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Life cycle assessment of a Danish office building designed for disassembly

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ABSTRACT

The building industry is responsible for a large proportion of anthropogenic environmental impacts. Circular economy (CE) is a restorative and regenerative industrial economic approach that promotes resource efficiency to reduce waste and environmental burdens. Transitioning from a linear approach to a CE within the building industry will be a significant challenge. However, an insufficient number of quantitative studies exist to confirm the potential (positive) environmental effects of CE within the built environment as well as a consistent method for characterizing these effects. This paper considers key methodological issues for quantifying the environmental implications of CE principles and proposes a life cycle assessment (LCA) allocation method to address these issues. The proposed method is applied to a case study of a Danish office building where the concrete structure is designed for disassembly (DfD) for subsequent reuse. The potential environmental impact savings vary between the different impact categories. The savings are significantly influenced by the building's material composition, particularly the number of component-use cycles as well as the service life of the building and its components. The substitution of other material choices (*e.g.* glass and wood) for the concrete structure exhibited a potential increase in impact savings.

KEYWORDS

building design; building materials; buildings; circular economy; design for disassembly (DfD); end of life; life cycle assessment; waste reduction

Introduction

The demands from a growing world population will have exceeded most limits on global resource reservoirs by 2050 if the present levels of human consumption continue (United Nations, 2012). Therefore, it is vital to improve the management of resource consumption and the associated environmental impacts.

Buildings are responsible for up to 40% of the materials produced and consumed globally (by volume), approximately 40% of the world's waste generation (by volume) (Becqué et al., 2016) and they account for 20–35% of the contribution to most environmental-impact categories such as global warming and smog formation (European Commission, 2006). By 2030, it is expected that the global middle class will have doubled from 2 billion to over 4 billion people (Kharas, 2017). It is estimated that over the next 40 years, the world needs to build more urban capacity than has been constructed in the past four millennia (Biello, 2012). Thus, the construction sector represents a major set of opportunities for achieving local and global environmental objectives, such as the UN Sustainable Development Goals (United Nations, 2015).

Some new low-energy buildings have radically reduced operational energy consumption. Energy generation for these new buildings is no longer considered to be the most important contributor to building-related environmental impacts (Anand & Amor, 2016; Anderson, Wulfhorst, & Lang, 2015; Birgisdottir et al., 2017; Blengini & Di Carlo, 2010; Dixit, Fernández-Solís, Lavy, & Culp, 2012). A recent Danish study found that the building materials of an office building assessed over an 80-year reference study period were responsible for 72% of the total greenhouse gas emissions and 50% of the total primary energy consumption (Birgisdóttir & Madsen, 2017). Recent building life cycle assessment (LCA) method development

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emphasizes that a narrow focus on just impacts associated with the energy consumption of building will not identify all demands on global resources, and other initiatives are needed to reach absolute sustainability in the building sector (Brejnrod, Kalbar, Petersen, & Birkved, 2017). Hence, there is an obvious need to regulate and optimize the environmental performance of new buildings by focusing on buildings' embodied energy and environmental impacts over their life cycle (Birgisdottir et al., 2017; Dixit et al., 2012; Rasmussen, Malmqvist, Moncaster, Wiberg, & Birgisdottir, 2017). A growing political and industrial interest exists to change from linear (take, make, use and dispose) to circular (reduce, reuse and recycle) business models. This will help to reduce environmental impacts and secure future needs, while at the same time exploiting remaining material value and ensuring the sought economic growth (Advisory Board for Cirkulær Økonomi, 2017; Ellen MacArthur Foundation, 2015b; European Commission, 2016, 2017a; United Nations, 2015). In recent years, various circular economy (CE) initiatives and policy agendas have emerged in the construction sector, *e.g.* the adoption of a CE action plan in the industrial sector by the European Commission in 2015, establishing a tangible and ambitious programme of actions along with a series of legislative proposals on waste (European Commission, 2017b) and the ongoing development of 14 new CE standards that may affect future legislation from the European Commission (Dansk Standard, 2017). Legislative proposals for waste in other industries (*e.g.* packaging, transportation and electronics) have been successfully adopted, but progress for the construction sector has been slow due to a lack of specific environmental indicators and targets/goals for the construction sector (European Commission, 2017b).

A case study of Denmark identifies CE opportunities for policy-makers, and it points to the construction industry as the sector with the highest potential for the implementation of CE models (Ellen MacArthur Foundation, 2015a). The CE models put a focus on design for disassembly (DfD) to extend the service life of building materials and elements through reuse and recycling, potentially reducing future resource consumption, waste generation and environmental impacts of future constructions (Bocken, de Pauw, Bakker, & van der Grinten, 2016; European Commission, 2016). DfD is not a new idea in construction, but it has not yet gained a foothold in the construction industry due to several obstacles (Rios, Chong, & Grau, 2015). According to Aye, Ngo, Crawford, Gammampila, and Mendis (2012), life cycle aggregated environmental impacts can be significantly reduced if the structural elements of a building are designed to be durable and reusable, and if these attributes are exploited. Although the majority of buildings are constructed using durable concrete structures, and although technical know-how exists on how to build durable buildings with long service lives, the service life of buildings in general has severely declined. There are numerous cases of 30–40-year-old buildings being demolished (for various reasons), indicating poor exploitation of the concrete's durability potential (Pomponi & Moncaster, 2017). As the primary ingredient in concrete, cement alone is responsible for 7–8% of anthropogenic global CO_2 emissions, and therefore there is a need to rethink the design of concrete structures from a life cycle perspective, *e.g.* through DfD (United Nations Environment Programme (UNEP), 2010).

The environmental and economic viability of CE solutions will need careful assessment to provide a successful and sustainable transition towards a circular built environment (Pomponi & Moncaster, 2017). Recently, a report by the Danish government's Advisory Board on CE recommended the development of new, consistent life-cycle and total-cost calculation tools and methodologies to assess the environmental sustainability of CE business models and products capable of handling repeating life cycles due to reuse and recycling (Advisory Board for Cirkulær Økonomi, 2017). This is also supported by researchers (Bocken et al., 2016; European Commission, 2017b; Ghisellini, Cialani, & Ulgiati, 2016). Furthermore, the European Commission is committed to working towards a common European approach to assess the environmental performance of buildings, based in part on existing work, *e.g.* technical standard EN 15978, as well as relevant research, and focusing on priority materials, *e.g.* concrete (European Commission, 2017b).

