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# More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings

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A R T I C L E I N F O

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Material flow analysis
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A B S T R A C T

On the long term, buildings could initiate less material flows and have improved environmental performance if they are designed for future disassembly and reuse. However, material flows in the building life cycle are difficult to map, especially those initiated by material replacements and at end-of-life. The calculation formula for the number of replacements in buildings in the Life Cycle Assessment standard EN 15978 neglects the effect such replacements may have on the surrounding interdependent building parts, and hence fails to capture the potential benefits of Design for Disassembly. In light of this shortcoming, we propose a method to model the flows of building parts initiated by the disassembly of a building, both during operational and end-of-life stages. This modeling method considers aspects of structural stability, accessibility, and the use of detachable connections. It offers a bottom-up time-based Material Flow Analysis of an entire building which can be integrated in a Life Cycle Assessment.

We apply our method on a pavilion and compare the method results to the those obtained with EN 15978, considering nine design options. The life cycle environmental impact estimated with our method is up to 162% larger than the impacts calculated with EN 15978 for a pavilion with non-detachable connections, which demonstrates the importance of this design parameter. Our method can be of interest to researchers, Life Cycle Assessment and Life Cycle Costing auditors, architecture, engineering and construction professionals, urban miners and any other actors interested in the design of demountable buildings.

## 1. Introduction

The construction, use, and demolition of buildings, although essential to meet human needs, put an unsustainable pressure on material stocks. From 1900 to 2005, the annual use of construction materials grew by a factor of 34 (Krausmann et al., 2009). Currently, the construction sector drives 50% of global material extraction (European Commission, 2020) and 35% of all waste in the European Union (Eurostat, 2018). For its high material consumption, along with its high potential for circularity, this sector is listed as one of seven key sectors in the European Commission's new Circular Economy Action Plan (European Commission, 2020). The material flows initiated by buildings and the environmental impact associated to these material flows should be reduced (UNEP, 2015).

Not only does the construction and demolition of buildings contribute to material consumption, waste generation, and environmental impact, but so do maintenance and refurbishment works. For example, a 2020 study on multifamily houses in Switzerland revealed that the replacement stage can represent up to 36% of the total amount of GHG emissions (Goulouti et al., 2020). In some cases, future refurbishments can represent more environmental impact than energy use to compensate for thermal losses (Vandenbroucke, 2016). Similarly, Rauf and Crawford (2015) estimated that the recurrent embodied energy (due to material replacements) in an Australian house equals or even surpasses the initial embodied energy when the service life of the house ranges from 75 to 150 years.

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### 1.1. Design for Disassembly towards efficient material use

A design strategy to reduce environmental impact associated with technical and functional changes in buildings is Design for Disassembly (DfD). By enabling the disassembly of buildings instead of demolition, this strategy aims to improve their material efficiency during their use and end-of-life stages (Debacker et al., 2015; Galle, 2016) thanks to a reduced material consumption, reduced waste, and increased on- and off-site reuse. DfD is therefore considered as a way to close material loops (Crawford, 2011; Dodd et al., 2017; IRP, 2020). Key DfD principles include detachability (i.e., parts can be separated without damage by using detachable connection techniques such as screws, bolts, and tape), independence (i.e., parts can be recovered without compromising the stability of the assembly), and accessibility (i.e., the access to a part is not prevented by surrounding parts) (Sassi, 2002; Paduart, 2012; Debacker et al., 2015; Akanbi et al., 2018).

As DfD gains momentum, it is important to accurately assess the benefits these key design principles could have on material flows and stocks. Unlike the design efforts to optimize the energy performance of buildings, improvements in material efficiency thanks to DfD are only expected after several refurbishments and at the ultimate disassembly of the building (Debacker et al., 2015). Current methods however fall short on adequately modeling material flows and stocks in demountable buildings, as highlighted in the following section.

### 1.2. Limitations in current assessment methods for demountable buildings

The environmental impacts of a building can be modeled via Life Cycle Assessment (LCA). An LCA is based on the quantification of input and output flows of energy, materials, (co-)products, waste, and emissions associated with product systems, such as shoes, cars, and buildings (ISO 14040, 2006). These flows can then be characterized with respect to potential environmental damage. A building LCA ideally covers its construction, use, and end-of-life. LCA frameworks for construction products and buildings are the subject of European standards EN 15804+A2:2019 (CEN, 2019) and EN 15978:2011 (CEN, 2011).

The calculation method for the number of material replacements in EN 15978 considers only a few design parameters, mainly the service life (i.e., the period of use) of the building and of its products, components, or elements (CEN, 2013), all three terms being indistinctively called ‘building parts’ or ‘parts’ in this paper. This calculation method considers that building parts are not interdependent and that the service life of a part does not affect the service life of the surrounding parts. For this reason, it fails to capture the potential benefit of designing a building for easy disassembly and reuse (Section 2.1). Among reviewed environmental assessments of conventional and demountable building parts, none propose a systematic quantitative method to model material flows during the Replacement (B4), Refurbishment (B5), Deconstruction (C1), and Waste Processing (C3) stages in three-dimensional assemblies of building parts, such as façade modules, post-and-beams systems, or whole buildings. In light of the above, there is a need for a method that captures the effects of demountable design principles on the input and output material flows during the replacement and end-of-life stages of built assemblies, and on the reusability of disassembled building parts.

### 1.3. Aim, scope, and outline

The aim of this study was to develop a method to model the material flows generated by a building from construction to decommission, including material replacements, and to measure how DfD affects these material flows and related environmental impact. In order to have a more realistic and detailed evaluation of the life cycle impact of buildings and potential environmental improvements associated with DfD, material flows and stocks in the building lifecycle need to be based on more refined models than those based on the European standards EN15804/15978, especially regarding the Replacement and End-of-Life stages. With a refined modeling method, the material efficiency of replacements can be better estimated, including the possibility of recovering and reusing building parts. Such a method would enable the comparison of design options with different assembly and connection types, helping building designers make better-informed architectural choices.

The scope of this study was set on how a more demountable design, given a set of required replacements, can contribute to reduced material consumption, waste, and hence, environmental impact of a building, in the Use stage. Therefore, in the modeling method developed here, the replacement of parts are based on their estimated service life (ESL) i.e., the service life that they would be expected to have in a set of specific in-use conditions (ISO, 2013). The method does not distinguish between technical, economic, aesthetical, or functional reasons for replacing a building part. In future research, a scenario-based approach could be adopted with that objective (Galle et al., 2017). When a building part must be replaced, the method evaluates whether it is technically feasible given the assembly and the connection types (not whether it is financially feasible) and which material flows it would generate.

In this paper, we first review existing methods to model material flows in (demountable) buildings (Section 2). Then, we propose a modeling method for bottom-up Material Flow Analysis (MFA) integrating DfD principles (structural independence, accessibility, and detachable connection design) based on the work of Denis et al. (2018) (Section 3). We test this method on the design and LCA of a simple pavilion and compare its output to the EN 15978 calculation for the impacts of replacements, in terms of mass flows and environmental impacts expressed in ReCiPe Endpoint points (Section 4). Finally, we discuss the added-value and limitations of the proposed modeling method (Section 5).

## 2. Literature review

The scope of this literature review includes two types of quantitative methods for modeling life cycle material flows in (demountable) built assemblies: service life modeling and disassembly sequence modeling. The former aims to estimate when a building part is replaced, and the latter defines the order in which assemblies can be disassembled as well as resulting material flows. As such, we do not cover semi-qualitative adaptability assessment methods which, via a set of rated criteria, score the level of implementation of DfD principles, such as the Design for Disassembly and Adaptability assessment method in ISO 20887 (ISO, 2020).

### 2.1. Service life modeling of buildings

In the European standard for Life Cycle Assessment of construction product and buildings EN 15978 (CEN, 2011), the number of replacements for a part $j$ ($N_R(j)$) is estimated as the Required Service Life of the building (*ReqSL*) over the Estimated Service Life of the part (*ESL(j)*), rounded up, and minus 1, to exclude the initial installation of the part at the construction of the building (Eq. (1)).

$$N_R(j) = \frac{ReqSL}{ESL(j)} - 1 \tag{1}$$

Such an approach assumes that building parts are unrelated, and that replacing one part will not affect the service life of surrounding parts. It does not consider unintended material losses due to conflicting interactions of an outdated building part with surrounding parts, as concluded by Galle et al. (2017) in the context of Life Cycle Costing. In reality, “the early failure of components with long life expectancies often results from the impact of failures in other components” (BCIS, 2006, p. 1). Furthermore, such an approach does not allow the evaluation of implemented DfD principles, such as using detachable connections and providing easy and direct access to parts that are often replaced or altered.

Few authors have developed service life models integrating DfD principles. Debacker (2009), Paduart (2012) and Vandenbroucke (2016) adopted a method to evaluate the life cycle environmental impact of demountable assemblies, based on an LCA method adapted from EN 15804 (CEN, 2012), EN 15804+A1 (CEN, 2013), and EN 15978 standards for the Belgian construction sector, namely the SuFiQuaD method (Allacker et al., 2011) that later led to the Milieugerelateerde Materiaalprestaties van Gebouwelementen (MMG) method (OVAM, 2012). With her method, Vandenbroucke (2016) demonstrated the environmental benefits of several demountable assemblies and identified the finishing layer as an important contributor in terms of life cycle impact. Her approach to the modeling of replacements could however be improved in several manners. First, her method works on layered assemblies, such as walls, floors, and roofs, wherein each layer is assumed to only interact with the preceding and following layers. It does not encompass three-dimensional assemblies with several possible disassembly sequences. Second, the demountability of an assembly is an input variable, not the result of a systematic evaluation of the design of the assembly. Third, in her approach, technically outdated layers within walls, floors or roofs are only replaced if they are easily accessible or if all layers in front must be replaced. In reality, an outdated acoustic insulation would be replaced even if the finishes are still adequate. Her method can therefore be developed further to identify, in three-dimensional assemblies, which surrounding building parts can be preserved and which are lost during the disassembly of a part.

Altogether, current methods to model the service life of buildings in the context of LCA do not consider DfD principles or assume that replacements of parts occur in a simplistic manner. Even dedicated methods for estimating material replacements have several shortcomings when it comes to capturing their three-dimensional complexity. To expand our perspective, in the following section, we review two methods developed outside of the LCA field, and we assess their potential for modeling realistic material flows in (demountable) buildings.

### 2.2. Building disassembly sequencing

Like service life modeling methods for building parts, disassembly sequence modeling methods for buildings are also scarce. To our knowledge, only two have been conceptualized and tested on case studies: Sequential Disassembly Planning for Buildings (SDPB) by Sanchez et al. (2020) and Disassembly Network Analysis (DNA) by Denis et al. (2018).

