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Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context

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Abstract

In construction, the focus of research and policy on sustainability broadened from reducing the energy consumption of a building in use, to a comprehensive sustainability strategy considering the building's entire life cycle. However, the implementation of life cycle thinking (and its operational counterpart the circular economy) in combination with an objective sustainability evaluation is still in its infancy. Therefore, the aim of this study is twofold. First, it is illustrative for the quantified assessment of the potential environmental and financial benefits and burdens of introducing circular design alternatives for internal wall assemblies to the Belgian market. Second, it reviews the methodological implications on the results of a consequential life cycle assessment (LCA) and a life cycle costing (LCC), acknowledging the time dependence and closed-loop nature of those circular design alternatives. That aim is achieved through a multi-model set-up. Evaluating the design alternatives through various methodological assumptions and service life models, allows understanding the relevance and robustness of the results by acknowledging the corresponding uncertainty.

In total seven alternative wall assemblies are assessed over a period of 60 years, with a refurbishment every 15 year.

The results, without considering the impact of biogenic CO_2 nor the influence of thermal mass, show that a low life cycle impact can be achieved for assemblies that are designed to be used again and have a higher initial impact, such as a plywood boarding connected in a reversible way to demountable metal frame substructure, as well as for assemblies with no possibilities for direct reuse that have a low initial impact, such as a drywall system with a wooden substructure. In addition to the environmental assessment, the life cycle cost of the demountable and reusable wall assemblies with a metal substructure is 10 and 17% lower than that of the conventional alternative with the lowest life cycle cost. Further, regarding the methodological scenarios on marginal supplier identification in the consequential LCA, the range of possible outcomes is however much larger for the demountable wall assemblies than for the conventional ones. For the conventional wall assemblies there is only a small divergence in results of around 10% between the scenarios, while for the demountable ones this deviation rises to 25%. Altogether, this case study points out the potential benefits of introducing demountable and reusable walls, but highlights at the same time the need for a comprehensive sustainability assessment before responsible conclusions can be drawn.

Keywords

Life cycle assessment, Life cycle costing, Circular economy, Construction sector, Uncertainty

Highlights

- Structured consequential LCA and LCC of seven alternative internal wall assemblies
- Exemplary comparison of conventional with demountable and reusable wall assemblies
- Environmental performance of demountable solutions performs at least similar
- Demountable solutions are financially feasible taking a life cycle perspective
- Design-determining differences up to 25% between methodological scenarios

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1 Introduction

During the last decade, the focus of researcher and policy makers addressing the construction sector broadened from reducing the energy consumption of a building in use, to a comprehensive approach considering the building's entire life cycle (Buyle et al., 2013; Cabeza et al., 2014). Following that shift, the present case study questions the methodological implications of consequential life cycle assessment (LCA) as a sustainability analysis in the construction sector. Therefore, it studies model uncertainties through a multi-model approach, while contributing to practice by illustrating the potential environmental benefits and financial feasibility of alternative wall assemblies that are designed for the circular economy in the Belgian context.

Due to the increasing requirements for the insulation level of the building's shell and the energy efficiency of its technical services, the share of all material-related environmental impacts gained importance, both in relative and absolute terms (Blengini and Di Carlo, 2009). In reaction, several studies aimed at finding a balance between energy efficiency and the corresponding material impact (Buyle et al., 2015; Himpe et al., 2013; Zuo et al., 2017). Simultaneously, the idea of the Circular Economy (CE) has been gaining momentum. The CE aims to overcome the divergent interests of economic and environmental prosperity by closing material loops through technological innovation, including recycling and reuse, as well as by introducing new business models, relying on sale-and-take-back or lease contracts (Ellen MacArthur Foundation, 2015).

Despite these efforts in building related research and development, the implementation of circular economy thinking in the construction sector is still in its infancy. It is mainly limited to minimising waste and maximising recycling as is illustrated by literature (Esa et al., 2017; Gillabel et al., 2016; Guo et al., 2017; Haneef et al., 2017; Jiménez-Rivero and García-navarro, 2017). Nevertheless, also more radical experiments are conducted and adopted in the academic debate. They optimise the valorisation of materials at the end of their first functional service life, e.g. by considering existing buildings as material banks ("Buildings As Material Banks," 2018; Miatto et al., 2017; Ortlepp et al., 2016) or by designing demountable and reusable building elements (Debacker et al., 2015) such as internal walls (Paduart et al., 2015a, 2015b).

Although promising, increasing circularity does not automatically lead to more sustainable products and buildings. For example, using construction waste as an input for other production processes not necessarily guarantees a reduction of the related environmental impact (Zink and Geyer, 2017). Given its prominence in academic research and policy documents, it is thus important that the concept of a circular economy is subject to critique and is assessed quantitatively (Gregson et al., 2015). Starting from a life cycle perspective, established methods for a quantitative impact assessment such as life cycle Assessment (LCA) (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) and life cycle costing (LCC) (Hoogmartens et al., 2014) proved their value for making well-informed design and construction choices and justifies their selection as a methodological basis for the present case study. However, there is not just one way of performing an LCA or LCC study despite the existence of a general framework, for example ISO 14040/44 for LCA. Still, many assumptions and methodological choices must be made throughout a study, which have an impact on the results (International Organisation for Standardization, 2006a, 2006b).

Often, attributional and consequential modelling in LCA are considered the two main modelling approaches and many definitions emerged over time describing their differences (Curran et al., 2005; Ekvall and Weidema, 2004; Weidema, 2003; Zamagni et al., 2012). Generally, attributional LCA is defined by its focus on describing the environmentally relevant flows within the chosen temporal window, while consequential LCA aims at describing how environmentally relevant flows will change in response to possible decisions. In the case of attributional LCA, contributions are traced backwards in time, making use of data on specific or market average suppliers at a certain moment. Consequential LCA on the other hand is market based, taking the actual affected suppliers into account.

Against the background of assessing the transition towards the Circular Economy, the market-based and change-oriented nature of the consequential approach is of great interest: it allows making environmentally responsible policy and design choices. Although its importance is already acknowledged from a theoretical point of view, to date, there is a lack of consequential LCAs evaluating and illustrating their relevance for the construction sector (Buyle, 2018). Complementary, the financial consequences will determine the initial and long-term feasibility of moving towards a Circular Economy (Klöpffer and Ciroth, 2011). Therefore, the present case study questions the methodological relevance and implications of consequential life cycle assessment and life cycle costing as a sustainability analysis of alternative building element assemblies for the circular economy in the Belgian context.

Making methodological choices, as it was introduced above, is nevertheless more complex than opting for consequential LCA and for LCC as defined by the ISO standard 15686-5. A literature review illustrates that, for example, the way the goal and scope of an LCA are defined can affect how marginal suppliers (Sacchi, 2018; Schmidt and Thrane, 2009) and substitution routes (Sevigné-Itoiz et al., 2015) are identified, whether or not elasticities of supply and demand should be taken into account (e.g. equilibrium models (Rajagopal, 2017)), if a process-based LCA must be replaced by an environmental Input-Output LCA (Crawford, 2008; Yang et al., 2017), etc. Academic discussions debating the most appropriate system model to answer specific research questions are abundantly available. Yet, very few studies account for the model uncertainties resulting from the selected method, though it can have a major effect on the resulting design choices (Buyle et al., 2017).

Only recently, the innovative assessment concept of a multi-model approach has been proposed in academic literature: evaluating collectively the results of multiple system models instead of relying on a single (class of) model(s) (Yang and Heijungs, 2018). When the predictions of several models are pointing in the same direction, they provide a more reliable indication of what could occur, whereas a lack of unanimity between models makes any outcome uncertain and the decision unreliable. A multi-model approach thus offers added value by providing more information and knowledge revealing risks in making decisions in these cases (Charles F. Manski, 2013). Adopting this approach, the present case study aligns with similar evaluation methods that can be found in, for example, the integration of divergent building transformation scenarios in life cycle cost analyses (Galle et al., 2017b) and environmental decision making (Mahmoud et al., 2009), and builds further on the academic debate on model uncertainty in environmental and financial life cycle assessment. A multi-objective optimisation as suggested by Zavala et al. (2014) and implemented by Yepes et al. (2015), might allow for increasingly holistic design insights, but extends beyond the objectives of the present case study.

In this context, the concrete goal of the present study is to assess the potential environmental benefits and burdens of introducing circular design alternatives for internal wall assemblies to the Belgian market. Therefore, this assessment is realised by performing a consequential LCA and an LCC analysis, acknowledging the time dependence and closed-loop nature of those design alternatives and the effect on the analysis outcomes of making specific modelling choices by adopting a multi-model approach. The corresponding objectives of this case study are (1) to collect alternative internal wall assemblies, (2) to introduce various LCA modelling approaches to understand the relevance and improve the robustness of the results and to explicitly account for the corresponding modelling uncertainty, (3) to include multiple end-of-life scenarios to address the uncertainty regarding future life cycle interventions and technical evolutions and (4) verify the financial feasibility of the alternative internal wall assemblies based on an LCC analysis.

For this case study, seven internal wall assemblies are assessed. To provide a sound basis for comparison, these assemblies include both conventional and demountable alternatives, which can be categorised as (1) conventional (or 'static') solutions, designed for a typical linear service life with a waste-generating refurbishment and end-of-life scenario, and (2) demountable and reusable (or 'dynamic') solutions, designed with a high reclaim and reuse[1] potential at the end of their functional service life.

2 Methods

As introduced above, in this case study LCA aims at validating the potential environmental savings associated to design choices that foster a circular economy with insight in the related methodological and contextual uncertainties and is complemented with an LCC analysis to verify the choices' financial feasibility and sustainability. When introducing alternative assemblies for internal walls in the idea of the circular economy, all possible and relevant consequences of choosing one alternative over the other should be considered when evaluating and comparing their environmental profile. In this regard, consequential LCA seems an appropriate approach to support well-informed decision making. In the present case study the theoretical framework of Weidema et al. (2009) was followed. This implies that only small and medium scale changes in demand and long-term effects were considered, assuming perfectly elastic markets. Within this methodological system delimitation, all wall assemblies and their alternatives are equivalent and compared with respect to the following functional unit:

> *a 1m² space dividing wall (non-load bearing) that meets, during a period of 60 years, Belgian requirements for energetic and acoustic performance of residential, school and office buildings.*

The definition of the functional unit is based on technical requirements only and is presented in detail in the Electronic Supplementary Material. Other functional requirements such as aesthetics at the scale level of the element, and hydro-thermal comfort at the building level are not considered in the

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[1] In this study the distinction is made between materials and components that are used again *directly* and *indirectly*. In the first case, they are applied in same building without additional treatment or transportation. In the second case, they are applied in another building or for another application, requiring at least extra transport.

