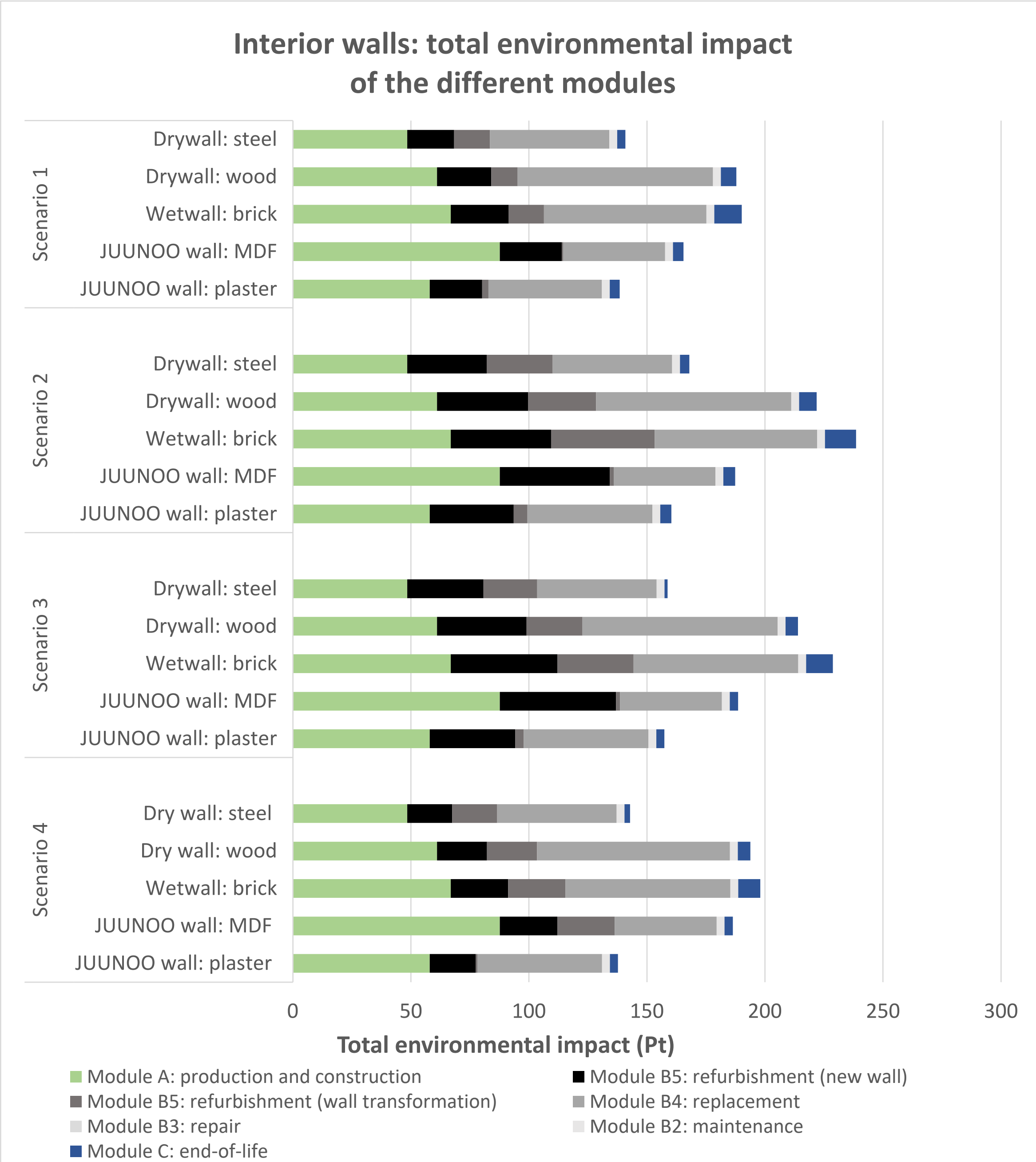


Figure 6.20: Overview of the environmental impacts of the different modules: production, construction, use and end-of-life stage, for the different interior walls for the four refurbishment scenarios.

The LCA results on scenario level conclude that the traditional drywall with metal studs is the environmentally most beneficial wall when no or a small number of refurbishments take place. For a high refurbishment frequency and/or big amount of transformed surface, the most beneficial wall is the JUUNOO wall with plasterboard. The higher the refurbishment frequency and the higher the transformed interior wall surface, the more the gains in total environmental impact increase by using the circular JUUNOO wall with plasterboard instead of traditional walls, and the other way around.

6.4.3 The results of the Life Cycle Costing

The financial costs over time for the different interior wall assemblies are compared for the four scenarios, namely scenario 1 'couple with children', scenario 2 'couple with doctor's practice', scenario 3 'couple with needy elderly', and scenario 4 'co-housing' in figure 6.21. In this graph, the same trends can be observed as in the environmental analysis over time on scenario level in figure 6.19.

The investment costs of the JUUNOO wall with MDF are the lowest. This is because this wall is not painted. However, it may be that the owner of the case house doesn't like a wooden finishing and wants a painted wall. In that case, the drywall with metal studs has the lowest initial financial costs, closely followed by the JUUNOO wall with plasterboard. Furthermore, the relative ranking in financial costs of the different interior walls remains the same for the total financial cost. The JUUNOO wall with MDF is the financially most beneficial wall for the future scenarios in the case house in Berchem. Nevertheless, the absolute financial costs increase significantly. The costs of the interior walls rises five- or sixfold, except for the JUUNOO wall with MDF threefold by taking the costs over the whole lifespan of the case study into account.

Subsequently, the graphs of the financial costs over time in figure 6.10 on the element level are compared with the graphs in figure 6.21 of the four scenarios. The ranking in total financial costs of the interior walls, which is the same for the four scenarios, equals the one for all the refurbishment frequencies on the element level. Only the proportions between the total financial costs of the different walls change for the different scenarios and refurbishment frequencies. Just as discussed in section 6.4.2, the proportions between the total financial costs of the four scenarios equal the proportions between the graphs of zero and one refurbishment on the element level. The reason for these results is discussed based on figure 6.22.

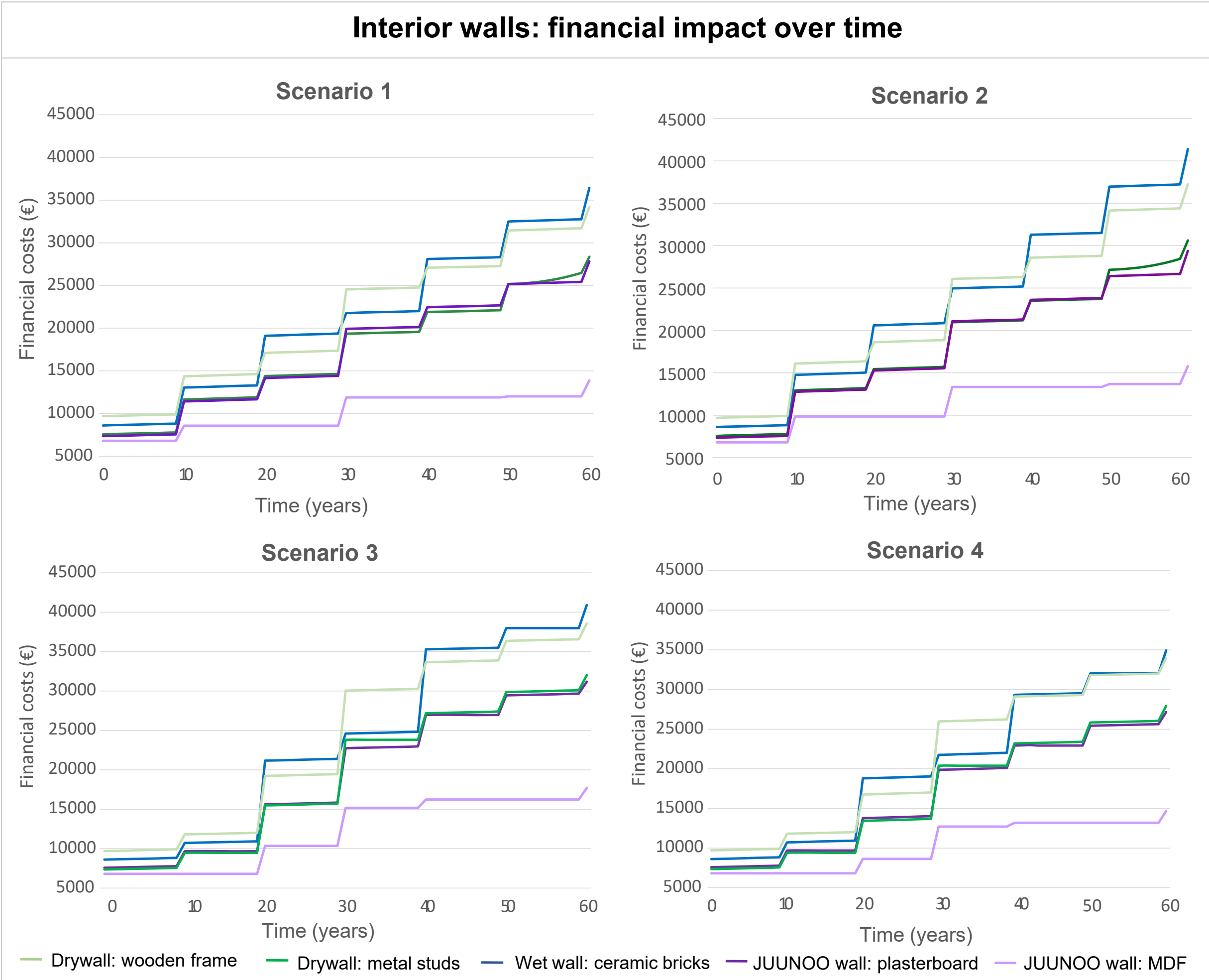


Figure 6.21: Overview of the financial costs over time for the different interior walls for the four scenarios on scenario level.

Figure 6.22 gives an overview of the contribution of the financial costs of each module: production, construction, use, and end-of-life stage, of the different interior walls during buildings' service life for the four scenarios. The production and construction phase has a large influence on the total financial cost for the four scenarios. It contributes 20 to 30 percent to the total financial costs of the interior walls. The end-of-life phase has a small influence of 10 percent. The major contributor to the total financial costs is the use phase, contributing 60 to 70 percent.

A closer look is taken at the contribution of the maintenance, replacement, and refurbishment modules in the use phase. Remarkably, the replacement module has an important contribution of 50 to 60 percent, in comparison to the refurbishment module with 20 to 30 percent. Also, the contribution of the refurbishment module to the financial costs is larger with a higher refurbishment rate and/or transformed surface of the interior walls. Furthermore, the refurbishment module can be split into two submodules: newly refurbished walls and transformed interior walls. Module B5 'refurbishment: new wall' contributes to more than 70 percent of the total refurbishment module. Consequently, the relative contribution of module B5 'refurbishments: wall transformations' is rather minor to the total financial cost. This is because a relatively small refurbishment frequency is assumed for the four scenarios. Moreover, there is a big difference between the surfaces of interior walls that are newly built and the interior walls that are repositioned by a refurbishment, as discussed in paragraph 6.4.2. In other words, it means that a large amount of interior wall surface never is repositioned in the case study house in Berchem. This explains why the proportions in total financial costs of the different walls for the four scenarios, relate the most to the proportions between these of zero and one refurbishment on the element level.

