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Published in:

World Multidisciplinary Civil Engineering, Architecture, Urban Planning Symposium (WMCAUS 2018)

DOI (link to publication from Publisher):

[10.1088/1757-899X/471/9/092051](https://doi.org/10.1088/1757-899X/471/9/092051)

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Publication date:

2019

Document Version

Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Malabi Larsen, L. C., Birgisdottir, H., & Birkved, M. (2019). Potential of Circular Economy in Sustainable Buildings. In M. Drusa, I. Yilmaz, M. Marschalko, A-M. Dabija, A. Segalini, J. Rybak, E. Coisson, & M. Decky (Eds.), *World Multidisciplinary Civil Engineering, Architecture, Urban Planning Symposium (WMCAUS 2018): 18–22 June 2018, Prague, Czech Republic* (Vol. 471, pp. 1-10). [092051] IOP Publishing. IOP Conference Series: Materials Science and Engineering Vol. 471 <https://doi.org/10.1088/1757-899X/471/9/092051>

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To cite this article: Leonora Charlotte Malabi Eberhardt *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 092051

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Potential of Circular Economy in Sustainable Buildings

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Abstract. The building industry contributes to resource scarcity by consuming vast amounts of natural resources and produces in addition large amounts of waste, both contributing to a considerable portion of the environmental impacts induced by the demands of a growing world population. Manufacturing of most building materials require large amounts of material and energy resources. These materials are nevertheless either down-cycled or ends up as waste after demolition. Consequently, the building industry only manages to exploit an insignificant percentage of the building materials' inherent economic value and durability. Hence, the need for improved resource efficiency will increase parallel to the growing human demands to ensure that future needs. Circular economy principles can potentially facilitate minimising the aforementioned pending issues emanating from the building industry through recirculation of building materials. E.g. existing mechanical joint solutions can enable design for disassembly, thereby potentially prolonging the service life of building materials and components through reuse in subsequent building projects. The research presented in the paper at hand aims at identifying the main challenges of implementing circular economy principles, as well as potentials here-off, within the building industry through a literature review. Furthermore, a conventional Danish office building is used as case study to support the literature review by quantifying potential environmental and economic benefits of designing the buildings concrete structure for disassembly, with the purpose of reuse, as well as to exemplify how circular economy can be applied in future building projects. Moreover, the paper aims at suggesting a more industry focused approach towards circular economy in order to seize the inherent potentials. As a result, it was found that recycling and energy recovery are the most common circular economy practices in the building industry, even though the economic and environmental benefits of reuse are believed to be much higher. This observation is supported by the findings of the case study, which revealed that reuse of the concrete structure can potentially avoid a noteworthy portion of the building's embodied CO₂ emissions and provide a reasonable economic gain. Moreover, increased impact savings were exhibited when substituting concrete with alternative materials e.g. wood, steel and glass, thereby enabling easier disassembly for both reuse and recycling. However, main challenges preventing the industry from seizing these potentials are identified as: focus on short term goals, complex supply chains, lack of collaboration between stakeholders and absence of a commonly agreed definition of circular economy within the industry. In conclusion, the study demonstrates an improved environmental performance of the office building when designed for disassembly. Furthermore, the choice of building materials has a noteworthy influence on the building's embodied environmental impacts. From the results obtained in this study it is estimated that the potential environmental impact savings as well as economic benefits can be further increased through a higher degree of design for disassembly.