LCA is a scientifically based and International Organization for Standardization (ISO)-standardized method for assessing resource consumption and environmental impacts of a given product, system or service over its entire life cycle (EN, 15978, 2012; ISO, 14040, 2008; ISO, 14044, 2006; ISO, 21931-1, 2010) and can facilitate CE decision-making by identifying the largest environmental impact-reduction potentials within building life cycles (Pomponi & Moncaster, 2017). Use of LCA is increasing within the construction industry, and LCA has been used in some recently published CE studies (Genovese, Acquaye, Figueroa, & Koh, 2016; Ghisellini et al., 2016). Despite the political attention CE is gaining, current political initiatives do not seem to build on existing LCA research covering construction and demolition processes (Pomponi & Moncaster, 2017). Although there are studies showing clear evidence of the environmental benefits of CE principles at building material and component level (Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017), few studies consider the overall building level and the LCA methodological issues related to CE design methods such as DfD (Aye et al., 2012). Hence, LCA faces considerable challenges in becoming a mainstream environmental assessment approach for decision-making/support in the building industry (Anand & Amor, 2016).

The present paper offers a contribution to the development of a future environmental performance evaluation method for CE within the built environment. It is structured as follows. First, the existing literature is reviewed to present the state of the art of CE in the European built environment, particularly issues pertaining to development of environmental performance assessment methods. Next, an LCA allocation method is proposed to address the identified key methodological issues of quantifying environmental performance of CE within the built environment. The proposed method is then applied in a case study to assess the potential embedded environmental impact savings of a Danish office building when it is designed for disassembly (DfD). A sensitivity analysis evaluates the influence of possible sensitive parameters. The paper concludes with a discussion of the methodological issues and how to further improve and advance environmental performance assessment of CE to promote the implementation of CE in the built environment.

Background

Haupt and Zschokke (2017) stress the importance of applying LCA to quantify the environmental impacts of implementing CE principles. Such quantification will clarify if the environmental performance of the new system based on CE principles contradicts the fundamental objective of the CE to improve environmental performance. However, multifunctional processes, such as the CE principles, reuse and recycling, constitute a methodological challenge in LCA, as the LCA method is based on the idea of analyzing environmental impacts of the primary function of individual product systems (Hauschild, Rosenbaum, & Olsen, 2018). Hence, in order for LCA to support CE, it needs to move from a 'one-life-cycle' approach towards a multiple life-cycle approach to support continuous loops of products and materials (Ghisellini et al., 2016; Niero, Negrelli, Hoffmeyer, Olsen, & Birkved, 2016). Furthermore, multifunctional processes are shared between more than one product system, and it is not always obvious to which product system the environmental impacts and benefits should be attributed. Nor is it always clear how substituted materials and products should be accounted for, which product system can claim the benefit and how resource quality is to be taken into consideration (Haupt & Zschokke, 2017; van der Harst, Potting, & Kroeze, 2016). In addition, the long lifespan of buildings increases assessment uncertainty. There may well be unknown aspects that need to be addressed in order to describe the future scenarios in which the environmental impacts and future reuse or recycling will occur in terms of LCA for long-term decisions, *e.g.* CE in the built environment (Niero, Ingvordsen, Jørgensen, & Hauschild, 2015). Moreover, differences in the LCA approaches applied make it difficult to compare the environmental performance of buildings (Genovese et al., 2016).

Although some general LCA recommendations on how to handle multifunctional issues have been provided by different recognized standards such as ISO 14049, ISO 14044 and EN 15978, several competing approaches exist, leaving room for interpretation (van der Harst et al., 2016). The ISO 14044 standard distinguishes between closed-loop product systems, where materials are reused/recycled in the same product to replace virgin materials, and open-loop product systems, where the materials are reused/recycled from one product system into a different product system. Consequently, there is a potential need to allocate the environmental benefits and burdens of reuse or recycling between multiple product systems (ISO, 14044, 2006). Furthermore, the ISO 14044 standard states that changes in the inherent properties of materials resulting from reuse or recycling should be taken into account, but the standard does not state which changes and how to account for them. ISO 14044 presents a hierarchical procedure to deal with multifunctional reuse and recycling from secondary material production and end-of-life (EoL) processes:

- Allocation between multiple product systems should be avoided by:
  - (a) dividing the processes into sub-processes
  - (b) system expansion, *i.e.* the secondary function should be integrated into the system boundary.
- If allocation cannot be avoided, allocation should be performed in the following order using:
  - (a) underlying physical relationship (*e.g.* mass)
  - (b) other relationships (*e.g.* economic value)
  - (c) number of subsequent uses of the recycled material.

In contrast, the International Reference Life Cycle Data System (ILCD) handbook recommends that the ISO hierarchy should be applied when determining the goals and scope of the LCA study (European Commission, 2010). However, there are limitations and weaknesses in each of the above approaches, *e.g.* subdivision is not always possible, suitable substitutes to perform system expansion cannot always be found and allocation can be based on an array of different parameters as there is currently no single, widely accepted modelling approach (Allacker et al., 2014; van der Harst et al., 2016). Allacker et al. (2014), however, state that when subsequent product systems are involved, allocation is necessary to model EoL processes and secondary material production (recycling, reuse, energy recovery and disposal). Allacker et al. studied 11 different secondary material production and EoL allocation approaches from recent modelling approaches and standards and found that the methods can be broadly grouped into three common approaches: 0:100, 100:0 and 50:50. The 0:100 approach attributes all impacts of the recycled material to the product producing the recycled material (Baumann & Tillman, 2004). The 100:0 approach attributes impacts of the virgin material production to the first product and impacts of the recycling process and final waste treatment to the second product using the recycled material (Baumann & Tillman, 2004). The 50:50 approach assumes that recycled material replaces virgin material and attributes impacts of virgin material production, waste treatment and recycling to the first and the second product (Baumann & Tillman, 2004).

After comparing these three methods, Aye et al. (2012) conclude that, since the potential future reuse of a material can never be guaranteed, it makes no sense to allocate any environmental credit to its initial use. Aye et al. consider that if the material is, after all, reused after its initial use, the building in which the material is reused should be rewarded with the environmental savings resulting from the avoided processing and manufacturing of virgin materials. As it is not always clear from previous case studies how environmental crediting of reuse/recycling is actually conducted (Allacker et al., 2014; Aye et al., 2012), EN 15978 (2012) states that benefits from reuse, recovery and recycling (module D in Table 1) should always be reported separately for reliable decision support. According to Allacker et al. (2014), an improvement in the product system modelling could potentially be to accommodate the average number of times a material or element is recycled or reused, *e.g.* using the principles in the ILCD handbook. Among other things, the handbook proposes a formula that takes into account the primary amount of material, the recycling rate and the number of recycling loops (European Commission, 2010). Some of the allocation methods analyzed by Allacker et al. (2014) incorporate a great number of other parameters, making them more comprehensive, but also more complex. The mainstream application of LCA for decision-making requires simplification and standardization to enable consistent and easy use in practice (Hellweg & Mila i Canals, 2014).