The conclusion of the LCC results on the scenario level is that the financially most beneficial wall is the JUUNOO wall with MDF for future refurbishment scenarios in the case study house in Berchem. Financially good painted alternatives are the JUUNOO wall with plasterboard and the traditional metal stud wall. The higher the refurbishment frequency and the higher the transformed interior wall surface, the higher the financial gains increase by using the circular JUUNOO wall with MDF instead of the traditional walls, and the other way around.

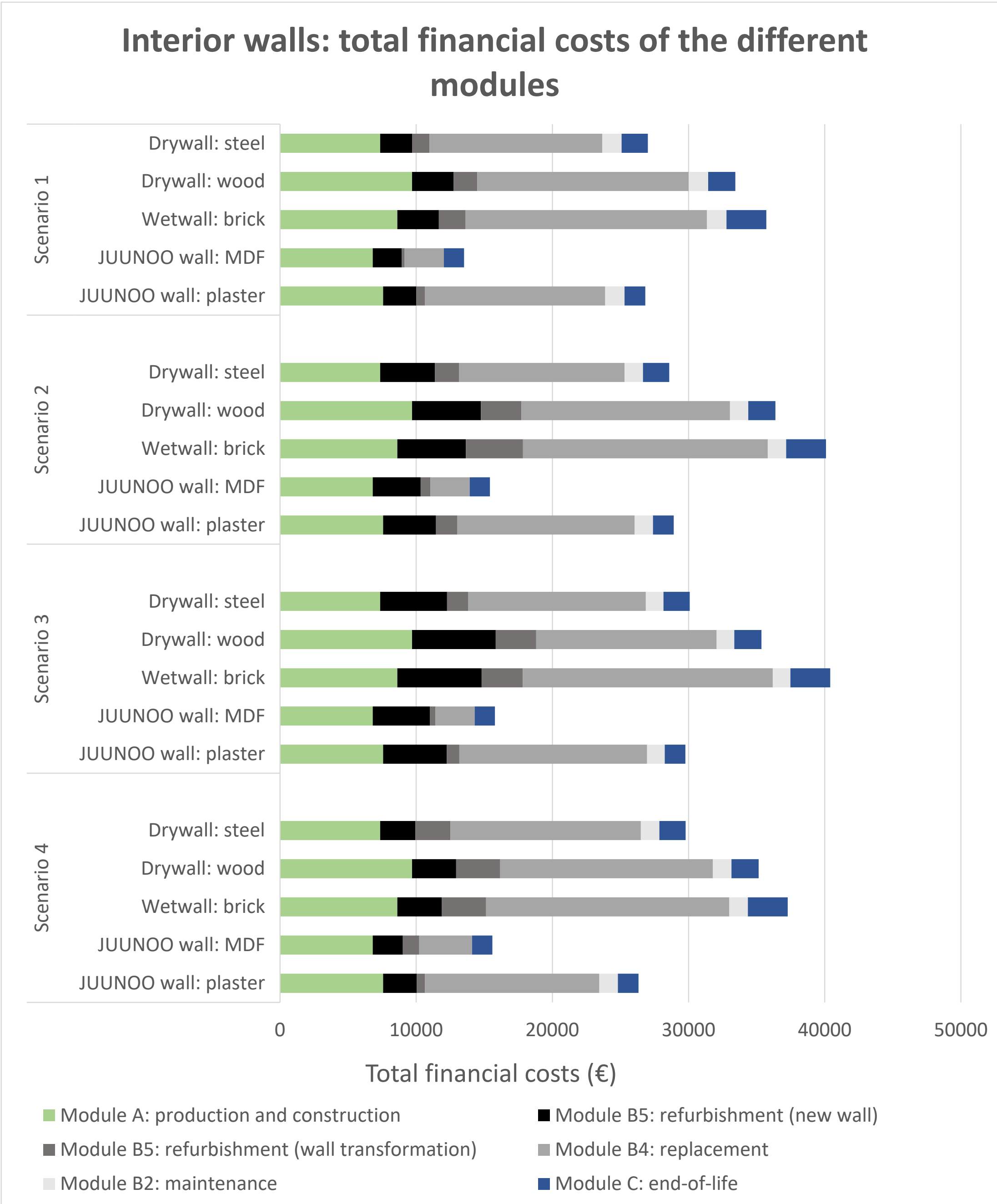


Figure 6.22: Overview of the financial costs of the different modules: production, construction, use and end-of-life stage, for the different interior walls for the four refurbishment scenarios.

6.4.4 Pareto fronts: the financial vs the environmental results

In figure 6.23, Pareto fronts are used to compare the investment cost to the initial environmental impact of the different wall assemblies, so that the initial environmentally and financially most beneficial interior wall can be identified for the four scenarios. The same walls as in the Pareto analysis on element level in figure 6.14 are located on the Pareto front. The JUUNOO wall with MDF has the lowest initial financial impact, while the traditional drywall with metal studs has the lowest environmental impact. However, in this research, the main focus lies on determining the most beneficial wall for the total service life of the case house.

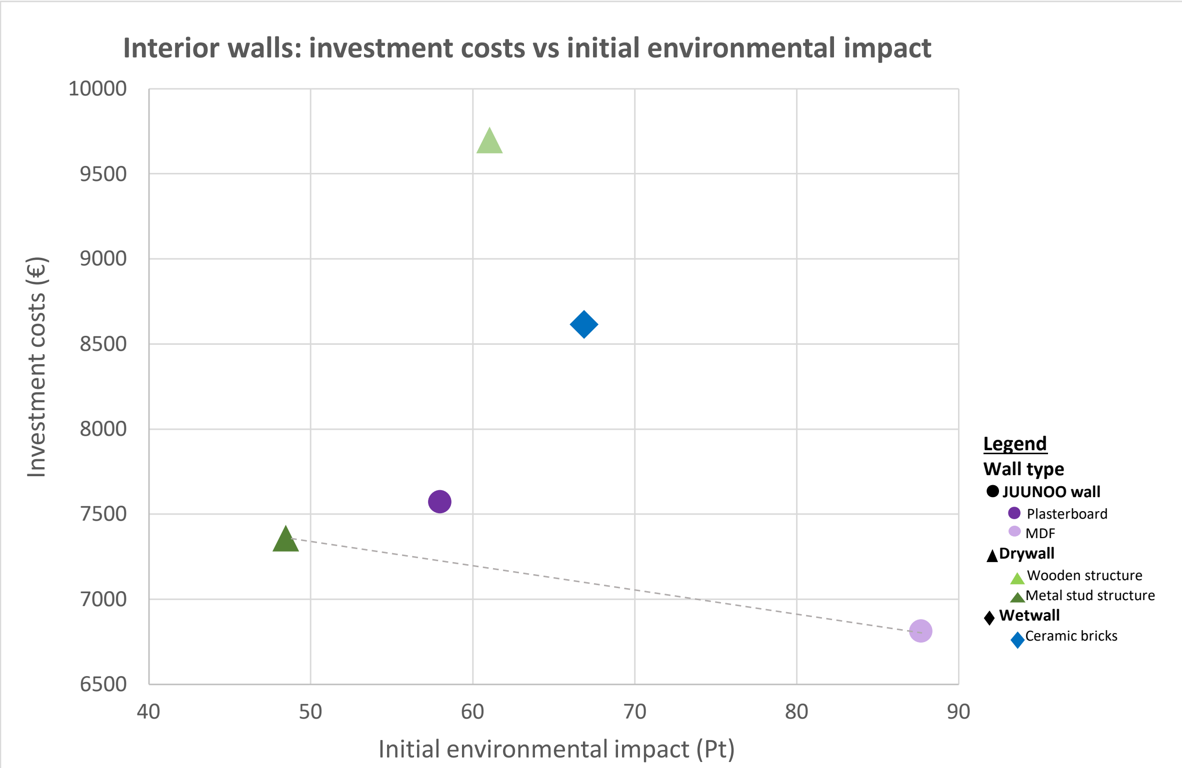


Figure 6.23: Investment costs vs initial environmental impact for the interior walls on scenario level.

Therefore, figure 6.24 compares the total environmental impact with the total financial cost of the different wall assemblies using Pareto fronts, so that the most beneficial wall for the four refurbishment scenarios can be identified. For all the scenarios, the JUUNOO wall with MDF has the lowest financial costs. Next to that, the best financial painted alternative is the JUUNOO wall with plasterboard, closely followed by the traditional drywall with metal studs. The JUUNOO wall with plasterboard is also the environmentally most beneficial wall for all the scenarios, except for the fourth scenario. In this scenario, the traditional drywall with metal studs has a slightly lower environmental impact than the JUUNOO wall with plasterboard due to the very low refurbishment frequency and transformed interior wall surface during the building's life span. Additionally, it is remarkable that in scenario 1 with a low refurbished surface and scenario 3 with a low refurbishment frequency, the total financial costs and environmental impact of the traditional drywall with metal studs is just slightly higher than the JUUNOO wall with plasterboard.

Furthermore, the benefits in total environmental impact and financial cost of the use of the circular JUUNOO walls instead of a traditional wall are determined for the four scenarios. The results of the JUUNOO wall with plasterboard are compared to the traditional drywall with metal studs and the wetwall. The difference in total financial costs fluctuates from 3 to 5 percent for the traditional metal stud wall and from 17 to 20 percent for the wetwall in the four scenarios. The difference in total environmental impact fluctuates from -5 to 5 percent for the metal stud wall and from 20 to 28 percent for the wetwall. In other words, small gains are won for the first three scenarios by using the JUUNOO wall with plasterboard instead of the traditional metal stud wall. In contrast in scenario 4, small losses in environmental impact are incurred by the small refurbished surface and refurbishment frequency. Then, the results of the reference JUUNOO wall with MDF are compared to the traditional metal stud wall. The environmental impact is 10 to 25 percent higher, but the financial costs are 45 to 55 percent lower for the JUUNOO wall with MDF in comparison to the traditional metal stud wall.

Lastly, the results of the different scenarios are compared with each other to investigate the influence of the refurbishment frequency and the transformed surface on the results. In the comparison of scenarios 1 with 4 and 2 with 3, it seems that the proportions in total costs and environmental impact between the circular JUUNOO walls and traditional walls increase with a higher refurbishment rate. Another trend can be noticed by comparing scenarios 1 to 2 and 3 to 4. The difference between the total costs and environmental impact of the JUUNOO walls versus the traditional walls rises with the increasing amount of transformed interior wall surface. In other words, this proves that the benefits of using circular JUUNOO walls improve with the number of refurbishments and the amount of refurbished interior wall surface. Consequently, the drywall with metal studs is proposed as the most beneficial wall when no or a very limited number of refurbishments take place. In all the other cases, the JUUNOO wall with plasterboard is put forward.