1. Introduction

It is suggested that a building can be considered absolute sustainable if its annual environmental burden is less than its share of the earth's environmental carrying capacity [1]. A recent study of a so-called Danish reference house has assessed that a house, representing prevailing Danish building practices, transgresses the climate change carrying capacity allocated for accommodation by no less than 1563% [1]. Similar results are expected for buildings in countries with similar building practices. This exceedance of carrying capacity allocated for buildings is caused by the building industry producing and consuming roughly 40% of all materials globally, while generating 35% of the world's waste [2] of which most is being landfilled or incinerated [3]. Buildings serving accommodation purposes contribute on a per capita level with 20-35% to most environmental impact categories such as global warming and smog formation [4] as well as loss of valuable resources [3] meaning that for some impact categories such as global warming the per capita carrying capacity is exceeded solely by accommodation [1] leaving little "environmental room" for other important consumption segments such as food, transportation etc. These observations suggest that the building industry is a long way from reaching sustainable goals, but perhaps also represents a major pool of opportunities in terms of achieving local and global sustainable objectives, such as UN's sustainable development goals [5]. The building industry is in addition faced with the expectation that the global middle class will have doubled from 2 billion to over 4 billion people by 2030 [6]. Consequently, in the next 40 years the world needs to build more urban capacity than has been built in the past 4,000 years in order to ensure contemporary and future well-being as well as progress [7]. At the same time, raw material prices are rising, pushing the building industry towards resource efficient alternatives of manufacturing materials e.g. reuse or recycling to cut production costs [8].

Circular economy (CE) has attracted both political and industrial interest as a more relatable and easier operationalized way to practice sustainability by potentially representing a way to overcome the contradiction between economic growth and environmental sustainability by moving away from the current linear business model (take, make, use and dispose) to a circular business model (reduce, reuse, recycle and recover) [8, 9]. CE can thus provide an economic incentive to work towards sustainable goals. By intent and design, CE can potentially manage resources in a way that is regenerative and restorative and does not deplete these by keeping materials at their highest utility and value at all times, distinguishing between technical and biological cycles, providing greater economic stability through resource security [10]. The building industry, however, struggles to efficiently and practically embrace CE practices that are successfully being implemented in many other industry sectors [11]. Several different general CE frameworks have so far been suggested [12–14], however as CE is relatively new in its conceptualization and implementation within the built environment, only few frameworks have been specified in relation to the complex problems of the building industry [11] and further research is needed to determine its appropriateness for application within the building industry [15].

The specific objectives of the research presented in the paper at hand are:

1. to illuminate main challenges of implementing CE principles as well as the inherent potentials within the building industry.
2. to suggest a more industry-focused approach towards CE and how to seize these potentials.

2. Methodology

The objectives are reached by the means of a literature review and case study, explained in further detail in the following section.

2.1. Literature review

To know how to seize CE potentials it is important to understand the context of the built environment that the concept is applied to. Since CE in the building industry is still at its infancy [11], the most obvious way to address the first objective is through a literature review, conducted in such a way that it covers the most recent literature published within the field of CE in order to give an up to date

picture. The paper at hand focus on pinpointing the most frequently highlighted challenges and potentials mentioned in the literature in relation to CE within the built environment as these are perceived to be of considerable importance. However, the challenges and potentials mentioned in this paper are for that reason not exclusive. In terms of the second objective, based on the identified key challenges and potentials, the paper also highlights the potential for a suggestive approach specific for the context of the building industry. The key challenges, potentials and suggested approach of CE in the building industry derived from the literature review are presented in section 3. Background.

2.2. Case study

Building on the findings of the literature review as well as to exemplify how CE can be applied in future building projects to seize the potentials, a conventional Danish office building was used as case study. The potential environmental benefits were quantified through a life cycle assessment (LCA) of: 1) design for disassembly (DfD) of the building's internal prefabricated concrete structure based on already existing potentially qualified mechanical steel joint solutions on the market, with the purpose of facilitating reuse after the buildings end-of-life (EoL), 2) optimizing scenarios (O) containing different material choice combinations of the building structure, enabling easier disassembly not necessarily benefitting reuse solely but also recycling. The economic benefits were also estimated by calculating the business case of reselling the concrete elements for reuse in a subsequent building [16]. The mass of the office building contains approximately 80% concrete, has a gross floor area of 37,839 m² and is made up of 8 wings in different heights with a total of 9 storeys. The building structure is predominantly made up of prefabricated concrete elements consisting of floor slabs, façades, core walls, columns and beams. With the expectation that some elements will not be suitable for reuse after the building's EoL the percentage of elements estimated to be suitable for reuse was:

- 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

Due to the long lifespan of concrete, the prefabricated concrete elements were estimated to be suitable for at least three reuse cycles in three different buildings with a lifespan of 80 years including the initial office building, requiring no maintenance during that period to uphold their quality.