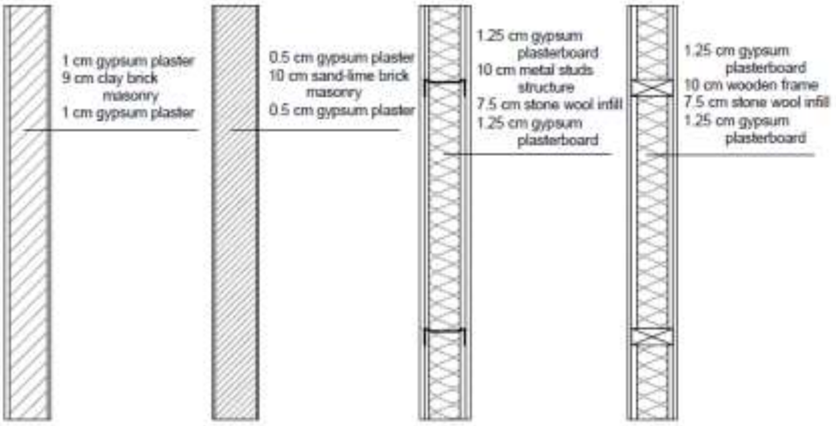
present case study as they are highly user, time and context dependent. For example, no attention has gone to the visual aspects of the finishing layer: a smooth and seamless paintable surface as well as a wood texture with visible seams and screws are considered. Neither the thermal inertia, nor the resulting energy performance was considered. Such consequences must be verified for every individual building and its context, and could be evaluated with, for example, a dynamic thermal simulation. This simplification will have only a minor effect on the results, as recent research concluded that the thermal inertia of a construction is only a minor parameter for the construction design in the moderate Belgian climate (Verbeke, 2017; Verbeke and Audenaert, 2018).

2.1 Case study and modelling the use phase

The present case study includes seven wall assemblies that have divergent specifications, but meet the same technical requirements. The first four alternatives (i.e. Wall 1 to 4) resemble the most commonly applied wall assemblies in the Belgian construction sector (Janssen et al., 2010). Masonry walls and drywall systems are regularly applied in residential, school and office projects in Belgium. They are well-documented by technical directives and product documentation, and are selected for that reason. These assemblies can be considered as 'static' building solutions. They do not follow any design guideline related to the circular economy, but they will serve as a reference when evaluating the environmental profile and financial feasibility of the alternative wall assemblies. Alternatives in the present cases study, i.e. Wall 5 to 7, feature a wood-based boarding, each time supported by a different demountable substructure. These assemblies are proposed by the authors following earlier prototyping by Paduart et al. (2015a, 2015b). They are not common practice but fulfil the same requirements as Wall 1 to 4. The fifth alternative consists of prefabricated wooden boxes and the sixth and seventh alternative include a single-profile and an assembled metal frame substructure. These assemblies can be considered as 'dynamic' building solutions following the design guideline for the circular economy (Debacker et al., 2015): the substructures are demountable, the boarding is connected in a reversible way and all components resist the wear and tear of repeated disassembly and reuse (e.g. plywood instead of gypsum board). An overview of all alternatives is presented in Table 1; full details can be found in the Supplementary Material.

Wall name	Substructure	Finishing
Wall 1. Clay brick masonry	Extruded clay bricks, cement mortar	Plaster, paint
Wall 2. Sand-lime brick masonry	Sand-lime bricks, adhesive mortar	Skim coat plaster, paint
Wall 3. Drywall - metal frame structure	Metal frame structure, stone wool filling	Gypsum plasterboards, gypsum putty (wet lining joints), paint
Wall 4. Drywall - wood frame structure	Timber frame structure, stone wool filling	Gypsum plasterboards, gypsum putty (wet lining joints), paint
Wall 5. Woodbox wall	Prefabricated wooden boxes (wood frame, OSB cover) filled with stone wool, attached with steel profiles	Plywood boarding, varnish
Wall 6. Cross-shaped metal frames	Structure composed of demountable cross-shaped steel profiles, stone wool filling (after Paduart et al., 2015)	Plywood boarding, varnish
Wall 7. Combined L-shaped metal frames	Structure composed of combined L-shaped steel profiles, stone wool filling (after Paduart et al., 2015)	Plywood boarding, varnish

Table 1 Overview of the composition of the wall assemblies

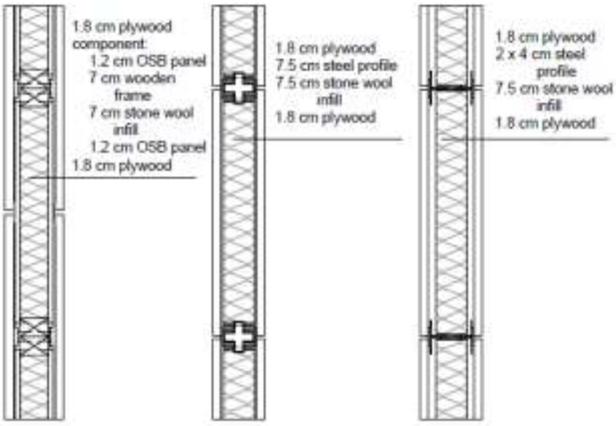


Wall 1. Solid clay brick masonry

Wall 2. Solid sand-lime brick masonry

Wall 3. Drywall on metal stud structure

Wall 4. Drywall on wood frame structure



Wall 5. Woodbox wall

Wall 6. Cross-shaped metal studs

Wall 7. Combined L-shaped metal studs

Fig. 1 Conceptual representation of the analysed wall assemblies

All walls meet the Belgian requirements for residential, school and office buildings regarding their energetic and acoustic performance. It is important to note that the studied alternatives do not have the same technology readiness level (TRL) (Bayus, 1998; European Commission, 2014). The conventional wall assemblies are mature systems that have proven their value over a long period. They have been thoroughly tested and it is safe to say that, if executed properly, they will meet all requirements (TRL 9). The demountable assemblies are still at an early development stage (TRL 2-3), with only a few prototypes realised. For these assemblies, no certificates are available and only some preliminary tests have been performed (Paduart et al., 2015). However, a space dividing wall assembly with demountable and reusable components is already commercially available. It is certified regarding its fire safety and acoustic performance (tecnibo, 2017). This system relies on a similar concept as Wall 6 and 7, as it consists of metal frames filled with stone wool insulation and is covered with a single panel at each side. Therefore, it can be assumed that even if no certified data are available for Wall 5 to 7, they too could meet all requirements of the functional unit and are thus sufficiently representative to be considered in the present case study.

The studied period is 60 years, which corresponds to the estimates in other Belgian research of the average (functional) service life of residential buildings; a market characterised by individual ownership and a large number of renovation and renewal initiatives (Debacker et al., 2013; Heylen et al., 2007; Himpe et al., 2013). Individual components can have a shorter service life though. For the classification of the repair and replacement routines, additional guidance documents specific for the construction sector were followed, namely EN 15804 and EN 15978, both developed by CEN TC 350. They introduce a modular methodological structure with more specific calculation rules than the ISO 14040-series and aim at facilitating the integration of Environmental Product Declarations (EPDs) of construction products in studies at building level (European committee for Standardiation, 2012, 2011). This is however an attributional framework that does not fit the goal and scope of this case study. Nevertheless, its clear classification of different life cycle stages is instructive and will be maintained for the LCA (use phase only) and LCC assessments in the present case study.

For the present study, the use and application of the construction products of which the wall alternatives are composed, include no relevant impacts (life cycle stage B1), and their maintenance (stage B2) is negligible. Replacement rates due to smaller repairs (stage B3) and the interaction between complete replacements (stage B4) and refurbishments with possible reuse (stage B5) are derived from Galle (2016). The repair regimes are defined by a periodicity, extensity and intensity and are evaluated component by component considering their form and material properties. For instance, damage can happen rarely or frequently (periodicity) and be local or widespread (extensity). In case of damage a component can be replaced entirely or partially (intensity). Technical replacements are based on the components' estimated service life[2] derived from BCIS (2006) (UK), while an average periodicity of 15 years is assumed for refurbishments as described by Galle (2016). During a functional refurbishment, maximising the reuse of each component is a material efficient construction strategy and reflects the potential savings of building according to closed material loops. The number of times a wall can be used again is nevertheless limited by its reversibility and the estimated service life of its components. For example, if the substructure of a reversible wall would have a service life of for example 30 years and it is assumed that refurbishments take place every 15 years, that wall can be reused once. The next time a refurbishment is needed, the substructure reaches the end of its service life and must be disposed of, for example by recycling. A similar reasoning applies to the third intervention and at the end of the building's service life. This is also schematically represented in Fig. 2.

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[2] In this study all components' estimated service life is taken from international datasets without considering user, time and context specific aspects (cf. definition of the functional unit in section 2 *Methods*). For considering the impact of the component quality, design level and work execution level, of the indoor and outdoor environment, and of the in-use condition and maintenance level, the factor method of ISO 15686-1 could be used.