Table 1. Life cycle stages.

Life cycle stages	Process	Module	DGNB
Production	Extraction of raw materials	A1[a]	×
	Transport	A2[a]	×
	Production	A3[a]	×
Construction	Transport	A4	
	Construction/assembly	A5	
Use	Commissioning	B1	
	Maintenance	B2	
	Renovation/repair	B3	
	Replacement	B4[a]	×
	Refurbishment	B5	
	Energy consumption for operation	B6	×
	Water consumption for operation	B7	
End of life	Deconstruction/demolition	C1	
	Transport	C2	
	Waste recovery	C3[a]	×
	Disposal	C4[a]	×
Next product system	Potential for reuse, recovery and recycling	D[a]	×

Notes: Life cycle stages are according to EN, 15978 (2012) and modules included in the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) certification scheme.
[a]Modules included in the study.

Case study method

Based on the knowledge gained from the literature review, LCA was applied to assess and, hence, quantify the potential environmental impact savings of a Danish office building DfD compared with traditional building methods. The LCA complies with the requirements stated in EN 15978 (2012), ISO 14040 (2008), ISO 14044 (2006) and the Danish building sector's implementation of the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) certification system for assessing and benchmarking sustainable buildings (Birgisdottir, Mortensen, Hansen, & Aggerholm, 2013). The present study does not use consequential LCA, *i.e.* LCA that applies broader system modelling to quantify potential environmental consequences of system changes. Instead, it applies attributional LCA, *i.e.* LCA that quantifies the environmental impacts that can be attributed to the product system (Hauschild et al., 2018) in accordance with the DGNB certification system (Green Building Council Denmark, 2014). Table 1 shows the life cycle stages as defined in EN 15978. It also shows which modules are included in the DGNB certification system.

The system boundary of the present study includes raw material extraction, transportation and production of building materials and components, replacement of building materials and components during the use stage, waste recovery and disposal at EoL, and credits for potential reuse, energy recovery and recycling of materials and components in subsequent product systems. The focus of this paper is on the material-related impacts, thus energy consumption for operation is not included.

The building lifespan can have significant effects on the overall environmental performance of a building (Marsh, 2017; Østergaard et al., 2018; Rasmussen & Birgisdóttir, 2016; Silvestre, Silva, & de Brito, 2015). Thus, it was set to 50 and 80 years respectively, according to the DGNB certification system for office buildings, in order to compare the effects of a longer and shorter building lifespan (Green Building Council Denmark, 2014). The functional unit was set to 1 m^2 of the building's gross floor area per year to provide comparability with other studies. As most current published sustainability research within the built environment tends to focus on a limited number of impact categories, thereby risking burden-shifting (Pomponi & Moncaster, 2017; The European Commission, 2017b), the LCA was performed using baseline characterization factors from the Centre for Environmental Studies baseline 2001 method according to the DGNB certification system. This is a commonly used and agreed-upon approach in the construction sector, using open LCA v1.4 software, but focusing on more impact indicator categories than commonly used in practice, *i.e.* a set of environmental, resource-use and toxicology midpoint impact categories (global warming potential [GWP], ozone depletion potential [ODP], photochemical ozone creation potential [POCP], acidification potential [AP], eutrophication potential [EP], abiotic depletion potential for elements [ADPe], abiotic depletion potential for fossil resources [ADPf], freshwater aquatic ecotroxicity potential [FAETP], marine aquatic ecotoxicity potential [MAETP], human toxicity potential [HTP] and terrestrial ecotoxicity potential [TETP]). The life cycle inventory (LCI) of the background system was based on the Ecoinvent 3.2 database using system processes to obtain aggregated results. The LCI of the foreground system was compiled using project-specific building information models provided by the construction company to extract building material and component volumes. Where data were lacking, estimation procedures and assumptions based on technical datasheets, environmental product declarations (EPDs) for different components and materials, as well as

Table 2. Construction materials by building element (including technical building services).

Building component	Elements	Element share (%)	Component share (%)	Mass (kg)
Columns	Reinforced concrete	1	1	1.E+05
Beams	Construction steel and reinforced concrete	3	3	4.E+05
Roof	Reinforced concrete	7	8	8.E+05
	Asphalt and plastic	1		8.E+04
	Rockwool insulation	0.3		3.E+04
Foundation	Reinforced concrete	6	6	7.E+05
Ground slab	Reinforced concrete	9	10	1.E+06
	Polystyrene insulation	0.03		4.E+03
	Screed, epoxy and leca stones	2		2.E+05
Concrete sandwich facade	Reinforced concrete	14	15	2.E+06
	Rockwool insulation	1		6.E+04
	Polystyrene insulation	0.03		4.E+03
	Brick shells, mortar and bitumen membrane	1		6.E+04
Floor	Varnish and oak tree flooring	0.1	38	1.E+04
	Glass wool insulation	0.2		2.E+04
	Gypsum	0.2		3.E+04
	Galvanized steel	0.4		5.E+04
	Reinforced concrete	37		4.E+06
	Tiles, mortar and adhesive	0.01		7.E+02
Internal walls	Gypsum	0.4	15	5.E+04
	Rockwool insulation	0.3		3.E+04
	Steel, stainless steel, aluminium	0.1		8.E+03
	Glass	0.4		4.E+04
	Acrylic paint	0.04		4.E+03
	Reinforced concrete	14		2.E+06
	Bitumen membrane	0.002		2.E+02
Staircase	Reinforced concrete	2	2	2.E+05
Technical building services	Stainless steel, galvanized steel and cast iron	1	1	7.E+04
	PVC	0.001		7.E+01
	Sanitary ceramics	0.03		4.E+03
Others	Aluminium windows, doors and solar shading	1	1	8.E+04
	Wooden doors	0.04		5.E+03
Total		100	100	1.E+07

Notes: All building related constructions and technical building services have been considered in the study.

information from manufacturers/suppliers and other professionals from the industry were used.

Office building

The case study office building assessed has a gross floor area of 37,839 m^2 with eight wings of different heights and a total of nine storeys. Owing to the large size of the building, the basis of the study was a representative section of the building. Table 2 lists the construction materials by building elements and respective quantities.