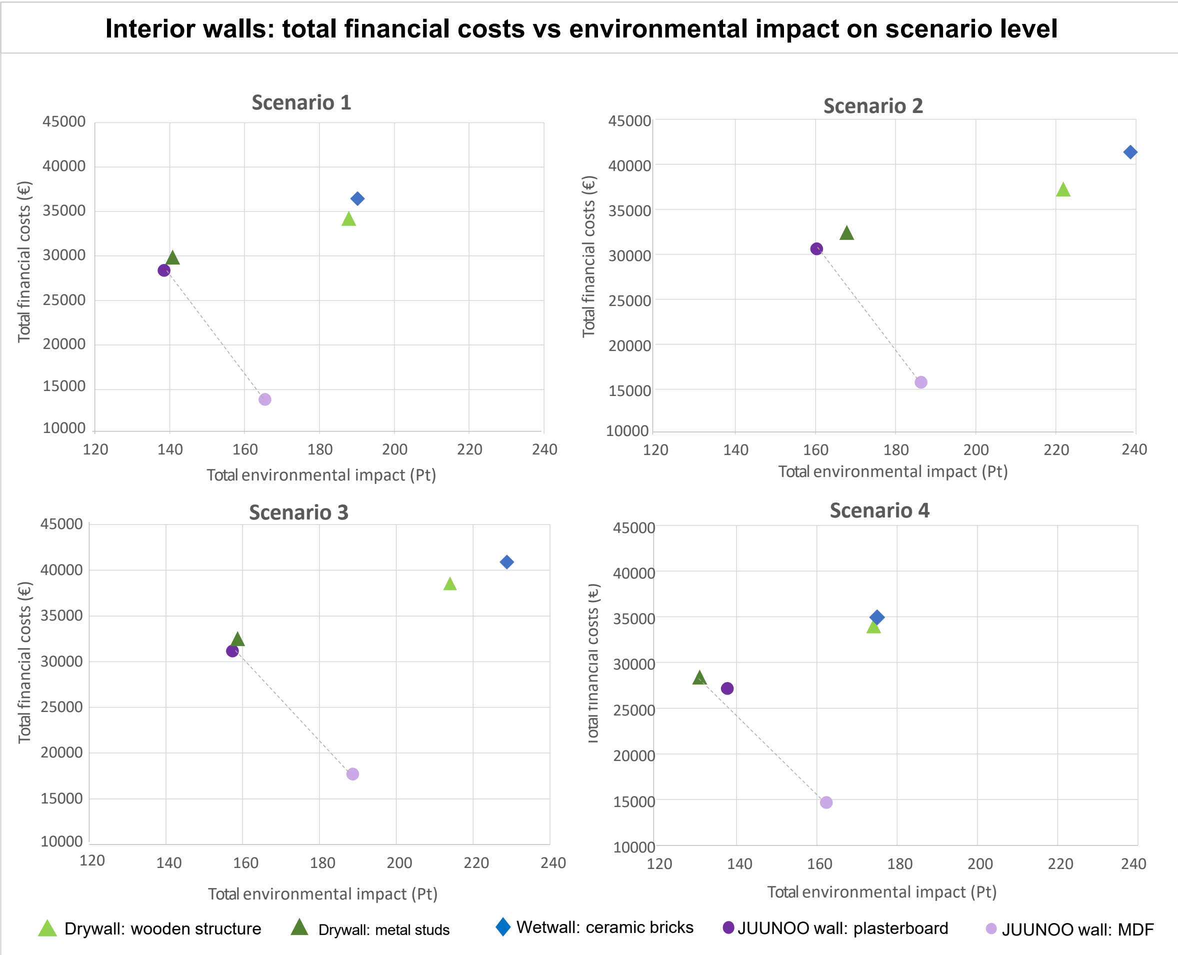


Figure 6.24: Total financial costs vs total environmental impact for the different interior walls for the four scenarios on scenario level.

6.4.5 Sensitivity analysis on the used methodology

In the last section, a sensitivity analysis is performed on the used methodology at the scenario level to assess the impact of certain simplifications on the results. The total financial cost and total environmental impact of three different wall types, namely the JUUNOO wall with MDF, the wetwall with ceramic bricks, and the drywall with wood, for scenario 1 of the case study are compared to the results calculated with the expanded method, used by Paduart (2013), and the detailed method, where each material in a whole wall is mapped, as described in section 6.4.1. The assumed materials can be found in appendix D.

First, the influence of the used methodology on the total environmental impact of the three walls in scenario 1 is assessed in figure 6.25. By comparing the results of the used method to the expansion method, it is remarkable that the deviations for the traditional walls are larger, around 11 percent, than for the circular walls, 3 percent. The slightly higher environmental impact of the expansion method is due to the assumption of two refurbishments in the expansion methodology. The refurbishment impacts of the newly-added refurbished walls and the construction and production impacts of the deconstructed wall in the first refurbishment are counted once too much. The difference is less for the JUUNOO wall with MDF because at the refurbishment only the construction and deconstruction impact should be taken into account, instead of also the production and end-of-life impact of the traditional walls.

Then, the environmental results calculated by the used and the detailed methodology are compared. The total environmental impact of the detailed method is 8 to 11 percent higher for the JUUNOO wall and drywall, while only 2 percent for the wet wall. The reason for the difference in total environmental impact is illustrated in figure 6.26. This figure compares the environmental impact of the production phase for the different materials, calculated with the used and detailed method. The environmental impact of the bearing structure of the JUUNOO wall and drywall is around 17 percent higher. The deviation is due to the simplification in the used method. In 1 m^2 interior wall, the volume of two beams or two metal studs is assumed with a bogie center distance of 60 centimeters. In the case study, the distance between the track centers can be smaller than 60 centimeters in the wall. Also, additional profiles or beams are used at the connection with other building elements and at door openings. This explains why the difference in total impact between the used and detailed method is larger for the JUUNOO and drywall than for the wetwall.

Furthermore, in the used method, the environmental impact of certain finishing materials, such as finishing profiles, silicon kits, and tapes, is neglected. In contrast, the impact of these materials is investigated in the detailed method to assess their contribution to the total environmental impact. Figure 6.26 illustrates that the impact of the additional materials contributes to the total environmental impact with 5 percent for the JUUNOO wall with MDF, with 2 percent for the wet wall and with 3 percent for the drywall.

Secondly, the total financial cost of the three walls is compared for the used method, expansion method, and the detailed method in figure 6.27. The comparison of the results of the used across the expansion method demonstrates that there is a difference of around 24 percent for the traditional walls and around 9 percent for the circular JUUNOO wall. As also discussed in the comparison of the environmental results of the methods, the higher financial costs are incurred by the assumption of two refurbishments. By comparing the difference in total environmental impact in figure 6.25 and total financial cost in figure 6.27 of the expansion and used method, it is remarkable that the biggest difference in environmental impact occurs for the drywall with wooden framework and in financial costs for the wetwall with ceramic bricks. This can be attributed to the minor influence of the construction impact on the environmental assessment and the high production and replacement impact of the OSB board in the wood frame wall. In contrast, the construction cost plays a major role in the contribution to the total cost and constructing a wetwall is a very labor-intensive process.

Afterward, the financial costs calculated by the used and the detailed methodology are compared. The total financial cost of the detailed method is around 8 to 14 percent higher for the drywall and JUUNOO wall, and 3 percent for the wetwall. These results are further elaborated in figure 6.28, which illustrates the difference in the financial cost of the production phase for the different materials, calculated with the used and detailed method. The financial results of the bearing structure for the JUUNOO and drywall are respectively 13 to 18 percent higher when calculated by the detailed instead of the used methodology. The deviation is due to the simplification in the used method, as discussed in the comparison of the environmental impact of the methods. Furthermore, the additional finishing materials taking into account with the whole wall, add a small contribution to the total cost. It contributes 6 percent for the JUUNOO wall with MDF, 2 percent for the wetwall, and 3 percent for the drywall with the wooden framework to the total financial cost.

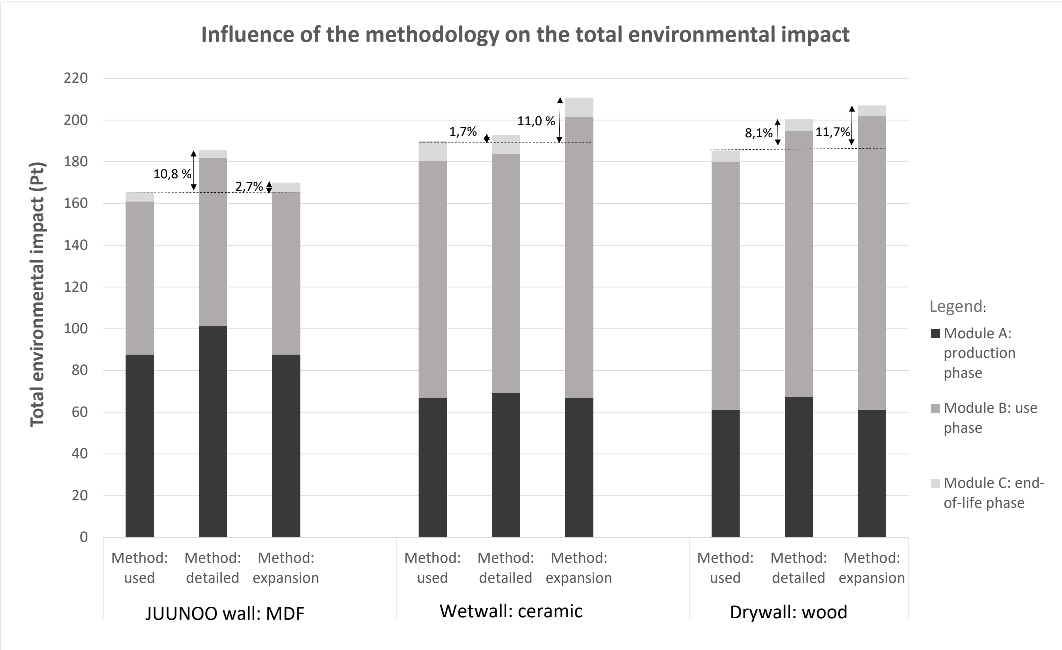


Figure 6.25: Sensitivity analysis on the total environmental impact of the wetwall with ceramic bricks, the drywall with wooden frame and the JUUNOO wall with MDF, calculated with the used, expanded and detailed method for scenario 1.

