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Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components

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ABSTRACT

The buildings' life cycle assessment is missing consensus on the methods for revealing the environmental benefits in the case of components that are designed for disassembly. To clarify conflicting guidelines, this study provides a new improved method and investigates its applicability by comparing it to two approaches suggested in previous literature. The study investigates the effects of methodological choices by applying them in the life cycle assessment of three buildings with the same spatial layout but different structural solutions: business as usual, wooden structures, and hybrid building with structures designed for disassembly. The method was streamlined by focusing solely on the category of global warming potential and by using table values in life cycle stages that have minor role. The assessment shows that design-for-disassembly could be as powerful climate protection strategy as wooden structures. The main result of this study is the verification of a new secure method for assessing the design-for-disassembly components. The suggested approach would improve the applicability of life cycle assessment in a normative context by improving the consistency of assessment in the case of circular economy. This study suggests further research on combining the utilization rate with buildings' life cycle assessment to provide even better applicability of the method in circular economy.

1. Introduction

Buildings cause 40% of global greenhouse gas (GHG) emissions while 15% of global climate emissions originate from new construction (Bajželj et al., 2013). In the global average emissions caused by neighborhoods, construction is the major sector with a 27.9% share (Nematchoua et al., 2021). Both construction and operation of buildings cause notable emissions but construction of a building causes a peak in emissions that has the quantity equivalent of multiple decades of operation (Säynäjoki et al., 2012). One of the problems in buildings' environmental impact is the limited service life. The outflow rate of building stock can reach over half of the quantity of new construction (Schiller et al., 2017). Researchers have tried to predict the service life of buildings with a statistical model that employs historical data (Kurvinen et al., 2021). The reasons for demolishing buildings are varied and mainly not related to durability of structures but rather to urban growth causing pressure to increase the floor area ratio on the lot, to inflexible technical and spatial design in changing functional needs, or too high renovation costs (Huuhka and Lahdensivu, 2016). As it is difficult to control the reasons for ending of service life, there is a call for strategies and solutions that extend the service life of buildings or building components.

Circular economy (CE) is providing a broad variety of solutions for service life extension in buildings with the objective to delink environmental impact and economic growth by decreasing the use of raw materials and preventing waste by sustaining the value of products as long as possible. In CE it is also necessary to move towards proper waste hierarchy by moving the emphasis from recycling and recovery towards waste prevention and reuse of products and components (Joensuu et al., 2020). The waste hierarchy is needed because the climate benefits in energy recovery from materials are uncertain (Pizarro-Alonso et al., 2018). The climate benefits of recycling can hardly be positive due to energy-intensive material processing, for example in the case of crushed concrete (Ding et al., 2016). There is a call for new kinds of design-out-waste strategies such as renovation, re-manufacturing, design for disassembly (DfD) and sharing economy.

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Reuse is the second priority of the waste hierarchy and it is expected to be an effective strategy for the prevention of waste and material extraction as it aims extending the service life of a component or a product, thus retaining the material value with minimal processing (Joensuu et al., 2020). As a strategy to overcome economic barriers of reuse by making the disassembly and remanufacturing costs lower than the market value of a second-hand product, scientists have suggested the concept of DfD (Zaman et al., 2018). DfD refers to a design strategy that uses standardized components with accessible mechanical connections rather than chemical ones, to enable easy separation of components (Minunno et al., 2018). Recent projects such as CiWoCo 1.0 in Amsterdam and Circle House in Denmark successfully tested the assembly and disassembly of concrete structures with bolt shear connections ("CiWoCo 1.0 - Amsterdam," n.d.; GXN Innovation et al., 2018). In both cases, certified Peikko joints are used ("SUMO® Wall Shoe," n.d.). Similar technology has been validated earlier by Pavlović and Veljković, (2017). The barriers for the adoption of DfD in construction are mainly not technical but rather related to markets and supply chains (Tingley et al., 2017). The results indicate that DfD should be recognized and promoted as one of the strategies for service life extension towards low-carbon CE.

One way to promote CE could be life cycle assessment (LCA) that is getting embedded into regulations and becoming a main environmental management tool in the construction sector. European researchers are investigating carbon budget as a tool for management of climate efficiency and experts in Nordic countries are at one with the goals to harmonize buildings' LCA in the normative context (Kuittinen and Häkkinen, 2020). In Finland, the Ministry of the Environment has suggested implementing LCA in the Land Use and Building Act with the aim to promote low-carbon development in the built environment (Ministry of the Environment, 2019). The recent development may be considered favourable, as better communication inside the supply chain and making suppliers responsible for the whole product life cycle have proved to be effective in promoting eco-innovations (Arfaoui, 2018). This kind of quantitative approach is also aligned with "open-ended" regulation that encourages innovations as long as they do not have negative external impacts (Staley Samuel R. and Claeys Eric R., 2005). While the recent development towards embedding LCA in building regulations is favourable, it also requires developing the consistency and reliability of the method (see e.g. Säynäjoki et al. 2017).

A variety of standards are already harmonizing the use of LCA by giving general guidelines for LCA (ISO 14040, 2006; ISO 14044, 2006) and building-specific standards (EN 15643, 2010; EN 15804, 2012; EN 15978, 2011). Despite standardization, many studies on buildings' LCA highlight comparability and consistency issues related to the functional unit, system boundary definition and the End-of-Life (EoL) modelling (Häfliger et al., 2017; Säynäjoki et al. 2017). They claim that the current standards fail to avoid uncertainty in EoL modelling choices, while the results are highly sensitive to different approaches.