The SDPB method aims to optimize the deconstruction of existing buildings, whereas the DNA method initially aims to support the design of new buildings. The SDPB method is based on an approach developed for product manufacturing, namely the Disassembly Sequence Structure Graph (DSSG) method (Sanchez and Haas, 2018). As in the DSSG method for products, the SDPB method relies on motion constraints for building parts in three dimensions. For each building part in an assembly, and for positive and negative x-, y,- and z-directions, the user must specify in a matrix the adjacent parts and fasteners that prevent the motion of the studied part in a certain direction. A second matrix should be created by the user to indicate motion constraints for each fastener. Several additional matrices indicate other constraints, e.g., physical contacts between parts and parts intersecting with the projection of each part in a given direction (Sanchez et al., 2019). Due to the amount of data required, the SDPB method is complex to implement (Sanchez et al., 2020); a barrier that could be countered, as the authors suggest, by an increased digitalization of building information. However, they do not provide any possible procedure to generate or retrieve this data. A disassembly modeling approach based on disassembly directions is relevant for product manufacturing, due, for instance, to the scale ratio between product, fasteners, and disassembly tools, and to the possibility to amortize disassembly modeling costs by the repetition of disassembly operations over a large volume of parts. We believe this approach is not adequate for buildings and construction products, because they are significantly less standardized and because construction products in buildings (e.g., a window frame in a façade) have many more potential positions than parts within manufactured products (e.g., a printed board in a laptop).

The DNA method by Denis et al. (2018) aims to identify disassembly sequences, estimate the flows initiated by the disassembly of a building part, qualify them as lost or preserved, and estimate the duration of the disassembly operation. The DNA method consists in modeling buildings as directed network graphs, wherein building parts (e.g., beams, foundations, insulation boards) are nodes, and connections between parts (e.g., a bolted connection between a column and a foundation, glue between an insulation board and a concrete wall) are lines or arrows between nodes. With DNA, Denis et al. laid the basis for a quantitative assessment of DfD buildings. This assessment is based on the evaluation of how DfD can improve material flows in the long-term, instead of on qualitatively assessed design criteria. As a shortcoming of DNA, the arrows of the directed network graph do not capture structural dependencies or the overall accessibility of a building part. Instead, arrows indicate the “direction of the connection” (Denis et al., 2018, p. 8), in other words: when two parts are connected, an arrow indicate the order of disassembly imposed by the accessibility of a connection. For example, an arrow from part A (e.g., a tile finishing) to part B (e.g., a solid insulation board) indicates that the connection must be undone or unfastened from A to B, because a worker could only access the connection by removing A, then B. Hence, modeling constraints due to structural dependencies and accessibility can vary with the subjectivity of the assessor.

### 2.3. Research gap

This research tackles the mostly unexplored topic of modeling material flows in demountable buildings. On one hand, there is very scarce literature about the modeling of material flows in buildings, conversely to cities for which the ‘Metabolism of Cities’ website currently references 287 MFA datasets, reports, and studies about neighborhoods, cities, and regions (Metabolism of Cities, n.d.). On another hand, the quantitative assessment of demountable buildings has only recently acquired interest from the research community and the industry, as illustrated by the European research project entitled ‘*BAMB - Buildings as Material Banks*’, started in 2015 (BAMB project, n.d.).

The literature review shows that several developed service life models integrating DfD principles are based on the European standards for Life Cycle Assessment, which fall short in capturing the interdependences of building parts. Methods to model sequential disassembly, the SDPB and the DNA methods, seem promising to analyze in detail the disassembly of buildings, during use and at end-of-life. The SDPB method, an adaptation from a product disassembly modeling method, is however complex to implement and data-intensive (Sanchez et al., 2020). We consider the reliance on multiple constraint matrices unpractical. The DNA method has the potential to improve the service life modeling of demountable buildings, but it suffers from significant shortcomings, notably on how to systematically model the structural dependencies and the constraints of accessibility. There is therefore a need to develop a new method that is less complex and data-intensive than the SDPB method and that capitalizes on the DNA method while integrating it with LCA.

## 3. Method

Starting from the conceptual Disassembly Network Analysis (DNA) method of Denis et al. (2018), we propose a modeling method for bottom-up time-based Material Flow Analysis (MFA) in demountable buildings, which considers interdependencies between building parts, and their potential disassembly and subsequent reuse. This method aims to advance the calculation of the life cycle inventory (LCI) of buildings and associated environmental impacts following a Life Cycle Assessment (LCA) methodology. In this section, we describe (1) the modeling method, (2) its link to LCA results, and (3) the proof of concept.

### *3.1. Material Flow Analysis method for demountable buildings*

The proposed method models the life cycle MFA of a building by considering the effects of replacing certain building parts on other surrounding parts. The method relies on information about the building parts, how they are assembled and connected, to establish periodical MFA balances, i.e., the accounting of all flows of parts occurring in the building at a year *y*. As illustrated in **Fig. 1**, it consists in four major steps: (1) defining parts to replace, (2) identifying the interdependent parts that must be removed for structural or accessibility reasons, (3) sorting parts according to their usability after disassembly and considering new parts replacing outdated ones, and (4) calculating periodic MFA balances from construction (year 0) to decommission (year D).

#### *3.1.1. Step 1: Defining target parts*

As a first step, we list the parts that are replaced at a year *y*, a year of MFA balance during the building operation, and called 'target parts'. These target parts are parts reaching the end of their Estimated Service Life (ESL) at year *y* and/or parts which will reach the end of their ESL before the next MFA balance (Section 3.1.4). Because the ESL of a part is the duration this part is expected to remain in the building in a set of specific in-use conditions (ISO, 2013), target parts are not *per se* technically outdated but could also be removed because of economic, aesthetic, or functional reasons.

#### *3.1.2. Step 2: Identifying interdependent parts*

As a second step, we identify interdependencies between building parts: when a building part is removed from the building, other parts must be removed alongside it. Interdependencies tend to complicate the disassembly and shorten the service life of surrounding building parts. In the proposed method, we identify part-to-part interdependencies by drawing a directed network graph of the building of interest, with building parts as nodes and interdependencies as arrows between nodes (**Fig. 2**). Interdependencies are related to two aspects: structural stability and accessibility.

Structural stability is an essential aspect of buildings, which, if not considered in the method, would lead to unrealistic disassembly sequences. When a part is removed from a building (e.g., a column), all parts attached to it and structurally depending on it (e.g., beams) must be removed as well. To be on the safe side, we assume the possibility to install stanchions or other temporary structural elements to preserve the stability of the building during the replacement of a part is discarded. We indicate that a part ('attached' part) is structurally dependent on another ('host' part) with an arrow in the 'structural' network graph between the nodes that represent the related building parts (**Fig. 2**, b). Unlike the DNA method (see Section 3.2), arrows here represent structural connections of an attached part to a host part.

Accessibility refers to the need for a worker and machinery to have access to the target part and to be able to remove it from the building. Compared to the DNA method (Section 3.2), the accessibility of a part is defined more pragmatically for each (interior or exterior) building space it touches. Each space is associated with an 'accessibility' network graph wherein the nodes represent parts that are not directly accessible, and the arrows indicate the order in which the other parts should be removed to access them (**Fig. 2**, c). If a part must be simultaneously accessed from different spaces, the order of disassembly should be indicated on a unique network graph. If a part can be accessed from different spaces, or if there are multiple ways of accessing a building part from one space, multiple network graphs must be considered.

Then, the structural and accessibility graphs are merged into one graph, unless there are alternative accessibility graphs. In this case, each accessibility graph is merged with the structural graph, resulting in alternative network graphs (**Fig. 2**, d). Based on the network graph(s), we can identify interdependent parts: when one part must be removed, all parts connected with an arrow towards that part must be removed alongside it. The list of parts to disassemble prior to the disassembly of a building part *p* forms a disassembly sequence. For each part in the disassembly sequence, we check iteratively whether there are additional interdependences due to structural stability or accessibility to consider, i.e., additional arrows to draw between nodes. If a building part to remove is part of a closed loop of arrows in the graph, it cannot be disassembled because there is no possible starting point in the disassembly sequence. Therefore, the directed graph must be acyclic: its arrows must never form a closed loop ("Directed acyclic graph," 2021).

#### *3.1.3. Step 3: Sorting parts according to their usability*

As a third step, we define whether the parts included in a disassembly sequence are lost (and proceed to waste treatment) or preserved (and are reusable, either immediately or later) depending on the detachability of the connection between two building parts. Four situations are considered when an attached part is detached from its host part: the integrity of the attached part can be either (1) preserved or (2) lost and the integrity of the host part can be either (3) preserved or (4) lost. The connection itself could be damaged beyond repair during disassembly (for example, it could be necessary to re-install a system of screws or hook-and-loop fasteners), hence the term "detachable" instead of "reversible". We neglect the material and environmental impact related to the loss of connections. A part is reusable if it is preserved during disassembly and still has a remaining service life. For instance, a finishing layer that is removed without damage to access a service duct could be directly re-installed and reused.

Altered parts are categorized into four flow types. Parts that are immediately reused in the building form the *REUSE* flow. Preserved parts leaving the building as secondary parts, fit for being reused in another building after only minor cleaning or repair form the *OUTP* flow (standing for *OUTflow Preserved*). Destructed parts leaving, only fit for waste treatment (they will be either landfilled, incinerated, or recycled), go into the *OUTD* flow (standing for *OUTflow Destructed*). Finally, new parts, replacing removed parts, form the *IN* flow.

As each part can be associated with a material mass, a purchase cost, a residual or reselling value, or an embodied environmental impact, each flow can be associated with multiple mass, cost, or environmental impact indicators. In case of alternative disassembly sequences (e.g. to recover the 'Cross bracing' in **Fig. 2**, d), one sequence is selected based on a pre-defined optimization objective: the maximization or minimization of an indicator in one of the four flows. Prior to the modeling, the assessor must choose the indicator to maximize or minimize in which flow.

#### *3.1.4. Step 4: Calculating periodic mass balances*

As a fourth and final step, *IN, OUTP, OUTD*, and *REUSE* flows of building parts are calculated for each periodical MFA balance (e.g. every 1, 5, or 10 years) in the building life, starting from year 0 (year of completion) to year *D* (expected year of decommissioning).

First, at year 0, all building parts are new, hence indicated in the $IN_0$ flow.