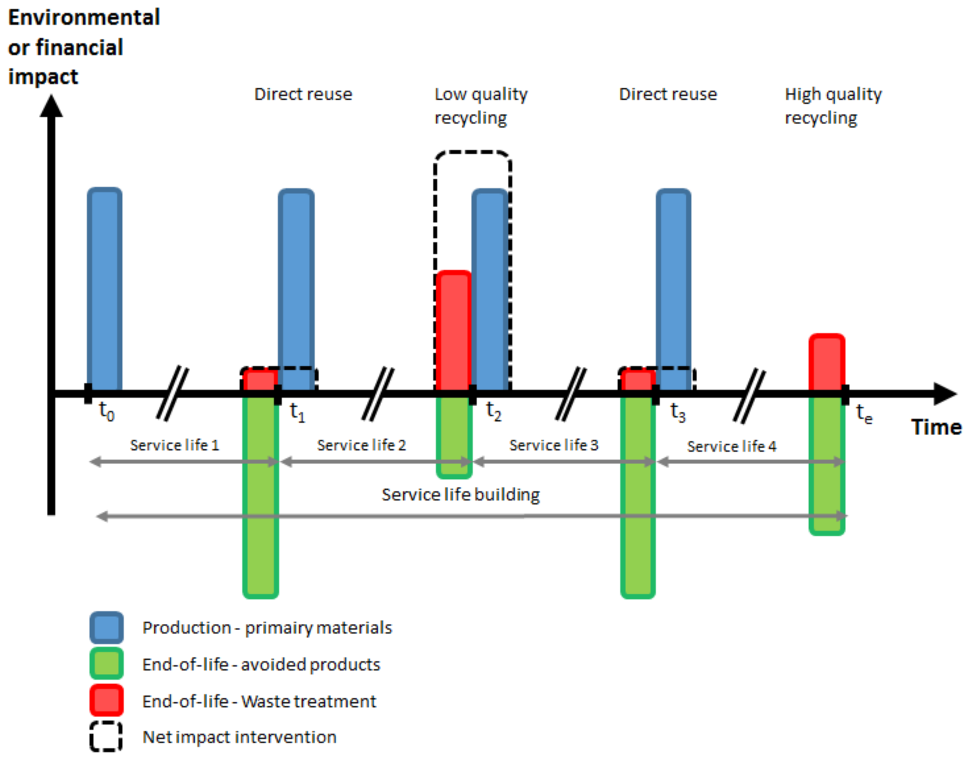


Fig. 2 Conceptual representation of life cycle replacements and the modelling approach

2.2 Inventory analysis and scenario description

In consequential modelling, the life cycle inventory for the environmental analysis is based on how the flows and activities are affected by a change in demand for a product or a process. In this case study, it is assumed that the production of the wall assembly together with the following replacements will lead to an increased (or decreased) demand for raw materials and energy. Following the end of each component's service life and its replacement, the removed material also needs further treatment. This can include waste treatment, but if the used materials still have a residual value they can be recycled or, in the ideal case, used again directly. The previous concepts can be linked to two of the most important aspects of consequential modelling, namely (1) the identification of marginal suppliers (i.e. the activities affected by a change in demand) and (2) the substitution of non-determining by-products on the market. In this fashion, as advised in ISO 14044, allocation can be avoided (ISO, 2006b). The concept substituting by-products applies to the end-of-life scenarios as well, where benefits of recycling and energy recovery are considered. The double counting of recycling benefits is avoided as only primary input materials are considered, given the constrained supply of secondary materials. Previous assumptions can also be explained in the context of supply- or demand driven production systems (Prosman and Sacchi, 2016). The production of goods is a typical example of a demand-driven system, the treatment at the end-of-life of a supply-driven system. The supply of discarded products is constrained by the consumption and disposal of the primary product it derives from and therefore cannot react to a change in demand (Ekvall and Weidema, 2004). This study focusses on the demand side of the circular economy, with wall assemblies designed to facilitate future reuse, remanufacturing and recycling in future, which explains the choice for recycling benefits over recycled content. Considering also the supply side and assessing both the consequences of recycled content and recycling benefits in separate scenarios could make this comparative LCA even more accurate. The life cycle inventory for the financial analysis also considers the production and installation of components, as well as their end of life transport and treatment. Economic consequences of change in demand for raw materials and energy are however not modelled in the financial feasibility analysis.

Given the importance of marginal supplier identification, substitution and the end-of-life practice for the resulting life cycle impact, multiple scenarios are included: four methodological scenarios regarding the identification of marginal suppliers and five end-of-life scenarios. The substituted activities and the avoided products are always the marginal ones (Weidema et al., 2009). Consequently, the methodological scenarios affect all life cycle stages including the end-of-life stage. An overview is presented in Table 2.

Assembly properties	**Affected life cycle stages**	**Method. scenarios**	**Relevant end-of-life scenarios**				
		All	**{Bau}**	**{En}**	**{Rec 1}**	**{Rec 2}**	**{Reuse}**
Conventional	Production	x	-	-	-	-	-
	B3, B4, B5, final disposal	x	x	x	x	-	-
Demountable	Production	x	-	-	-	-	-
	B3, B4, final disposal	x	x	x	x	x	-
	B5	x	x	x	x	x	x

Table 2 Overview included relevant end-of-life scenarios per life cycle stage and assembly type. {Bau}: Business-as-usual, {En}: Maximal energy recovery, {Rec 1} First optimisation recycling, {Rec 2}: Second optimisation recycling, {Reuse}: Maximized reuse

Methodological scenarios in LCA: marginal supplier identification

The identification of the marginal suppliers can have a major effect on the final results of an LCA study (Buyle et al., 2017; Lund et al., 2010; Mathiesen et al., 2009; Schmidt and Weidema, 2008). The two most important steps in the procedure of Weidema et al. (2009) are the delimitation of geographical market boundaries and a systematic identification of market volume trends to identify the suppliers the most sensitive to a change in demand. Two approaches to identify geographical market boundaries are included, proposed by Buyle et al. (2017) and Pizzol and Scotti (2017). The first approach is a bottom-up approach based on an iterative procedure (referred to as scenario [IT]) is starting from the specific location of the change in demand, using trade and production data. The central concept is to define market boundaries by comparing the traded volume of a product to the total production volume of a market. The underlying idea is that if a traded amount is small compared to the total production volume of a market, it can be assumed that the contribution of that partner country can be neglected and the country therefore does not need to be included within the geographical market boundaries. In this procedure, values for two parameters need to be selected. The outcome of the procedure is compared to a chosen value, the first parameter T_{market}. If the result is higher than T_{market} the evaluated import is considered as relevant and the exporting country will become part of the geographical market, otherwise it is not. For this parameter, a value of 0.25% was selected. Previous research pointed out that this can be interpreted as a study of almost all potential suppliers, assuming that the existence of a trade link is a sufficient precondition to react to a change of demand (Buyle, 2018; Buyle et al., 2017). The second parameter T_{year}, for which a value of 75% was selected, represents the required minimum frequency a supplier should be included in a market over the analysed period (11-13 years depending on the data availability of a specific product). Previous research pointed out that markets are relative stable over the analysed period, so the value of 75% for T_{year} is set to exclude errors and unrealistic outliers in the input data (Buyle, 2018; Buyle et al., 2017). More details on the method and the effect selecting specific values for both parameters can be found at Buyle et al. (2017) and Buyle (2018). The second approach is a top-down approach based on a network analysis (referred to as scenario [NA]) applied to global trade data where the clusters represent geographical markets. More info can be found in Pizzol and Scotti (2017).

Next, the suppliers the most sensitive to a change in demand are identified. Within a stable or growing market, suppliers are evaluated based on their potential for expanding production capacity, which is a proxy of their competitiveness. In this case study the trend in production volume was chosen as a criterion, under the assumption that the suppliers yielding the largest increment in production volume are the most competitive ones. The trend in production volume was calculated by applying a linear regression analysis to the time series of yearly production data. Based on this calculation principle, the marginal suppliers were tracked down using two types of data. The retrospective approach (referred to as RETRO) is based on historical data available from statistical agencies, reflecting current trends (see section 2.3). The prospective approach (referred to as PRO) is based on forecasted data obtained from other models, reflecting expected trends. The retrospective approach is characterised by a high availability of data with a low level of uncertainty. A key assumption in this case is that historical trends are representative for future situations. The prospective approach relies on forecasting models. They can provide a more nuanced image of expected future developments and they are relevant when a structural reformation of a segment of the economy can be expected. Yet, future predictions are per definition uncertain.

A pairwise combination of the previous approaches results in four methodological scenarios: RETRO[IT], RETRO[NA], PRO[IT] and PRO[NA].

End-of-life scenarios

The seven wall assemblies have a different end-of-life potential, varying from direct reuse to demolition with limited recycling potential. However, what will happen is highly context and also user dependent, and might not yield the expected benefits. To illustrate what could happen, five possible end-of-life scenarios are considered. For the modelling of these end-of-life scenarios, the Belgian reference study for LCA in the construction sector, namely *Environmental Profile of Building elements* (EPBE) (Debacker et al., 2013), was followed as guideline. This attributional study applies a cut-off approach, yet it contains relevant information about the current Belgian practice concerning the pre-processing of disposed products and the share per treatment process. The pre-processing includes onsite sorting, transport and pre-treatment at a collection point or sorting facility, while the share per treatment process affects the distribution between landfill, incineration and recycling. Fig. 3 shows a scheme of the general modelling of waste processing after deconstruction or demolition. Percentages per waste type and an overview of the avoided materials can be found in the Electronic Supplementary Material. It is based on the EPBE study, but it is adapted to include the substitution of recycled products. The five scenarios are briefly described below (for more details see Supplementary Material).

- Business-as-usual {Bau}: This represents the current practice in Belgium, as described in the Belgian LCA reference study for in the construction sector EPBE.
- Maximised energy recovery {En}: All combustible waste is sent to waste incineration plants featuring energy recovery. For non-combustible waste the {Bau} scenario is applied.
- Improved recycling {Rec 1}: An improved recycling practice is assumed, based on higher recycling rates compared to the {Bau} scenario, anticipating future technological developments.
- Optimised recycling {Rec 2}: This is a further improved recycling practice, including higher recycling rates and off-site reuse, enabled by Design for Change.
- Maximised reuse {Reuse}: Components are used again directly in the same building without any additional treatment or transport; a 5% material loss in considered for every refurbishment with direct reuse.

Not all scenarios apply to every wall alternative (see Table 2). For the conventional walls, only the three most conservative scenarios can be included. Direct reuse of the components is technically not possible in those cases as they cannot be disassembled, so both the most advanced recycling scenario {Rec2} and the {Reuse} scenario are excluded. The inclusion of {Rec2} is justified as soon as the substructure is demountable while the {Reuse} scenario can only be included for wall assemblies with a demountable and reusable finishing too. Furthermore, per wall assembly, scenarios may be omitted if they turn out to be irrelevant. For instance, the scenario on maximizing the energy recovery is excluded in the case of masonry walls.