From the perspective of CE, the buildings' LCA has its shortcomings especially in modelling the benefits of DfD components. The shortcomings of the current standard for buildings' LCA are linked to defining system boundaries through a reference study period which is typically 50 years (Hossain and Ng, 2018). The service life of indoor load-bearing structures exceeds the system boundaries defined this way and represents a major role in the overall environmental impact in the construction of a building. By assimilating reuse to recycling, the standards EN 15643 and EN 15978 on buildings' LCA advise reporting the benefits outside the system boundaries always in the separate module D, while product-stage impacts are counted in module A, impact of use in B and impact of EoL in C (EN 15643, 2010; EN 15978, 2011). Reporting benefits outside system boundaries in module D calls for an allocation method to avoid risk of error from double counting impacts and benefits between multiple product systems (Eberhardt et al., 2019).

The allocation method causes the actual problem providing issues of missing unified and consistent terminology, and lack of consensus on the method to be employed (Heijungs and Guinée, 2007). Allacker et al. (2014) found 11 different allocation methods. They classified them into the categories of "100/0", "0/100", and "50/50" depending on how they allocate the burdens of virgin material and EOL process between the first and the next product system. For example ISO 14044 suggests applying a closed-loop procedure (100/0) to reuse but the method does not consider material degradation and economic issues over extensive service life, leading to false results on the benefits of reuse in buildings (Bourke and Kyle, 2019). The approach in the EoL modelling naturally affects whether the method gives incentives to recycling of used materials or to producing recyclable products (Tillman et al., 1994). According to De Wolf et al. (2020), a method that brings balance in promoting upstream and downstream reuse is needed. With upstream reuse they refer to pre-use phase design actions, such as DfD, to enable reuse in the EoL phase, whilst downstream recycling refers to building components' second-hand use.

Apparently because of missing consensus on allocation method, ISO 14044 gives instructions on options to avoid allocation in case of multifunctional reuse and recycling. The options are (a) dividing the processes into sub-processes or (b) expanding the product system, i.e. by integrating the secondary function into the system boundary. A method reminiscent of option (b) is included in the study by De Wolf et al. (2020): distributed allocation method, as it is called in the British Publicly Available Specification 2050. A similar method is also suggested by Allacker et al. (2014) and investigated in depth in a study by Eberhardt et al. (2019). The method divides the whole building into sub-processes and provides different equations for components that could be reused and those that are landfilled. The environmental impacts from manufacturing and disposal of reusable components are finally allocated on the speculative number of use cycles. This approach is aligned with instructions of ISO 14044 that advise allocation, if it cannot be avoided, on the basis of the following features in prioritized order: (1) physical properties (e.g. mass) (2) economic value (3) number of subsequent uses of the recycled (or reused) material. In general, this approach seems effective and aligned with standards.

De Wolf et al. (2020), focusing on allocation methods, do not study the option (b) suggested by ISO 14044 for avoiding allocation that integrates the secondary function into the system boundary (ISO 14044, 2006). This kind of approach for avoiding allocation through expanding the product system has been previously applied in the construction sector by Arrigoni et al. (2018) and Akbarnezhad et al. (2014). This provides a method that seems quite secure for recognizing the benefits of reuse.

Yet another and a new option for modeling the environmental impact of DfD components in the whole building LCA might be available. The new method divides the process of the whole building into sub-processes similarly to the method used in Eberhardt et al. (2019). In contrast to the method by Eberhardt et al. (2019), this paper suggests a method that uses years of technical service life as an allocation factor. The new approach is inspired by Densley Tingley and Davison (2012) who also demonstrated the effect of service life on embodied emissions of structural components (Fig. 1). It is also aligned with the idea of shearing layers of change (See Fig. 2) presented by Brand (1995) who demonstrates the importance of paying attention to the fact that each structural or technical system in the building has its individual service life (Iacovidou and Purnell, 2016). Navarro-Rubio et al. (2019) used the functional unit of $CO_2e/m^2/a$ in a study that focused to a structural system only. This study calls the new method 'component-specific service life approach' and was the first to apply it in the whole building context in comparison to the other methods suggested in the current standards. A somewhat similar Swiss method that was investigated earlier by De Wolf et al. (2020) recognizes the expected technical service life of a component, but in contrast to this study, it also counts the number of use cycles, thus adding unnecessary complexity.

This study contributes to the current discussion on low-carbon buildings and communities and environmental footprint accounting

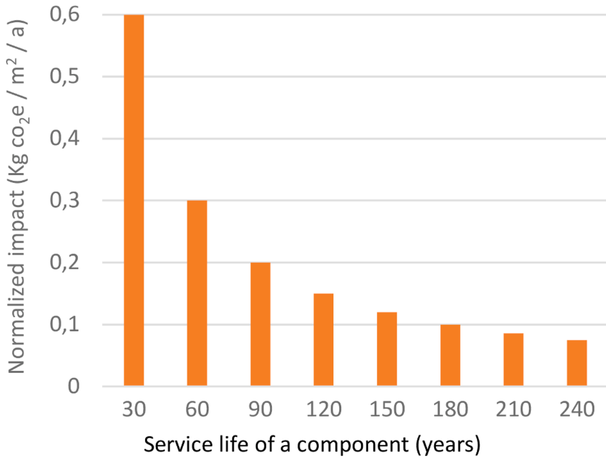

Fig. 1. The effect of the service life to normalized impact, after Tingley and D., (2012).

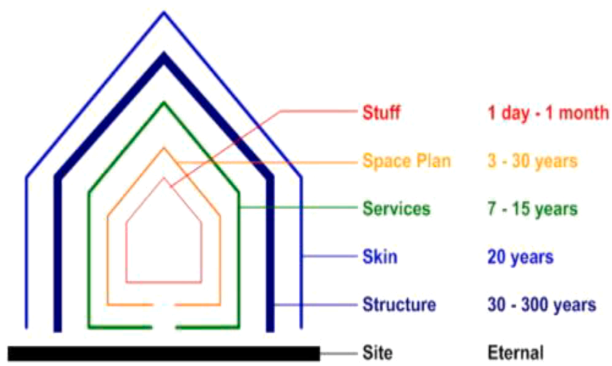

Fig. 2. The shearing layers of a building (Iacovidou and Purnell, 2016).

and management in the built environment. Specifically, this study continues the discussion for finding a method that will bring balance in incentives between initial production and secondary use of buildings' components while not overemphasizing the benefits of reuse over other low-carbon construction technologies. This study therefore asks the question: "Is there a way to develop buildings' LCA towards better consistency by assessing the benefits of reuse inside the product system?"