The building's structure was predominantly made up of prefabricated concrete elements consisting of floor slabs, facades, core walls, columns and beams.

DfD assumptions

The present study focuses on the internal building structure in terms of DfD and relies on the following assumptions:

- assembly/disassembly are based on existing joint solutions (Sommer & Guldager, 2016)
- the building is to be built today and decommissioned in 50 or 80 years after the start of the assessment (Green Building Council Denmark, 2014)
- the building materials are free of hazardous substances due to decontamination before disassembly, *i.e.* contaminants have been designed out in the design phase (Sommer & Guldager, 2016)
- owing to the long lifespan of concrete, no maintenance of the prefabricated concrete elements will be required during their service life to maintain their quality and the elements are suitable for at least three reuse cycles in three different buildings (Sommer & Guldager, 2016)

The percentage of elements suitable for reuse at the building's EoL was estimated by a demolition company to be:

- 90% of the concrete columns
- 90% of the composite steel/concrete beams
- 80% of the concrete beams
- 60% of the concrete roof hollow core slabs
- 90% of the concrete floor hollow core slabs
- 80% of the concrete core walls

Modelled scenarios

A traditional case study building was used as reference scenario T (all materials are disposed of after use either by recycling, incineration or landfill) for comparison with all other modelled scenarios. Two types of scenarios were modelled:

- DfD: two scenarios where the structural elements are assumed to be DfD for reuse at EoL in one or two future subsequent product systems.
- O: four scenarios where the structural elements are tested in terms of material choices, *e.g.* steel, wood and glass, enabling easier disassembly, not necessarily benefitting reuse solely but also for recycling to potentially further decrease the building's overall environmental impacts. The four scenarios focus on the structural concrete elements that make up the largest percentage of the building's total mass, *i.e.* potentially the largest environmental impacts.

Table 3 provides an overview of the material compositions of the different scenarios modelled.

As the concrete facade was not considered for reuse in the DfD scenario, despite making up 15% of the building's total mass (Table 2), in all O scenarios the concrete facade of the traditional building design was substituted with a lighter glass double-skin facade with load-bearing columns for reuse and recycling. Besides the glass double-skin facade, the effect of using different materials for the load-bearing columns at the facade was tested. As the concrete hollow core slabs comprise 37% of the building's total mass (Table 2), the effect of substituting them with bubble-deck slabs containing less concrete due to plastic bubbles mixed with aggregate but with

Table 3. Percentage of material shares by weight (kg).

	Scenarios					
Material shares (%)	**T**	**DfD**	**O1**	**O2**	**O3**	**O4**
Concrete	81.8	81.4	80.6	76.6	78.0	73.8
Mortar	0.2	0.2	0.01	0.01	0.01	0.01
Glass	1.3	1.3	3.0[a]	3.1[a]	3.1[a]	3.6[a]
Gypsum	1.2	1.2	1.3	1.3	1.4	1.6
Insulation	1.7	1.7	1.2	1.2	1.3	1.5
Metals	6.6	7.6[a]	7.2	10.4[a]	7.2	10.5[a]
Paints and varnishes	0.5	0.5	0.5	0.6	0.6	0.7[a]
Plastic	0.2	0.2	0.2	0.2	0.2	0.6
Ceramics and clay	1.5	1.5	0.8	0.8	0.8	1.0
Stone and gravel	0.8	0.8	0.8	0.9	0.9	1.0
Wood	0.4	0.4	0.6	0.6	2.2[a]	0.7
Asphalt	3.8	3.8	4.1	4.2	4.3	4.9

Notes: Material shares (kg) over a building lifespan of 80 years taking material replacements into account.
[a]Obvious material share shifting between the scenarios as a result of substituting concrete for other materials.
DfD = design for disassembly; O1 = optimization scenario 1 (concrete columns); O2 = optimization scenario 2 (steel columns); O3 = optimization scenario 3 (wooden columns); O4 = optimization scenario 4 (bubble decks); T = traditional building design.

increased reinforcement steel was also tested. Hence, the O scenarios consisted of:

- O1: load-bearing concrete columns at the facade assumed for reuse
- O2: load-bearing steel columns at the facade assumed for reuse
- O3: load-bearing timber columns at the facade assumed for recycling
- O4: load-bearing concrete columns at the facade assumed for reuse and concrete bubble deck slabs assumed for recycling

The reuse percentages assumed for the DfD scenarios were applied to all additional concrete elements in the O scenarios.

Allocation method

Reuse, recycling and energy recovery of materials were modelled as avoided impacts according to the recommendations described in EN 15978 (2012). Thus, the impacts of the primary material production that is substituted by the reused, recycled or energy-recovered material substitutes were subtracted from the net impacts in module D. The amount of material recycled and the amount disposed of at the EoL of the buildings were estimated according to Danish waste statistics and existing markets (Clean Innovation Green Solutions, 2014).

For all scenarios, the LCA only focused on the first product system from which the reusable building elements originate. In this case, the study takes into account a simple combination of the allocation approaches 0:100 and 50:50 depending on the reusability and recyclability of the different building materials and elements using their physical relationship, *i.e.* mass. Hence, the impacts of the building materials and elements in reference scenario T, with no reuse but material rates for disposal through recycling, incineration or landfill at EoL, can be represented mathematically by equation (1) by applying the 0:100 approach and allocating all the environmental impacts and benefits of these materials and elements to the first product system:

$$\sum I_T = I_{\text{production}} + I_{\text{use}} + I_{\text{EoL}} + I_{\text{Next product system}}, \quad (1)$$

where $\sum I$ represents the total life cycle-aggregated environmental impacts; and I_j represents the environmental impacts of the jth life cycle stage. For the DfD and O scenarios, equation (1) applies for all building materials and elements that cannot be reused. However, reusable elements were modelled using the allocation approach 50:50, where all burdens and credits from the reusable elements are split between the buildings that will potentially share them. Thus, one system will not benefit over another based on the assumed number of future reuse cycles. This also enables the LCA to take into account and credit multiple future reuse loops, thereby promoting CE. The impacts from the reusable elements can thus be represented mathematically by:

$$\sum I_{\text{DfD},O} = (I_{\text{production}} + I_{\text{use}} + I_{\text{EoL}} + I_{\text{Nextproductsystem}})/U, \quad (2)$$

where U represents the assumed number of use cycles; and I_{EoL} refers to the terminal EoL.