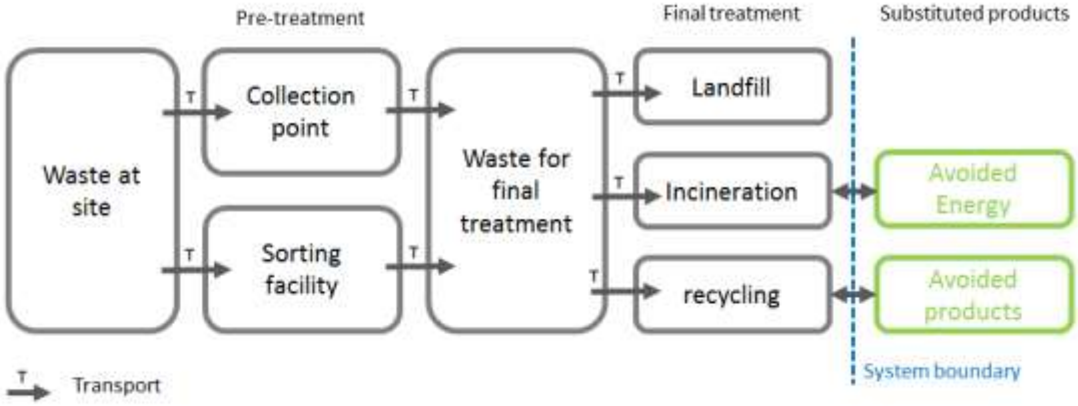


Fig. 3 General modelling of waste processing after deconstruction or demolition, modified from the EPBE study *(after Debacker et al., 2013)*

2.3 Data collection and modelling

In the methodological scenarios for LCA, marginal suppliers are identified at country level. The required trade and production data are derived from statistical agencies such as FAOSTAT, EUROSTAT and UN Comtrade (Eurostat, 2018; FAO, 2018; United Nations, 2016). The only exception here is electricity, for which the marginal technologies per country were identified. Only domestic production is included, which is the default assumption in the ecoinvent consequential system model too (Weidema et al., 2013). This results in identical retro- and prospective electricity mixes for both the [IT] and [NA] scenarios.

Country specific life cycle inventories (LCIs) were built for all identified marginal suppliers. The ecoinvent database v3.3 was used to model background processes and its principle of separating *market* and *production* processes was also applied in this case study (Weidema et al., 2013). Country specific markets include the mix of identified marginal suppliers and the corresponding transport modes and distances, with respect to the location of supply and demand. For the production processes, ecoinvent records were used as a starting point, while data on the marginal mixes of fuels and energy production were modelled in detail for all materials, e.g. electricity, gas, coke and coal. Furthermore, in the case of wood-based products, more specific data were added, among which the production yields and the direct land use based on the climate zone, the dominant species and the forestry practice of the supplying countries. Finally, the marginal mixes of the most important raw materials were modelled in detail. For instance, Poland is a marginal supplier of the Belgian market for gypsum plasterboards, so the marginal gypsum suppliers for the Polish market were identified as well. However, prospective data were not always available, they are missing for bricks and gypsum-based products among others. But, most of these materials have a low price-to-mass ratio with small geographical market boundaries. So, in these cases the retrospective scenario was assumed to be a relevant proxy. A complete overview of all used data can be found in the Supplementary Material.

Consistent to the adopted LCC assessment procedure (Davis Langdon Management Consulting, 2010) and corresponding standards (ISO, 2008), the financial impacts of the alternative wall assemblies are studied per life cycle stage as discussed above. The residual value of disassembled components, approximated by a straight-line depreciation of the components' initial material cost over their estimated service life, at the end of the period of analysis is evaluated too, but due to discounting and the long-term perspective of this study too small to influence the results.

2.4 Impact assessment

To quantify environmental impacts two approaches can be identified, namely the problem-oriented (midpoints) and damage-oriented (endpoints) ones (Ortiz et al., 2009). The results of the latter are easier to understand, but tend to be less transparent and more subjective (Blengini and Di Carlo, 2009; Finnveden et al., 2006). To facilitate interpretation of the effect of methodological choices in the LCI modelling on the results, a single score indicator is applied, namely ReCiPe v1.13. This method implements both midpoint and endpoint categories and contains a set of weighting factors allowing the calculation of a single score impact. The default perspective, namely the hierarchist ReCiPe version with European normalisation and average weighting set, was applied. Previous research pointed out the importance of the choice of impact method. Similar to the ReCiPe method and LCA standards like EN15804 (CEN, 2018), biogenic CO_2 is not accounted for under the assumption that the uptake equals the emissions over the entire life cycle. However, land use change effects, static or dynamic account of carbon fluxes, the choice of climate indicator and time horizon applied all have an effect on climate impact results (De Rosa et al., 2018). The main goal of this case study is to evaluate different modelling approaches, no sensitivity analysis is added by using various impact methods (Buyle et al., 2013; Finnveden et al., 2006; Schmidt and Pizzol, 2014). However, in addition to the single scores results of all midpoint impact categories are included in the Electronic Supplementary Material. More information about the selected impact assessment method can be found in literature (Goedkoop et al., 2013; PRé, 2013; Sleeswijk et al., 2008).

For the LCC study, the considered impacts include labour, material and equipment costs and are taken from the extensive database of average contractor prices in Belgium (ASPEN, 2014a, 2014b). For non-conventional building product, in particular the tailor-made metal frames for the cross-shaped metal substructures (Wall 6), the labour cost of a conventional metal frame was combined with its material price adjusted to correspond with the necessary steel quantity in mass. In the assessments below, these impacts are inflated at an annual nominal growth rate of 2,2%, 3,6% and 2,5% respectively to take into account long-term price evolutions and are discounted at a nominal rate of 4% to take into account time preference, risk and loss aversion, as well as endowment and other psychological factors reflecting people's economic behaviour during the aspired feasibility analysis (Galle, 2016).

2.5 Sensitivity analysis

Given the uncertainty regarding future life cycle interventions, two additional refurbishment scenarios are included as a sensitivity analysis. In the general scenario, a refurbishment is assumed each 15 years (B5). In the extra scenarios, two more extreme situations are described, with a refurbishment each 5 or every 30 years. The interaction with replacements for technical reasons (B4) is modelled identically in all three use phase scenarios, based on the estimated service life of the materials (Galle et al., 2017a). Repairs (B3) are not affected by the extra use phase scenarios, as these only cover occasional repairs.

3 Results

This section presents the results of both the environmental and the financial analyses. For the environmental analysis, the life cycle impact that takes into account the total service life and the end-of-life scenarios will be presented first and afterwards, the effect of methodological scenarios on these results will be discussed. After the assessment of the assemblies' financial feasibility, this section will be completed with the results of the sensitivity analysis on the pace of future refurbishments.

The wall assemblies are assessed over the studied period of 60 years, with a refurbishment each 15 years. The conventional walls serve as a reference. To enhance the readability of the graphs, the impact of the end-of-life treatment and the avoided products are added up to a single number. Also, the data of repairs (B3) and replacements (B4) are summed, given the small contribution of repairs. The non-aggregated results for all wall assemblies can be found the Supplementary Material.

3.1 Environmental analysis

Initial impact

Interpreting first the environmental impact of the initial construction phase, conventional Wall 1 to 4 have a lower initial impact compared to the ones with a demountable substructure (see Fig. 4). Comparing the demountable wall assemblies with Wall 4, i.e. the conventional assembly with the lowest impact, the initial impact is a factor of 4.8 to 5.8 higher for Wall 5. 3.5 to 4.1 for Wall 6 and 3.7 to 4.4 for Wall 7. The ranges represent the outcomes based on the different methodological scenarios, which will be discussed in the next sections.

The largest share of the demountable assemblies' environmental impact is related to the plywood boarding. This boarding is identical for the three alternative wall assemblies, so the discrepancies in initial impact between Wall 5 to 7 can mainly be explained by their different structural system. The frames of the wooden boxes of Wall 5 have a lower impact compared to the metal studs of Wall 6 and 7, but an additional layer of OSB is required to close them in a reversible way. All in all, this results in a higher initial impact of Wall 5 compared to the two other demountable wall assemblies. The lower impact of Wall 6, compared to that of Wall 7, is a direct consequence of the first's slimmer profiles. The fact that in Wall 7 steel profiles with standardised sections are applied, can be seen as a practical benefit, but has no environmental advantages.

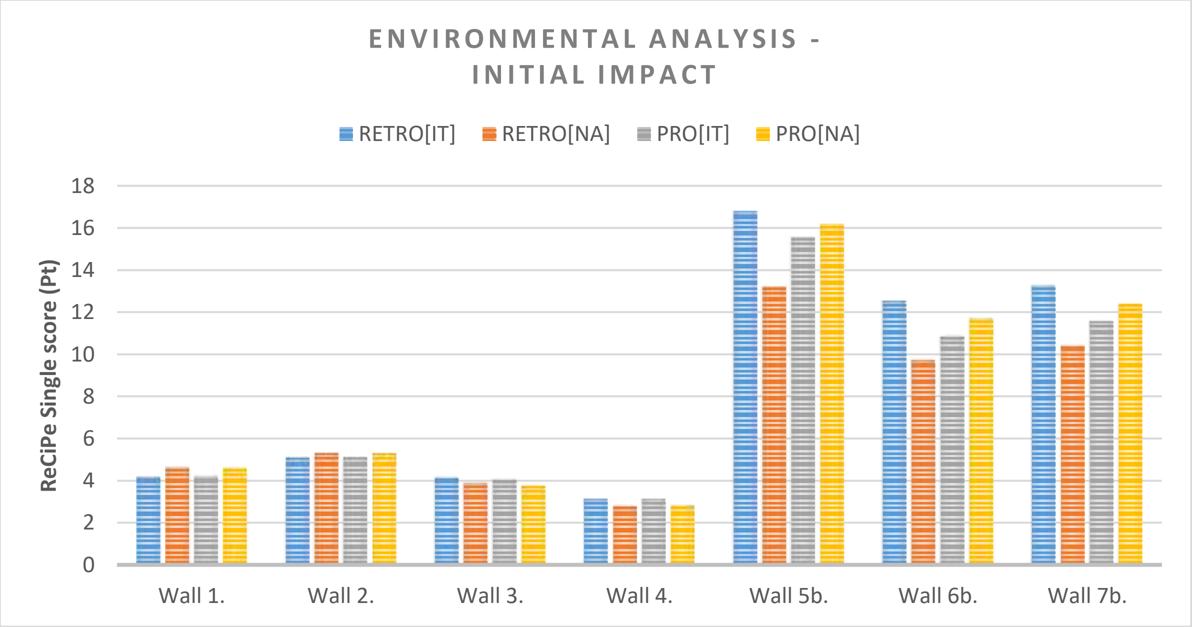


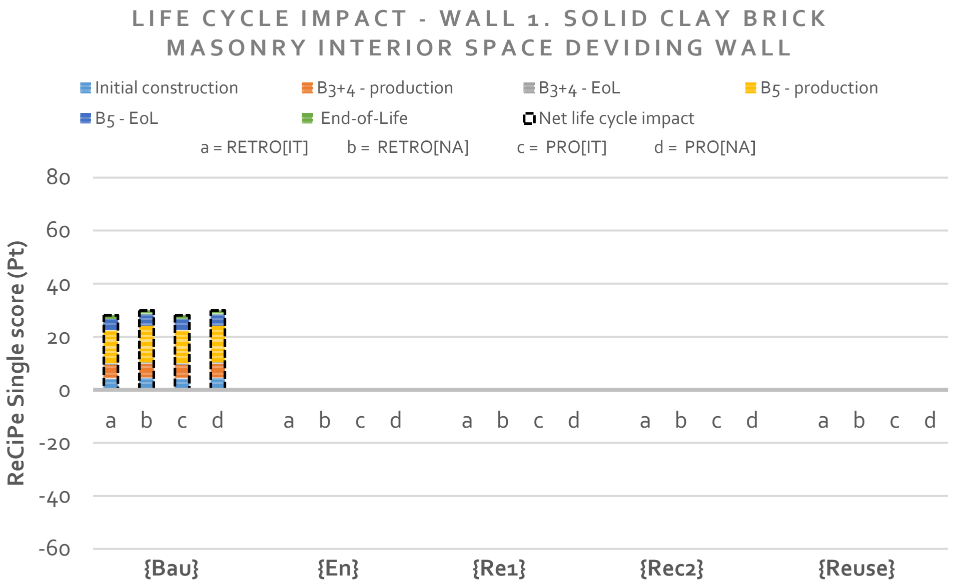
Fig. 4 Initial impact for all wall assemblies.