This study suggests and verifies the new approach by comparing it with the approaches for avoiding allocation suggested in ISO 14044. The comparative study is similar to the one employed by De Wolf et al. (2020). The new and previous methods were tested in three optional structural solutions in a building with the same spatial layout. The results provide information on the reliability and nature of compared LCA approaches by revealing any difference between them in crediting the use of DfD components. The comparison of different structural scenarios also strengthens the knowledge on the potential of solutions for cutting emissions in the construction sector. The main contribution and novelty of this study is the verification of a new secure method for whole building LCA to enable consistent assessment of the DfD components.

2. Compared methodological approaches and functional units

Three different methodolgical approaches were compared to depict the impacts of different choices and to show their strengths and weaknesses, and particularly how they treat the benefits of DfD components. A crucial difference between these approaches lies in defining the system boundaries which leads to different choices in the assessments. The three approaches are explained in detail in the following sections, and named as:

- M1: Extending the system boundaries
- M2: Partitioning and dividing by use cycles
- M3: Component-specific service life approach

Of these three, M1 manages to avoid allocation by including the whole service life of reusable components and its subsequent contexts into the product system. M2 and M3 are similar in the sense that they start with partitioning to enable analyzing reusable components separately. M2 leaves subsequent uses outside the system boundaries but avoids using module D when the impact is divided by use cycles. M3 defines system boundaries to exactly follow each component's service life through dividing the impact by service life to enable the calculation of the whole building impact. The difference in the definition of the system boundaries is demonstrated in Fig. 3.

M1 Expanding the product system

Allocation in option M1 will be avoided by extending product system to include first building and subsequent building into the assessment. In this option, emissions from the manufacturing of components with extensive service life will be calculated only once, along the assessment of the first building. The method could enable 'what if' scenarios where the future energy systems and construction technologies are applied in the subsequent building, but in this case the energy system of the subsequent building was assumed to be functioning the same way as the first one. The assumption was made because the objective of this study is to compare methodological choices in analyzing the benefits of DfD components, which requires comparable scenarios. The mathematical representation of the approach is:

$$\sum E = E_{\text{production,I}} + E_{\text{use,I}} + E_{\text{EoL,I}} + \ldots E_{\text{production,n}} + E_{\text{use,n}} + E_{\text{EoL,n}}$$

where n represents the running number of subsequent use cycle and *E* represents the environmental impact. The results of M1 are reported using the functional unit of kg CO_2e over the assessment horizon.

M2 Partitioning and allocation by use cycles

In contrast to option M1, M2 divides the process into sub-processes which is also called partitioning in the literature. In this case the aim is not to avoid allocation but to investigate reusable components separately from the whole building assessment. In case of reusable components, the allocation will be performed based on the number of use cycles, which is aligned with the guidelines of ISO 14044. The aim is to provide a fair share of benefits in environmental impact between the first and potential subsequent use (Eberhardt et al., 2019). After allocating climate emissions of separately assessed components, they will be summed up to calculate the climate impact of the whole building. Such a method is called grouping in ISO 14044. The impacts from the reusable elements can thus be represented mathematically by:

$$\sum E = \left(E_{\text{production}} + E_{\text{use}} + E_{\text{EoL}}\right) \big/ U$$

where U represents the assumed number of use cycles. The results of M2 are reported using the functional unit of kg CO_2e over the assessment horizon.

M3 Component-specific service life approach

Alike in M2, the idea in option M3 is to start with the partitioning but, in allocation, the use of component-specific service life as an allocation factor in M3 differs from M2. The idea in the method is to enable composing the whole building model from components with varying service by using $CO_2e/m^2/a$ as a functional unit. Applying the

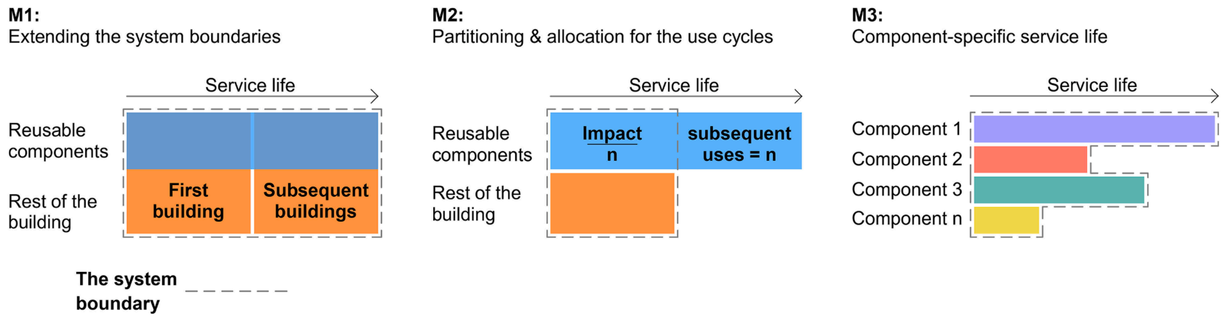

Fig. 3. The definition of system boundaries in different methodological approaches of this study.

terminology of ISO 14044, the methods used in this approach are called partitioning (investigating building components separately), normalization (use of service life as an allocation factor) and grouping (composing the whole building model). M3 deviates from the other methods as it does not calculate the impact of component replacements but this aspect will be threatened through short service life. The method could be represented mathematically with the following equation:

$$\sum \mathrm{E} = \left(E_{\mathrm{production}} + E_{\mathrm{use}} + E_{\mathrm{EoL}}\right) \Big/ (T * A)$$

where T represents component's technical service life and A represents building's area.