Results

Figure 1 shows how the individual life cycle stages contribute to the environmental impacts over an 80-year building lifespan in scenario T and DfD, with two and three reuse cycles respectively. Note that for T and DfD the life cycle stages' relative impact contributions are very similar. The slight difference in the life cycle stages between T and DfD is a result of the life cycle impacts of the reusable components being allocated equally between the use cycles relying on equation (2), thereby crediting reuse in the Next product system. The largest impact contribution is found for the production and replacements stage in all impact categories due to high impacts from production of the building materials. Owing to recycling and energy recovery, the life cycle stage and the Next product system exhibit impact savings across all impact categories. The large savings obtained in the Next product system within FAETP, HTP and TETP are a result of the high recycling rate applied for steel (99%) and for concrete and glass (both 90%).

Figure 2 presents the environmental impact contributions from the individual building components over an 80-year building lifespan for scenario T and DfD with two and three reuse cycles respectively. The majority of the building's embodied environmental impacts originate from many of the structurally important concrete components with long lifespans, *e.g.* floor slabs and inner walls are responsible for large contributions to the majority of the impact categories. The technical building services also provide noticeable contributions to most categories due to high replacement of metals occurring during the lifespan of the building. Windows, doors, roof, foundation, solar shading, staircases, columns and beams account for a minor share of the impacts, since these components account for a minor share of the building's total mass (Table 2). For

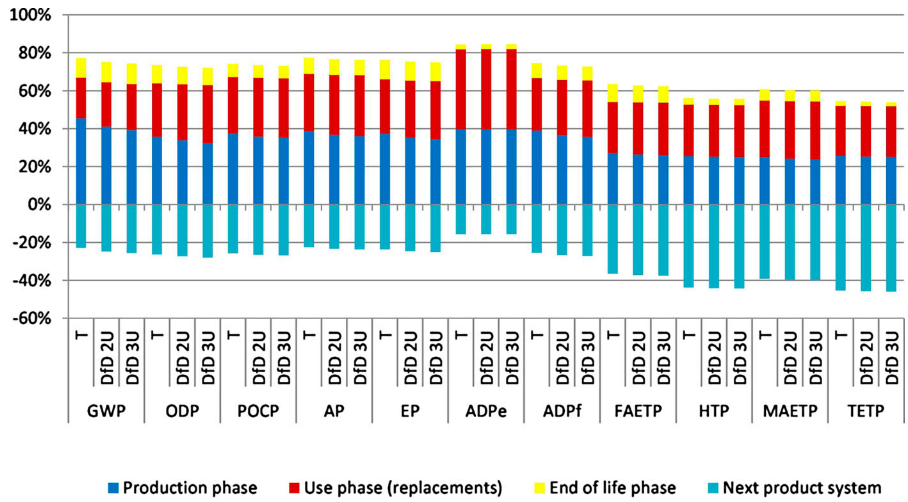

Figure 1. Contribution of life cycle stages' of environmental impacts over an 80-year building lifespan.

DfD, the impact shares decrease for those building components groups containing reusable elements, *e.g.* floors, beams and columns, and increase for those building component groups containing no reusable components as a result of allocating the life cycle environmental impact of the reusable components between the respective use cycles using equation (2).

The environmental impact contributions over an 80-year building lifespan from building materials are presented in Figure 3 for scenario T and DfD, with two and three reuse cycles respectively. As seen in Table 3, although metal only makes up 6.6% of the reference building's total mass, it accounts for a large share of most impact categories; however, it is most pronounced among the toxicological impact categories FAETP, HTP, MAETP and TETP with 54%, 50%, 36% and 75% respectively, and 75% of ADPe caused by the technical building services. The steel ventilation system is solely responsible for a large share of these impacts due to a high replacement rate of every 25 years. Compared with the metals, concrete accounts for 81.8% of the building's total mass, with dominating contribution to GWP ODP, POCP, AP, EP and ADPf amounting to 48%, 32%, 22%, 24% and 26% respectively of the total impact within each category. Despite their minor share the building's total mass, the insulation, paint and varnishes also account for a noticeable contribution to many impacts due to the energy demands associated with manufacturing glass and stone wool and a frequent replacement rate of the paint and varnishes of every 10 and 5 years respectively. Wood-based materials yield a negative GWP because CO_2 from the atmosphere is bound to/stored in the wood (*i.e.* wood serves as a carbon sink), hence there is a negative GWP value. For those

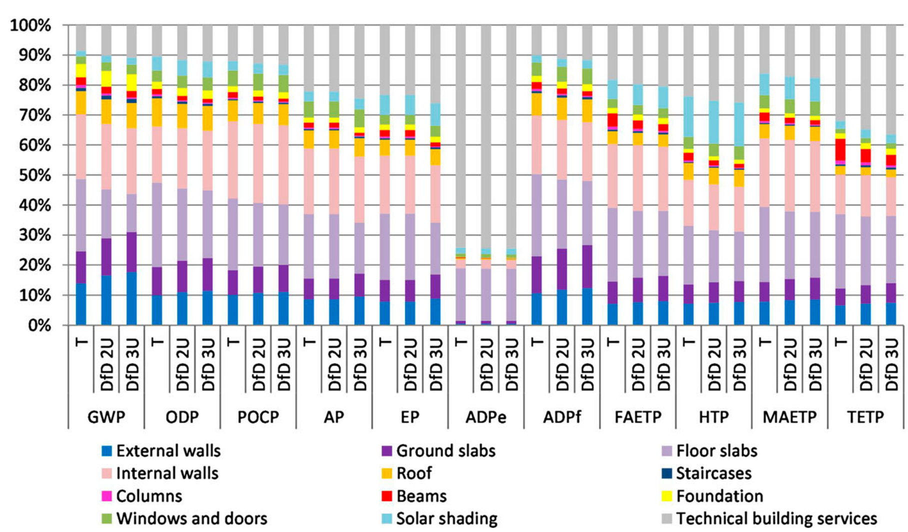

Figure 2. Contribution of building components' environmental impacts, T, over an 80-year building lifespan.