Then, for each year *y*, the flows of parts are calculated following the first three steps of the method. The $IN_y$, $OUTP_y$, and $OUTD_y$ flows calculated at year *y* comprise one or several target part(s) purposely replaced at a year *y* and possible interdependent parts. The $REUSE_y$ flow

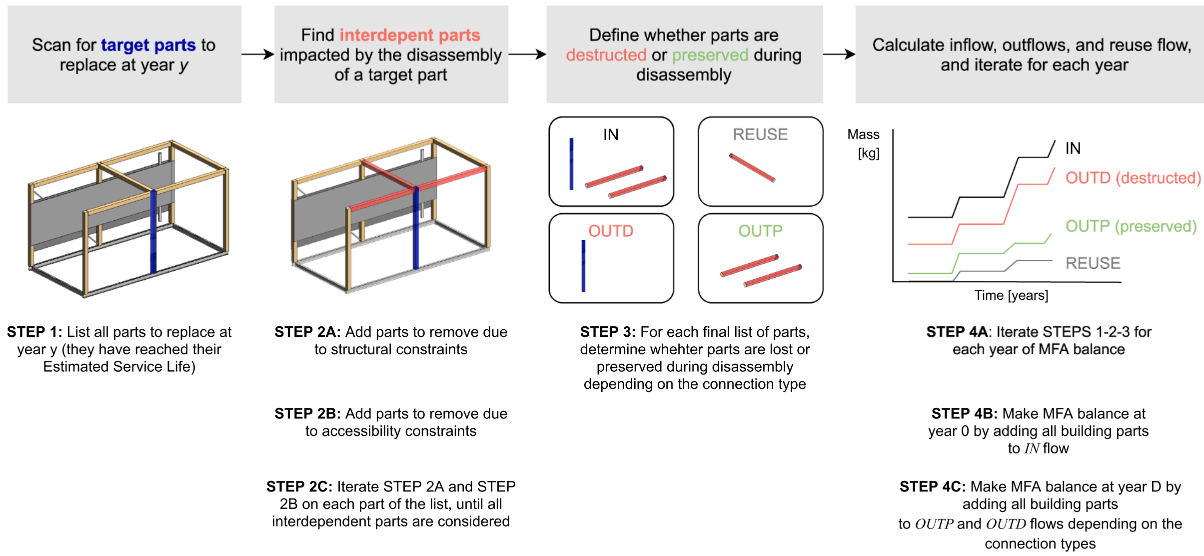


**Fig. 1.** Concept of the MFA method for demountable buildings. Four flows of parts are calculated periodically over the life cycle of the building, at each year *y*, from the first (year 0) to last (year D) year of use.

of parts that are immediately disassembled and reassembled on-site only consists of interdependent parts, since we assume that parts which have reached their ESL are removed from the building. This flow forms a closed loop and does not affect the stock at the building level. It is important to note though that if $REUSE_{p,y}$ decreases or increases, there will be more or less inflows and outflows, respectively. Also, as each part is replaced identically[1], the inflows due to a replaced target part *p* and due to interdependent parts *ip* always equals the sum of lost and preserved outflows. Hence, the stock variation at each year *y* equals 0 (Eq. (2)).

$$dSTOCK_y = \sum_{p=1}^{P}\left(IN_{p,y} - OUTP_{p,y} - OUTD_{p,y} + \underbrace{\sum_{ip=1}^{IP} IN_{ip,y} - OUTP_{ip,y} - OUTD_{ip,y} \pm REUSE_{ip,y}}_{\text{Stock variation due to interdependent parts}}\right) = 0 \tag{2}$$

Where: d$STOCK_y$ is the stock variation in building *B* at year *y* in kg; *y* is the year of the MFA balance; *p* is a part of the building *B*; $IN_{p,y}$ is the list of parts entering the building in replacement of target parts; $OUTP_{p,y}$ is the list of target parts leaving the building as potential secondary product; $OUTD_{p,y}$ is the list of target parts leaving the building as waste; $IN_{ip,y}$ is the list of parts replacing interdependent parts; $OUTP_{ip,y}$ is the list of interdependent parts leaving the building as potential secondary product; $OUTD_{ip,y}$ is the list of interdependent parts leaving the building as waste; $REUSE_{ip,y}$ is the list of reused parts.

When the MFA balance is not established yearly but, for instance, every 15 years, we check at each mass balance whether each part will not reach the end of its ESL before the next MFA balance. If the remaining Service Life of a part is not sufficient to reach the next MFA balance, then it is replaced with the previous one. For example, when an insulation layer has an ESL of 25 years and the MFA balances are established every 10 years, the insulation layer will be replaced at year 20 and 40. Obviously, some building parts never reach the end of their ESL because they are replaced by new parts along with other parts with shorter ESL. Therefore, flows of parts do not evolve linearly, instead they depend on the effects of previous replacements in the building.

Finally, at year *D*, all parts constituting the building are split amongst the $OUTP_D$ and $OUTD_D$ flows. The same procedure as for calculating the flows at year *y* is repeated with the parts 'to replace' being all parts in the building and without any *IN* flow.

These four steps form the modeling method for a time-based MFA of the building that considers the interdependence of its parts. From our experience, this modeling method can be easily conducted without relying on automated algorithms for simple buildings and built assemblies of less than 15 building parts. However, as the number of building parts increases, it becomes valuable, if not crucial, to automate the method. To facilitate the deployment of the method on large buildings, we collaborated on developing a software tool developed in the C# programming language and coupled with the Building Information Modeling (BIM) software Autodesk Revit® 2021. This software tool will be the object of a future publication.

### 3.2. From Material Flow Analysis to Life Cycle Assessment

As mentioned in the introduction, the MFA that results from the proposed modeling method can be used as an input for LCA. With this input, LCA allows to understand the consequences of alternative types of connection and assembly, and evaluate the life cycle impact of, for example, a wall finishing glued to its substructure when having to replace the underlaying insulation. This is possible because, unlike the EN 15978 approach, the proposed method takes into account that the wall finishing must be removed prior to the insulation and that, as the

[1] as in the EN 15978 formula. This assumption is however questioned by Vandenbroucke (2016). The replacement of a part by a more technologically advanced one is not yet considered in the method.

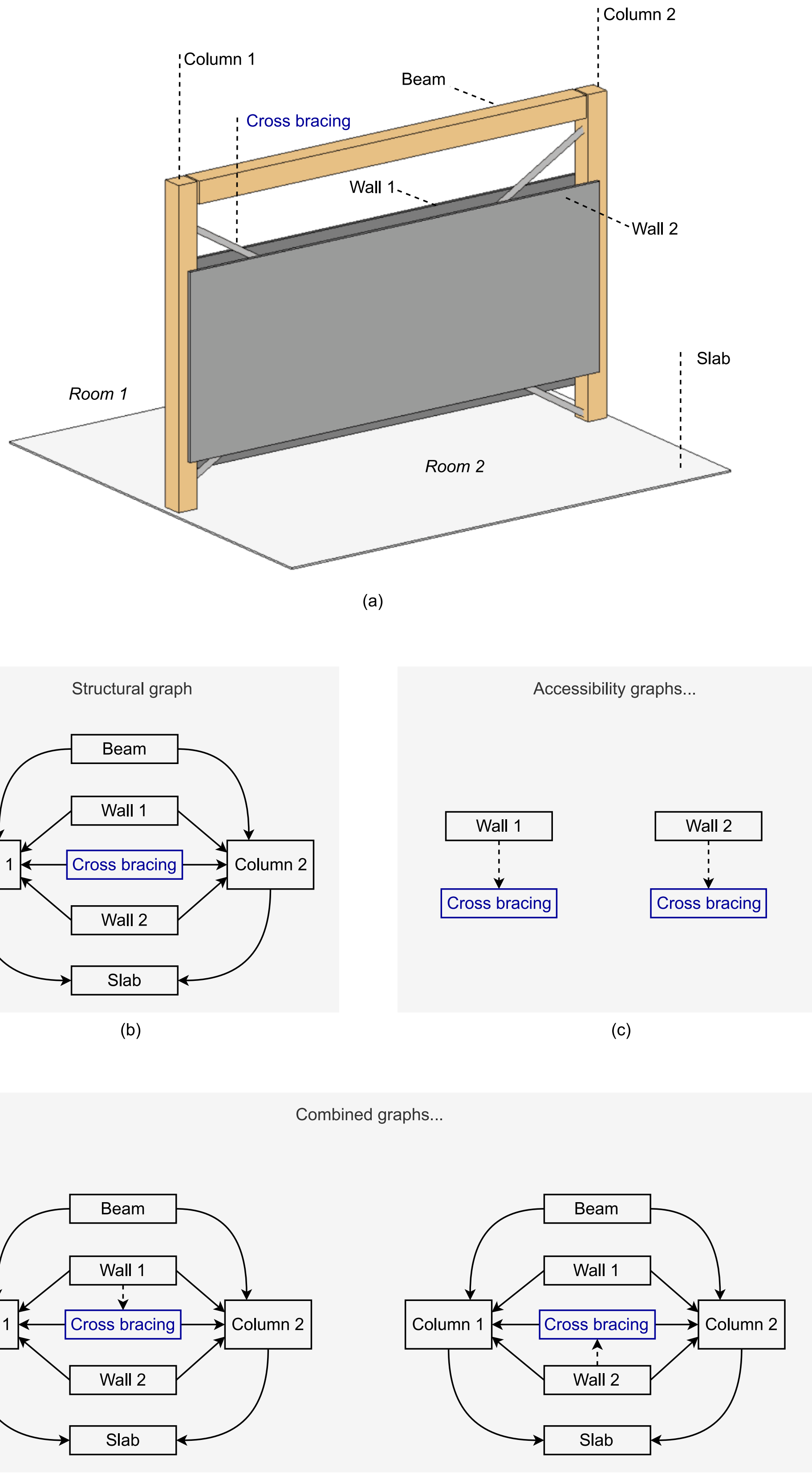


**Fig. 2.** Modeling interdependencies between building parts as arrows in directed network graphs. Starting from (a) a building model, (b) a structural graph indicates the parts that are attached together (plain line arrows), and (c) two accessibility graphs indicate two alternative ways to access the cross bracing (dashed line arrows). They form (d) two combined directed network graphs showing interdependencies between building parts.

glued connection is likely to damage the finishing, it cannot be simply reused and reinstalled.

To translate the MFA into an LCA, it is necessary to associate these flows of building parts to the upstream inventory of products and activities. In this Belgian case study, we obtain this upstream inventory following the recommendations of EN 15978 and specific scenarios for the Belgian construction sector (NBN, 2017; Allacker et al., 2020). Further, we associate this product and activities inventory to upstream substances flows using the process-based inventory database Ecoinvent (Wernet et al., 2016) in the LCA software SimaPro (PRé Consultants, n. d.). Finally, we translate this environmental flow inventory into environmental impact assessment through the ReCiPe life cycle impact assessment method, which considers environmental impacts through midpoint (i.e., single environmental problems) and endpoint (i.e., global areas of environmental protection) indicators (Huijbregts et al., 2017). The results are characterized, normalized, weighted, and aggregated in a single score to support building design decision-making based on a global consideration of environmental problems, not specifically on, for example, global warming. As mentioned in Section 3.1.1, our modeling method distinguishes between lost parts ($OUTD_{p,y}$) and parts that are preserved and reusable as secondary products ($OUTP_{p,y}$, standing for *OUTflow Preserved*). However, whether these preserved parts should receive environmental credit for being reused in another building (accounted for in Module D in EN 15804) depends on the remaining service life of the part, and whether the part is at the "End-of-Waste state", i.e., it fulfills the criteria for not being considered as waste, but as a secondary product, as defined in EN 15804+A2 §6.4.3.3. The End-of-Waste state of a part must thus be checked case by case.

Environmental data in LCA is integrated over space and time (ISO 14040, 2006), and gives no precision on when and where environmental impact is created. Accordingly, when translating flows of parts into environmental impact, we sum the flows over the whole period of the building life cycle. This sum is translated in a time-independent environmental impact score associated to each design option. While dynamic LCAs (DLCA) consider that the environmental impact associated with building parts evolves with technological progress (Collinge et al., 2013), we consider that the associated impact is constant: e.g. the production of a steel beam carries the same environmental impact when the beam enters the building at year 0, 25, and 50.