The procedure in component-specific service life approach in M3 proceeds as follows:

- Divide the processes into sub-processes (beams, columns, foundation, HVAC, operational energy, etc.)
- Elaborate component-specific data if necessary (for example, if only whole building data on waste management is available)
- Include the impact of the construction phase and disassembly in the whole building product system
- Normalize the impact of each component per year of use by employing functional unit of kg $CO_2e/m^2/a$
- Compose the whole building model by summing impacts of materials, components and operational energy

3. Materials and Methods

To investigate the feasibility of three different methodological choices in assessing the benefits of DfD components, life cycle emissions of three different structural options in the same architectural layout were calculated by employing each method. The idea is to detect possible errors or deviations in some of the methods, by assuming that a false equation causes radically different results in the assessment. According to Crawford (2011), the applied method could be called streamlined LCA as it focuses solely on the category of global warming potential and uses table values in life cycle stages with minor role. All methodological choices were guided by the objective of making the results in different options comparable.

The LCA follows the method for the whole life carbon assessment of buildings published by the Finnish Ministry of the Environment. The method is based on the European Commission's Level(s) Method, and it is made specifically for the Finnish environment and for the Finnish building stock (Ministry of the Environment, 2019). The life cycle of a building is separated in the method for three main parts: before the use (A), during the use (B) and after the use (C) following Fig. 5. In this method, the data of the material emissions is taken from EPDs as explained in Section 2.3. For certain factors, such as transport, repair, site operations in part A and part C, the Ministry of the Environment (2019) has provided default emission values to be used in the cases where exact values are not known.

3.1. Case building and assessment boundary

The case building used in the calculations is a district heated multistory apartment building. The gross floor area of the building is 3,630 m^2 on five floors, representing conventional residential construction of today's Finland. Four of the floors are above ground and one is a heated underground floor. The energy consumption values of the building are 45.0 $kwh/m^2/a$ of electricity, and 63.5 $kwh/m^2/a$ for district heat according to the energy certificate of the building. The architetural plan of the case building is presented in Fig. 4.

Three different structural options were compared. Structures in different scenarios were defined so that they would have the same values of district heating consumption and electricity consumption taken from the energy certificate of the original building. The assessed structural options are:

- **Business as usual (BAU):** In this option, all the main parts (slabs, balconies, load-bearing walls) of the building frame are concrete. Approximately half of the façade material is brickwork and half are plaster. Main part of the base floor is ground-based and approximately 40% is ventilated and structured with hollow-core slabs.
- **Wooden structure (WS):** In this scenario, the highest feasible share of the structures in the building is made of wood. Load-bearing walls are mainly wood-structured excluding the underground floor. The majority of slabs (84%) are wood-structured, and the rest are hollow-core slabs and cast-in-place slabs. Concrete structures are used in staircases and some of the slabs to improve stability of the construction. 100% of the base floor is ground-based cast-in-place slab. Balcony slabs are wooden and over 90% of the façade material is wood. A limited number of details in outer walls are made with concrete structure and plaster.
- **Design for disassembly (DfD):** The building will be built as a hybrid building. As with WS scenario, it has an exterior wall with wooden structures and mostly wooden façades, but structures inside the building are made of concrete. It is assumed that all the concrete structures without exceptional requirements can apply DfD technologies (see Table 1). Concrete structures are jointed together with bolt shear connections and the component joints are sealed with removable mass to enable easy and fast disassembly in the end of the first use cycle (GXN Innovation et al., 2018). DfD concrete structures with bolt shear connections were expected to have 25% more steel compared to conventional concrete structures. Additional casting in the floors is avoided with a raised floor system while building services are installed with easily removable coverings that also increase flexibility in the apartments (Kingspan, 2019). Structural components that are exposed to weather conditions, such as façades, foundations and the bomb shelter that need to be casted on site would be demolished after the first service life.

Despite of uncertainties related to DfD, the presumption in all the approaches was that these components will be reused after the first

Fig. 4. Architectural plan of the studied building

Table 1
Quantities of reusable components in the DfD scenario

Components	Material quantities
Load-Bearing Walls	Concrete 667 t; steel 31 t
Hollow Core Slabs	Concrete 1,241 t; steel 18 t
Concrete staircases	Concrete 117 t; steel 6 t
Raised floors	Chipboard 49 t; steel 21 t

service life because technological solutions radically increase its probability. Such an assumption was accepted as it would be irrational to spend resources on crushing easily removable and installable solid components with extensive service life remaining. Due to technological choices made, it is assumed that DfD components would have 100 or 90 years of service life. Researchers on service life prediction of concrete structures have recognized the role of durability in the life cycle impact and are well aware of damage mechanisms in different environmental conditions. For example, in the standard EN 206-1, exposure category XO refers to the climate inside a building with low air humidity, where correctly designed structures can last virtually infinitely. (Alexander and Beushausen, 2019; EN 206, 2013)

The rest of the structures would end up in waste management after 30 or 50 years if the building was demolished. Whole building service lives for the purpose of methodological study are hypothetical but still realistic as Huuhka and Lahdensivu (2016) show that most of the residential buildings demolished between years 2000 and 2012 in Finland are less than 60 years old and some of them can be as young as 30 years old. According to the prediction curve based on long-term statistical data of Finnish residential and public building stock, the mortality rate of under 60 years old residential buildings is approximately 25% (Kurvinen et al., 2021). Table 2 presents the material choices of the three structural options, highlighting the differences. Table 1 lists the inventory of the reusable material in the DfD scenario.

The system boundary includes modules A-C following the standard EN 15804, see illustration in Fig. 5. All the structural scenarios apply cradle-to-grave scenario, meaning that no recycling activities were considered in the EoL phase and module D was not employed. This is because the goal of this study is to investigate modelling choices in DfD components inside the product system. Different EoL scenarios and modelling options would have brought an unreasonable amount of irrelevant issues into this study. Also in the case of wood, benefits outside of the system boundaries, such as carbon sink or carbon storage and predicted benefits in EoL, are also uncertain (Häkkinen and Haapio, 2013). These aspects are included in module D and were left outside the assessment in this study.