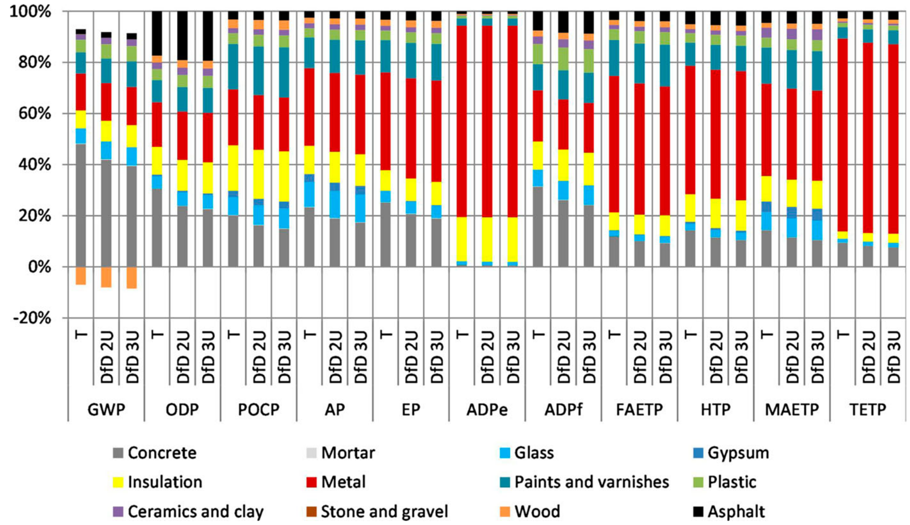

Figure 3. Contribution of building materials' environmental impacts, T, over an 80-year building lifespan.

material groups related to the reusable components, *e.g.* concrete, it is seen that the impact share is reduced for DfD due to allocation of the life cycle environmental impacts of the reusable components between the respective use cycles using equation (2).

The accumulated embodied CO_2 emissions of T, DfD and O with two and three reuse cycles over an 80-year building lifespan are presented in Figure 4. For all scenarios, a drop in the graphs occurs after 80 years due to the potential embodied CO_2 emissions savings obtained in module D from crediting reuse, recycling and energy recovery. T and DfD mimic each other well, since the only difference between them is that the impacts of the reusable components are allocated using equation (2), *i.e.* these impacts are split between the assumed number of reuse cycles. The embodied CO_2 emissions of T is large due to material replacements accounting for 21% of the building's total embodied CO_2 emissions over the 80 years. Reuse of the concrete structure two and three times results in potential CO_2 emissions savings of 15% and 21% respectively compared with T. Substitution of concrete with different material choices such as steel, wood and glass in O reveals higher CO_2 emissions saving potentials compared with DfD. Table 4 presents the potential embodied environmental impact emissions savings of the reusable components compared with no reuse.

Considerable savings are observed for all components across all impact categories, as is also evident from the weighted impact savings calculated as the average saving of each component group using equal weighting factors for each impact category assessed. The floor slabs represent the largest savings in all impact categories compared with the other components, as they account for 37% of the building's total mass (Table 2). The lowest savings are found for the core walls compared with the

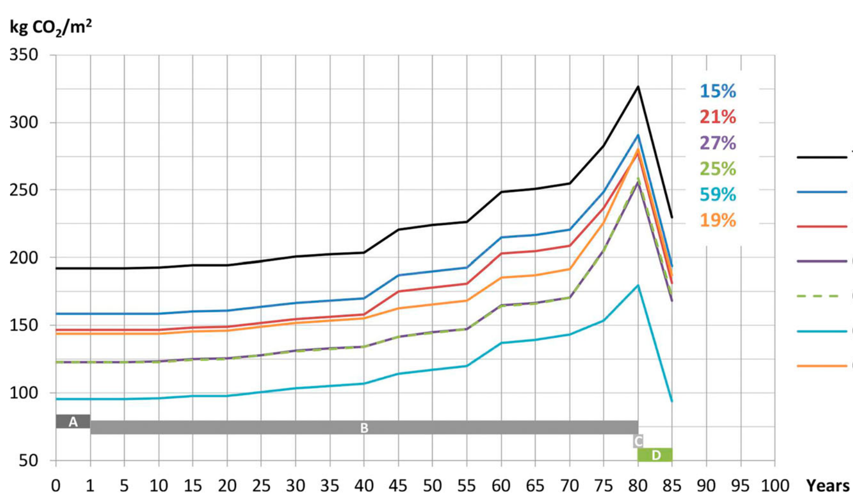

Figure 4. Accumulated embodied CO_2 emissions over an 80-year building lifespan.

Table 4. Potential embodied impact savings of the reusable component compared with no reuse.

Reusable components	Use cycles	Impact saving [%] GWP	ODP	POCP	AP	EP	ADPe	ADPf	FAETP	HTP	MAETP	TETP	Weighted impact savings [%]	
Floor slabs	2	45	46	45	45	46	46	46	46	43	44	45	45	
	3	60	61	60	60	60	60	61	61	59	60	60	60	
Core walls	2	36	32	27	30	28	11	32	13	20	18	7	23	
	3	50	47	43	46	44	31	47	31	38	37	28	40	50-60
Roof slabs	2	31	32	34	33	33	43	32	43	39	38	51	37	40-50
	3	41	42	44	46	44	53	42	53	47	48	62	47	30-40
Columns	2	41	32	37	38	37	28	38	29	32	32	29	34	20-30
	3	57	54	55	55	55	48	56	49	51	51	49	53	10-20
Beams	2	25	28	34	31	34	42	31	41	39	40	43	35	0-10
	3	33	38	46	42	45	56	42	55	52	53	58	47	<0

Note: Weighted impact savings are calculated as the average impact savings of each reusable component compared with no reuse using equal weighting factors for each environmental impact category assessed. This includes GWP, ODP, POCP, AP, EP, ADPe, ADPf, FAETP, MAETP, HTP and TETP. For abbreviations, see the text.

beams and columns, which make up a smaller percentage share of the building total mass (Table 2). This is due to the much more environmentally burdensome construction steel within the beams and the high reuse percentage of the columns compared with the core walls. Table 5 shows the potential embodied environmental impact savings for the different building scenarios for 50 and 80 years compared with no reuse.

Although potential savings are obtained across most impact categories covered, compared with the large relative savings exhibited for the reusable components in Table 4, it is evident from Table 5 that these considerable savings cannot be matched at building level. This is because the material composition has a big influence on the savings and magnitude of the savings obtained for the individual building scenarios within the different impact categories. Impact categories such as ADPe, FAETP and TETP that are mainly influenced by the buildings metals will benefit less from reusing the concrete components. Consequently, the largest weighted impact savings are 14.5% and 22.9% for O1, as well as 15.3% and 22.6% for O3 for 50 and 80 years of building lifespan respectively. The only savings obtained that match those of Table 4 are found for the O3 GWP for two component-use cycles: 54% and 49%, and for three component-use cycles: 59% and 55%, for a building lifespan of 50 and 80 years respectively using wooden columns compared with concrete or steel columns. However, similar savings are not found for O3 across the remaining impact categories. This is also reflected by the much lower weighted impact saving for two component-use cycles: 12.1% and 18.7%, and for three component-use cycles: 15.3% and 22.6% for the 50 and 80 years building lifespans respectively. Although the bubble decks in O4 use 41% less concrete compared with hollow core slabs, the average impact savings obtainable from the bubble decks are very low compared with the other cases using hollow core slabs. This is because of the increased amounts of reinforcement steel needed for the bubble decks. O2 performs worse

Table 5. Potential embodied impact savings of the building scenarios compared with T.