### 3.3. Proof of concept

In this section, we present (1) the underlying reasons for a case study approach, (2) the scope, functional unit, and system boundary for a proof-of-concept LCA, (3) the corresponding modeling assumptions and the explored scenarios, (4) our method for the environmental impact assessment, and (5) the surveyed parameters in the sensitivity analysis.

#### 3.3.1. Rationale and selection of the case

The objective of the proof of concept is to illustrate how the method can be used to generate a bottom-up MFA of a building considering part interdependencies as well as a refined LCA of that building. In addition, the proof of concept shows how a designer can compare alternatives design options regarding the structural design of an assembly, the accessibility of its parts, and the detachability of the connections. The two underlying questions to address with the proof of concept are:

- *How much do the MFA results (mass flows in kilograms) and subsequent LCA results (environmental impact in ReCiPe points) differ in the proposed modeling method from the EN 15978 modeling approach when applied to a simple case study?*
- *How design choices regarding the structural design of an assembly, the accessibility of its parts, and the detachability of the connections affect the MFA and subsequent LCA results within the case study?*

This type of 'how' and 'why' questions are well-suited for the use of case studies and research experiments (Yin, 2018). A revelatory case study, which aims at testing different combinations of parameters to better understand their effect on the developed model, suits the analysis of interdependencies, a scarcely studied aspect of the building service life. Hence, we selected a single case and compared nine design variations (in terms of assembly and connection types). We also assessed the sensitivity of the results to two parameters which are inherently uncertain, namely the ESL of the building parts and the material losses during on-site reuses. To avoid over-complication and to keep the proof of concept illustrative, we use a fictitious case where we have control over most design parameters (e.g., geometry, materials, connection design).

#### 3.3.2. Scope, functional unit, and system boundary

The proof of concept consists of a simple pavilion, with a wall and service duct, built in Belgium, with a service life of 60 years. The pavilion consists of 20 building parts and 29 connections between parts (**Fig. 3**). The functional unit is the use of this pavilion for 60 years.

Stages included in the LCA calculation are production and construction (A1-A5), replacement (B4&5) and end-of-life deconstruction and waste treatment (C1-C4). We do not distinguish reasons for replacing a building part, e.g. technical, economic, or functional, hence a combined B4&5 stage. The total life cycle impact of the building ($I_b$) is calculated by:

$$I_b = I_b^{A1-A3} + I_b^{A4-A5} + I_b^{B4\&5} + I_b^{C1-C4} \tag{3}$$

Where: $I_b^{A1-A3}$ is the production impact of the building parts, based on Ecoinvent data, $I_b^{A4-A5}$is the transport and construction impact of the parts, $I_b^{B4\&5}$ is the replacement impact of the building (including production, transport, and end-of-life impact for the parts to replace and interdependent parts), and $I_b^{C1-C4}$ is the end-of-life impact of the building.

#### 3.3.3. Data, assumptions, and scenarios

The load bearing structure of the pavilion consists of 6 timber columns and 6 timber beams which stand on 4 steel beams (**Fig. 3**). The other elements of the pavilion are a diagonal bracing, agglomerated wood particle boards and a vertical service duct. For illustrative purposes, the service duct is not attached to any other building part, it is only used for the continuity of services from adjacent unmodeled building parts.

Three design options are considered, in which the accessibility to the duct varies according to DfD principles. In the base option (BASE), the duct is placed between the interior and exterior boards. In the second option (PACE), the duct is placed in front of the interior board, this design relates to pace-layering (Debacker et al., 2015), a concept popularized by Stewart Brand (Brand, 1994). In the third option (MODU), the duct is placed between the wall panels, but the interior board is split in two parts $Wall_{int,1}$ and $Wall_{int,2}$. A more complete overview of the building parts, including their mass, for each design option is publicly available through Figshare[2] (Vandervaeren, 2021).

For each design option, three connection design options are considered, summing to nine variations of the pavilion:

- Fully detachable connections (BASE_FD, PACE_FD, MODU_FD), where the integrity of all products is preserved after separation, which allows reassembly;
- Partially Detachable (BASE_PD, PACE_PD, MODU_PD), where the wall panels are connected to the columns in a non-detachable way, but the columns are not damaged by the removal of the wall panels;

[2] https://figshare.com/articles/dataset/_/14740734

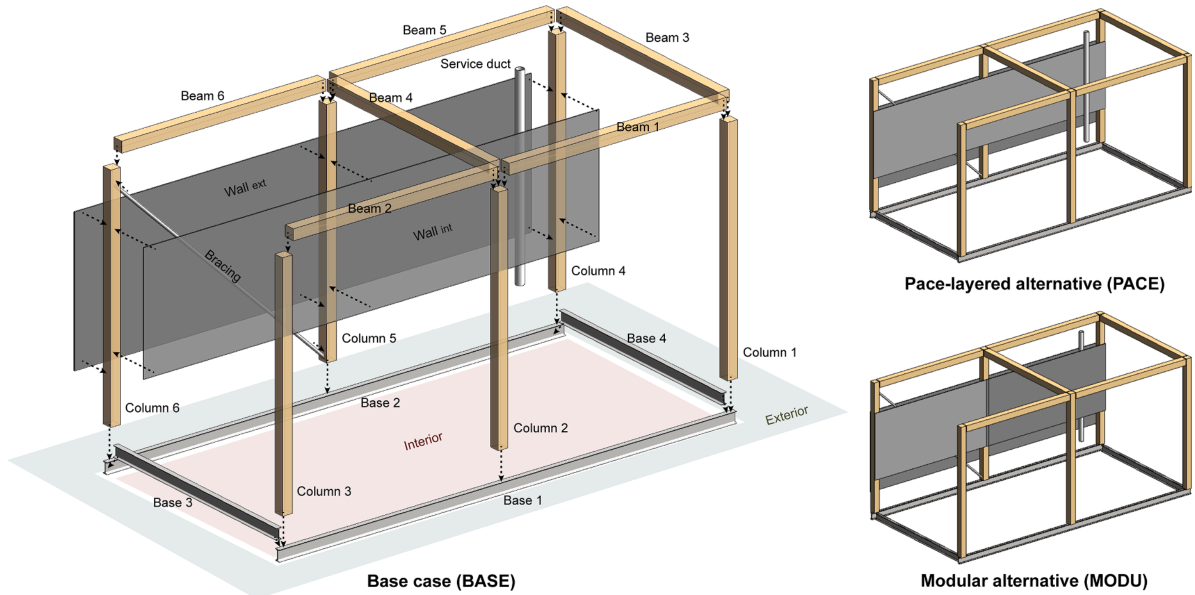


**Fig. 3.** Three design options for the pavilion. The base case design (BASE), a pace-layered design alternative with service duct outside the wall (PACE), and a modular design alternative where $Wall_{int}$ is divided in two parts (MODU).

**Table 1**
Minimal, average, and maximal Estimated service life (ESL) in years, based on (BCIS, 2006), per part of the pavilion.

| | $ESL^{min}$ | $ESL^{av}$ | $ESL^{max}$ | Entry name in (BCIS, 2006) |
|---|---|---|---|---|
| **Timber columns and beams** | 35 | 60 | 95 | 2A Timber Frame: Generally |
| **Steel beams** | 50 | 75 | 100 | 2A Columns and Beams: Steel (Grade 43): Exposed; UBs and RSCs primed |
| **Wall panels** | 15 | 30 | 40 | 2E External Wall Coverings: Timber: Board infill panels |
| **Bracing** | 50 | 75 | 100 | 2A Columns and Beams: Steel (Grade 43): Exposed; UBs and RSCs primed |
| **Duct** | 15 | 25 | 30 | 5D Pipes: Medium Density Polyethylene (MDPE): Installations Pipework and fittings |

- Non-detachable (BASE_ND, PACE_ND, MODU_ND), where the integrity of product is lost after separation, i.e., they cannot be reassembled.

The Estimated Service Life ($ESL_p$) of each part of the pavilion is determined from a report by the Royal Institution of Chartered Surveyors (BCIS, 2006), and listed in **Table 1**. We consider that the replacement of a part can never be delayed, even when this replacement would be too close to the end of the service life of the building (called 'suspension period' in Allacker et al. (2020)), or too close to the next MFA balance (see Section 3.1.4).

The MFA balances are established every 2 years, for 60 years. During the replacement of outdated parts, if more than one disassembly sequence is possible, we choose the sequence with the lowest mass of waste lost (i.e., *OUTD*). At the end of the required service life of the building (60 years in this case), the building is disassembled as much as the detachability of the connections allows it, otherwise it is demolished.

**Table 2**
Ecoinvent v3.1 entry name for each building part used in the LCA calculation. When the Ecoinvent entry is expressed per cubic meter, it is converted in mass units via the mass volumetric values indicated in the last column.

| | Unit | Ecoinvent v3.1 entry | Volumetric mass |
|---|---|---|---|
| **Timber columns and beams** | kg | Sawnwood, beam, softwood, kiln dried, planed {RoW}\| planing, beam, softwood, kiln dried \| Alloc Rec, U | 550 kg/m$^3$ |
| **Steel beams, bracing, and duct** | kg | Steel, low-alloyed, hot rolled {RER}\| production \| Alloc Rec, U | |
| **Interior wall panel $Wall_{int}$** | kg | Particle board, for indoor use {RER}\| production \| Alloc Rec, U | 600 kg/m$^3$ |
| **Exterior wall panel $Wall_{ext}$** | kg | Particle board, for outdoor use {RER}\| production \| Alloc Rec, U | 600 kg/m$^3$ |

We follow a recycled-content approach, and consider in stage C4 the share of materials being landfilled and incinerated. The impact associated with recycling is allocated to the next product system and is not considered.

Assumptions regarding transport (A4), waste transport (C2), and waste treatment scenario (C4) are in line with recommendations for LCA of buildings and construction products in Belgium (Allacker et al., 2020). By lack of data, and limited relevance in the scope of this study, we exclude the contributions of packaging (in stage A3) and material sorting (in stage C4). As the pavilion is manually assembled, its construction impact (A5) is null. We consider 0% material losses, so no impact, during reuse (B4&5) and no specific impact during pavilion deconstruction (C1).

### 3.3.4. *Impact assessment and interpretation*

**Table 2** shows the chosen entries from Ecoinvent v3.1 database used to associate the flows of parts resulting from the MFA to an inventory of substance consumption and emission. As mentioned in Section 3.2, this inventory is converted to an aggregated ReCiPe single score via the impact assessment method ReCiPe (ReCiPe Endpoint (H) V1.12/ Europe ReciPe Hierarchist/Average), in SimaPro 8. For information, the LCA results are also reported for the impact category Global Warming Potential (GWP), via the ReCiPe Midpoint method. Infrastructure processes are included, long-term emissions are excluded.