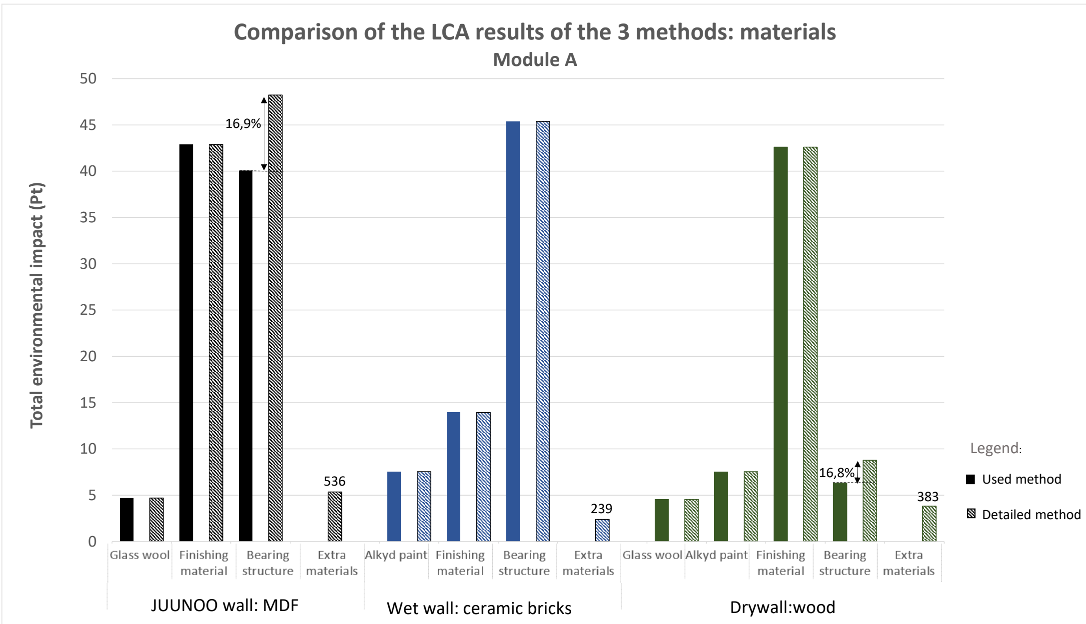


Figure 6.26: Sensitivity analysis on the environmental impact of the materials of the wetwall with ceramic bricks, the drywall with wooden frame and the JUUNOO wall with MDF, calculated with the used, expanded and detailed method for scenario 1.

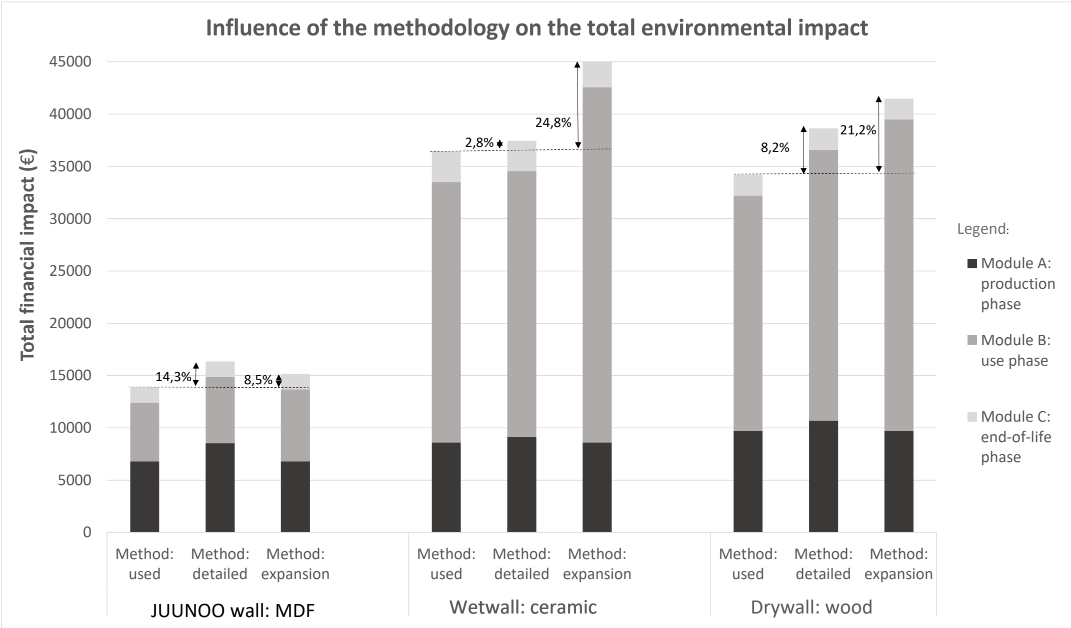


Figure 6.27: Sensitivity analysis on the total financial cost of the wetwall with ceramic bricks, the drywall with wooden frame and the JUUNOO wall with MDF, calculated with the used, expanded and detailed method for scenario 1.

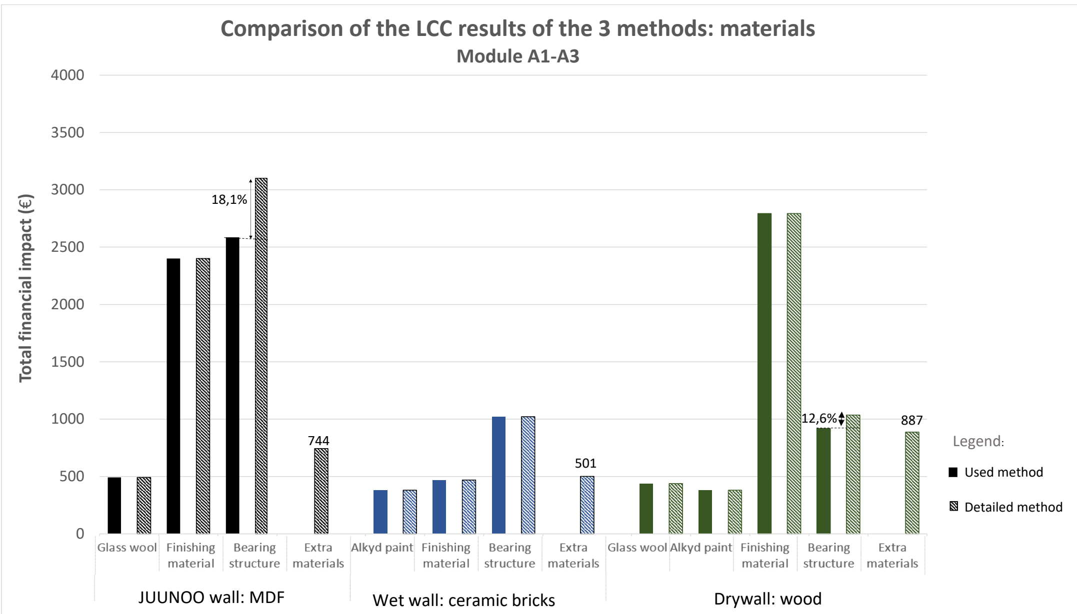


Figure 6.28: Sensitivity analysis on the financial cost of the materials of the wetwall with ceramic bricks, the drywall with wooden frame and the JUUNOO wall with MDF, calculated with the used, expanded and detailed method for scenario 1.

Chapter 7

Conclusion and future work

7.1 Conclusion

The goal of this master's thesis was twofold. First, a methodology was investigated to assess the environmental impact and financial cost of a circular building element during building's life span. Thereafter, the developed methodology was applied to the case study house in Berchem to compare the environmental impact and financial cost of the circular JUUNOO walls with frequently used interior walls in the Belgian construction industry for different refurbishment scenarios, on the element and scenario level.

In the first part of the study, the main research question was **'How do current LCA and LCC methods need to be adapted to be able to determine the environmental and financial impact of a circular building element during buildings life span?'**.

The literature lacks a governmental recognized and consistent methodology to credit the reuse potential of reusable building elements and the many uncertain future refurbishment scenarios during building's service life. Therefore, this research proposed the R-LCA framework, based on the traditional LCA framework according to the European standard EN 15804 (2019). In this method, the environmental benefits and burdens of using circular instead of traditional building elements during the building's life span are assessed in multiple building element use cycles within the same life cycle of the building. The environmental impact of the reuse of building elements during the buildings life span is accounted for in the additional module B5 'refurbishments' in the use stage, besides the production, construction, use (replacement and maintenance), and end-of-life impact of the traditional framework. In module B5, the (de)construction impact and material losses are included for the circular building products, along with the production, construction, and end-of-life impact for the traditional products, for each refurbishment in the case building. The concept of multiple building element's use cycles in the same building's life cycle avoids the complex allocation of the reuse benefits over multiple life cycles of building products, as heavily discussed in the literature. Furthermore, the R-LCC method, using the traditional LCC framework according to the international standard ISO 15686 (2011), was suggested to assess the total financial costs of circular building elements over the building's lifetime. In this framework, the same assumptions and system boundaries are applied as in the R-LCA framework. Afterward, the environmental impact and the financial costs of different traditional and circular building elements can be compared with each other in a multi-objective Pareto front analysis.

In the second section of this research, the main research question was **'In which refurbishment scenario is it beneficial in terms of environmental impact and financial cost to use circular interior walls in the residential project in Berchem?'**. To that end, the total environmental impact and the total financial cost of circular JUUNOO walls were compared to those of frequently used interior walls, namely the dry and wet-walls, in the Belgian building industry. The seven investigated interior walls were the JUUNOO wall with plasterboard, the JUUNOO wall with MDF (and paint), the wetwall with ceramic building blocks, the wetwall with sand-lime building blocks, the drywall with wooden framework, and the drywall with metal studs. Because the life cycle approach was essential in this comparison, the R-LCA framework was used to assess the total environmental impact and the R-LCC methodology to evaluate the total financial costs on element and scenario level.

First, an analysis of the total environmental impact and financial cost on the element level was performed for the seven interior walls. The functional unit was assumed to be one squared meter of interior wall surface and the refurbishment frequency ranged from zero to three refurbishments. In this part of the research, the influence of the refurbishment rate was investigated on the relative ranking and the proportions between the results of the seven walls. The study on element level demonstrated that without refurbishments, the JUUNOO wall with MDF was the financially most beneficial interior wall, while the traditional wall with metal studs was the environmentally most beneficial wall. With a non-zero refurbishment rate, the JUUNOO wall with MDF also had the lowest financial costs, while the JUUNOO wall with plasterboard had the lowest environmental impact. It stood out that the JUUNOO wall with MDF had the lowest financial impact in both

cases. This was caused by unpainted wooden finishing material. However, not all building owners love wooden finishing. Therefore, the financially best alternative was the JUUNOO wall with plasterboard, followed by the traditional wall with metal studs.
The study on element level for different refurbishment frequencies also illustrated that the profits in total environmental impact and the gains in total financial costs increased for circular JUUNOO walls with an increasing number of refurbishments. For instance, when comparing the JUUNOO wall with plasterboard to the traditional metal stud wall, the relative difference in environmental impact rose from 5 percent with one refurbishment to 30 percent with three refurbishments, while the relative difference in financial costs climbed from 10 to 20 percent.

Subsequently, the analysis on the element level was extrapolated to scenario level for the determination of the financially and environmentally most beneficial interior wall for future refurbishment scenarios in the case house in Berchem. To that end, four scenarios were modelled with the scenario planning methodology featuring different refurbishment rates and transformed interior wall surfaces. The conclusion was that the JUUNOO wall with MDF had the lowest financial costs for each scenario. Next to that, the best financial painted alternative was the JUUNOO wall with plasterboard, closely followed by the traditional drywall with metal studs. The JUUNOO wall with plasterboard was also the environmentally most beneficial wall for all the scenarios, except for the fourth scenario. In this scenario, the traditional drywall with metal studs had a slightly lower environmental impact than the JUUNOO wall with plasterboard due to the very low refurbishment frequency and transformed interior wall surface during the building's life span.
Overall, the profits in environmental performance and financial costs of the circular JUUNOO walls increase with the number of refurbishments and the refurbishment frequency. The four investigated refurbishment scenarios in the case study house in Berchem had a relatively small refurbishment frequency and transformed interior wall surface. Consequently, in these refurbishment scenarios, the use of the JUUNOO wall with plasterboard instead of the traditional drywall with metal studs in the case house yielded small gains around 5 percent in environmental impact and financial cost. Additionally, when no or very small refurbishments take place, the drywall with traditional metal studs had a slightly lower environmental impact than the JUUNOO walls.