Building scenario	Use cycles	GWP		ODP		POCP		AP		EP		ADPe		ADPf		FAETP		HTP		MAETP		TETP		Weighted impact savings [%]		
		80	50	80	50	80	50	80	50	80	50	80	50	80	50	80	50	80	50	80	50	80	50	80	50	
DFD	2	15	18	8	12	7	9	7	10	8	11	0.3	0.6	10	13	7	10	5	10	6	9	17	22	8.2	11.3	
	3	21	25	14	19	9	12	10	13	11	13	0.6	1	14	18	11	15	8	14	9	12	13	8	11.0	13.6	
O1	2	21	28	12	20	8	16	5	14	14	20	0.4	1.7	11	18	9	15	13	23	8	13	12	22	10.3	17.3	
	3	27	35	19	27	10	19	8	18	17	25	0.5	2	16	24	18	28	19	32	12	19	13	23	14.5	22.9	50-60
O2	2	18	26	12	20	4	11	2	10	9	14	-0.5	0	8	15	-2	-0.5	7	14	2	4	-13	-23	4.2	8.2	40-50
	3	24	34	17	26	8	16	6	15	14	20	1.4	0.9	14	21	7	10	12	21	7	12	3	4	10.3	16.4	30-40
O3	2	54	49	10	22	2	13	3	13	11	19	0.1	1.5	10	19	11	15	15	24	7	14	10	16	12.1	18.7	20-30
	3	59	55	15	25	5	16	6	17	14	23	0.3	1.8	13	23	15	22	17	27	10	18	14	21	15.3	22.6	10-20
O4	2	17	23	8	11	3	14	0.3	8	8	14	-0.3	0.5	4	10	-6	-4	7	16	2	5	-9	-5	3.1	8.4	0-10
	3	19	25	9	13	4	16	1	9	10	14	-0.3	0.6	5	12	-4	-1	11	17	3	7	-6	-2	4.7	10.1	<0

Impact saving [%] spans GWP through TETP.

Notes: Energy consumption during operation is not included. Weighted impact savings are calculated as the average impact savings of each building scenario compared with no reuse of the reusable components using equal weighting factors for each environmental impact category assessed. This includes: GWP, ODP, POCP, AP, EP, ADPe, ADPf, FAETP, MAETP, HTP and TETP. For abbreviations, see the text.

DfD = design for disassembly; O1 = optimization scenario (concrete columns); O2 = optimization scenario 2 (steel columns); O3 = optimization scenario 3 (wooden columns); O4 = optimization scenario 4 (bubble decks).

compared with O1 due to the use of burdensome steel columns, resulting in higher impacts across many of the covered impact categories compared with concrete columns. Both O2 and O4 show worse performance within the impact categories ADPe, FAETP and TETP compared with T due to increased amounts of steel for columns and bubble decks respectively (Table 3).

Table 5 shows that the highest weighted impact savings are obtained for a building lifespan of 50 years as a result of the reduced number of material replacements over the shorter building lifespan. Thus, the reusable concrete structures thereby represent an increased share of the total environmental impacts resulting in larger saving potentials. Furthermore, the impacts are spread out over a shorter time period, making the impacts as well as the savings appear larger. However, the DGNB in Denmark is about to phase out the use of a building lifespan of 50 years in favour of 80 years for office buildings instead, thereby deviating from the other DGNB countries in Europe.

Both Tables 4 and 5 show that, with the proposed allocation method, the more reuse cycles, the higher the potential impact savings.

Discussion

This section discusses the results of the case study obtained by applying the life cycle impact assessment method as well as the proposed allocation method described in the methodology . Recommendations are provided on how to apply LCA within CE based on the experiences gathered from the present study.

Focusing on more impact indicator categories than usual revealed that the magnitude of the savings varies from impact category to impact category as well as from scenario to scenario, as the material composition has a significant influence on the building's embodied environmental impacts and greatly depends on the number of component reuse cycles, the material's life span and the building's lifespan. Thus, optimization of a single component group leading to potentially high environmental impact savings (Table 4) may not necessarily benefit the overall building level to the same extent (Table 5). Hence, it is not obvious which scenario performs best and which material choices to aim at. Since studies identifying material interdependencies and influences on the environmental performance of different building types are lacking, the material choices applied in this study are based on intuition. Other material choices than those used here might improve the building's overall environmental burden even further.

It is considered realistic to expect that the potential impact savings of DfD with three reuse cycles should be even larger compared with two reuse cycles (Table 5). However, a fraction of the prefabricated concrete elements will not be suitable for reuse. Thus, the impacts from these elements are allocated to the initial building, making the potential impact savings of three reuse cycles smaller than expected. Furthermore, for the DfD scenarios, only a moderate share of the building's concrete and metals (approximately 50% and 20% respectively) can be reused, because only the internal concrete structures are considered for reuse. Since concrete and metals are responsible for the largest shares of most impacts (Figure 3), this also results in smaller savings within the different building scenarios (Table 5). This is also reflected in the small difference in impacts between T and DfD seen on Figure 1. Hence, it is likely that considering additional building components for reuse will potentially further increase future impact savings.

Virgin material states were assumed for all materials used for the initial building, as it is still unclear how to account for multiple material uses with changing material qualities in LCA (Haupt & Zschokke, 2017). As a result, high recycling and energy recovery rates were assumed at the EoL, providing high avoided impacts in the Next product system (Figure 1). Diverting material from recycling to reuse at the building's EoL will most likely increase the potential future environmental impact savings.

As the material composition of the building scenarios significantly affected the results, the sensitivity coefficient resulting from a 10% input value increase was calculated for input parameters that control the material amounts, *i.e.* the material's mass, material's service life and the building's service life in scenario T, since all scenarios derive from T (see the sensitivity analysis in the supplemental data online) (Hauschild et al., 2018). The input parameters that exhibited highest sensitivity coefficients were found to be the service life of the ventilation ducts (25 years) in AP, EP, ADPe, HTP and TETP with –30%, –20%, –516%, –26% and –11% respectively. Furthermore, the material mass of the ventilation ducts has a high contribution of –66% in ADPe. The high negative sensitivity coefficient in ADPe is caused by the technical building services' high contribution to ADPe (Figure 2). However, the building's service life was found to have the highest sensitivity coefficient in all impact categories assessed (between 21% and 93%). All other input parameters tested only had minor sensitivity coefficients in comparison.