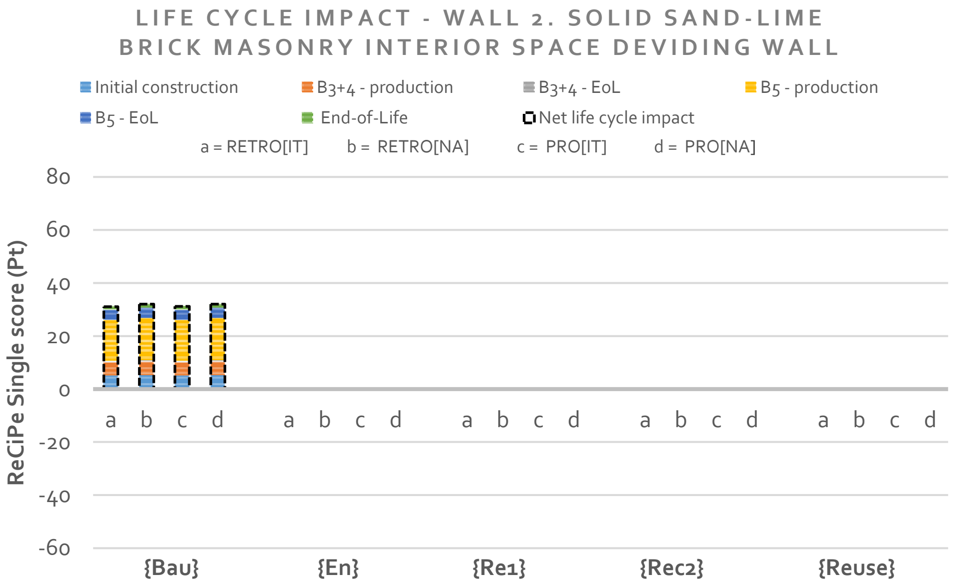
Total service life and end-of-life scenarios

Three assemblies show the best environmental performance when the entire service life and the different end-of-life scenarios are taken into account: the conventional drywall with a wooden substructure (Wall 4) and the two assemblies with a demountable metal frame structure but only for the maximised reuse end-of-life scenario (Wall 6 and 7). Apparently, the lowest life cycle impact can be achieved for assemblies designed to be used again but with a higher initial impact, as for assemblies with no possibilities for direct reuse but with a low initial impact. The reason for the high life-cycle impact of the demountable assemblies is that some materials of the demountable walls have a short estimated service life compared to the total studied period. Plywood for example has an estimated service life of 35 years. In other words, even though these walls are designed to be fully reusable, after 35 years they need to be replaced by new ones. The benefits of a single replacement with reuse are almost cancelled out by the higher initial impact over the entire studied period (see previous section). Wall 5 has a much larger initial impact compared to Wall 6 (27 to 44% higher) and to Wall 7 (24 to 41% higher). So, given a refurbishment rate of 15 years, this wall assembly is not competitive with Wall 6 and 7, nor with the reference Wall 4 from an environmental point of view. Wall 6 and 7 show almost identical results, with a slight preference for Wall 6 with an impact that is 1.5 to 3 % lower than Wall 7.

The different end-of-life scenarios affect the life cycle impact of the demountable walls more than those of the conventional alternatives, with a considerable difference up to a factor of two between the worst-case scenarios {Bau} or {En} and the best-case scenario {Reuse}. This difference can be explained by the fact that much of the used materials still have a substantial residual technical service life and reuse potential, like the steel profiles or the plywood boarding. Conventional walls on the other hand are composed of materials with less potential after treatment, resulting in a narrower range of outcomes for the different end-of-life scenarios. For example, plaster, gypsum board and stone wool are mostly landfilled for technical reasons, while inert waste like masonry and concrete is often recycled as a low-quality substitute for gravel in road foundations (LNA - ALBON, 2014).

Using assemblies again directly is clearly the most preferred option, but the differences with the outcomes of the other four end-of-life scenarios are not negligible. Off-site reuse and an improved recycling practice can result in 50% more avoided impacts compared to the current practice {Bau}. These benefits are in the first place relevant for linear systems without reuse potential, yet such developments are pertinent for demountable assemblies too, once their estimated service life is reached. Similar conclusions could be drawn for all but two of the impacts categories based on the result at midpoint level, i.e. agricultural land occupation and freshwater eutrophication (see Electronic Supplementary Material for all results)


LIFE CYCLE IMPACT - WALL 1. SOLID CLAY BRICK MASONRY INTERIOR SPACE DEVIDING WALL
Initial construction
B3+4 - production
B3+4 - EoL
B5 - production
B5 - EoL
End-of-Life
Net life cycle impact
a = RETRO[IT]
b = RETRO[NA]
c = PRO[IT]
d = PRO[NA]
ReCiPe Single score (Pt)
80
60
40
20
0
-20
-40
-60
a b c d
a b c d
a b c d
a b c d
a b c d
{Bau}
{En}
{Re1}
{Rec2}
{Reuse}


LIFE CYCLE IMPACT - WALL 2. SOLID SAND-LIME BRICK MASONRY INTERIOR SPACE DEVIDING WALL
Initial construction
B3+4 - production
B3+4 - EoL
B5 - production
B5 - EoL
End-of-Life
Net life cycle impact
a = RETRO[IT]
b = RETRO[NA]
c = PRO[IT]
d = PRO[NA]
ReCiPe Single score (Pt)
80
60
40
20
0
-20
-40
-60
a b c d
a b c d
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a b c d
a b c d
{Bau}
{En}
{Re1}
{Rec2}
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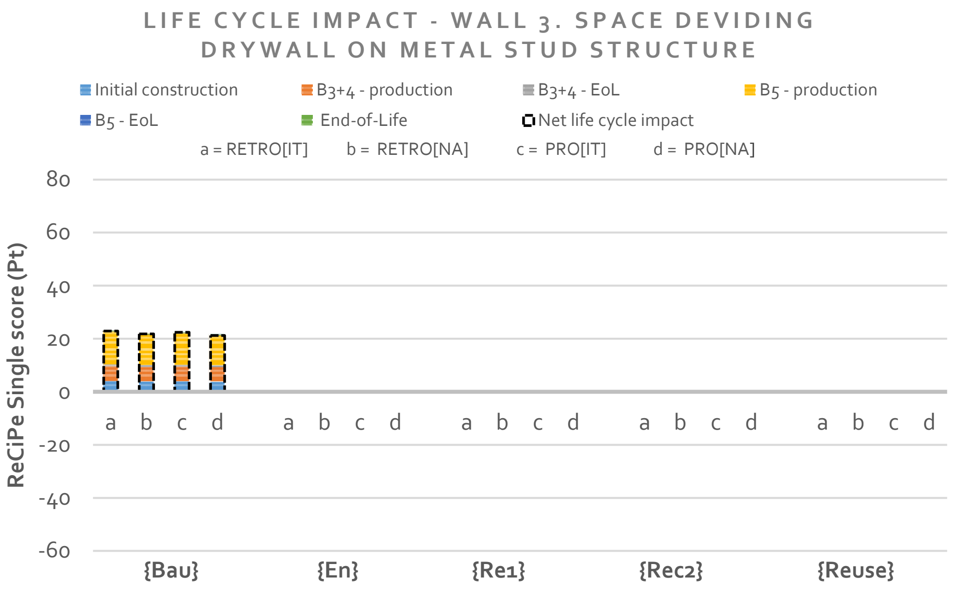
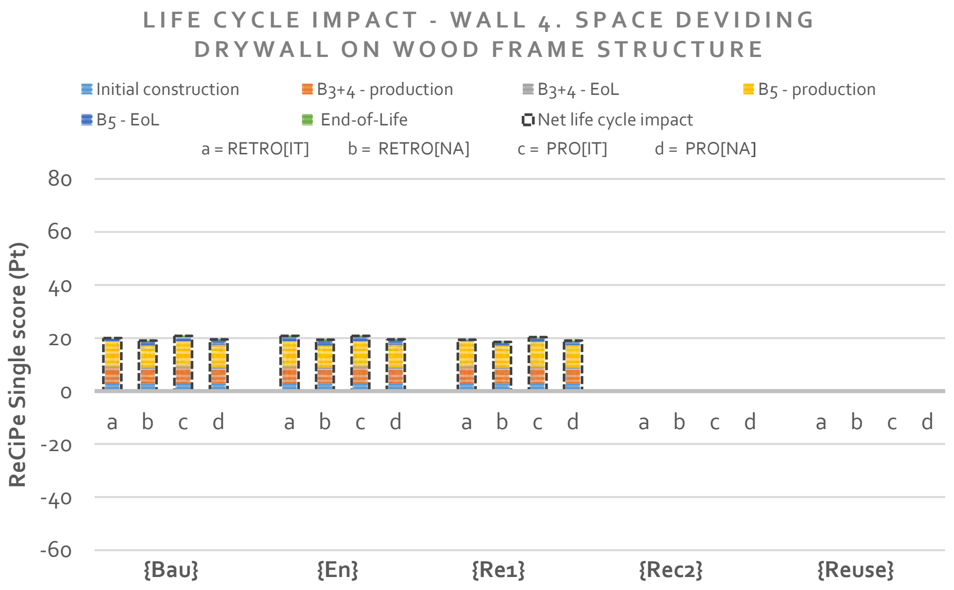
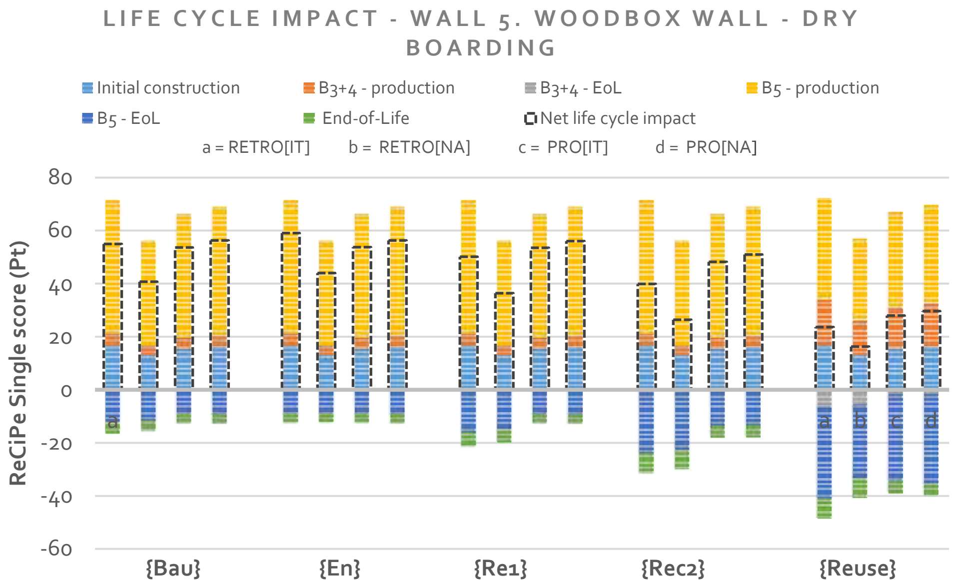
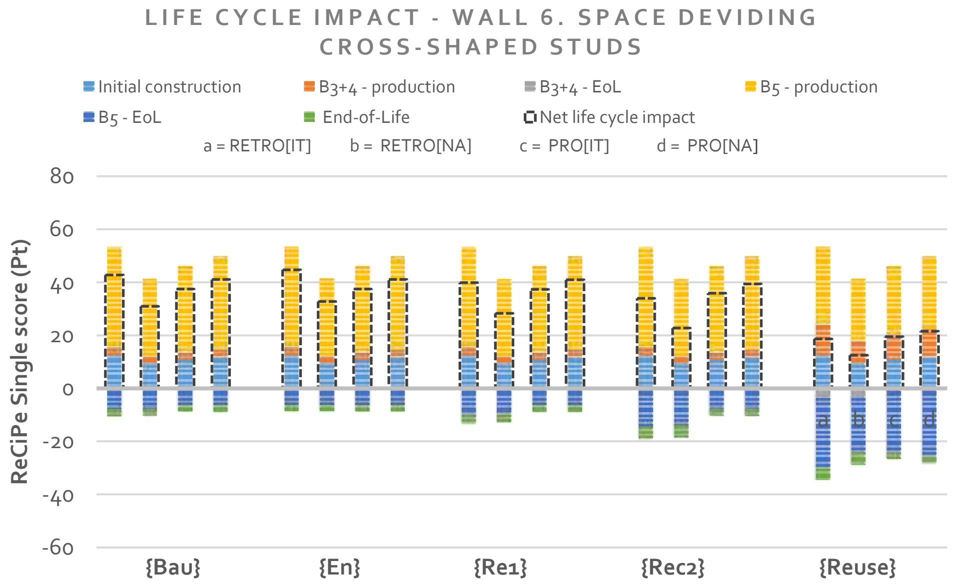