Therefore raises the question **whether traditional terraced houses are effectively good potential candidates for the use of the circular JUUNOO interior walls considering the small number of refurbishments and transformed interior wall**

surfaces during the building's lifespan? Or are there other building typologies that have more potential for the implementation of circular interior walls?.

Lastly, some critical side notes should be applied to the performed study. First, a lot of assumptions were made in the R-LCA framework for the assessment of the environmental impact and in the R-LCC framework for the evaluation of the financial costs. As demonstrated in the sensitivity analysis, the assumptions had a large influence on the absolute environmental impact and financial cost. Therefore, only the ranking and the ratio between the results of the different wall assemblies were used in the analysis. The assumptions made for a specific wall assembly, namely the material properties, also influenced the ratio between the results of the interior walls. The main contributor was the assumed technical service life for the building products. By prolonging the technical service life of MDF from 30 to 60 years, the JUUNOO wall with MDF became a better environmental alternative than the JUUNOO wall with plasterboard. Additionally, the environmental impact of the drywall with wooden structure became smaller than the JUUNOO wall with MDF by prolonging the technical service life of OSB from 30 to 60 years. Therefore, it is important to take the assumptions on a specific wall assembly into mind by analyzing the results of the case study.
Secondly, only the financial cost and environmental impact of the refurbishment of the interior wall itself were taken into account. However in practice, at the deconstruction of a traditional interior wall, the floor finishing under the wall must be restored. Additionally, the floor finishing is broken out at the construction of a traditional wall. In contrast, the floor finishing can remain at the transformation of the JUUNOO walls because the JUUNOO profiles are clamped between ceiling and floor. This means that the benefits of the JUUNOO walls are slightly higher in practice compared to traditional walls.
Thirdly, the reusable materials of the JUUNOO walls were assumed to be temporarily stored in the case house during a deconstruction. These walls could be reused in a reconstruction at the following refurbishment. With this assumption, it was possible to assess the reuse potential of a circular building element in the same building. Another scenario could be that the circular JUUNOO walls were transported to a material depot. Then the environmental impact and costs of the transport and storage have to be taken into account. This was out of the scope of this research.

7.2 Future work

This research has run into a number of limitations of the proposed R-LCA methodology and the used R-LCC framework. Additionally, the analysis of the costs and environmental performance of the interior walls in the case study in Berchem raised new questions. Therefore in the following section, five topics for future research are proposed. Lastly, the important role of the government in the implementation of circular building strategies in the construction sector is discussed.

1. The technical service life of building products

In the environmental and financial analysis of building elements, assumptions were made about the technical service life for the different materials in the wall assembly. This technical service life determined the number of replacements during the building's lifespan. However, in practice, the assumed replacements do not always occur when the lifespan of the material is expired. This uncertainty aspect can be taken into account by including adjustment factors in the methods of the research. The assumed technical service life is prolonged or extended with factors for the local setting, execution, and degradation of a certain material (Daniotti et al., 2008). However, the prolonged/extended service life is, just like the original estimated technical service life, established by a chosen deterministic value. For a more detailed and accurate analysis, this deterministic value should be replaced by stochastic distributions.

2. Other interior wall types, materials, and material properties

In the case study, three circular JUUNOO walls and four traditional interior walls were compared to each other. In the construction practice, there is a broad variety of other traditional interior wall types, such as the glass wall, the massive wooden wall, and the concrete walls, and other circular wall types, like the woodbox wall and the Quickpanell wall. In future research, the current study can be expanded with an analysis of more interior wall types.

Additionally, all the different wall types can have various finishing materials, like plasterboard, plaster, MDF board, and different kinds of paint. On top of that, each material in the building element can have different standard sizes and properties. Therefore, an additional sensitivity analysis can be carried out to map the influence of the different material thicknesses and finishing materials on the total environmental impact and financial cost of the interior walls. To arrive at a more detailed and accurate assessment of the interior walls, the deterministic value of a single thickness should be replaced by multiple thicknesses using stochastic distributions.

3. The end-of-life treatment of the materials after the building's service life

In this master's thesis, the reuse benefits of a building product on the total environmental impact and financial cost were assessed within the same building for various refurbishment scenarios. At the end of the building's life span, all the building materials were disposed, recycled, or incinerated. At that moment, the materials could have a residual reuse value. Therefore, future research is necessary to evaluate the reuse benefits of a building product in multiple buildings and include the residual reuse value in the proposed R-LCA framework and the used R-LCC methodology.

4. The assessment of other building elements in the case house

In the case study, the total financial cost and environmental impact of circular JUUNOO walls were compared to traditional interior walls for the single-family home in Berchem for the four predefined refurbishment scenarios. Future research could focus on other circular building elements in the case house, like the exterior walls, the floors, and the ceilings. On top of that, the environmental performance and financial cost of traditional technical installations should be compared to more ecological alternatives, like heat pumps. Furthermore, the analysis on element and building layer level can be extrapolated to the building level, so that the costs and environmental impact of the entire building constructed with traditional and circular materials may be compared for the different refurbishment scenarios.

5. The assessment of other building typologies

In the conclusion above, the question raised if the terraced house typology was the prime candidate for the construction with circular JUUNOO walls instead of traditional interior walls. The potential gains of the reuse are rather small in this typology, due to the small refurbishment frequency and transformed interior wall surface. Future research should be performed on the gains of circular JUUNOO walls in different building typologies with different functions and transformation rates, so that the typology with the potentially highest benefits for the use of circular JUUNOO walls could be identified. In addition, a literature study and interviews with contractors, building owners, and facility managers should be undertaken, to better estimate the average refurbishment frequency and refurbishment scenarios for the different building typologies. This study would only cover JUUNOO walls, so the same research should be performed for other building elements. That would make it possible to identify the building elements that are subject to the most transformations in each building typology, so that these can be further explored.

6. The role of the government

The government has a prominent role in the implementation and promotion of sustainable building strategies in the construction sector. Currently, there is an overly focus on regulating the energy performance in sustainable construction standards in Flanders. Thereby, the most important indicator is the E-score (K-score), which represents the environmental performance of a building in terms of yearly energy consumption compared to a committed reference value.

In contemporary passive houses, the contribution of the operational energy consumption in the use phase to the total environmental impact decreases, while other phases, namely the production, construction, use (maintenance, replacement, and refurbishment), and end-of-life phase gain more importance (Himpe et al., 2012). Therefore, the regional Belgian authorities launched the TOTEM tool to stimulate the awareness of Life Cycle Analysis in the construction sector. However, this initiative is still in its infancy and its use is voluntary. This means that building owners yet receive no regular and financial incentives for the use of sustainable building products and circular construction methods. Future research is essential to further develop the TOTEM tool. Additionally, it is also necessary to investigate the integration of the environmental LCA scores in the current sustainability building standards. Maybe in the future, one sees the appearance of an M-score in the regulations and best practices of the building industry?

List of Figures

List of Tables

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Appendix A

Interior wall assemblies

JUUNOO wall: plasterboard						
Material	**Thickness (m)**	**Surface area (m^2)**	**Volume (m^3)**	**Density (kg/m^3)**	**Service life (years)**	**Mass (kg)**
Metal JUUNOO profiles	0,08	/	0,00	7850	60	2,66
Glass wool	0,05	1,00	0,04	25	75	1,12
Plasterboard	0,01	1,00	0,03	664	30	16,60
Screws	0,03	0,00	0,00	7850	50	0,04

Material	Surface per liter (m^2/l)	Weight per liter (kg/l)	Surface area (m2)	Service life (years)	Mass (kg)
Alkyd paint	8,00	1,35	1,00	10	0,34

JUUNOO wall: MDF						
Material	**Thickness (m)**	**Surface area (m^2)**	**Volume (m^3)**	**Density (kg/m^3)**	**Service life (years)**	**Mass (kg)**
Metal JUUNOO profiles	0,08	/	0,00	7850	60	2,66
Glass wool	0,05	1,00	0,04	25	75	1,12
JUUNOO tape (NYLON)	0,00	0,02	0,00	1150	30 or 60	0,37
Clicwall MDF panels Unilin	0,01	1,00	0,02	720	30	14,40

JUUNOO wall: MDF & paint						
Material	**Thickness (m)**	**Surface area (m^2)**	**Volume (m^3)**	**Density (kg/m^3)**	**Service life (years)**	**Mass (kg)**
Metal JUUNOO profiles	0,08	/	0,00	7850	60	2,66
Glass wool	0,05	1,00	0,04	25	75	1,12
JUUNOO tape (NYLON)	0,00	0,02	0,00	1150	30 or 60	0,37
Clicwall MDF panels Unilin	0,01	1,00	0,02	720	30	14,40

Material	Surface per liter (m^2/l)	Weight per liter (kg/l)	Surface area (m2)	Service life (years)	Mass (kg)
Alkyd paint	8,00	1,35	1,00	10	0,34

Vet wall: ceramic building blocks						
Material	**Thickness (m)**	**Surface area (m2)**	**Volume (m3)**	**Density (kg/m3)**	**Service life (years)**	**Mass (kg)**
Gypsum plaster	0,01	1,00	0,02	900	25	21,60
Ceramic building blocks	0,09	1,00	0,09	850	100+	76,50

Material	Surface per liter (m2/l)	Weight per liter (kg/l)	Surface area (m2)	Service life (years)	Mass (kg)
Alkyd paint	8,00	1,35	1,00	10	0,34

Material	Surface per liter (m2/l)	Density (kg/m3)	Surface area (m2)	Service life (years)	Mass (kg)
Masonry mortar	/	2000	1,00	100+	6,00

et wall: sand-lime building blocks						
Material	**Thickness (m)**	**Surface area (m2)**	**Volume (m3)**	**Density (kg/m3)**	**Service life (years)**	**Mass (kg)**
Gypsum plaster	0,01	1,00	0,02	900	25	21,60
Sand-lime blocks	0,09	1,00	0,09	1300	100+	117,00

Material	Surface per liter (m2/l)	Weight per liter (kg/l)	Surface area (m2)	Service life (years)	Mass (kg)
Alkyd paint	8,00	1,35	1,00	10	0,34

Material	Surface per liter (m2/l)	Density (kg/m3)	Surface area (m2)	Service life (years)	Mass (kg)
Masonry mortar	/	2000,00	1,00	100+	6,00

Drywall: wooden framework						
Material	**Thickness (m)**	**Surface area (m^2)**	**Volume (m3)**	**Density (kg/m^3)**	**Service life (years)**	**Mass (kg)**
Wooden frame	0,08	0,05	0,01	740	75	5,00
OSB board	0,01	1,00	0,02	600	30	13,80
Glass wool	0,05	1,00	0,04	25	75	0,96
Plasterboard	0,01	1,00	0,03	664	30	16,60
Screws	0,03	0,00	0,00	7850	50	0,04

Material	Surface per liter (m^2/l)	Weight per liter (kg/l)	Surface area (m2)	Service life (years)	Mass (kg)
Alkyd paint	8,00	1,35	1,00	10	0,34