The system boundary is wide, including all the underground

Table 2
Material choices in main structures of the studied options

Business as usual (BAU)	Wooden structure (WS)	Design for disassembly (DfD)
FO1 Foundations Concrete plinth and steel piles	FO1 Foundations Concrete plinth and steel piles	FO1 Foundations Concrete plinth and steel piles
BS1 Bottom Slab Against the Ground Concrete, EPS insulation and gravel	BS1 Bottom Slab Against the Ground Concrete, EPS insulation and gravel	BS1 Bottom Slab Against the Ground Concrete, EPS insulation and gravel
IF1 Cast-In-Place Intermediate Floor Concrete, steel rebars	IF2 Wooden Frame Intermediate Floor Plasterboard, wood beams, mineral wool, acoustic metal studs	IF3 Hollow Core Intermediate Floor Slab Concrete, steel rebars
PW1 Load-Bearing Partition Walls with Concrete Structure Concrete, steel rebars	PW2 Load-Bearing Partition Walls Plasterboard, plywood, wood frame, mineral wool	PW1 Load-Bearing Partition Walls Concrete, steel rebars
OW1 Outer Walls Against the Ground Bitumen sheets, concrete, steel rebars, EPS insulation	OW1 Outer Walls Against the Ground Bitumen sheets, concrete, steel rebars, EPS insulation	OW1 Outer Walls Against the Ground Bitumen sheets, concrete, steel rebars, EPS insulation
OW2 Outer Walls with Concrete Structure and Plaster Façade Plaster façade, concrete, steel rebars, mineral wool	OW3 Outer Walls with Wooden Structure and Façade Wooden cladding, wood frame, mineral wool, plasterboard, plastic film, plywood, plasterboard	OW3 Outer Walls with Wooden Structure and Façade Wooden cladding, wood frame, mineral wool, plasterboard, plastic film, plywood, plasterboard
OW4 Outer Walls with Brick Façade Brick façade, mineral wool, concrete, steel rebars		
RS1 Concrete Roof Slab Concrete, steel rebars, polyurethane insulation	RS2 Roof with Wooden Structure Plasterboard, wood beams, stone wool insulation	RS1 Hollow Core Roof Slab Concrete, steel rebars, polyurethane insulation

structures, slabs, load-bearing and non-load bearing walls, staircases, balconies, windows and doors. The system boundary also includes the building services such as electric systems, pipings, ventilation etc. They are often left out but actually cause an significant share of the embodied GHGs (Heinonen et al. 2016).

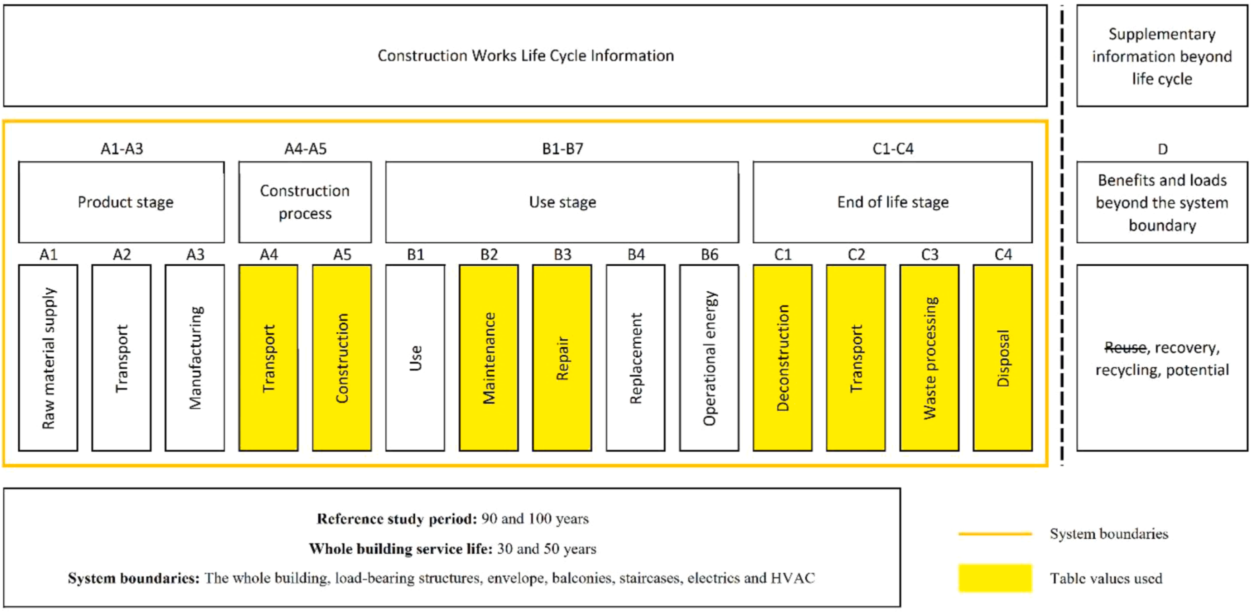

Fig. 5. Life cycle stages, boundary setting of this study

3.2. Life cycle inventory (LCI)

Pre-use phase: As the basis of the calculations in stages A1-A3 and B4, the GWP potential data used in this study is gathered from the environmental product declarations (EPDs). As multiple EPDs are typically available for the same products, this study used EPDs and data best suitable for the Nordic conditions. The list of used EPDs is provided in the supplementary data file 1. Material quantities have been counted according to the Talo 80 quantity calculation instructions typically applied in Finnish building projects. The impact of material losses during the construction phase is included in stage A5. The core data including volumes, emissions per unit, total quantities, losses and service lives are presented in supplementary data file 2. The emissions of transportation to the site and construction in phases A4 and A5 are taken from table values by the Ministry of the Environment (2019).

