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To cite this article: M Buyle *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **323** 012057

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Consequential LCA of demountable and reusable internal wall assemblies: a case study in a Belgian context

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Abstract. The transition from a linear to a circular economy is essential to reduce the environmental burden of our society. A key issue is to prevent a shift of the environmental burdens and take the consequences of a decision into account, for example based on a consequential life cycle assessment (LCA). However, limited practical guidance is available on how to implement consequential LCA in the context of the construction sector. Therefore, the aim of this study is twofold. First, to quantify the potential environmental and burdens of introducing circular design alternatives for internal wall assemblies to the Belgian market. Second, to review the methodological implications on the results of a consequential LCA with a particular focus on consistently identifying marginal suppliers and substitution routes, acknowledging the time dependence and closed-loop nature of the design alternatives. In total seven wall assemblies are assessed over a period of 60 years, with a refurbishment every 15 year.

The results 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 reversibly to a 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. Further, regarding the methodological scenarios on marginal supplier identification, the range of possible outcomes is however much larger for the demountable wall assemblies than for the conventional ones.

1. Introduction

The transition from a linear to a circular economy is essential to reduce the environmental burden of our society by overcoming the divergent interests of economic and environmental prosperity [1]. Despite the 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 [2–4]. Nevertheless, more radical experiments appear in the academic and



innovation 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 [5], or by designing demountable and reusable building elements such as internal walls [6–8].

However, increasing circularity does not automatically lead to more sustainable products and buildings, which emphasises the need for a quantitative assessment. Established methods such as life cycle assessment (LCA) proved their value for making well-informed environmentally sound design and construction choices [9]. Yet, there is not just one single way of performing an LCA despite the the general framework of ISO 14040/44 [10,11]. Still many methodological choices must be made throughout a study. Against the background of assessing the transition towards the circular economy, the market-based and change-oriented nature of the consequential modelling approach is of great interest, as it allows to make environmentally responsible policy and design choices. To date, there is a lack of consequential LCAs evaluating and illustrating their relevance for the construction sector [12].

In this context, the 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. This assessment is realised by performing a consequential LCA, acknowledging the time dependence and closed-loop nature of the design alternatives. The corresponding objectives of this case study are to (1) collect alternative internal wall assemblies, (2) introduce various consequential modelling approaches to understand the relevance and improve the robustness of the results and to explicitly account for the corresponding modelling uncertainty and (3) include multiple end-of-life scenarios to address the uncertainty regarding future life cycle interventions and technical evolutions.

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. The first are designed for a typical linear service life with a waste-generating refurbishment and end-of-life scenario, the latter are designed with a high reclaim and reuse potential at the end of their functional service life.

2. Methods

2.1. Case study

The present case study includes seven wall assemblies that have divergent compositions, but meet the same technical requirements (see Fig. 1). The first four alternatives (i.e. Wall 1 to 4) resemble the most commonly applied wall assemblies in the Belgian construction sector [13], namely masonry walls and drywall systems. They do not follow any design guideline related to the circular economy, but they will serve as a reference. The alternatives (i.e. Wall 5 to 7) feature a wood-based boarding, each time supported by a different demountable substructure. They are proposed by the authors following earlier prototyping by Paduart et al. [7,8]. The fifth alternative consists of prefabricated wooden boxes, while the sixth and seventh alternative rely on a single-profile and an assembled metal frame substructure. These alternative assemblies follow the design guidelines for the circular economy [6]: 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. More detailed information can be found in Buyle et al. [14].