Drywall: steel profiles						
Material	**Thickness (m)**	**Surface area (m^2)**	**Volume (m^3)**	**Density (kg/m^3)**	**Service life (years)**	**Mass (kg)**
Metal profiles	0,07	/	0,00	7850	60	1,65
Glass wool	0,05	1,00	0,04	25	75	1,08
Plasterboard	0,02	1,00	0,03	640	30	19,20
Screws	0,03	0,00	0,00	7850	50	0,04

Material	Surface per liter (m^2/l)	Weight per liter (kg/l)	Surface area (m2)	Service life (years)	Mass (kg)
Alkyd paint	8,00	1,35	1,00	10	0,34

Assumptions: life cycle stages

Production phase: assumptions	
Material	**Production Process (Simapro)**
Metal JUUNOO profiles	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, S
Glass wool	Glass wool mat {CH}| production | Cut-off, S
Plasterboard	Gypsum plasterboard {CH}| production | Cut-off, S
Screws	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, S
Alkyd paint	Alkyd paint production, white, water-based, product in 60% solution state | Cut-off, S
JUUNOO tape (nylon)	50 % Nylon 6, glass-filled {RER}| production | Cut-off, S
	50 % Polypropylene, granulate {RER}| production | Cut-off, S
Clickwall MDF panels	Medium density fibreboard {RER}| medium density fibre board production | Cut-off, S
Gypsum plaster	Gypsum plaster {CH}| production | Cut-off, U
Ceramic building blocks	Clay brick {RER}| production | Cut-off, S
Masonry mortar	Cement mortar {CH} | Cut-off, S
Sand-lime blocks	Sand-lime brick {DE}| production | Cut-off, S
Wooden frame	Sawnwood, hardwood, dried (u=10%), planed {RER}| production | Cut-off, S
OSB board	Oriented strand board {RER}| production | Cut-off, S
Traditional metal profiles	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, S

Construction phase: assumptions		
Material	**Transport scenario to building site (Simapro)**	**Distance (km)**
Metal JUUNOO profiles	Prefabricated products: lorry 16-32 metric ton, EURO 5	117,5
Glass wool	Insulation materials: lorry 16-32 metric ton, EURO 5	117,5
Plasterboard	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Screws	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Alkyd paint	Finishing products paints: lorry 7,5-16 metric ton, EURO 5	117,5
JUUNOO tape (nylon)	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Clickwall MDF panels	Finishing products: coverings: lorry 16-32 metric ton, EURO 5	117,5
Gypsum plaster	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Ceramic building blocks	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Masonry mortar	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Sand-lime blocks	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Wooden frame	Prefabricated products: lorry 16-32 metric ton, EURO 5	117,5
OSB board	Loose products: lorry 16-32 metric ton, EURO 5	117,5
Traditional metal profiles	Prefabricated products: lorry 16-32 metric ton, EURO 5	117,5

End-of-life phase: deconstruction assumptions	
Material	**Deconstruction Process (Simapro)**
Metal JUUNOO profiles	No impacts by non-deconstructive methods
Glass wool	No impacts by non-deconstructive methods
Plasterboard	No impacts by non-deconstructive methods
Screws	No impacts by non-deconstructive methods
Alkyd paint	No impacts by non-deconstructive methods
JUUNOO tape (nylon)	No impacts by non-deconstructive methods
Clickwall MDF panels	No impacts by non-deconstructive methods
Gypsum plaster	Waste brick {CH}| treatment of, recycling | Cut-off, S with adaptions
Ceramic building blocks	Waste brick {CH}| treatment of, recycling | Cut-off, S with adaptions
Masonry mortar	Waste brick {CH}| treatment of, recycling | Cut-off, S with adaptions
Sand-lime blocks	Waste brick {CH}| treatment of, recycling | Cut-off, S with adaptions
Wooden frame	No impacts by non-deconstructive methods
OSB board	No impacts by non-deconstructive methods
Traditional metal profiles	No impacts by non-deconstructive methods

End-of-life phase: transport assumptions		
Material	**Transport scenario to building site (Simapro)**	**Distance (km)**
Metal JUUNOO profiles	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30
Glass wool	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	105
Plasterboard	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	80
Screws	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30
Alkyd paint	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	80 (30 by wet walls)
JUUNOO tape (nylon)	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	80
Clickwall MDF panels	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	130
Gypsum plaster	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30
Ceramic building blocks	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30
Masonry mortar	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30
Sand-lime blocks	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30
Wooden frame	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	130
OSB board	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	130
Traditional metal profiles	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}|	30

End-of-life phase: waste processing assumptions		
Material	**Waste processing Process (Simapro)**	**Waste category**
Metal JUUNOO profiles	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Metals: iron, steel, non-ferro
Glass wool	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Insulation: organic insulation
Plasterboard	Waste brick {CH}| treatment of, sorting plant, crusher | Cut-off, U	Gypsum elements
Screws	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Metals: iron, steel, non-ferro
Alkyd paint	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Finishing layer fixed to stony waste
JUUNOO tape (nylon)	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Remaining waste: non-combustible
Clickwall MDF panels	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Wood: composite woodproducts
Gypsum plaster	Waste brick {CH}| treatment of, sorting plant, crusher | Cut-off, U	Finishing layer fixed to stony waste
Ceramic building blocks	Waste brick {CH}| treatment of, sorting plant, crusher | Cut-off, U	Stony & glass: bricks
Masonry mortar	Waste brick {CH}| treatment of, sorting plant, crusher | Cut-off, U	Stony & glass: bricks
Sand-lime blocks	Waste brick {CH}| treatment of, sorting plant, crusher | Cut-off, U	Stony & glass: bricks
Wooden frame	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Wood: surface treated, solid wood
OSB board	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Wood: composite wood products
Traditional metal profiles	Waste brick {CH}| treatment of, sorting plant, without crusher | Cut-off, U	Metals: iron, steel, non-ferro

End-of-life phase: waste disposal	
Material	**End-of-life scenario (Simapro)**
Metal JUUNOO profiles	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S
Glass wool	50% waste mineral wool, for final disposal {CH}| treatment of waste mineral wool, inert material landfill | Cut-off, S
	50% municipal solid waste {BE}| treatment of, incineration | Cut-off, S
Plasterboard	Waste gypsum {Europe without Switzerland}| treatment of waste gypsum, inert material landfill | Cut-off, S
Screws	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S
Alkyd paint	r final disposal|cut-off,S=Waste paint on wall {CH}| treatment of, collection for final disposal | Cut-off, SWaste paint on wall {CH}| trea
JUUNOO tape (nylon)	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | Cut-off, S
Clickwall MDF panels	Waste wood, untreated {CH}| treatment of, municipal incineration | Cut-off, S
Gypsum plaster	Waste brick {CH}| treatment of, recycling | Cut-off, S
Ceramic building blocks	Waste brick {CH}| treatment of, recycling | Cut-off, S
Masonry mortar	Waste brick {CH}| treatment of, recycling | Cut-off, S
Sand-lime blocks	Waste brick {CH}| treatment of, recycling | Cut-off, S
Wooden frame	Waste wood, untreated {CH}| treatment of, municipal incineration | Cut-off, S
OSB board	Waste wood, untreated {CH}| treatment of, municipal incineration | Cut-off, S
Traditional metal profiles	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S

Appendix B

Inventoried actualized material and construction prices

Discontovoet 1,5 %, growth rate labour 2,3% and growth rate materials 1,6%

JUUNOO wall: plasterboard						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
JUUNOO I-profile + taoe	32,09					JUUNOO
Glass wool	6,11					ASPEN INDEX
Plasterboard	16,94					ASPEN INDEX
Screws	0,39	0,40	35,00	14	20,00	ASPEN INDEX
Alkyd paint	4,73	0,40	35,00	14	22,24	ASPEN INDEX

JUUNOO wall: MDF						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
JUUNOO I-profile + taoe	32,09					JUUNOO
Glass wool	6,11					ASPEN INDEX
JUUNOO tape	2,23					JUUNOO
Clickwall MDF panels	27,56	0,40	35,00	14	20,00	ASPEN INDEX

JUUNOO wall: MDF & paint						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
JUUNOO I-profile + taoe	32,09					JUUNOO
Glass wool	6,11					ASPEN INDEX
JUUNOO tape	2,23					JUUNOO
Clickwall MDF panels	27,56	0,40	35,00	14	20,00	ASPEN INDEX
Alkyd paint	4,73	0,40	35,00	14	22,24	ASPEN INDEX

Wet wall: ceramic building blocks						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
Gypsum plaster	5,82	0,46	35,00	16	26,47	ASPEN INDEX
Ceramic building blocks & mortar	12,69	1,00	35,00	35	58,36	ASPEN INDEX
Alkyd paint	4,73	0,40	35,00	14	22,24	ASPEN INDEX

Wet wall: sand-lime building blocks						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
Gypsum plaster	5,82	0,46	35,00	16	26,47	ASPEN INDEX
Ceramic building blocks & mortar	20,84	1,00	35,00	35	57,94	ASPEN INDEX
Alkyd paint	4,73	0,40	35,00	14	22,24	ASPEN INDEX

Drywall: wooden framework						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
Wooden frame, wood styles	9,05					ASPEN INDEX
Wooden frame, wooden beams	2,36					ASPEN INDEX
Glass wool	5,45					ASPEN INDEX
Plasterboard	15,13					ASPEN INDEX
Screws	0,39					ASPEN INDEX
OSB	20,15	0,99	35	34,65	57,96	ASPEN INDEX
Alkyd paint	4,73	0,40	35,00	14	22,24	ASPEN INDEX

Drywall: steel profiles						
Material	Material costs (€)	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Construction costs (€)	Source
Metal profile, styles	7,03					ASPEN INDEX
Metal profile, beams	2,22					ASPEN INDEX
Glass wool	5,45					ASPEN INDEX
Plasterboard	15,13					ASPEN INDEX
Screws	0,39	0,81	35	28,35	46,94	ASPEN INDEX
Alkyd paint	4,73	0,40	35,00	14	22,24	ASPEN INDEX

Inventoried actualized deconstruction and e-o-l treatment prices

Deconstruction prices

Deconstruction prices walls					
Material	Calculation norm labour	Labour costs/hour (€)	Labour costs (€)	Deconstruction costs (€)	Source
JUUNOO wall: plasterboard	0,3	35,00	10,50	10,90	JUUNOO + ASPEN INDEX
JUUNOO wall: MDF	0,3	35,00	10,50	10,90	JUUNOO + ASPEN INDEX
JUUNOO wall: MDF + paint	0,3	35,00	10,50	10,90	JUUNOO + ASPEN INDEX
Wet wall: ceramic building blocks	0,61	35,00	21,35	22,79	ASPEN INDEX
Wet wall: sand lime blocks	0,61	35,00	21,35	22,79	ASPEN INDEX
Drywall: wooden framework	0,52	35,00	18,20	18,60	ASPEN INDEX
Drywall: steel profiles	0,48	35,00	16,80	17,20	ASPEN INDEX