Use phase: Data for the energy consumption is taken from the energy certificate, which is demanded for all Finnish buildings. The electricity consumption of the building, as presented in Section 2.1, is 45 kwh/m^2/a, causing emissions of 1.2 kg CO_2e/m^2/a, whilst district heat consumption is 63.5 kwh/m^2/a causing emissions of 2.8 kg CO_2e/m^2/a following the energy certificate of the building, which is demanded for all Finnish buildings. The emission factors of district heating and electricity are 100-year averages elaborated from the scenario by the Ministry of the Environment (2019) that considers the regulated decrease of the emissions of energy production. This means that the emissions of certain energy production methods apply a decreasing emission factor scenario but the average emission factor was used in this study to enable methodological comparison.

EoL phase: In the Ministry of the Environment (2019) method, the emissions in EoL phase are drawn from table values. The table values created an issue of missing component-specific data in case of DfD. Component-specific data is needed because minor additional savings are achieved from avoided demolition, transportation and waste processing when the building will be easily disassembled and DfD components carried to the new site for reuse instead of crushing in EoL phase. Calculating these avoided emissions would have required component-specific data, which in this case was not available. The best available indication of physical relationship was the shares of masses, that were used as coefficients when the missing data were elaborated from the table values. Because the EoL process plays a minor role in buildings' environmental impact, the error possibly caused by that inexact coefficient was seen as not significant.

4. Results

The results show through comparative LCA that all of the methods investigated in this study can provide a similar outcome. This confirms the reliability of all suggested approaches including the new one called M3. M3 results in minor deviation due to a different approach to replacement of parts during use. Method M3 has its advantages over other tested methods in the normative context, as it enables minimal number of user-made choices in assessing the benefits of DfD and is capable of using data from service life planning.

A secondary finding of the comparative LCA is that when cradle-to-grave scenario applies, a hybrid building with wooden façades and concrete DfD structures can reach lower life cycle emissions compared to single use WS building. The results underline the importance of promoting both short and long term emissions reduction strategies in the construction sector. This is why the methodological development suggested in this research is needed.

4.1. Methodological analysis

The comparison of the results shows quite a similar emission reduction potential with every tested approach, including the new method M3. As the functional unit is not the same in all methodological approaches, they are not comparable as such. The comparison was enabled through calculating a percentage of the emissions reduction potential between the different methods as shown by the analysis.

In the comparison, a minor deviation between M3 and the other analyzed methods was found. The deviation was less than 1% when using a 100-year reference study period and a 50-year service life, and less than 0.5% when using a 90-year reference study period and a 30-year service life. The deviation in M3 originates from defining the system boundaries more strictly than in the other methods. The idea in the approach is not to account for the component replacements but to calculate the yearly impact of a component by employing component-specific service life as a dividing factor. In the other methods, replacement of some of the components just before the end of whole building service life results in higher impact in the assessment. Since the components that are replaced during whole building service life play a minor role in the whole building assessment, the sensitivity of the method in this aspect is minor. Considering the speculative nature of the method, all three investigated methods may be considered equivalent.

Despite similar results, different methods have their unique features with advantages and disadvantages. The nature and number of assumptions makes different methods applicable in different purposes (Table 3). M1 is able to clearly identify the phase where savings from environmental impact can be achieved. Also, M1 enable responding to the suggestion by Bourke and Kyle (2019) to model the impacts of changing future functions but requires the most assumptions, including number of use cycles, service life and nature of future buildings in which the reusable components are installed. This may not be recommendable in a normative context due to the theoretical nature related to 'what if' scenarios (Heijungs and Guinée, 2007).

As it would be recommendable to give as small a number of assumptions as possible in a normative context to avoid 'what if' scenarios, M2 or M3 would have advantage over M1, as M2 only makes an assumption on the number of use cycles and M3 on the service life of the component. Option M2 has its advantage of simplicity and minor required changes to current standards in buildings' LCA. The challenges in M2 are similar with M1, as the assumed number of subsequent use cycles is imaginary information. The nature of the assumptions makes the difference between methods M2 and M3, as assumption on the number of use cycles makes M2 handy but the method is still open for speculation as the number could with good reason be anywhere between 1 and 3 or more. Simultaneously, the results are also quite sensitive to a change of this factor, as results decrease 23% if the assumed number of subsequent use cycles shifts from 2 to 3.

The most fundamental difference in M3 to the other approaches is that it uses the functional unit of kg $CO_2e/m^2/a$ and divides components' impact by its unique service life to normalize the results from components with varying service lives. M3, like M2, divides the total impact of a component's service life with its allocation factor but M3 uses years of service life instead. This would enable employing data from service life planning to recognize historical material and system degradation as suggested by Bourke and Kyle (2019). A more speculative approach such as M1 would be useful for scientific purposes, while applying LCA in normative context would benefit of higher consistency in M3 approach.

4.2. Life cycle emissions

The analysis highlights the importance of the embodied emissions, or the A component, as even with the reduced scope in materials / building components included in the study, the embodied component contributes with a share of tens of percentages, up to over 50% (Fig. 6). For the comparison between the three options, Fig. 6 shows that a cradle-to-grave scenario in WS building can provide 13% climate emissions savings over two 50-year service lives compared to a building with BAU concrete structures. Respectively, a scenario using DfD components with a 100-year service life provided 16% climate emissions savings compared to BAU concrete structures. A cradle-to-grave scenario with 90-year DfD structures provided 23% savings in climate emissions, while a WS scenario with three 30-year service lives provided 15% savings compared to three 30-year service lives with BAU structures. The results underline that the more uncertain the context in which a building is built, the greater the benefits of DfD technology. The results must be considered preliminary, as detailed structural designs were not made.