### 3.3.5. Sensitivity analysis

We evaluate the sensitivity of the inventory and LCA results to a variation of the material loss during on-site reuse (from 0% loss to 5% loss in mass) and to minimal and maximal Estimated Service Life values. Sensitivity to material loss is important to evaluate because on-site operations can lead to material wastage due to poor craftsmanship,

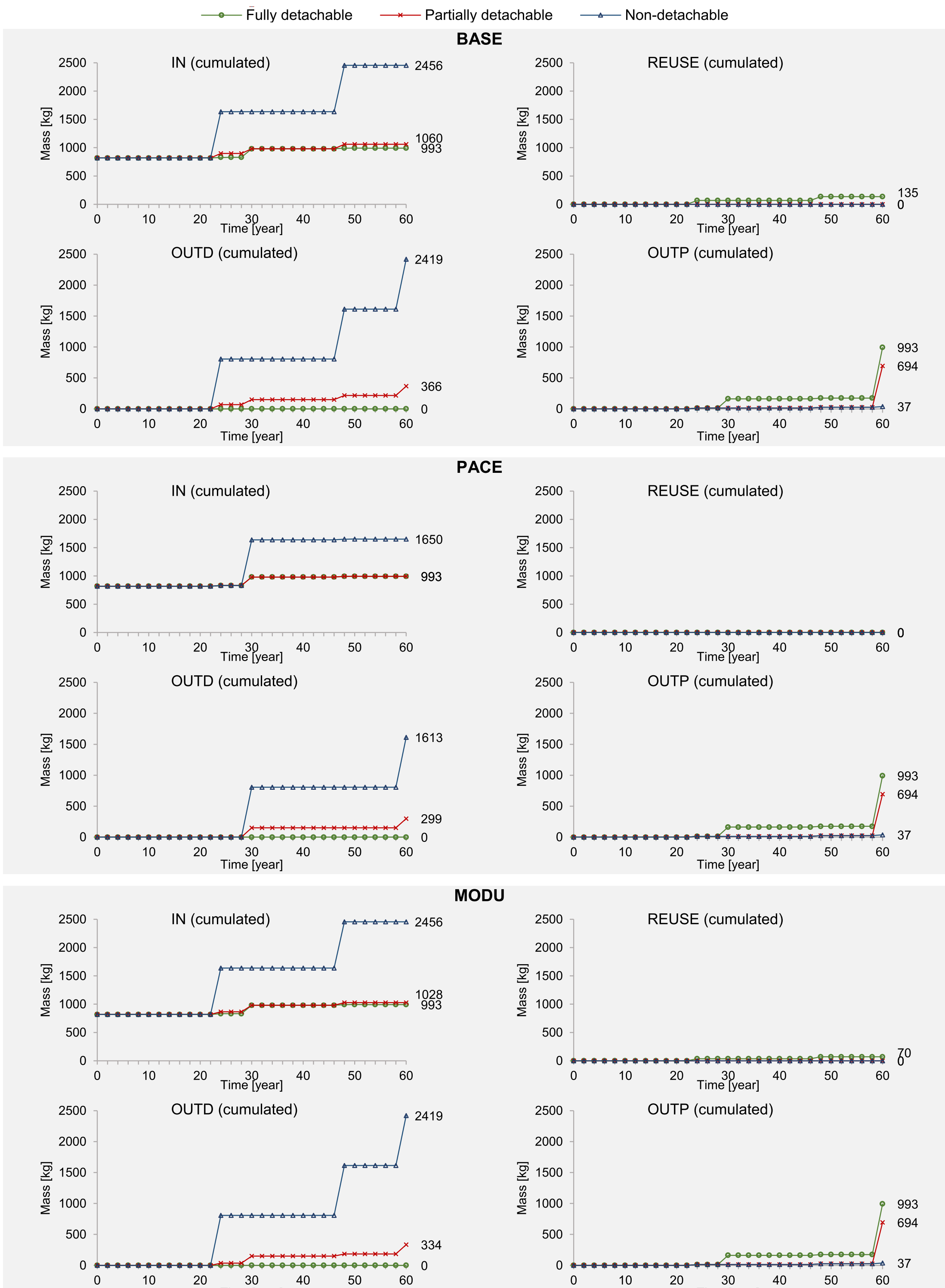


**Fig. 4.** Evolution of cumulated mass flows for three design options and three connection designs. The pavilion's designers can anticipate how much and when new materials are required, waste is created and building parts are reused; they can compare the 9 design options based on their material efficiency.

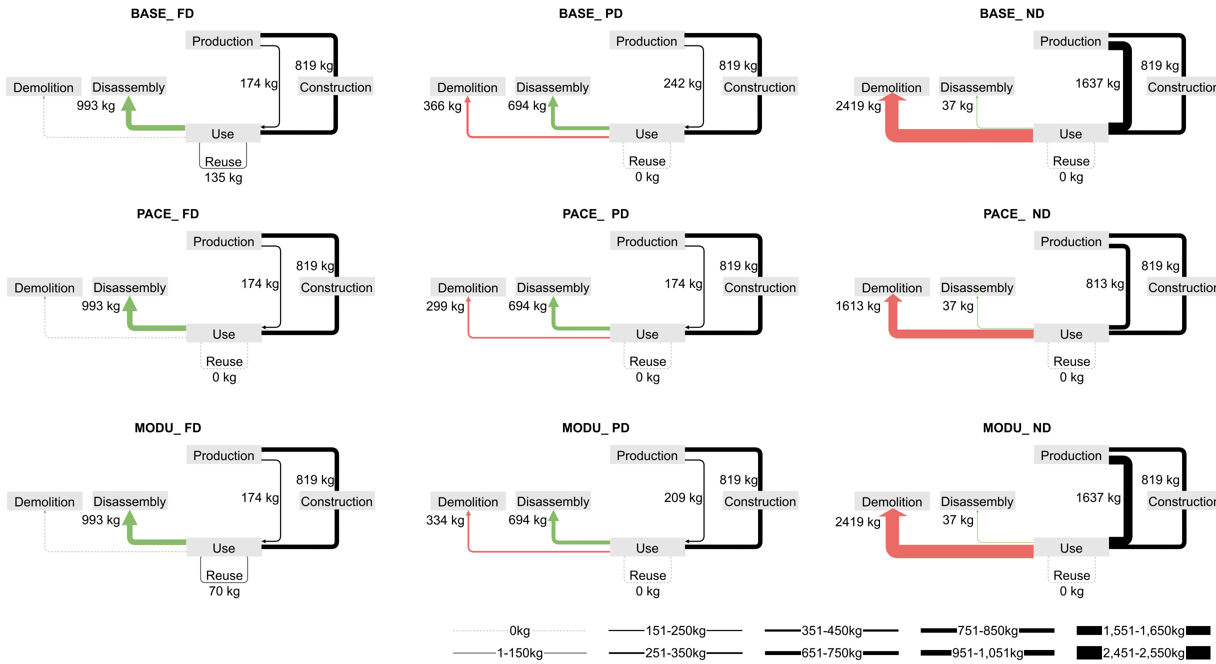


**Fig. 5.** Lifecycle mass flows in the nine design options presented as Sankey diagrams. Choosing partially detachable connections (PD) in place of fully detachable ones (FD) generates up to 366 kg demolition waste over the pavilion's lifecycle.

accidents, improper handling, or defects. A 5% material loss is recommended for LCA studies in the Belgian construction sector set, for all types of projects, not specifically for buildings designed for future disassembly (Allacker et al., 2020). We assume that reuse operations with material losses greater than 5% would not take place in practice, as they would be logistically complicated and off-set their potential benefits.

## 4. Results

The results section is divided into three parts: (1) bottom-up MFA obtained with the modeling method on the nine design options; (2) associated environmental impacts expressed in ReCiPe points and (3) sensitivity analysis.

### 4.1. Material flows

The MFA for the three design options and three connection options is displayed as a cumulated graph of the mass of input (*IN*), reused (*REUSE*), output lost (*OUTD*) and output preserved (*OUTP*) materials over time (Fig. 4) and as static Sankey diagrams (Fig. 5). The initial mass of the pavilion in all options is 819 kg. The first replacement of a building part, the service duct with an ESL of 25 years (Table 1), occurs at year 24, because material flows are accounted every two years.

In BASE, the duct is accessed by removing the interior panel (68 kg), which is lighter than the exterior panel (82 kg) and is henceforth part of the disassembly sequence leading to the least waste. When all connections are fully detachable (FD), the interior panel is preserved during disassembly, is put back in place, and remains in the building for 5 more years, as both panels reach their Estimated Service Life (ESL) at year 30. If all connections are non-detachable (ND), then the whole pavilion is demolished and replaced. When only the wall panels are connected in non-detachable way to the structure (Partially Detachable, PD), the interior wall is lost and replaced along with the duct. On the graph of the BASE_PD option (Fig. 4, BASE, red line), the *IN* mass flow increases accordingly by 80 kg at year 24. A similar procedure results in the variation of *IN* and *OUTD* mass flows at year 30 (replacement of the wall panels) and at year 48 (second replacement of the service duct). The

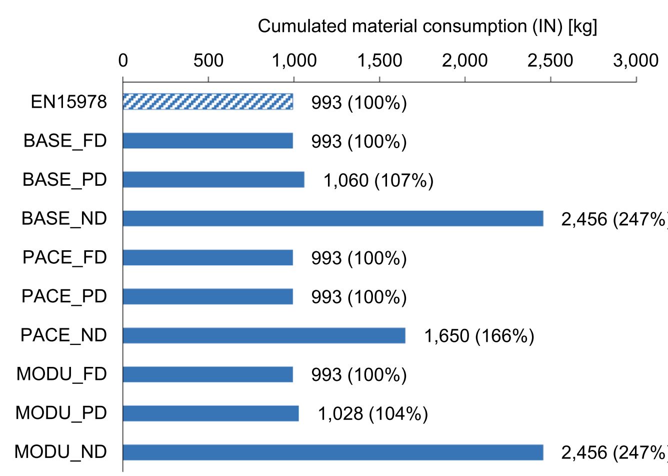


**Fig. 6.** Cumulated material consumption over the pavilion lifecycle calculated with the EN 15978 method and the proposed material flow accounting method. A non-detachable design generates up to a 147% increase in material consumption compared to EN 15978 method.

structural elements having an ESL longer than 60 years are not replaced during the service life of the pavilion. No part is reused in BASE_PD and BASE_ND options. In BASE_FD, the interior panel is reused (at year 24), then replaced (at year 30), and reused again (at year 48), resulting in 135 kg for the cumulated *REUSE*[3] flow at year 60. In PACE, the duct is not integrated in the wall panels and is therefore directly replaced by a new duct without interfering with other building parts. As the pavilion is disassembled at year 60, the design options with fully detachable connections (FD) have all their building parts attributed to the *OUTP* flow.

As shown by the Sankey diagrams, non-detachable (ND) design options lead to more demolition waste (*OUTD*) than partially detachable

[3] The *REUSE* flow increases each time a part *p* is reused, even when the same part is reused multiple times. This could lead to a cumulated *REUSE* flow larger than the *IN* flow of new parts.