Container prices

JUUNOO wall: plasterboard					
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source
JUUNOO I-profile + taoe	0,00	508,20	12,00	0,01	Containers MAES
Glass wool	0,04	508,20	12,00	2,01	Containers MAES
Plasterboard	0,03	508,20	12,00	1,12	Containers MAES
Screws	0,00	508,20	12,00	0,00	Containers MAES
Alkyd paint	0,00	508,20	12,00	0,00	Containers MAES

JUUNOO wall: plasterboard					
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source
JUUNOO I-profile + taoe	0,00	508,20	12,00	0,01	Containers MAES
Glass wool	0,04	508,20	12,00	2,01	Containers MAES
JUUNOO tape + MDF panels	0,02	314,60	12,00	0,57	Containers MAES

JUUNOO wall: plasterboard					
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source
JUUNOO I-profile + taoe	0,00	508,20	12,00	0,01	Containers MAES
Glass wool	0,04	508,20	12,00	2,01	Containers MAES
JUUNOO tape + MDF panels	0,02	314,60	12,00	0,57	Containers MAES
Alkyd paint	0,00	314,60	12,00	0,00	Containers MAES

Wet wall: ceramic building blocks					
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source
Gypsum plaster	0,02	508,20	12,00	1,08	Containers MAES
Ceramic building blocks & mortar	0,09	508,20	12,00	4,04	Containers MAES
Alkyd paint	0,00	508,20	12,00	0,00	Containers MAES

Wet wall: sand-lime building blocks					
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source
Gypsum plaster	0,02	508,20	12,00	1,08	Containers MAES
Ceramic building blocks & mortar	0,09	508,20	12,00	4,04	Containers MAES
Alkyd paint	0,00	508,20	12,00	0,00	Containers MAES

Drywall: wooden framework					
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source
Wooden frame	0,01	314,60	12,00	0,19	Containers MAES
Glass wool	0,02	314,60	12,00	0,64	Containers MAES
Plasterboard	0,04	508,20	12,00	1,72	Containers MAES
Screws	0,00	508,20	12,00	0,00	Containers MAES
OSB	0,03	508,20	12,00	1,12	Containers MAES
Alkyd paint	0,00	508,20	12,00	0,00	Containers MAES

Drywall: steel profiles						
Material	Volume material	Price container, incl BTW	Volume container (m3)	Price material container (€)	Source	Source
Metal profile, styles	0,00	508,20	12,00	0,01		Containers MAES
Glass wool	0,04	508,20	12,00	2,01		Containers MAES
Plasterboard	0,00	508,20	12,00	0,00		Containers MAES
Screws	0,03	508,20	12,00	1,35		Containers MAES
Alkyd paint	0,00	508,20	12,00	0,00		Containers MAES

Container transport prices

JUUNOO wall: plasterboard				
Material	Distance transport (km)	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
JUUNOO I-profile + taoe	< 50 km	139,15	0,00	Containers MAES
Glass wool	> 100 km	260,15	1,56	Containers MAES
Plasterboard	> 50 km	193,60	0,65	Containers MAES
Screws	< 50 km	193,15	0,00	Containers MAES
Alkyd paint	> 50 km	193,60	0,00	Containers MAES

JUUNOO wall: plasterboard				
Material	Distance transport (km)	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
JUUNOO I-profile + taoe	< 50 km	139,15	0,00	Containers MAES
Glass wool	> 100 km	260,15	1,56	Containers MAES
Plasterboard	> 100 km	260,15	0,71	Containers MAES

JUUNOO wall: plasterboard				
Material	Distance transport (km)	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
JUUNOO I-profile + taoe	< 50 km	139,15	0,00	Containers MAES
Glass wool	> 100 km	260,15	1,56	Containers MAES
Plasterboard	> 100 km	260,15	0,71	Containers MAES
Screws	> 50 km	193,60	0,00	Containers MAES

Wet wall: ceramic building blocks				
Material	Distance transport (km)	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
Gypsum plaster	< 50 km	139,15	0,45	Containers MAES
Ceramic building blocks & mortar	< 50 km	139,15	1,67	Containers MAES
Alkyd paint	< 50 km	139,15	0,00	Containers MAES

Wet wall: sand-lime building blocks				
Material	Distance transport (km)	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
Gypsum plaster	< 50 km	139,15	0,45	Containers MAES
Ceramic building blocks & mortar	< 50 km	139,15	1,67	Containers MAES
Alkyd paint	< 50 km	139,15	0,00	Containers MAES

Drywall: wooden framework				
Material	Price container, incl BTW	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
Wooden frame	> 100 km	260,15	0,23	Containers MAES
Glass wool	> 100 km	260,15	0,80	Containers MAES
Plasterboard	< 50 km	260,15	1,33	Containers MAES
Screws	< 50 km	139,15	0,00	Containers MAES
OSB	< 50 km	193,60	0,65	Containers MAES
Alkyd paint	< 50 km	193,60	0,00	Containers MAES

Drywall: steel profiles				
Material	Price container, incl BTW	Prize transport container, incl BTW (€)	Prize transport material (€)	Source
Metal profile, styles	> 100 km	260,15	0,01	Containers MAES
Glass wool	> 100 km	260,15	1,56	Containers MAES
Plasterboard	< 50 km	139,15	0,00	Containers MAES
Screws	> 50 km	193,60	0,78	Containers MAES
Alkyd paint	> 50 km	193,60	0,00	Containers MAES

Appendix C

C1: scenario waste categories

Product group / Waste category	Description	Landfill (%)	Incineration[39] (%)	Reuse (%)	Recycling (%)	sorted on building site[40] (%)
Stony & glass	Bricks, roof tiles	5%	0%	0%	95%	75%
	Bulk materials (e.g. sand, gravel, expanded clay grains)	5%	0%	95%	0%	90%
	Concrete	5%	0%	0%	95%	75%
	Flat glass	5%	0%	0%	95%	70%
	Other stony waste (e.g. tiles, natural stone, slates, sand-lime blocks)	5%	0%	0%	95%	75%
	Porcelain and ceramics (e.g. toilet, bath, washbasin)	15%	0%	0%	85%	75%
Wood	Chemically treated, impregnated wood (e.g. railway sleepers, wood used for carports, outdoor playsets, garden screens)	0%	100%	0%	0%	40%
	Composite wood products (e.g. fibreboards (like plywood, chipboard, OSB, MDF), veneer, laminate)	0%	95%	0%	5%	40%
	Surface treated, solid wood (e.g. painted or varnished (like window frames, solid parquet))	0%	85%	0%	15%	40%
	Untreated, uncontaminated wood (e.g. roofs, structures, formworks, auxiliary timber)	0%	25%	0%	75%	40%
Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5%	0%	0%	95%	85%
Packaging (on construction site)[41]	EPS packaging	10%	30%	0%	60%	50%
	Pallets	0%	40%	20%	40%	50%
	Paper and cardboard packaging	0%	5%	0%	95%	50%
	Plastic films packaging	5%	60%	0%	35%	50%
Insulation materials	Mineral insulation materials (e.g. stone wool, glass wool)	50%	50%	0%	0%	0%
	Organic insulation materials (e.g. vegetable fibres (like wood, coconut, hemp, flax), cellulose (in bulk or blankets), sheep wool, cork (in bulk or boards))	5%	95%	0%	0%	0%
	Synthetic insulation materials (e.g. polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), phenolic foam, expanded polystyrene (EPS))	5%	95%	0%	0%	0%
Fibre cement products	Fibre cement products (e.g. fibre cement slabs or slates)	100%	0%	0%	0%	75%

Product group / Waste category	Description	Landfill (%)	Incineration[42] (%)	Reuse (%)	Recycling (%)	sorted on building site[43] (%)
Gypsum elements	Gypsum elements (e.g. gypsum blocks, gypsum (fibre/plaster)boards)	80%	0%	0%	20%	50%
Aerated / cellular concrete	Aerated autoclaved concrete (e.g. elements, blocks)	70%	0%	0%	30%	30%
Bitumen	Bitumen (e.g. bituminous roofing, vapour barrier, waterproofing membrane)	85%	5%	0%	10%	0%
Polyolefins (PP, PE)	Polyolefins (PP, PE) (e.g. kraft paper or polyethylene (PE) vapour barrier, ducts), excluding packaging	10%	85%	0%	5%	0%
Elastomers	Elastomers (e.g. EPDM roofing)	90%	0%	0%	10%	0%
PVC	PVC cabling (e.g. electric cables and wire insulation)	10%	40%	0%	50%	0%
	PVC pipes (e.g. for sewerage)[44]	10%	30%	0%	50%	0%
	PVC profiles (e.g. window frames)	10%	45%	0%	45%	0%
	PVC sheets (e.g. PVC roofing, waterproofing membranes (like for swimming pools))	20%	65%	0%	15%	0%
Supple flooring	Supple flooring (e.g. linoleum, fixed carpet, vinyl)	0%	95%	0%	5%	0%
Finishing layers[45]	Finishing layer fixed to stony waste (e.g. plaster (like gypsum plaster, calcareous plaster, loam plaster), paint, coatings, adhesives)	5%	0%	0%	95%[46]	0%
	Finishing layer fixed to wood, plastic or metal (e.g. paint, coatings, adhesives)	0%	100%[47]	0%	0%	0%
Remaining waste	Combustible remaining waste	0%	100%	0%	0%	0%
	Non-combustible remaining waste	100%	0%	0%	0%	75%
Other hazardous waste	Aerosols and kits (e.g. PU foam, silicones)	0%	100%	0%	0%	100%
	Asbestos (bounded, unbounded)	100%	0%	0%	0%	100%
	Fluorescent lamps	30%	0%	0%	70%	100%
	Liquid construction site waste (e.g. paints, adhesives, resins, form mould oil, white spirit)	0%	75%	0%	25%	100%

Waste categories, MMG report of OVAM (2018)

C2: scenario waste sorting

1. Electricity use (Belgian low voltage electricity mix) for mechanical sorting processes:

- Sorting plant without a crusher: 0.0022 kWh/kg material (for materials sorted out prior to the crusher (e.g. mineral wool ,boards, …) or causing no resistance in crushing (e.g. paints)
- Sorting plant with a crusher: 0.0037 kWh/kg material (e.g. concrete materials)

2. Diesel for loading and unloading waste: 5.9 MJ diesel burned in a hydraulic digger/ m3 bulk volume of waste

3. Sorting plant infrastructure including land occupation and transformation and energy for administrative facilities: 1 x 10-10 plant/kg material (NBN 2017).