Most of the environmental benefits from DfD are achieved by avoiding emissions from material production in the module A of subsequent use cycle, while avoided waste management processes in module C of the first use cycle play only a minor role. The benefits of WS and DfD technology are quite limited since the operational energy has a major role in buildings' life cycle emissions. Better efficiency in operational energy, lower emission factor or a context that requires less operational energy would emphasise the role of emission from construction. Another reason for a limited role of structural solution is that large share of structural components cannot be made of wood or by applying DfD technology. Investigating possibilities for applying DfD technologies in larger share of structural components could help in cutting the life cyle emissions of a building. An even more powerful tool for cutting the construction emissions could be extending the service life of the whole building by applying architectural solutions such as design for flexibility (Assefa and Ambler, 2017). However, given the current urgency in finding solutions to mitigate climate change, solutions offering low embodied first cycle emissions together with DfD technology in high demand.

The results show that extending life cycle of the structural components is a powerful way to cut emissions in the construction sector. WS have traditionally been discussed as a climate friendly structural solution while the energy and emission intensiveness of concrete production is also widely known. This study strengthens this understanding by showing 13% savings in life cycle emissions from WS with cradle-to-grave scenario compared to a building with conventional concrete structures. Despite the high initial climate impact of DfD structures made of concrete, the 100-year service life could provide even lower emissions compared to WS building with two 50-year cradle-to-grave scenarios. The results indicate that life cycle extension would be as competitive tool as WS for cutting climate emissions of construction. The finding takes nothing away from the fact that there is urgency for short-term climate benefits provided by low-carbon building material production but underline the importance of service life extension and the fact that WS do not justify take-make-dispose culture. This is why decision-makers should emphasise developing an unambiguous method for crediting production and use of reusable components in buildings' LCA. The next phase in the development towards low-carbon construction would be putting emphasis on DfD and service life extension in WS buildings.

Table 3
Comparing features of the approaches

Method	M1	M2	M3
Assumptions	Nature of subsequent building, number of use cycles, whole building service life	Number of use cycles, whole building service life	Component-specific service life
Advantages	Enables speculation which may suit scientific purposes	Simplicity of the method	Flexibility, consistency and minimal amount of assumptions
Disadvantages	Not suitable for legislative purposes due to a large number of invented assumptions	Speculative number of use cycles as an allocation factor	Needs more component-specific data. Complicated functional unit of $kgCO_2e/m^2/a$.

5. Discussion

The idea of this study was to improve buildings' LCA so that it would simultaneously encourage construction with new and second-hand DfD components without overemphasizing the benefits of reuse. A new method "Component-specific service life approach", named M3 in this study, was compared to other available methods by asking whether there is a way to develop buildings' LCA towards better consistency by assessing the benefits of reuse inside the product system. As method M3 was able to provide similar results with the other tested methods, this study is capable to respond to the research question at least by confirming the availability of a new reliable method.

This study recommends the use of the M3 approach in the normative context due to its advantages of flexibility and minimal amount of assumptions made by user. The main benefit with the M3 approach is that it provides a consistent method for modelling reusable components. M3

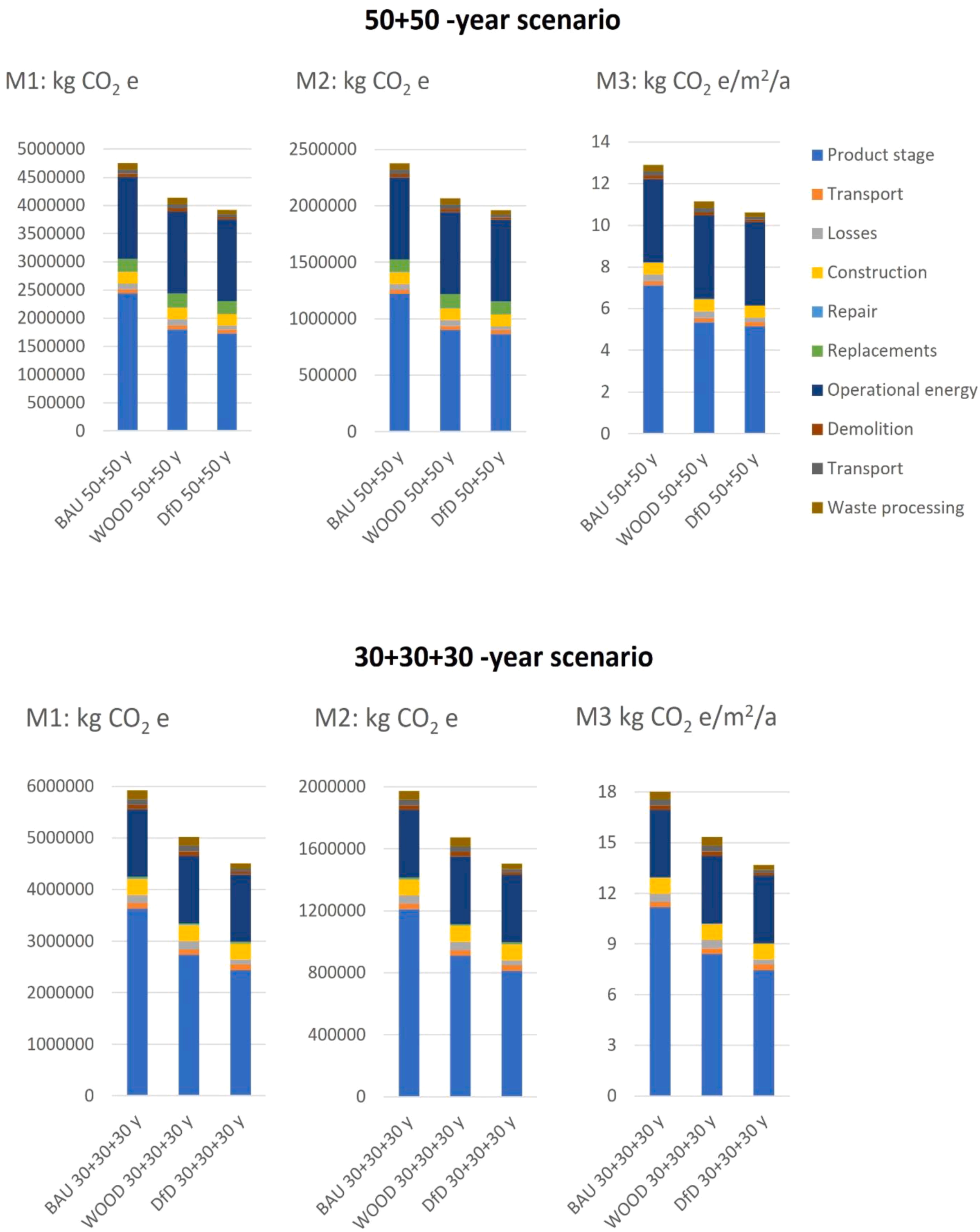

Fig. 6. Carbon footprint of the building calculated with different structures and methodological choices.