LIFE CYCLE IMPACT - WALL 3. SPACE DEVIDING DRYWALL ON METAL STUD STRUCTURE


LIFE CYCLE IMPACT - WALL 4. SPACE DEVIDING DRYWALL ON WOOD FRAME STRUCTURE


LIFE CYCLE IMPACT - WALL 5. WOODBOX WALL - DRY BOARDING
Initial construction
B3+4 - production
B3+4 - EoL
B5 - production
B5 - EoL
End-of-Life
Net life cycle impact
a = RETRO[IT]
b = RETRO[NA]
c = PRO[IT]
d = PRO[NA]
ReCiPe Single score (Pt)
80
60
40
20
0
-20
-40
-60
a
a
b
c
d
{Bau}
{En}
{Re1}
{Rec2}
{Reuse}


LIFE CYCLE IMPACT - WALL 6. SPACE DEVIDING CROSS-SHAPED STUDS
Initial construction
B3+4 - production
B3+4 - EoL
B5 - production
B5 - EoL
End-of-Life
Net life cycle impact
a = RETRO[IT]
b = RETRO[NA]
c = PRO[IT]
d = PRO[NA]
ReCiPe Single score (Pt)
80
60
40
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0
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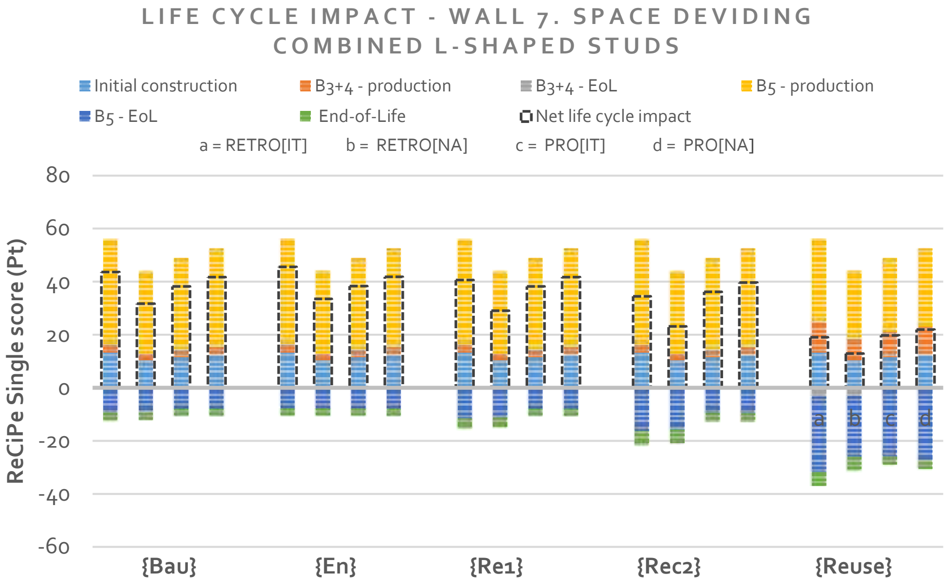


Fig. 5 Life cycle environmental impact for all wall assemblies.

Methodological scenarios on marginal supplier identification

In Fig. 6 the minimum and the maximum values of the life cycle impact of all assemblies for the various methodological scenarios are presented. It is clear that the range of possible outcomes is much larger for the demountable walls based on the four methodological scenarios. In the case of the conventional wall assemblies there is only a small divergence in results of around 10% between the scenarios, while for the demountable ones this deviation can range up to 25%. Many of the typical construction products such as aggregates, clay, bricks, cement and gypsum products are traded on relatively small markets. Therefore, the identified marginal suppliers do not vary that much amongst the scenarios, nor does the impact per supplier.

The situation for wood-based products is completely different than for all other materials, which apparently leads to larger differences in the outcomes for the demountable walls. First, the trade in these products occurs more intensively and over larger distances. This results in bigger deviations between the iterative procedure [IT] and the network analysis [NA] when the geographical market boundaries are defined. Second, climate, forestry practice and dominant tree species can all have a major effect on the final environmental impact, in particular for the midpoint impact category 'land use'. In case of plywood for example, having sawlogs as the most important raw material, the network analysis [NA] results in a market dominated by European countries, as they have intensive trade relationships. The iterative procedure [IT] adds China as an important partner country too, given its direct trade connection with Belgium. Obviously the inclusion of China leads to increased transport distances, yielding higher impacts for the [IT] scenarios. Additionally, in the retrospective approach, the Chinese market for sawnwood is mainly covered by imports, among others from Russia having less favourable climate conditions, poorer forestry practices and larger transport distances. In the prospective approach the domestic Chinese sawnwood production, which has a lower impact compared to Russia's production, has a much larger share. A similar reasoning applies to the [NA] results, with a shift from Western to Eastern European countries in the retro- and prospective scenarios. However, in this modelling option, the impact increased in the prospective scenario due to higher transport distances and less favourable climate conditions between others. This is clearly visible for the demountable walls with the lowest impact for RETRO[NA], but increases in the prospective PRO[NA], and the highest for RETRO[IT], which decreases for PRO[IT].

The demountable walls show a similar impact for most of the methodological scenarios when compared to Wall 4. Only for the RETRO[NA] scenario a clear preference can be observed for the demountable walls. The discrepancies between the methodological scenarios are mainly induced by the plywood boarding as explained above. Combining multiple methodological scenarios results in a more robust assessment outcome. It can be concluded that, if the potential of the demountable walls is used to its maximum, the worst assessment outcome regarding environmental impact is comparable to the best performance of the conventional wall assembly.