Waste sorting processes, *MMG report of OVAM (2018)*

C3a: scenario transport to building site

product group/material category	Arrangement of transportation		Means of transportation from							Average transport distance of transportation from		
	% directly from factory to site	% via an intermediary supplier	factory to site			factory to supplier	supplier to site			factory to site	factory to supplier	supplier to site
			Lorry 16-32 ton (EURO 5)	Lorry 7.5-16 ton (EURO 5)	Lorry 3.5-7.5 ton (EURO 5)	Lorry >32 ton (EURO 5)	Lorry 16-32 ton (EURO 5)	Lorry 7.5-16 ton (EURO 5)	Lorry 3.5-7.5 ton (EURO 5)	km	km	km
bulk materials for structural work (e.g. cement, sand, gravel, ...)	75%	25%	100%	0%	0%	100%	90%	10%	0%	100	100	35
poured concrete	100%	0%	100%	0%	0%	n/a	n/a	n/a	n/a	100	100	35
prefabricated products for structural work (e.g. beams, columns, ...)	100%	0%	100%	0%	0%	100%	100%	0%	0%	100	100	35
loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	40%	60%	100%	0%	0%	100%	85%	15%	0%	100	100	35
insulation	40%	60%	100%	0%	0%	100%	85%	15%	0%	100	100	35
finishing products: floor coverings (e.g. carpet, linoleum, ceramic tiles, ...)	10%	90%	90%	10%	0%	100%	90%	10%	0%	100	100	35
finishing products: plasters (e.g. gypsum plaster, external plaster, ...)	40%	60%	50%	50%	0%	100%	50%	50%	0%	100	100	35
finishing products: cabinet work (e.g. window frames, stairs, ...)	90%	10%	50%	45%	5%	100%	40%	50%	10%	100	100	35
finishing products: paints and varnishes	10%	90%	0%	100%	0%	100%	0%	80%	20%	100	100	35
installations (e.g. heating boiler, radiators, ventilation, ...)	0%	100%	n/a	n/a	n/a	100%	0%	80%	20%	100	100	35

Transport to site scenarios, *MMG report of OVAM (2018)*

C3b: e-o-l transport

1. Transportation distances:

- From demolition site to sorting facility or collection point: 30 km
- From collection point or sorting facility to landfill: 50 km
- From collection point or sorting facility to incinerator: 100 km

2. Means of transport:

- 100% with lorry 16-32 ton (EURO 5)

E-o-l transport, *MMG report of OVAM (2018)*

C4: scenario construction waste factors

In the absence of detailed data for each material and each application, but also for practical reasons, a global add-on of 5% has been applied in the model regardless of product group.

Construction waste factors, *MMG report of OVAM (2018)*

C5: scenario maintenance

Name process	Details of process
No cleaning	Nothing/no environmental impact.
Dusting	Manual labour/no environmental impact.
Vacuuming	0,02 kWh of low voltage electricity use per m2 of floor area.
Cleaning with water	5 litre of tap water per 60 m2 of cleaned surface, which equates to 0.083 litre water per m2 of surface.
Cleaning with water and soap	5 litre of tap water per 60 m2 with 1.5 caps of 30 ml of all-purpose cleaner[1] per 60 m2 of cleaned surface, which equates to 0.083 litre water and 0.009 litre cleaner per m2 of surface.
Cleaning with high pressure cleaner	330 litre of tap water and 1,5 kWh of low voltage electricity use per hour of using a high pressure cleaner.
Vacuuming and cleaning with water (and soap)	See details of the separate processes.
Lawn mowing	Diesel consumption and emissions to air from combustion and emissions to soil from tyre abrasion due to using a motor mower with a petrol engine of 8 kW and an operation time of 2 hours per ha mowed area.

Building			MMG2017/TOTEM	
Building part	**Building element**			
	Type	**Composition**	**Cleaning process**	**Frequency per year**
Structure				
Internal walls	Relocatable partition	Glass and full panels	Cleaning with water and soap	12
	Internal wall finish	Plaster	No cleaning	-
		Plasterboard		
		Spray fill		
		Wooden boards		
		Gypsum boards		
		Paint	Cleaning with water and soap	1 (and only 10% of the surface area)
		Wall paper		
		Natural stone tiles		

Maintenance scenarios, TOTEM (2021)

C6 : scenario deconstruction

1. Non-destructive removal

Given that deconstruction often consists exclusively of manual operations, there are no environmental impacts attributed to the non-destructive removal of building materials.

2. Destructive removal

The composition of the materials and the method of connecting with other materials/work sections determined the type of demolition process.

Deconstruction scenarios, *MMG report of OVAM (2018)*

Appendix D

Material thicknesses and additional finishing materials

Materials		
Material	**Thickness (m)**	**Link product sheet**
Metal JUUNOO profiles	0,075	https://www.juunoo.com/wp-content/uploads/2021/05/JUUNOO-Technical-Documentation-ENG.pdf
Glass wool	0,045	https://pim.knaufinsulation.com/files/download/acoustifit_tech-prod_11-2017_nl.pdf
Plasterboard	0,013	https://www.gyproc.nl/producten/gyproc%C2%AE-a
Screws	0,030	https://www.gyproc.nl/producten/gyproc%C2%AE-snelbouwschroeven
Alkyd paint	0,001	https://resources.boss.be/dam?recordid=152130&filename=Technische_nota_TOPSOFT_Nederlands
JUUNOO tape (nylon)	0,002	https://www.juunoo.com/wp-content/uploads/2021/05/JUUNOO-Technical-Documentation-ENG.pdf
Clickwall MDF panels	0,010	https://www.unilinpanels.com/nl-be/interieur/decoratief-plaatmateriaal/clicwall
Gypsum plaster	0,013	https://adammateriaux.be/storage/doc/32/technische-fiche-knauf-goldband-nl.pdf
Ceramic building blocks	0,090	https://www.wienerberger.be/technical-infosheet/wall/Thermobrick%2010N%20-%20Zonnebeke.pdf
Masonry mortar	0,090	https://scheysbeton.be/site/assets/files/1323/1462950444.pdf
Sand-lime blocks	0,090	https://storefrontapi.commerce.xella.com/TD-Silka-Elementen_nl/TD-Silka-Elementen-nl.pdf
Wooden frame	0,075	https://ba-vermeiren.be/droogbouw/
OSB board	0,012	https://www.joostdevree.nl/bouwkunde2/jpgo/osb_6_documentatie_osb3_www_centrumhout_nl.pdf
Traditional metal profiles	0,075	https://medias.knauf.be/docs/files/TECH-PROD/Metalen%20staanderwand_TECH-SYS_W11_11-2019_NL.pdf

Additional finishing materials per wall	
Wall type	**Additional finishing materials**
JUUNOO wall: MDF	Inox corner profile (connection 2 interior walls, connection interior wall and facade) & inox ceiling profile
	JUUNOO tape (connection 2 interior walls) & screws (connection interior wall and facade)
	Antislip tape (rubber), plint, EPDM rubber
Wet wall: ceramic blocks	Connection L-profile (connection 2 interior walls, connection interior wall and facade)
	Silicon kit (interior wall and facade, between 2 interior walls, ceiling, floor)
	Steel lintel, plint
Dry wall: wooden framework	Inox corner profile (connection 2 interior walls, connection interior wall and facade) & inox ceiling profile
	Screws (connection interior wall and facade, 2 interior walls)
	Connection L-profile (connection 2 interior walls, connection interior wall and facade)
	Silicon kit (ceiling, floor)
	Plint

Appendix E

0 refurbishments

	0 years	10 years	20 years	30 years	40 years	50 years	60 years
JUUNOO wall: plasterboard	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Urepl: paint & plasterboard	Urepl: paint	Urepl: paint	E: interior wall
JUUNOO wall: MDF	P: interior wall C: interior wall			Urepl: MDF			E: interior wall
JUUNOO wall: MDF & paint	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Urepl: paint & MDF	Urepl: paint	Urepl: paint	E: interior wall
Dry wall: wooden structure	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Urepl: paint & plasterboard	Urepl: paint	Urepl: paint	E: interior wall
Dry wall: metal studs	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Urepl: paint & plasterboard	Urepl: paint	Urepl: paint	E: interior wall
Wet wall: ceramic	P: interior wall C: interior wall	Urepl: paint	Urepl: paint & plaster	Urepl: paint	Urepl: paint & plaster	Urepl: paint	E: interior wall
Wet wall: sand-lime	P: interior wall C: interior wall	Urepl: paint	Urepl: paint & plaster	Urepl: paint	Urepl: paint & plaster	Urepl: paint	E: interior wall

1 refurbishments

	0 years	10 years	20 years	30 years	40 years	50 years	60 years
JUUNOO wall: plasterboard	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	UrefC: interior wall	Urepl: paint	Urepl: paint	E: interior wall
JUUNOO wall: MDF	P: interior wall C: interior wall			Urepl: MDF (tape) UrefC: interior wall			E: interior wall
JUUNOO wall: MDF & paint	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Urepl: MDF (tape) UrefC: interior wall	Urepl: paint	Urepl: paint	E: interior wall
Dry wall: wooden structure	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Uref: interior wall	Urepl: paint	Urepl: paint	E: interior wall
Dry wall: metal studs	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Uref: interior wall	Urepl: paint	Urepl: paint	E: interior wall
Wet wall: ceramic	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Uref: interior wall	Urepl: paint	Urepl: paint & plaster	E: interior wall
Wet wall: sand-lime	P: interior wall C: interior wall	Urepl: paint	Urepl: paint	Uref: interior wall	Urepl: paint	Urepl: paint & plaster	E: interior wall

2 refurbishments

	0 years	10 years	20 years	30 years	40 years	50 years	60 years
JUUNOO wall: plasterboard	P: interior wall C: interior wall	Urepl: paint	UrefC: interior wall	Urepl: paint	UrefC: interior wall	Urepl: paint	E: interior wall
JUUNOO wall: MDF	P: interior wall C: interior wall		UrefC: interior wall	Urepl: MDF (tape)	UrefC: interior wall		E: interior wall
JUUNOO wall: MDF & paint	P: interior wall C: interior wall	Urepl: paint	UrefC: interior wall	Urepl: paint & MDF (tape)	UrefC: interior wall	Urepl: paint	E: interior wall
Dry wall: wooden structure	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	E: interior wall
Dry wall: metal studs	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	E: interior wall
Wet wall: ceramic	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	E: interior wall
Wet wall: sand-lime	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	Uref: interior wall	Urepl: paint	E: interior wall

3 refurbishments

	0 years	10 years	15 years	30 years	45 years	50 years	60 years
JUUNOO wall: plasterboard	P: interior wall C: interior wall	Urepl: paint	UrefC: interior wall	UrefC: interior wall	UrefC: interior wall	Urepl: paint	E: interior wall
JUUNOO wall: MDF	P: interior wall C: interior wall		UrefC: interior wall	Urepl: MDF (tape) UrefC: interior wall	UrefC: interior wall		E: interior wall
JUUNOO wall: MDF & paint	P: interior wall C: interior wall	Urepl: paint	UrefC: interior wall	Urepl: MDF (tape) UrefC: interior wall	UrefC: interior wall	Urepl: paint	E: interior wall
Dry wall: wooden structure	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Uref: interior wall	Uref: interior wall	Urepl: paint	E: interior wall
Dry wall: metal studs	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Uref: interior wall	Uref: interior wall	Urepl: paint	E: interior wall
Wet wall: ceramic	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Uref: interior wall	Uref: interior wall	Urepl: paint	E: interior wall
Wet wall: sand-lime	P: interior wall C: interior wall	Urepl: paint	Uref: interior wall	Uref: interior wall	Uref: interior wall	Urepl: paint	E: interior wall

Legenda	P: production phase	C: construction phase	Uref: use phase refurbishment	All materials replaced Except insulation material reused	UrefC: use phase refurbishments	All materials reused Except paint & plasterboard replaced	Urep: use phase replacements	E: end-of-life phase

FACULTY OF ENGINEERING
AND ARCHITECTURE

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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in de ingenieurswetenschappen: architectuur

Academic year 2021-2022

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