2.2.1. Life cycle assessment. The LCA follows the LCA methodology of the DGNB sustainability certification scheme, according to the standard EN 15978, focusing on the material related environmental impacts; hence the energy consumption during operation is excluded. The LCA was carried out for a building life span of 80 years and a functional unit of 1m² gross floor area pr. year. focusing on a representative section of the building. The life cycle impact assessment was performed using baseline characterisation factors from CML-baseline 2001 in openLCA v1.4 software, for environmental-, resource use and toxicology impact categories. The study focused on potential CO₂ emissions as well as weighted impacts that were calculated as the average impacts of each building scenario compared to no reuse of the reusable components using equal weighting factors for each environmental impact category assessed including: GWP (global warming potential), ODP (ozone depletion potential), POCP (photochemical ozone creation potential), AP (acidification potential), EP (eutrophication potential), ADPe (abiotic depletion potential for non-fossil resources), ADPf (abiotic depletion potential for fossil resources), FAETP (freshwater aquatic eco-toxicity potential), MAETP (marine aquatic eco-toxicity potential), HTP (human toxicity potential) and TETP (terrestrial eco-toxicity potential). The life cycle inventory (LCI) of the background system was based on the Ecoinvent 3.2 database using system processes to get aggregated results and the foreground system was compiled using project specific BIM-models provided by the entrepreneur company. Where data

were lacking estimations and assumptions based on technical datasheets, environmental product declarations (EPDs) for different elements and materials as well as information from manufacturers/suppliers and other professionals from the industry.

2.2.2. *Business case.* The economic benefits of designing the prefabricated concrete structure for disassembly were estimated on the basis of two EoL calculations [16]:

1. The cost of traditional decommissioning by demolition: the concrete is crushed to substitute natural resources such as stone and gravel and the reinforcement steel sold as scrap metal for recycling.
2. The potential profit of resale: the prefabricated concrete elements are resold for reuse in a subsequent building.

The calculations are based on present price levels for construction, the concrete elements, resources and landfill as well as additional costs for DfD of the concrete elements. Further detail of the business case calculation can be found in [16].

The findings of the case study are presented in the results section and discussion section, where the results of both the literature review and the case study in relation to the papers specific objectives 1. and 2. are discussed.

3. Background

The potential of CE is expected to be high as it has been estimated that applying CE in the European built environment by 2030 could potentially save £300 billion through primary resource and energy savings [17]. However, the building industry is characterised by a strong project-based institutionalized practice as well as market mechanisms that in many aspects do not fit the facilitation of CE principles. Among others, the completion of building projects require inputs from a great number of stakeholders within a complex international supply chain [18], where each stage of the chain contributes to further environmental impacts and economic cost of the production of the building [19]. Thus, CE cannot be successfully achieved without collaboration and engagement of all supply chain stakeholders through system thinking, being the stakeholder's abilities to understand how parts influence one another within a whole to ensure CE impact. However, the varying goals and focuses of the stakeholders, cause the different stakeholders to work against each other to achieve the largest profit margin of the respective building projects, leading to insufficient collaboration and mistrust [20]. Some industrial stakeholders foundation for business are even built on exploiting the market failure i.e. the current fragmented practice of the industry, resulting in unwillingness to support industry change [20]. On top of this, sustainability initiatives are being viewed as extra work because the potential profits are not visible to the stakeholders [20].

A clear business case is a strong incentive for all stakeholders of the supply chain, however the stakeholders focus on short-term goals and benefits e.g. short term profit, does not benefit long-term perspective goals such as sustainability [15, 20]. However, long-term investment and partnership could mean long-term savings by working together to maximize the collective gain that is greater than that of the individual benefits achieved from acting alone [20]. This suggests that without an economic incentive for CE the industry stakeholders will most likely not engage and collaborate on achieving CE. A better understanding of the cost benefit of applying CE for each actor involved is needed [15]. However, the benefits of adopting CE may not be shared equally across the supply chain [15].