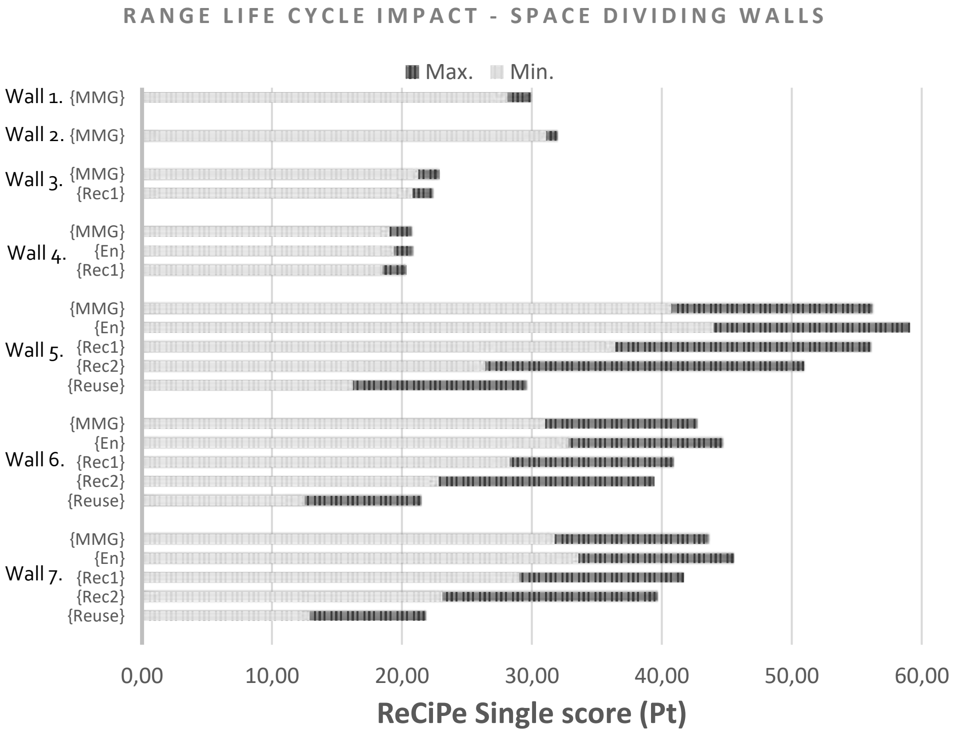


Fig. 6 Range life cycle impact of methodological scenarios per wall type and end-of-life scenario for space dividing and partitioning walls

3.2 Life cycle cost analysis

Studying the overall financial feasibility of innovative, demountable wall assemblies includes an evaluation of their initial cost, which is preferably not much higher than that of the conventional alternatives, and of their life cycle cost, which should be lower or at least competitive with that of conventional alternatives if those innovative assemblies have a demonstrated environmental benefit and might be preferred for that reason. Correspondingly, only the best-case end-of-life scenario is considered in the LCC analysis in this section, reflecting the advantages of reuse whenever possible. From the LCC analyses (Fig. 7), it is clear that for the demountable space dividing assemblies, the initial cost is 31 to 69% higher than that of the cheapest conventional alternative. The life cycle cost of the two so-called 'dynamic' alternatives with a metal substructure (Wall 6 and 7) have however a life cycle cost that is 10 and 17% lower than that of the conventional alternative with the lowest life cycle cost. It are conventional Wall 2 (sand-lime brick) and Wall 3 (metal stud) that have both the lowest initial and life cycle cost respectively when a refurbishment rate of 15 years is considered. To understand that, a closer look at the financial impact of the construction, replacements, refurbishments and end-of-life separately reveals the following findings.

Choosing reversible connections and durable materials to enable disassembly and reuse of the 'dynamic' wall assemblies (Wall 5, 6 and 7) requires the use of additional and more expensive components. For example, to guarantee the acoustic performance and reuse potential of Wall 7 with cross-shaped metal studs, a plywood boarding and air tightness strips are necessary, increasing the initial construction cost to € 189 per square meter.

Although durable materials, such as plywood boarding, resisting the wear and tear of repeated disassembly and reuse, are chosen for the demountable wall assemblies, the estimated service life of these components appears to be (according to the data that is available) not significantly longer than that of a conventional gypsum board wall lining. On average a plywood wall finishing would last 35 years; that is 5 years longer than a conventional wall lining. As a result, the finishing of the demountable wall assemblies can be reused only once if a refurbishment rate of 15 years is considered, and thus the increased construction cost adds to the life cycle cost with every necessary replacement.

Nevertheless, over the period of analysis the expected reduction of the operational costs (i.e. B3, B4 and B5 together) in the total cost resulting from material reuse is noticeable. Over the period of analysis, the share of discounted operational costs in the life cycle cost of the conventional solution is 74 to 75%, and 64 to 66% of that of the demountable alternatives. All together, these savings do outweigh the increased initial cost.

In the present LCC analysis, the end-of-life costs (including demolition, transport and waste processing) and possible residual values (i.e. material resell value) are calculated and added to or deducted from the sum. Although conventional wall assemblies have the highest net-present end-of-life cost (varying between € 4 and 12 per square meter for the conventional solution, and € 2 to 3 for the demountable alternatives) and the demountable walls have a net-present residual value of € 3 to 4 per square meter, the weight of these impacts is too small to influence the resulting preference for one assembly above another, because discounting has the highest consequences for these far-future impacts.

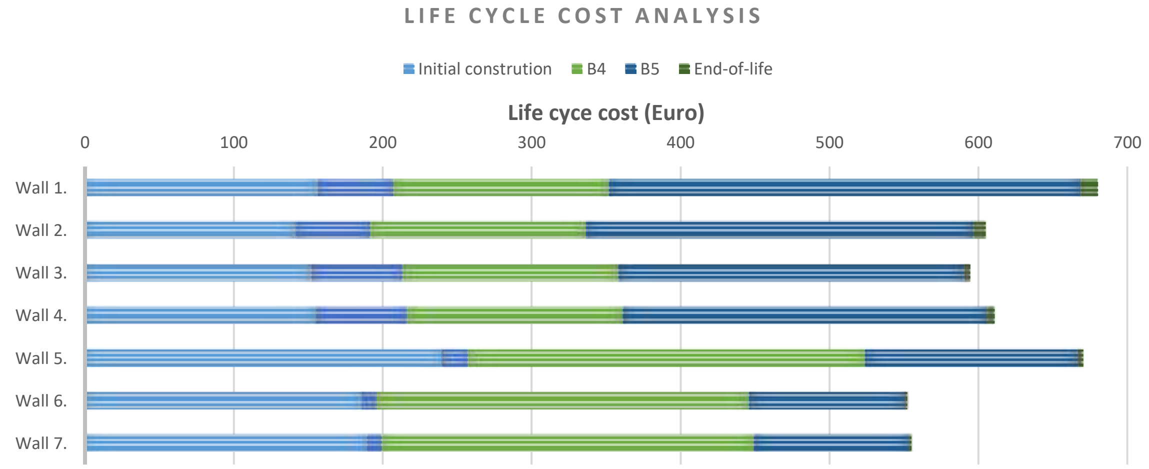


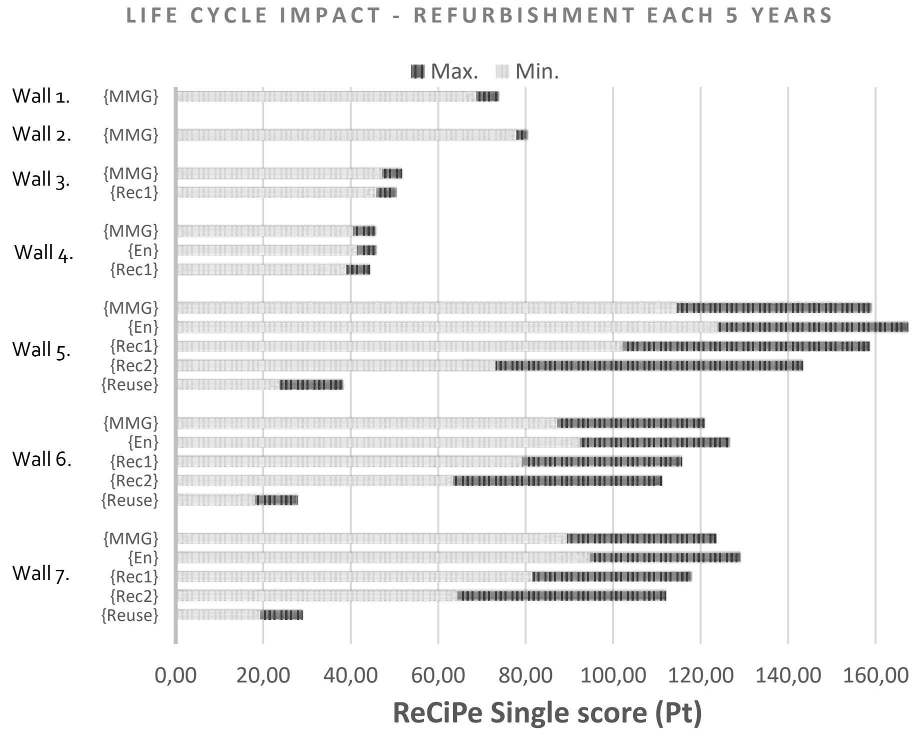
Fig. 7 Life cycle cost analysis for all wall assemblies, including only the optimal end-of-life scenario

3.3 <u>Sensitivity analysis</u>

The results of the two additional use phase scenarios are presented in Fig. 8. As one would hope, in the scenario with a refurbishment every five years, the environmental life cycle impact of the demountable and reusable Wall 5, 6 and 7 is lower compared to that of the conventional ones if their reuse is maximised over the entire service life. This observation is valid for all methodological scenarios. However, the differences between the results obtained by the conventional wall assemblies and the sub-optimal end-of-life scenarios for the demountable walls have grown as well. This indicates an increasing risk on a lower environmental performance of the reusable walls due to improvident use and building management

For the scenario with a refurbishment after 30 years, no direct reuse is possible. Because the methodological scenarios show a rather wide variation in their results, no clear conclusions can be drawn here. The minimum values for Wall 6 and 7 suggest a potential preference for these two wall assemblies, yet the results are less uniform compared to the results of the conventional ones.

As a final remark it is notable that the environmental impact of the demountable wall assemblies is almost identical for the three use phase scenarios - if they are reclaimed properly. The impact is almost completely due to the initial production and the replacement after 30 years for technical reasons, which is a prerequisite for all included use phase scenarios. This illustrated the robustness of the demountable wall assemblies. Due to discounting and the limited share of material costs and saving in the life cycle cost this was also observed after the life cycle cost analysis, but in a less explicit way.