(PD) and fully detachable (FD) options (Fig. 5, in red), whereas reuse only occurs in BASE_FD and MODU_FD for this case. Four design options require the smallest amount of material inflow, i.e., 993 kg, namely BASE_FD, PACE_FD, PACE_PD and MODU_FD, while BASE_ND and MODU_ND initiate the largest amount of material inflows, 2456 kg (Fig. 6). As expected, the fully detachable (FD) options lead to the lowest amount of consumed material, as they enable the reuse of the parts in-situ. Interestingly, PACE_PD is among the least material consuming designs although no reuse is taking place, illustrating the advantages of a pace-layered design. There, the duct can be replaced without creating unnecessary waste, even when the wall panels are not connected in a detachable way (PACE_PD). When no connection is detachable, the material consumption of the pavilion drops from 2456 kg for BASE_ND and MODU_ND to 1650 kg for PACE_ND. The careful design of accessible building parts can thus be as effective as detachable connections to avoid demolition and unnecessary replacements.

Alternatively, following the EN 15978 method to calculate the number of replacements, the service duct (with an ESL of 25 years) is replaced twice and each wall panel (with an ESL of 30 years) is replaced once. The resulting mass of material input is 993 kg, identical to the value obtained from the proposed modeling method on design options with fully detachable (FD) connections. Indeed, the EN 15978 modeling method for the replacement (B4&5) is only based on a ratio of the ESL of a part to the building ESL. It therefore implicitly considers that all connections are fully detachable, there are no losses or extra impacts from reuse. The proposed modeling method yields an increase of 7% of input material mass compared to the EN 15978 method in the base design with partially detachable connections (BASE_PD) and an increase of 147% in the base design with non-detachable connections (BASE_ND) (Fig. 6). The differences between the two approaches are therefore important even in the case of a simple pavilion made of 20 building parts.

### 4.2. Life cycle environmental impact

In terms of life cycle impact, the largest differences with the EN 15978 method are noted on the designs with non-detachable connections (Fig. 7, left). The aggregated life cycle impact that results from the proposed method of the replacement (B4&5, in dark blue) stage is larger than the one obtained from EN 15978 by 28% in three options (BASE_PD, MODU_FD, and MODU_PD), by 611% for PACE_ND and, notably, by 1290% for the BASE_ND and MODU_ND. The overall life cycle impact increases up by 162% for BASE_ND. The life cycle impact remains unchanged in four out of the nine options (BASE_FD, PACE_FD, PACE_PD, MODU_FD). The LCA results in terms of Global Warming Potential impact are similar to those calculated in terms of aggregated ReCiPe points (Fig. 7, right). Clearly, a more detailed account of the material replacements allows the detection of design configurations with a considerably larger environmental impact.

### 4.3. Sensitivity analysis

To evaluate the influence of key parameters on the results, we increase the material loss during reuse from 0 to 5%. The overall observations remain the same in this case, as only the interior wall panels are reused. Considering a 5% material loss during reuse increases the B4&5 environmental impact in BASE_FD and MODU_FD by 3% and 1% respectively. Losses during reuse seem to have a negligible effect on the results.

Conversely, the results vary significantly with a variation to the ESL of building parts, as demonstrated by Rauf (2016). Regarding the MFA (Fig. 8), we observe two main consequences when using minimal values for the ESL of the building parts ($ESL^{min}$ in Table 1). First, the differences in material flows between BASE, PACE and MODU design options are fading: for example, the cumulated *IN* flow in BASE_ND, PACE_ND and MODU_ND respectively varies in from 2456 kg; 1650 kg; and 2456 kg (with $ESL^{av}$) to 4093 kg; 4093 kg; and 4094 kg (with $ESL^{min}$). This is explained by the fact that the pace-layered design options (PACE), with direct access to the duct, does not provide an advantage anymore: the wood panels and the service duct must be replaced at the same time every 15 years. Second, flow values increase significantly compared to $ESL^{av}$, as expected when building parts have shorter service lives, and are thus replaced more often. For instance, the cumulated *IN* mass flow increases from 2456 kg (with $ESL^{av}$) to 4093 kg (with $ESL^{min}$, +67%) for BASE_ND and MODU_ND. It even increases by 148% for PACE_ND. With a higher replacement rate of the pavilion parts, reuse occurs more often: for instance, the base steel beams and the bracing are replaced at year 50, while the rest of pavilion is dis- and re-assembled on site in BASE_FD. For this option, the total amount of reused materials is 413% larger. Altogether, shorter service lives tend to increaser material consumption and waste, through more frequent replacements and reuse opportunities, as expected.

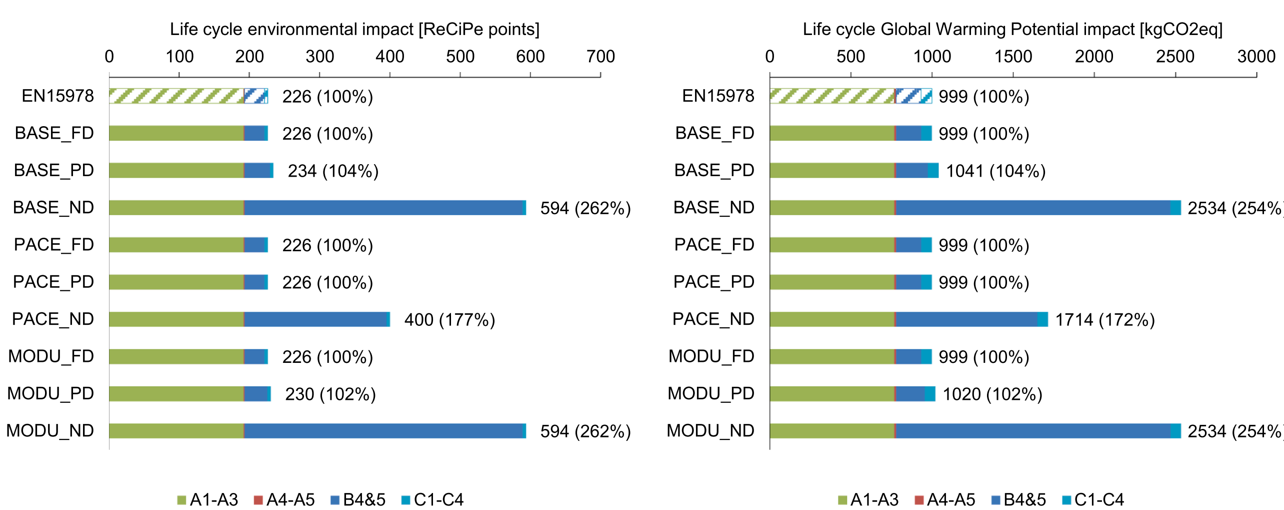


**Fig. 7.** Life cycle environmental impact of the pavilion, expressed in (left) ReCiPe points and (right) Global Warming Potential, calculated with the EN 15978 method and the proposed MFA method (9 design options). A non-detachable design generates a 162% and 154% increase in respectively environmental and Global Warming Potential impact compared to the impact calculated with EN 15978 method. A1-A3 = material extraction and component production stage, A4-A5 = transport and construction, B4&5 = replacements during operation, C1-C4 = end of life.

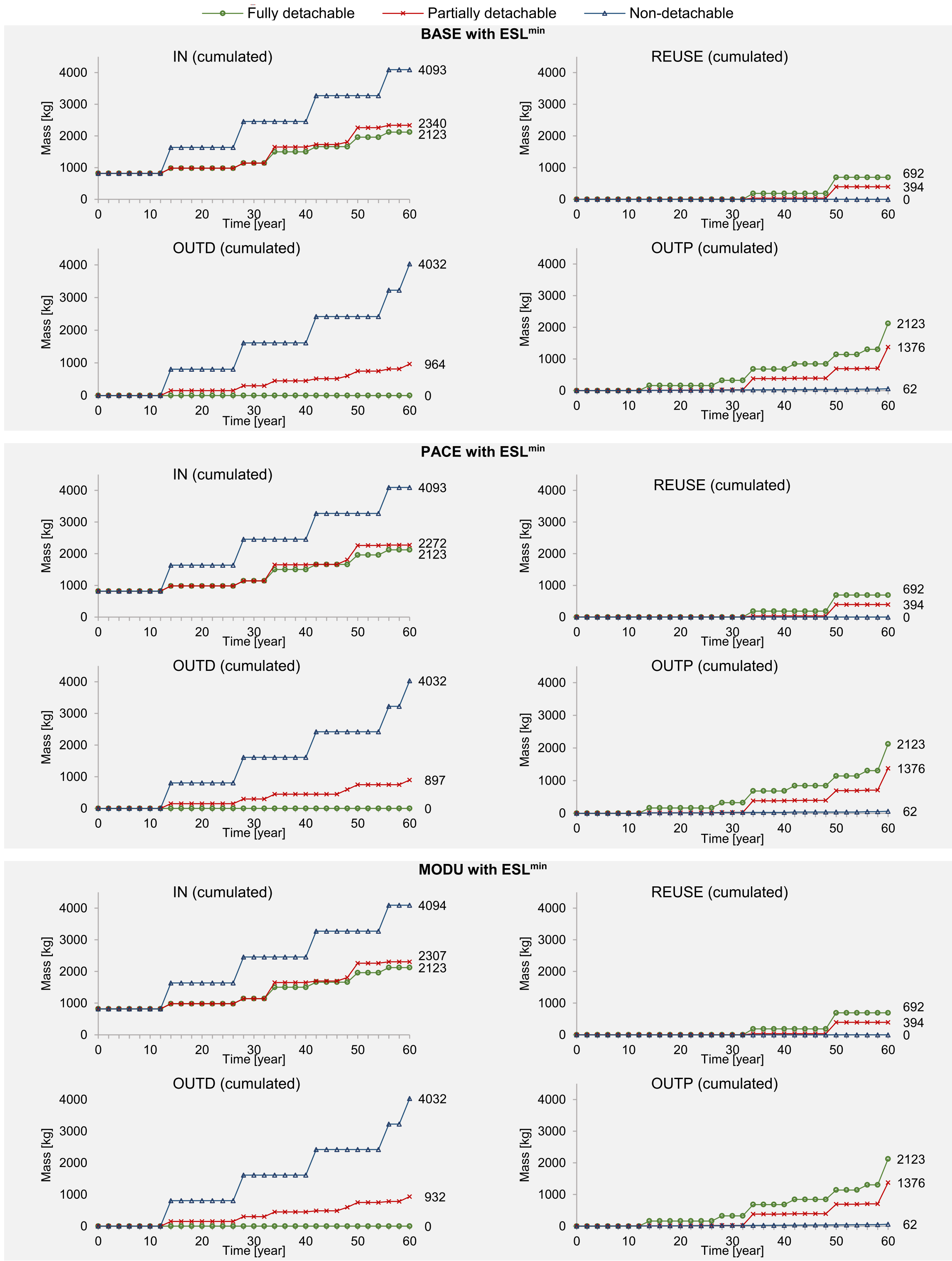


**Fig. 8.** Evolution of cumulated mass flows for three design options and three connection design, considering minimal Expected Service Life ($ESL_{min}$) values. Compared to $ESL_{av}$, material flow values increase because building parts have shorter service life values and are thus replaced more often.