provides connection to the service life planning which is needed, as a reliable assessment of the benefits of reuse needs to recognize expected and historical material and system degradation (Bourke and Kyle, 2019). The method is technology-neutral in the sense that, in addition to DfD components, it could be applied in future work to adaptive reuse projects or buildings that are designed for flexibility. Also, M3 does not exclude the use of module D in a study that considers recycling activities. While this study focuses solely on the category of global warming potential, the method M3 fits to assessing other impact categories as well. Despite advantanges of the M3 in the normative context, its implementation may face barriers as it requires more detailed component-specific data.

This study confirms some conflicting guidelines in current standards of LCA with regards to EoL modelling, recognized earlied by Eberhardt et al. (2019). In the case of a multifunctional product system, such as a building, ISO 14044 recommends avoiding allocation as far as possible by dividing the process into sub-processes or by extending system boundaries. Conversely, EN 15978 advices reporting the benefits from reusable components separately in module D outside the system boundaries defined by whole building service life. As this study shows that it is quite simple and consistent to give credit of reuse inside the product system of a building component, it is recommended to open the standard EN 15978 to interpret a building as a group of separate product systems.

Regardless of the method, reliability in assessing the benefits of DfD suffers from a few similar sensitivity issues. One is related to expected and actual service life of the whole building, which treats the BAU scenario unfairly compared to DfD if service life is longer than expected but this does not cause underestimation in the impact of construction. Another one is the uncertainty related to emissions intensity of any building material or its option in the future that is likely to have a lower embodied GHG content than today. One solution could be utilizing a discount factor in LCA of buildings, or any objects with long service lives, which should be one important direction of future work. Ignoring these aspects, such as not assuming any improvement in the GHG intensities in the future, leads to a bias towards overestimating the future impacts. On the other hand, the expected declining scenario in GHG intensities could be biased as well. This is why LCA, especially in a normative context, must be seen as an agreement on future prediction where the steering effects are open for continuous critical public discussion.

Future work on the field of CE and LCA should pay more attention to the relationship between matter and time (Campioli et al., 2018). Cutting environmental impacts in the construction sector not only calls for extending service life but also promoting of more intense use of the buildings and spaces (Krausmann et al., 2017). When the carbon footprint is presented on a yearly basis, as suggested in method M3, it opens an opportunity for an assessment recognizing the benefits of other CE practices such as sharing economy. In future research, the next step could be integrating the perspective of utilization rate to the assessment of the carbon footprint of a building. As suggested in assessment of buildings' energy performance, environmental assessment would require recognizing utilization rates, for example by counting user hours and by employing the functional unit of $CO_2/m^2/a$/person-hour (Francart et al., 2020). It would enable paying attention to not only design choices but also to everyday decisions made in real estate management.

6. Conclusion

Carbon budget defined through life-cycle approach will be embedded in building regulations in multiple countries, requiring highest possible consistency for the applied method. Methodological development has a lot of ground to cover still, especially in revealing the benefits of reuse and DfD.

This study suggests methodological approach that interprets building with DfD structures as a group of individual components with unique service lives. The approach uses a methodological combination of partitioning the building into components, normalizing components' impact by employing a functional unit $kgCO_2e/m^2/a$, and grouping the results into a whole building model. This enables assessing the benefits of reuse inside the product system in contrast to EN 15978 that advices counting benefits of reuse outside system boundaries in a separate module D.

This study validates the new method by comparing it to two other methods used in previous studies. One extends the system boundaries by including the whole context of next use cycle into the assessment. Another is reminiscent of the new method but it divides impact of a component for number of use cycles. The comparisons were made between three cases: a typical building with concrete structures (BAU), a building with wooden structures (WS), and a hybrid building with DfD structures (DfD). By assessing these cases with the new method and the previously used methods, it was assumed that false equation would favor a case over another.

The main finding of this study is the confirmed reliability and consistency of a new method for buildings' LCA to account for the benefits of DfD components. The advantages of the new method compared to the previous ones are its flexibility, consistency and minimal amount of assumptions made by user, making it useful especially in the normative context. The method is capable of using component-specific data on expected service life provided by service life planning. The shortcoming of the new method is that it requires more detailed data in the EoL phase, as table values of whole building scale cannot be used.

A secondary finding of this study shows that a building with DfD structures made of concrete can reach lower climate emissions compared to a single-use building with wooden structures. When the scenario of two 50-year service lives applies, a building with wood structures can provide 13% savings and a building with DfD structures 16% savings in emissions compared to BAU structures when benefits outside system boundaries are not accounted for. The results must be considered preliminary, as detailed structural designs were not made. The results indicate that both short-term and long-term strategies for promoting emissions reductions are needed

This study highlights the essential relationship between matter and time in defining buildings' environmental impact. The method suggested in this study encourages the construction sector to think of buildings as a set of separate product systems with potential for reuse. In further research, it is recommended to investigate applying utilization rates along buildings' LCA to provide knowledge on buildings' environmental performance with better resolution. The final objective is to provide an unambiguous and reliable method that makes recent practices of CE, such as DfD and sharing economy, comparable with other practices for sustainable consumption and production.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2021.103499.

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