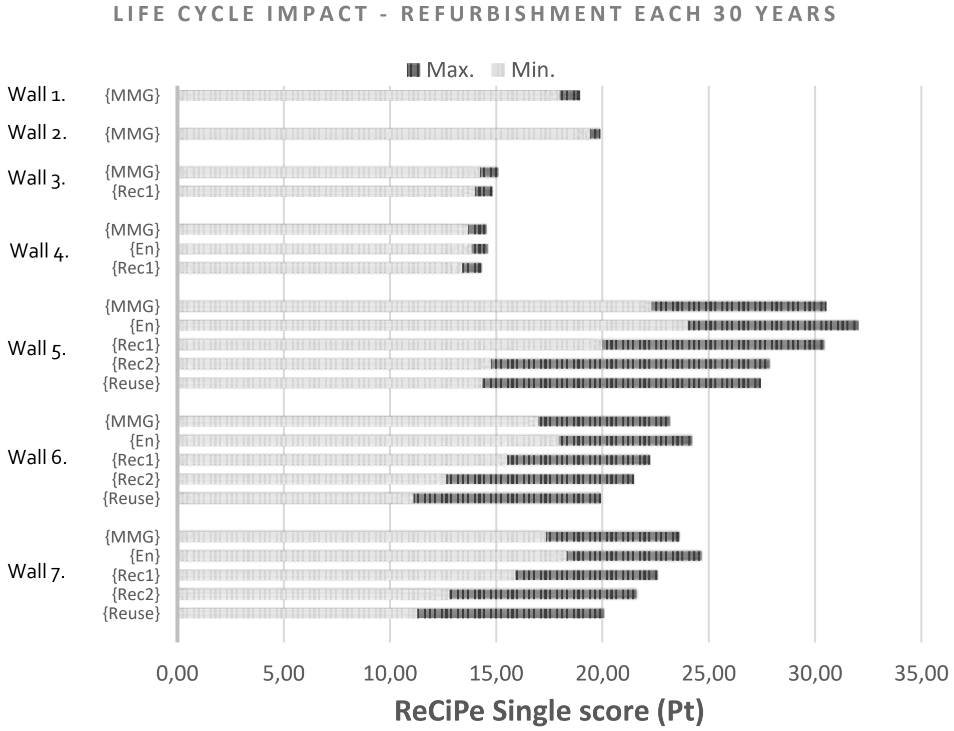


Fig. 8 Sensitivity analysis: life cycle impact for additional use phase scenarios accounting for a refurbishment each 5 or 30 years

4 Discussion

The present case study contributes to the methodological theory of consequential LCA by making explicit the implications of different modelling choices. Therefore, it takes a multi-model approach, evaluating seven alternative internal wall assemblies and subjecting each of them to four methodological scenarios. Additionally, five possible end-of-life scenarios were considered. The results show that the demountable and reusable wall alternatives have a similar or better environmental profile and are financially competitive compared to the conventional ones, if regular refurbishments or transformations are realised by reusing existing components. However, the large range in possible outcomes illustrates the importance of a quantitative environmental and financial assessment in the search for well-informed design choices.

Up till now there are only a few studies in which a quantitative assessment of demountable and reusable internal wall designs is included. According to Vandenbroucke *et al.* reusable designs clearly outperform the conventional ones (Vandenbroucke et al., 2015). This research followed an attributional modelling approach and observed a higher initial impact of the demountable walls, but the differences are less pronounced compared to current case study: around 25% more than the conventional designs. In the present case study the need for intermediate replacements turned out to be the main reason why the benefits of demountable and reusable wall designs were substantially smaller over the entire studied period than in the case of a single refurbishment. In different cases studied Debacker et al. assessed demountable and reusable internal walls too (Debacker et al., 2015). In the case of those walls' application in an apartment building, similar conclusions were drawn compared to Vandenbroucke et al. (Vandenbroucke et al., 2015). Also, if they were applied in a school building, the demountable and reusable wall turned out to be beneficial if regular refurbishments with reuse take place.

Other studies of prototypes mainly focus on a conceptual design assessment and are based on fixed criteria or rules of thumb. Two examples are the SEDA design guide '*Design for deconstruction*' (Morgan and Stevenson, 2005) the '*D12 Feasibility report*' from horizon 2020 project *Buildings As Material Banks* (Goens et al., 2015). The latter aims at trying to enable a systemic shift to the circular economy and mainly focuses on criteria such as the possibility to demount and reclaim, the use of reclaimed building materials and the assembly speed (Goens et al., 2015). But even though wall assemblies and prototypes are not assessed quantitatively in those studies, they may still be relevant for further optimisation of the included demountable and reusable wall assemblies. Currently the plywood finishing layer is the component with the largest environmental impact. If this layer could be replaced by another reusable material, the benefits of demountable walls would become more distinct. In the same way, the risk of a higher life cycle impact due to premature replacements and sub-optimal building management can be reduced as well. Assemblies with a MDF (e.g. Juunnoo ("Juunoo. Leef dynamisch," n.d.)) or particle board finish (e.g. Tecnibo (tecnibo, 2017)) could become an alternative to reduce the initial impact. The latter two examples follow a similar concept as Walls 6 and 7, with a metal frame substructure.

From a conceptual point of view, expected trends in competitiveness are the preferred source to identify the most sensitive suppliers. However, the uncertainty of the predictions can be perceived as too high or such data may not even be available with a sufficient level of detail. So in this work, both a retrospective and a prospective approach were included. Clear differences in results were observed when applying the retrospective or the prospective approach. Both approaches have their strengths and weaknesses. The retrospective approach is characterized by a high availability of data with a low level of uncertainty. A key assumption in this case is that historical trends are representative for future situations. Such data are in particular relevant for a relative short time horizon. In reality however development is typically not a linear process, but it follows rather a S-shaped curve (Hetemäki, 2014). The prospective approach relies on forecasting models. They can provide a more nuanced image of expected future developments and they are relevant when a structural reformation of a segment of the economy can be expected. The latter can be market driven, e.g. a decreasing demand for pulpwood in the paper industry, combined with a sharp increasing demand for wood fuel (Hetemäki, 2014), or due to legislation, e.g. the prevalence of renewable electricity production in expected newly installed generation capacity (Capros et al., 2013). Yet future predictions are per definition uncertain. For example, future predictions for the forestry sector differ notably between studies (Buongiorno et al., 2012; Hetemäki, 2014; UNECE/FAO, 2014).

The results of the methodological scenarios were presented and discussed simultaneously, as was done in the multi-model approach proposed by Yang and Heijungs (2017). Only one technique of measuring the competitiveness was considered for the identification om the suppliers the most sensitive to a change in demand, namely an assessment based on a linear regression analysis of time series of production data. This procedure is state-of-the-art in LCA studies focusing on marginal supplier identification for the moment (Deng and Tian, 2015; Schmidt, 2015). Yet more advanced regression techniques could have been applied and other types of data could have been used, such as the information on costs and capacity adjustments. Furthermore the included scenarios follow the assumptions of the theoretical framework of Weidema et al. (2009), but in future research other models could be included as well. Sacchi (2017) and Prosman and Sacchi (2016) proposed a trade based criterion for supplier selection focusing on circular supply chains, by taking into account import-only, import-export and export-only markets (also called end-markets) (Prosman and Sacchi, 2016; Sacchi, 2018). The effect of a change in demand was followed directly down the supply chain until the end-markets with sufficient unconstrained production capacity are reached. An important advantage here is that indirect trade can be accounted for, which appeared to be relevant in both linear and circular supply chains. This method contrasts to the current case study, in which markets were defined first and then the sensitive suppliers in these markets were determined.

The financial feasibility of the alternative internal wall assemblies was verified based on an LCC analysis. The two ‘dynamic’ alternatives with a metal substructure (Wall 6 and 7) have a life cycle that is 10 and 17% lower than that of the conventional alternative with the lowest life cycle cost and could thus be preferred when a refurbishment rate of 15 years is considered reasonable. A further optimisation of the wall assemblies could consist of finding materials that can be reused more often at the same cost, or that have a lower cost and can be reuses as often as in the studied scenario. Other studies, confirming the results above, have shown that those components that have a larger share in the initial cost of components with a longer expected service life, their life cycle cost is more advantageous (Galle, 2016). Moreover, optimising the building lay-out and deciding which components should be adaptable and which not, allows to allocate construction costs wisely (Galle et al., 2015).

The context of this study is the introduction of demountable and reusable internal wall assemblies to the Belgian market is. This geographical delimitation may not directly affect design related aspects such as the technical details or the energetic and acoustic performance, however since the wall assemblies have to meet national and/or regional regulations the results cannot be extrapolated without additional verification. Also the end-of-life- and transport-scenarios and the identification of marginal suppliers are specific to the Belgian context. No studies with a sufficient level of detail are available for other countries or regions, making it impossible to distinguish between design-related effects and effects induced by the geographical context. Future research should focus on examining the possible benefits of demountable and reusable wall assemblies in a broader international context.

Overall, it must be understood that the outcomes of the present case study cannot be generalised but must be verified for every construction project and its specific context and use. In particular, the consequences at building scale of applying a wall alternative should be considered before making a final choice. Such consequences include for example the hydro-thermal performance and related comfort, and could be evaluated after a dynamic thermal simulation at building level. Such a simulation was however out of the scope of the presented study that focused on methodological assessment and design choices, and that resulted in the following conclusions.

5 Conclusion

The introduction of demountable walls on the market can assist the transition towards a more circular economy by facilitating reclaiming and reusing building components, valorising the materials and components to their maximum potential. The two demountable and reusable wall assemblies with a metal substructure (Wall 6 and 7) assessed in the present case study, have proven to have a lower or at least similar life cycle impact compared to the conventional walls, over the entire studied period. The previous statement applies to both the results of the environmental and the financial assessment. If wall assemblies are to be replaced more frequently, the wall assembly composed of wooden boxes comes into the picture as well. This only applies under the condition of good practice and a proper building management, as only for the optimal end-of-life scenario the demountable scenarios returned favourable results. Definitely, there is still room for improvement, so after optimising the designs in further stages, their feasibility is expected to increase.

The range of possible outcomes of the methodological scenarios and the lack of a quantitative assessment in literature also demonstrate the importance of quantitative environmental assessments of circular building strategies rather than focusing on qualitative criteria only. It was shown that simply focusing on reusability does not automatically lead to environmental savings. A strength of this study is that the consequences of introducing demountable and reusable walls were assessed with the help of multiple methodological scenarios. This way, more insightful results could be obtained compared to a conventional LCA with a single set of model assumptions. Additionally, by making the range of possible outcomes explicit and interpreting the results in parallel, the reliability of the assessments increases. Yet, more scenarios could be included in future research, through continuous sensitivity analyses or probabilistic uncertainty analyses.

To conclude, this case study points out the potential benefits of introducing demountable and reusable walls. Further research will need to focus on optimising and refining the mentioned wall assemblies and expanding the number of methodological scenarios. Therefore, in addition, an assessment and multi-objective optimisation at the building level is an opportunity for further research, taking into account the building- and user-specific context.

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Electronic Supplementary Material

Following annexes are included as Electronic Supplementary:
https://www.dropbox.com/sh/niq33o1se2n1la7/AAAzMBY-FkIKNar1-2n-o3YZa?dl=0

Annex 1 - Details Wall Assemblies

Description:

- *All technical drawings of the assemblies*

- *Full details on the requirements for and properties of the included designs*
- *Full details on the End-of-life scenarios*
    - *Part 1: list of avoided products per waste type*
    - *Overview of assumptions per waste type based on EPBE-study*

Annex 2 - Details LCA

Description:

- *Full details on the marginal supplier identification, including intermediate results*
- *All LCIs, including importable Simapro .csv files*
- *Impact assessment*
- *Full details on the data collection*
- *Final calculation file: LCI & LCIA - Calculations & results*

Annex 3 - Details LCC

Description:

- *Final calculation file: LCC - Calculations & results*

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