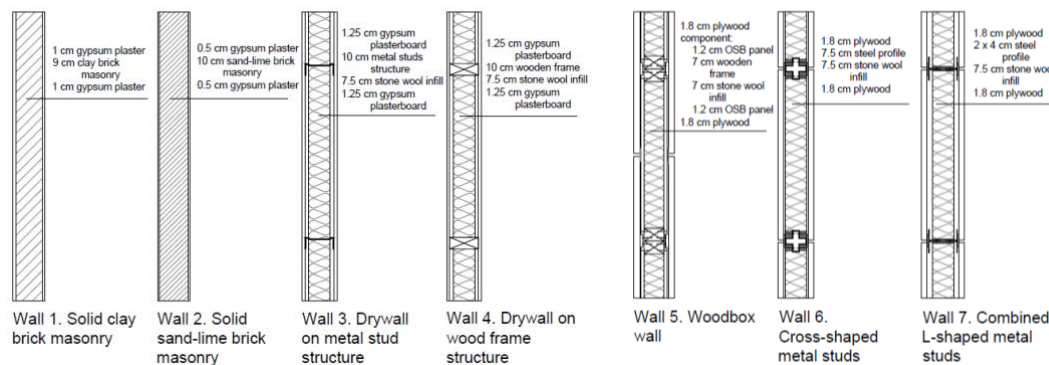


Fig. 1 Conceptual representation of the analysed wall assemblies

2.2. Life cycle assessment

2.2.1. Goal and scope. In the present case study the theoretical framework for consequential LCA of Weidema et al. was followed [15]. This implies that only small and medium scale changes in demand and long-term effects were considered, assuming perfectly elastic markets and no interaction between 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 Belgian requirements for energetic and acoustic performance of residential, school and office buildings, during a period of 60 years,*

2.2.2. Life cycle inventory. In consequential modelling two of the most important aspects are (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. Additionally, the seven wall assemblies have a different end-of-life potential, varying from direct reuse to demolition with limited recycling potential. However, the actual practice at the end-of-life is highly context and user dependent. Given this uncertainty, 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 [15]. Consequently, the methodological scenarios affect all life cycle stages including the end-of-life stage.

2.2.2.1 Methodological scenarios: marginal supplier identification The two most important steps in the procedure of Weidema et al. [15] 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. In this context, a market should be interpreted as all countries in the world from which materials are imported to Belgium, directly or indirectly. Two approaches to identify geographical market boundaries are included, proposed by Buyle et al. [16] and Pizzol and Scotti et al. [17]. 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 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.

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. The prospective approach (referred to as PRO) relies 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. However, a key assumption in this case is that historical trends are representative for future situations. Indeed, the prospective approach can provide a more nuanced image of expected future developments, 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]. Marginal suppliers are identified at country level, so country specific life cycle inventories (LCIs) were built for all identified marginal suppliers. The ecoinvent database v3.3 was used to model background processes.

2.2.2.2 End-of-life scenarios For the modelling of end-of-life scenarios, the Belgian reference study for LCA in the construction sector, namely Environmental Profile of Building elements (EPBE) [13], was followed as guideline. The five scenarios are briefly described below. Not all scenarios apply to every wall alternative. For the conventional walls, only the three most conservative scenarios can be included ({Bau}, {En}, and {Rec 1}). 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.

- Business-as-usual {Bau}: This represents the current practice in Belgium according to 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 assumed for every refurbishment.

2.2.3. Life cycle impact assessment. The method used for the impact assessment is ReCiPe v1.13, applying a hierarchist perspective. To facilitate the interpretation of the effect of methodological choices in the LCI modelling, a single score indicator is applied. However, in addition to the single scores, results of all midpoint impact categories are included as well and available online (see *Appendices* and [14]).