How the nine design options compare to one another is not affected by an extension nor a shortening of the service lives of the parts in this case (Fig. 9). Life cycle environmental and GWP impacts calculated with $ESL^{min}$ values approximately double those calculated with $ESL^{av}$ values. Those resulting from $ESL^{max}$ and $ESL^{av}$ are close to one another, except for the ND design options (i.e., extreme situations where not even one building part remains functional after disassembly). In other words, in this case study, extending service lives is not necessary to reach a low life cycle environmental impact for the same functional unit. A similar conclusion was drawn by Rauf (2016), as he warned against using long-lasting materials in a building with a relatively short useful life.

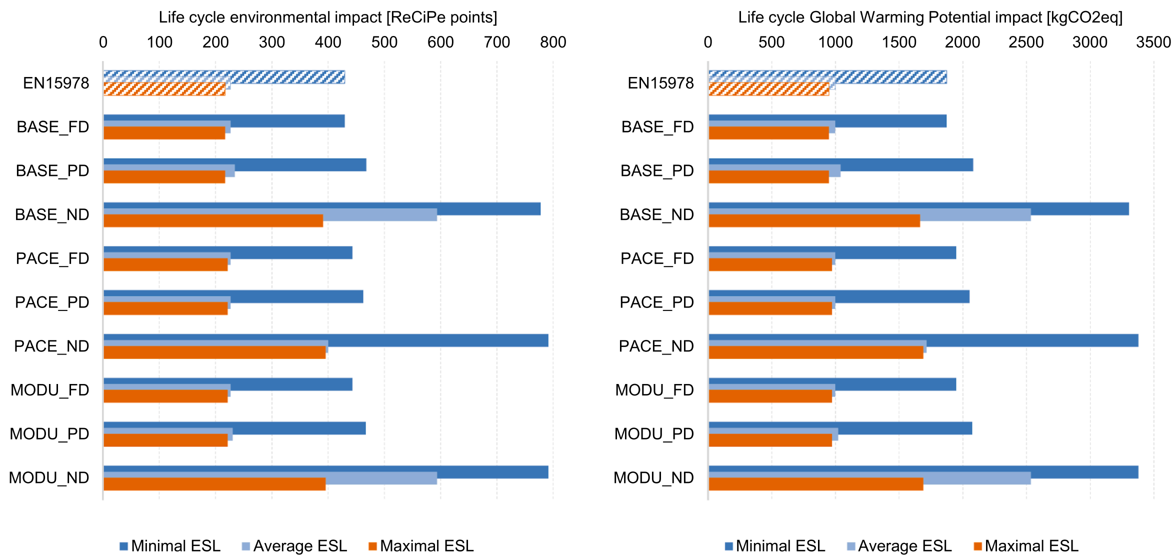


**Fig. 9.** Life cycle environmental impact of the pavilion, expressed in (left) ReCiPe points and (right) Global Warming Potential, calculated with the EN 15978 method and the proposed MFA method for average, minimal and maximal values for the Estimated Service Life (ESL) of the pavilion parts. Life cycle environmental impact for average and maximal ESL values are similar, except in extreme non-detachable connection designs (ND). The initial conclusions of the comparative LCA remain the same.

## 5. Discussion

### 5.1. Added value of the modeling method

The modeling method for bottom-up MFA yields new insights regarding the interdependence of building parts and its long-term consequences, a focal point in DfD. The number of replacements calculated with this method is not only based on the Estimated Service Life as in the EN 15978 approach, but also on the structural interdependence of building parts, their accessibility, and the use of detachable connections. Further, all building parts that must be removed to access and replace an obsolete part are also considered. For these reasons, the proposed modeling method marks a major step forward in life cycle inventory accounting of demountable buildings. The life cycle inventory and associated environmental impact calculated with this method are therefore more realistic and detailed for the assessment of demountable buildings, where the possibility to preserve the integrity of a product is an important design incentive. The method enables the assessment of the material consumption and environmental impact of three-dimensional demountable built assemblies, and on this aspect, it offers more possibilities than the layer-by-layer, part-by-part method that is currently adopted. Our method incorporates the concepts laid down in the DNA method (see Section 2.2) for disassembly sequences and material flows, and it also systemizes the process of modeling and sorting the disassembly sequences and integrates it within a Life Cycle Inventory.

Besides a more nuanced and realistic assessment of the Life Cycle Inventory and its related impact, the method also offers a time-based assessment. Knowing when building parts might become obsolete, and the repercussion on the surrounding parts, can be beneficial to building managers, as they will know when large maintenances are best planned, and to actors of the urban mining field, as they can anticipate the moment and the volume at which reusable products are introduced in and released by buildings (Stephan and Athanassiadis, 2017). Time-based flows of building parts and their associated environmental impact can also indicate how the building complies with, for instance, emission reduction policies with paced objectives. In addition, keeping the time component is relevant in Life Cycle Costing since the cost impacts are scaled in time by discounting future impacts (ISO, 2008), as illustrated in LCC studies (Galle et al., 2017; Kneifel, 2010) and mixed LCA-LCC studies (Schmidt and Crawford, 2018; Stephan and Stephan, 2020).

Data needed to model the material flow is limited to the list of building parts with their mass, their Estimated Service Life, the list of structural dependencies (i.e., the edges of the network), the connection types (i.e., whether the two parts are preserved or lost), and for each part, whether other parts must be removed to access the part and from which building space. Additionally, the assessor must indicate the pace and the last year at which the MFA balance is established (every 2 years for 60 years in this case study). For the pavilion of 20 parts used in the proof of concept, 280 data fields are needed to feed into the model, and only 239 if the assessment is solely based on the mass of parts, not on cost or environmental impact. In comparison, the nine matrices in the SDPB method (Sanchez et al., 2019) require 688 data fields for a building with 20 components and 29 fasteners. The method is based on logical relationships and is implementable as a software tool, in combination with a Building Information Model, which significantly eases data collection and processing. For instance, the mass of parts is embedded in the Building Model; the user must only define the geometry of the part and its material(s).

Regarding the applicability of the modeling method, building parts are not linked to a specific building level, they can be any building material (e.g., insulation foam), component (e.g., a tile floor covering), module (e.g., a prefabricated office box), as long as the assessor can qualify the detachability of the connections between two parts. Although we developed this method to assess buildings in the design phase, where the potential for implementation is the highest, it could also be used as an audit or decision support tool to guide the transformation of existing buildings.

### 5.2. Limitations and future improvements

Our study has several limitations regarding (1) the MFA method, (2) the translation of material flows into environmental impact, (3) the proof of concept, and (4) the difficulty to validate the results.

First, the proposed modeling method currently assesses the impact of periodic replacements of individual parts, while DfD most often benefits from (unexpected) functional changes at the building level, such as when a shop is refurbished, or an office is converted into a school. We could partially overcome this limitation by introducing a second temporal parameter, associated with functional changes like by Galle et al. (2017). This aspect needs further investigation.

In addition, in the definition of surrounding parts to remove, only structural and accessibility aspects are considered. In the future, other functional aspects, such as thermal and acoustic continuity, air and water tightness, could also be included in the method.

While the nuances brought by the method already improve the assessment of demountable buildings, more precision and realism could be reached by refining, among others, the definition of accessibility of building parts and the condition for preserving a part during disassembly. Currently, a part is considered accessible only if the entire part and all its connections are entirely accessible by workers and their tools for disassembly. In the future, we could model the situation where a fraction of the part remains inaccessible (e.g., a floor finishing under a wall partition) and the part must be partially cut or divided into smaller subparts. Similarly, the use of non-detachable connections could lead to the loss of only a fraction of the building part. For these two aspects, a parameter for material loss during disassembly could be introduced in the model. Alternatively, the current method could still be used while the parts are modelled as smaller entities with different accessibility and connection status. The modeling method, like most methods, still depends on a subjective interpretation by an assessor when inputting parameters. For instance, in the absence of information provided by the manufacturer or the contractor, it is the assessor that must define the detachability of the connection. Similarly, the assessor must define the parts preventing access to the other parts. In the PACE design option of the proof of concept, it is interpreted that the duct in front of the wall is not preventing access to the wall panel, and the interior panel can be disassembled without interfering with the duct, which is however uncertain. When assessors doubt the practicality of modeling choices, they might want to compare different configurations.

Second, no method to translate material flows into environmental impact is unanimously accepted in the LCA field, and the combination of Ecoinvent and ReCiPe is no exception. On the one hand, Ecoinvent is based on process data, i.e., specific production process data collected from manufacturers and industries (Crawford et al., 2017). Inventory analyses based on process data are considered more reliable but less complete than input-output data, i.e. based on macroeconomic data collected by national statistics agencies in the form of input-output tables (Crawford et al., 2017). Hybrid inventory analyses, combining the reliability of process data and the completeness of input-output data, are often preferred for studying embodied impacts (Rauf and Crawford, 2015), because process analyses tend to underestimate the environmental impact of products, due to a systematically truncated system boundary (Crawford et al., 2017). In this study, we assume that this underestimation of impact is of similar order of magnitude for all parts of the pavilion, as did Vandenbroucke (2016). On another hand, we chose to report the LCA results in ReCiPe points and Global Warming Potential. The former indicator combines midpoint and endpoint environmental indicators, with impact results that are normalized, weighted and aggregated, in order to cover a wide range of environmental mechanisms, and enables a straightforward comparison of different design options. However, this comes with more uncertainty about the long-term environmental effects and more subjectivity about the relative importance of one environmental mechanism over the others. The GWP indicator is more objective, but does not cover all aspects of an LCA. Nevertheless, our study aims to highlight the differences in material flows calculated from the proposed method and EN 15978, rather than the effects of choosing a different LCA approach or impact indicator. Depending on the scope and objectives of the assessment, the MFA resulting from our method could instead be linked to specific environmental midpoint indicators (e.g. terrestrial acidification, marine eutrophication, and water depletion), or to environmental impact assessment through other inventory databases, such as USLCI ("U.S. Life Cycle Inventory Database," 2021), and other impact assessment methods, such as TRACI (Bare, 2011).

Third, the proof of concept might also suffer from modeling assumptions. Because we expected their impact to be negligible in our proof of concept, the mass and environmental impact of connections were omitted. Yet, a glued connection could have a higher environmental impact than a taped connection; in some cases, the assessor would have to verify the sensitivity of the results to these aspects. Besides, all design options of the proof of concept have the exact same bill of quantity. Demountable and non-demountable buildings may not be built with the exact same building parts: the demountable option may need more robust, hence more material-intensive, parts. For this reason, the method should be tested on more complex and realistic case studies, especially to check whether the material consumption and environmental impact estimated for the non-demountable options are still more than double those calculated for the demountable options. Also, the effects of introducing a 'suspension period' keeping parts in the building longer than their ESL to match the next MFA balance should be investigated.