As existing studies in the field are limited, validation of the results found from this study is challenging. However, comparing the result with an LCA study of an office building (Rasmussen & Birgisdottir, 2015), the material composition is similar to that of the office building assessed in this study except for metals which are more pronounced in the present study. Comparing the life cycle stages impact share shows that trends in GWP, ODP, POCP and AP assessed in the LCA study are similar to those found in the present study, except for the impacts at EoL and the Next product system, which yield much higher negative impacts in the present study, indicating differences in EoL modelling and crediting. Comparing the building components impact share show for both studies that the floors have large contributions; however, the trends for the other building components differ. Comparing the material impacts shares shows that the cement-based materials have by far the highest contribution in both studies, followed by the metals. Comparing the elements share of the CO_2 emissions in the present study with that of a related study of prefabricated reusable building modules (Aye et al., 2012) shows similar trends, *i.e.* the external walls and floors have the highest contribution. However, due to differences in assessment method and building elements included in the study, it is difficult to make a direct comparison.

Module D (Next product system) in Table 1 acknowledges the design for reuse and recycling concept, and quantifies the net environmental benefit or loads resulting from reuse, recycling and energy recovery beyond the conventional system boundaries (EN, 15978, 2012). However, using equation (2) means that credits for reusing the building elements are not directly reported separately in the Next product system as stated by EN 15978, since the life cycle impacts as well as credits of each reusable element are split between the respective use cycles that will share them. Hence, some form of crediting occurs within each life cycle stage of the elements.

The results obtained from applying the proposed allocation method shows benefits of prolonging the service life of the structural components, *i.e.* the more reuse cycles the better, thereby both avoiding the generation of new products consuming virgin raw materials and waste production as well as reducing environmental impacts in accordance with the CE idea. However, as made evident in previous studies (Allacker et al., 2014; Aye et al., 2012), several different allocation approaches exist. Hence, using another allocation methodology is likely to influence the results significantly, *e.g.* if the impacts and benefits of reuse are allocated entirely to the first or second use and the result does not display the benefits of product service life extension. Furthermore, allocating the impacts and benefits to the first use will ascribe no environmental benefits for a subsequent system, and allocating to a subsequent system potentially means that no product takes responsibility for these parts if no reuse occurs in the future. There is also a risk of double-counting impacts and benefits between the systems when allocating to one system over another. Although the proposed allocation method is based on an uncertain number of assumed future reuse cycles, a fairer share of the environmental impacts and benefits of the reusable components is credited to the first use and potential subsequent uses, thus promoting CE.

As noted above in the literature review, the long lifespan of buildings and change in use during their building lifespan lead to increased uncertainty about future scenarios and future environmental impacts (Haupt & Zschokke, 2017; Niero et al., 2015). The present study relies on the traditional LCA methodology, *i.e.* a restricted system boundary limited to the initial building from where the reusable elements originate (EN, 15978, 2012; ISO, 14040, 2008; ISO, 14044, 2006). In this study, subsequent uses of the reusable elements are taken into account indirectly through allocation of the potential environmental impacts based on the assumption of two or three future reuse cycles. Hence, any potential additional future reuse cycles beyond the assumed two or three cycles before the terminal EoL are not taken into account. Furthermore, the lifespan of the reusable elements will be 2×80 years and 3×80 years with two and three reuse cycles respectively, with a building lifespan of 80 years. However, the potential future reuse of a material can never be guaranteed (Aye et al., 2012), neither can the actual lifespan of the building. Additionally, a static LCA approach was used, *i.e.* dynamic changes during the building's long life span were not included in the study. Such dynamic changes include future resource scarcity, future waste systems, nearing tipping points (global warming), and future economy and energy systems. Thus, the potential of reuse in the future found in this study is not guaranteed, as these future circumstances are not known nor easily predictable. A solution could be to perform LCA scenario analysis allowing for inclusion of estimated future projections and of the uncertainty relating to prospective assessments (Niero et al., 2015). Consequently, instead of a single output analysis, a range of possible scenarios will give an output in the form of a span within which the future impacts can be expected to be present.

The temporal representativeness of the data used in the study is challenging, as the building is assumed to be built today and decommissioned in 50 or 80 years. Hence, calculation of the potential environmental impact savings in future is based on environmental impacts from production today; however, the potential future reuse will not occur until 240 years (after three use cycles), when module D is expected to occur.

Although potentially qualified joint solutions exist in the market allowing assembly and disassembly of concrete structures with the purpose of subsequent reuse

(Sommer & Guldager, 2016), a concept such as DfD also requires changing traditional building methods and construction waste management to store and relocate reusable components (Sommer & Guldager, 2016).

Conclusions

In order to reduce the negative impacts on the natural environment, successful implementation of CE principles, such as DfD, is both necessary and attractive. The potential for the reuse of materials and components by the construction sector can be aided and accelerated by identifying the most effective long-term improvement opportunities and efforts. This will require clear decision support for environmental performance assessment, *e.g.* LCA. The literature review identified the lack of a unified method for how to credit reuse and the many uncertain future circumstances in which the environmental impacts and benefits will potentially occur.

To address these concerns, a simplified allocation method was presented. This method divides a fairer share of the impacts between the potential use cycles and was applied to an LCA of a case study of a Danish office building with a concrete structure DfD. The case study found that the material's composition has a significant influence on the building's embodied environmental impacts and greatly depends on the number of component reuse cycles, the material's service life and building's service life. However, the longer the lifespan and the more reuse cycles the better, as the service life of materials is prolonged. This, in turn, postpones the production of new products consuming virgin raw materials.

Before a consistent prospective LCA concept promoting CE in the building industry can be formulated, further research is needed:

- to identify improvement opportunities by understanding the interdependencies and influence that material compositions have on the environmental performance of different building types
- to account for substituted materials and products as a result of reuse and recycling
- to generate consensus on how to handle future circumstances in which the potential environmental impacts and benefits of CE concepts will occur
- to determine how to best implement these factors into environmental performance assessments

This will provide key stakeholders (designers, clients, users, authorities *etc.*) with a valid and consistent basis for life cycle-based decision-making and policy initiatives to better link CE concepts to the environmental performance of buildings. It will help to establish clear objectives and targets regarding CE concepts.

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