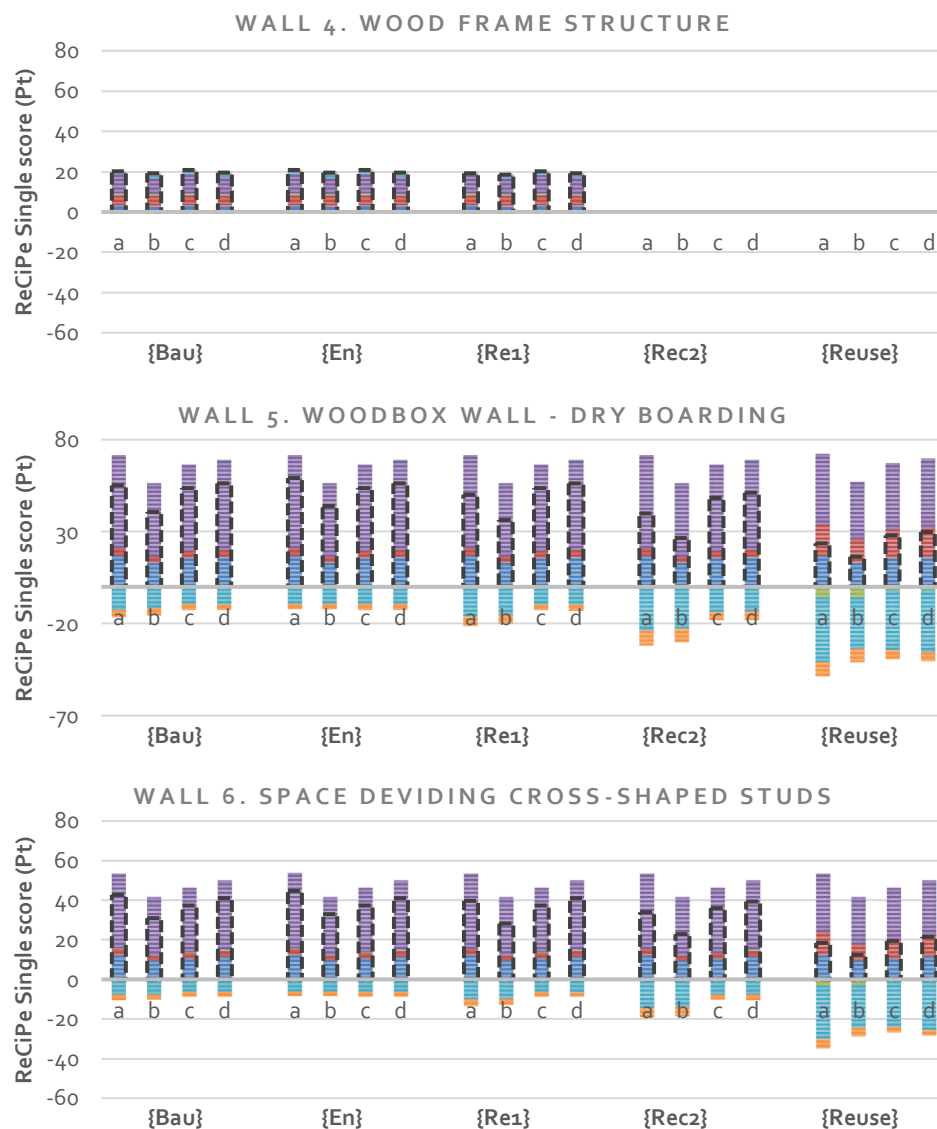
3. Results

This section presents the results of the consequential LCA, considering the total service life of the wall assemblies. The studied period is 60 years, which corresponds to the estimates in other Belgian research, though individual components can have a shorter service life. An average periodicity of 15 years is assumed for refurbishments as discussed by Galle [18]. The results will be presented based on the classification of different life cycle stages as described in EN 15804 and EN 15978 [19,20]. These guidance documents describe an attributional framework that does not fit the goal and scope of the present case study. Nevertheless, its classification is instructive and will be maintained, even though this is a full consequential LCA.

The life cycle impact of the three demountable and reusable wall assemblies (Walls 5-7) is compared with the conventional assembly with the lowest impact, namely the drywall on wood frame structure (Wall 4), see **Error! Reference source not found.** For full details, see *Appendices* and [14]. Three assemblies show the best environmental performance when the entire service life and the different end-of-life scenarios are considered: 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 during the second refurbishment. 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.

In Fig. 2 **Error! Reference source not found.** the results for the methodological scenarios are presented as well. 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.