Finally, as the material flow is modelled at the building level, and as buildings usually have a very long lifespan, it would be difficult to validate the results by comparing the output of the method to a real-life accounting of material flows. Nevertheless, this could be done either retrospectively on a demolished building in which maintenance operations have been precisely documented or by the monitoring of a new building.

## 6. Conclusions

To understand the effect of demountable design choices on the building material flows (i.e., consumption, waste generation, and reuse), the consequences of building disassembly during use and at end of life must be more accurately and realistically modelled than with the framework provided by EN 15978, or current layer-by-layer, part-by-part methods.

We developed a method for time-based MFA in demountable buildings. This bottom-up modeling method is based on replacement scenarios and on design parameters related to the building parts, how they are assembled, and the connections between parts. When parts of the building must be replaced, the method identifies the surrounding parts which must also be removed due to structural interdependence or accessibility issues. Accordingly, it helps identify practical disassembly sequences for all parts which must be removed in a certain year of the building's life. It assesses the preservation or the loss of a building part in a disassembly sequence based on the detachability of a connection, a parameter that is entered by the assessor.

This life cycle MFA method for demountable buildings was implemented as a Building Information Modeling (BIM) plug-in and tested on the design of a simple pavilion, with interesting results. For a non-demountable design of the pavilion, the life cycle environmental impact is up to 162% larger with this method than with the EN 15978 formula (Eq. (1)) which does not consider the interdependence of building parts, but only 77% larger if the pavilion follows a pace-layered design (where more frequently replaced parts are directly accessible). These results are specific to this case study and not meant to provide any design direction. They only demonstrate the importance of considering interdependent building parts in the life cycle inventory of buildings, whether these are designed for future disassembly or not.

Such a method can be useful for auditors in Life Cycle Assessment and Life Cycle Costing, for the building design and construction team (e.g., architects, engineers, and contractors) and for urban miners. Indeed, life cycle assessors could more realistically model the effects of replacement and deconstruction. Building designers could detect where the implementation of DfD principles results in reduced material use and environmental flows: for instance, they could evaluate the effect of a detachable connection at a specific location of the building on the consumption of materials. Finally, urban miners and urban metabolism assessors could benefit from the spatial, temporal, and qualitative differentiation in the modeling of material flows within built assemblies. Furthermore, modeling the impact of DfD principles on material and environmental flows can prevent greenwashing on claimed 'circular' buildings. While some buildings may include some DfD principles, they might not be effectively demountable nor easy to maintain.

## CRediT authorship contribution statement

**Camille Vandervaeren:** Conceptualization, Methodology, Software, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Waldo Galle:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **André Stephan:** Methodology, Writing – review & editing, Supervision. **Niels De Temmerman:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. Resour. Conserv. Recycl. 129, 175–186. https://doi.org/10.1016/j.resconrec.2017.10.026.

Allacker, K., De Troyer, F., Trigaux, D., Geerken, T., Spierinckx, C., Debacker, W., Van Dessel, J., Janssen, A., Laetitia, B., Putzeys, K., 2011. SuFiQuaD Sustainability, Financial and Quality Evaluation of Dwelling types: Final Report Annex 2 Min of the Follow-Up Committee Meetings. Belgian Science Policy, Ku Leuven, WTCB, VITO, Brussels.

Allacker, K., Delem, L., De Nocker, L., De Troyer, F., Janssen, A., Peeters, K., Van Dessel, J., Servaes, R., Rossi, E., Deproost, M., Bronchart, S., 2020. Environmental Profile of Building Elements [update 2020]. OVAM, Mechelen.

BAMB project, 2021. About BAMB [WWW Document]. n.d.. BAMB. URL. https://www.bamb2020.eu/about-bamb/ (accessed 9.10.21).

Bare, J., 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technol. Environ. Policy 13, 687–696. https://doi.org/10.1007/s10098-010-0338-9.

BCIS, 2006. Life Expectancy of Building components: surveyors' Experiences of Buildings in use ; a Practical Guide. BCIS, London.

Brand, S., 1994. How Buildings learn: What happens After They're Built. Viking Press.

CEN, 2019. EN 15804+A2 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

CEN, 2013. EN 15804+A1 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

CEN, 2012. EN 15804-0 2012 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

CEN, 2011. EN 15978 2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2013. Dynamic life cycle assessment: framework and application to an institutional building. Int. J. Life Cycle Assess. 18, 538–552. https://doi.org/10.1007/s11367-012-0528-2.

Crawford, R., 2011. Life Cycle Assessment in the Built Environment, 1 edition. ed. Routledge, London ; New York.

Crawford, R.H., Bontinck, P.-A., Stephan, A., Wiedmann, T., 2017. Towards an automated approach for compiling hybrid life cycle inventories. Procedia Eng 180, 157–166. https://doi.org/10.1016/j.proeng.2017.04.175.

Debacker, W., 2009. Structural Design and Environmental Load Assessment of Multi-Use Construction Kits For Temporary Applications Based On 4Dimensional Design (Doctoral Thesis). Vrije Universiteit Brussel, Brussels.

Debacker, W., Galle, W., Vandenbroucke, M., Wijnants, L., Lam, W.C., Paduart, A., Herthogs, P., De Weerdt, Y., 2015. Design For Change: Development of an Assessment and Transitional Framework (summary). OVAM, Mechelen.

Denis, F., Vandervaeren, C., De Temmerman, N., 2018. Using network analysis and BIM to quantify the impact of design for disassembly. Buildings 8, 113. https://doi.org/10.3390/buildings8080113.

Directed acyclic graph, 2021. Wikipedia.

Dodd, N., Cordella, M., Traverso, M., Donatello, S., 2017. Level(s) – A common EU framework of core sustainability indicators for office and residential buildings - Part 3: how to make performance assessments using Level(s) (Draft Beta v1.0) (JRC Technical Reports).

European Commission, 2020. A New Circular Economy Action Plan For a Cleaner and More Competitive Europe. European Commission.

Eurostat, 2018. Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [WWW Document]. URL https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN_custom_1009531/default/table?lang=en (accessed 5.30.21).

Galle, W., 2016. Scenario Based Life Cycle Costing, an Enhanced Method For Evaluating the Financial Feasibility of Transformable Building (Doctoral Thesis). Vrije Universiteit Brussel, Brussels. https://doi.org/10.13140/RG.2.2.16926.02884/1.

Galle, W., De Temmerman, N., Allacker, K., De, Meyer, R., 2017. Geometric service life modelling and discounting, a practical method for parametrised life cycle assessment. Int. J. Life Cycle Assess. 22, 1191–1209. https://doi.org/10.1007/s11367-016-1230-6.

Goulouti, K., Padey, P., Galimshina, A., Habert, G., Lasvaux, S., 2020. Uncertainty of building elements' service lives in building LCA & LCC: what matters? Build. Environ. 183, 106904 https://doi.org/10.1016/j.buildenv.2020.106904.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

IRP, 2020. Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future (A Report of the International Resource Panel.). United Nations Environment Programme, Nairobi, Kenya. https://doi.org/10.5281/ZENODO.3542680.

ISO, 2020. ISO 20887:2020 Sustainability in buildings and civil engineering works — design for disassembly and adaptability — principles, requirements and guidance.

ISO, 2013. ISO 15686-4 Buildings and constructed assets - Service life planning - part 4 Service life planning using building information modelling.

ISO, 2008. ISO 15686-5 buildings and constructed assets - Service life planning - part 5 life-cycle costing.

ISO 14040, 2006. ISO 14040 environmental management — life cycle assessment — principles and framework.

Kneifel, J., 2010. Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. Energy Build. 42, 333–340. https://doi.org/10.1016/j.enbuild.2009.09.011.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-.H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use, GDP and population during the 20th century. Ecol. Econ. 68, 2696–2705. https://doi.org/10.1016/j.ecolecon.2009.05.007.

Metabolism of Cities, (2021)n.d. Case studies | metabolism of cities library [WWW Document]. URL https://library.metabolismofcities.org/casestudies/ (accessed 9.7.21).

NBN, 2017. NBN/DTD B 08-001:2017 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products - National supplement to NBN EN 15804+A1:2014.

OVAM, 2012. Milieugerelateerde materiaalprestatie van gebouwelementen.

Paduart, A., 2012. *Re*-design For Change: a 4 Dimensional Renovation Approach Towards a Dynamic and Sustainable Building Stock (Doctoral Thesis). Vrije Universiteit Brussel, Brussels.

PRé Consultants, 2021. Simapro. n.d.. PRé Consultants, The Netherlands.

Rauf, A., 2016. The Effect of Building and Material Service Life On Building Life Cycle Embodied Energy. The University of Melbourne.

Rauf, A., Crawford, R.H., 2015. Building service life and its effect on the life cycle embodied energy of buildings. Energy 79, 140–148. https://doi.org/10.1016/j.energy.2014.10.093.

Sanchez, B., Haas, C., 2018. A novel selective disassembly sequence planning method for adaptive reuse of buildings. J. Clean. Prod. 183, 998–1010. https://doi.org/10.1016/j.jclepro.2018.02.201.

Sanchez, B., Rausch, C., Haas, C., 2019. Deconstruction programming for adaptive reuse of buildings. Autom. Constr. 107, 102921 https://doi.org/10.1016/j.autcon.2019.102921.

Sanchez, B., Rausch, C., Haas, C., Saari, R., 2020. A selective disassembly multi-objective optimization approach for adaptive reuse of building components. Resour. Conserv. Recycl. 154, 104605 https://doi.org/10.1016/j.resconrec.2019.104605.

Sassi, P., 2002. Study of current building methods and products that enable dismantling and their classification according to their ability to be reused, recycled or downcycled. Proceedings of World Sustainable Building Conference 2002. Presented at the SB2002 conference, Oslo, Norway.

Schmidt, M., Crawford, R.H., 2018. A framework for the integrated optimisation of the life cycle greenhouse gas emissions and cost of buildings. Energy Build. 171, 155–167. https://doi.org/10.1016/j.enbuild.2018.04.018.

Stephan, A., Athanassiadis, A., 2017. Quantifying and mapping embodied environmental requirements of urban building stocks. Build. Environ. 114, 187–202. https://doi.org/10.1016/j.buildenv.2016.11.043.

Stephan, A., Stephan, L., 2020. Towards zero life cycle GHG emissions apartment buildings in Lebanon, in: IOP Conference Series: Earth and Environmental Science. p. 022055. 10.1088/1755-1315/588/2/022055.

UNEP, 2015. Sustainable consumption and production Indicators for the future SDGs.

U.S. Life Cycle Inventory Database [WWW Document], 2021. Natl. renew. energy lab. URL https://www.lcacommons.gov/nrel/search (accessed 5.5.21).

Vandenbroucke, M., 2016. Design, Dimensioning and Evaluation of Demountable Building Elements (Doctoral Thesis). Vrije Universiteit Brussel, Brussels.

Vandervaeren, C., 2021. Description of three fictitious pavilions used to study the effects of interdependent building parts on building MFA/LCA. 10.6084/m9. figshare.14740734.v2.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Yin, R.K., 2018. Case Study Research and Applications: Design and Methods, Sixth edition. ed. SAGE Publications, Los Angeles, USA.