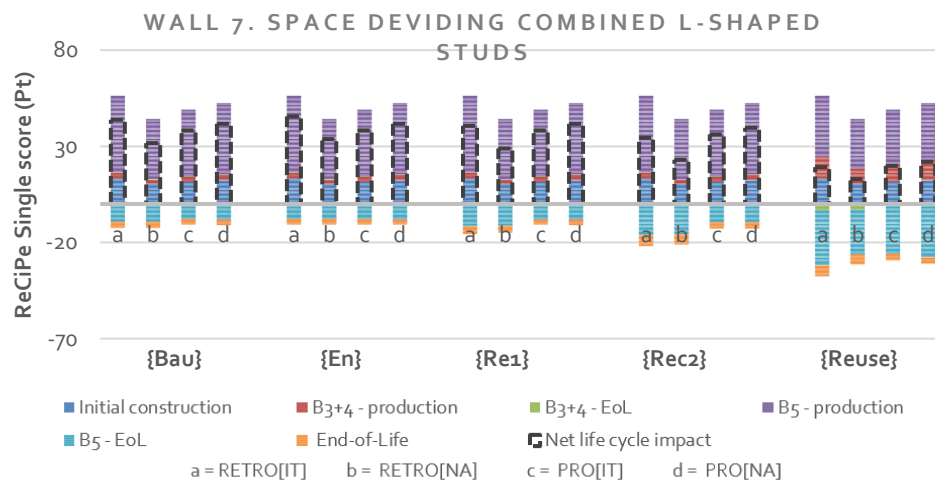


Fig. 2 Life cycle impact for wall assemblies 4-7

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, these products are traded 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.

4. Discussion and conclusion

The present case study contributes to the methodological theory of consequential LCA by making the implications of different modelling choices explicit. 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 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 in the search for well-informed design choices.

The theoretical framework of Weidema et al. [15] is the most widely used framework which focuses on long term changes in perfectly elastic markets. However, in most studies the suppliers affected by a change in demand and the consequences of a decision are identified based on observations of historical or current trends [16]. In this study clear differences in results were observed when applying both a retrospective and a prospective approach, indicating the limited relevance of retrospective trends when trying to estimate long-term consequences. In reality however development is typically not a linear process, but it follows rather a S-shaped curve [21]. Such non-linear trends can be captured by forecasting

models which output forms the basis for the prospective approach. So even though such data are per definition more uncertain, they can provide a more nuanced image of expected future developments. They are particularly 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 [21], or due to legislation, e.g. the prevalence of renewable electricity production in expected newly installed generation capacity [22].

The methods used in this work consists of two distinct and independent steps. First markets are identified applying an iterative procedure ([IT]) or a network analysis ([NA]), which results in a list of countries. Afterwards the most sensitive suppliers are identified based on their increment in production volumes. In these procedures some criteria were introduced, e.g. to decide when a trade flow is relevant to consider to define geographical market boundaries or the minimum increment in production required for a supplier to be considered as being competitive. Such an approach has some pros and cons. There is no scientific ground for selecting a threshold value, making it an arbitrary choice by default. However, this does not mean that attributing a value to a criterion is a priori a meaningless and random decision. Taking the values attributed to the criteria that affect the size of the identified market as an example. The choice of a low value can be interpreted as a study of all potential suppliers, assuming that the existence of a trade link is a sufficient precondition to react to a change of demand. Choosing a higher value prioritizes the most important trade partners, which indirectly upgrades the magnitude of a trade connection to a criterion for competitiveness as well. So, the inclusion of well-chosen threshold values can obviously be an advantage, as the modelling assumptions can easily be tailored to the goal and scope definitions. In this study the goal was to identify the potential marginal suppliers, so a low value was applied. For statistical support of this interpretation, see Buyle [12]. An alternative approach is proposed by Sacchi [23] and Prosman & Sacchi [24], namely a trade-based criterion for supplier selection focusing on circular supply chains. 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.

A limitation of this study is that the method was only applied on products without specific function-based requirements supplied to a general market. For such products more data is available and at the same time no additional customer segmentation is needed. Such an additional customer segmentation might result in much smaller market niches or even in a direct link between suppliers. In this case, even if data is available, it might be more efficient to take a shortcut and identify the marginal suppliers qualitatively. More research on this topic is needed.

In this work the main focus was on consequential LCA by following the theoretical framework of Weidema et al. [15]. This framework entails some strong assumptions such as suppliers being fully constrained or perfectly elastic. By relaxing these assumptions, a model could yield a better reflection of reality. There are some other models that can provide relevant results as well. An interesting approach is to integrate equilibrium models in consequential LCA. Such models form a counterpart to the framework of Weidema et al. as typically a short time horizon is considered and the consequences of a change in demand are modelled based on elasticity of supply and demand. Both models are complementary. Weidema's heuristic approach focuses on long term changes in perfectly elastic markets, while equilibrium models assess short term effects. So, a symbiosis of both models could help achieving the long-term goals without inducing short-term negative consequences.

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. 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.

Appendices

Supplementary information can be found at:

<https://www.dropbox.com/sh/j6tgmphfaoz6u0s/AAAgOWA0eTbxFzost-XJRiq1a?dl=0>

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