The time aspect of building projects is also challenging for adopting CE principles within the building industry for several reasons. Firstly, CE has mainly been focused on short- and medium-lived consumer goods [15], whereas buildings are often unique long-lived products with possible change in use during their service life leading to increased uncertainty about future circumstances of e.g. reuse of building materials and components [11]. In addition, construction parties tend to build focusing on the contractual framework of how they are held responsible during an insurance and warranty period after

project completion, usually 5 years, after which no responsibility for the building is taken misaligning with the long-term goals of CE [20]. Along with the discontinuity of stakeholders across the buildings life cycle, it makes it difficult for stakeholders to take ownership of building material flows.

Furthermore, the abundance of CE conceptualisations and no commonly accepted definition or approach across the supply chain makes CE susceptible to lack of understanding, misinterpretation and misuse among different industry stakeholders potentially depriving CE of its underlying principles, impact and values [20] [21]. This is confirmed by [22] who found several different degrees of CE adoption by different companies in different industry practices with different perspectives [14]. Thus, there is a lack of knowledge on how to practice impactful CE within the building industry [15].

As most environmental, social and economic cost factors have already been determined sometimes up to 80% during the design phase of a building project [19], the design phase plays a crucial role in ensuring resource efficiency [23]. As waste prevention in the design phase is being more considered, research to date has largely been focused on waste management, resulting in well-established high recycling rates of construction and demolition waste within the industry, however with low value due to down-cycling [15]. Figure 1, shows that a more economically and environmentally beneficial use of recovered building materials is direct reuse of materials and components, which requires minimal energy consumption compared to the energy and material resources needed for material recycling [9]. Figure 1 suggest that the most economically and environmentally impactful CE within the built environment, can be achieved by a high degree of reuse material recoverability e.g. by the means of DfD. Reuse of entire buildings are believed to have the highest economic and environmental benefits [9], although they are often not designed for this purpose [15].

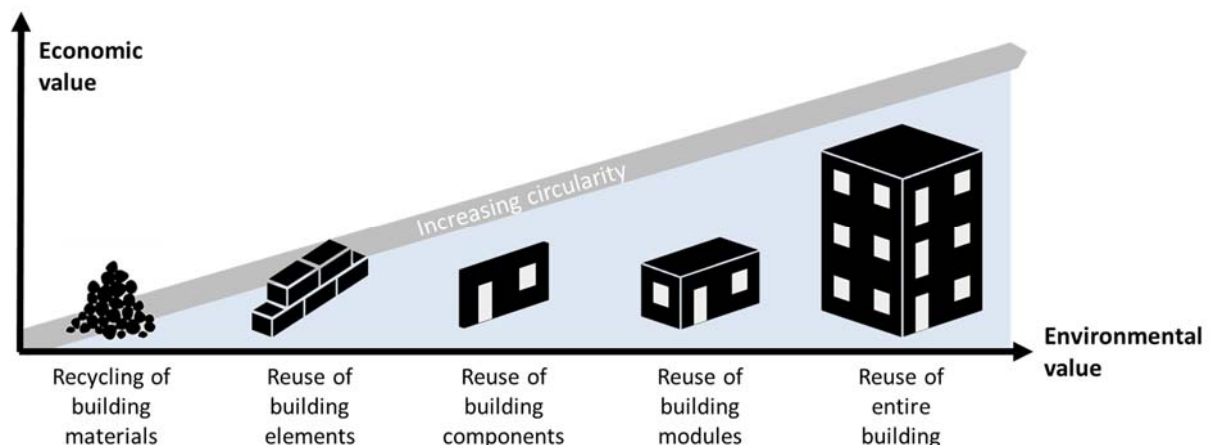


Figure 1. Conceptualization of the value of recycling and reuse degree. Authors' interpretation of [9].

An example demonstrating the principle of Figure 1 is prefabricated structural concrete elements that have a long lifespan and high durability as well as a high economic and environmental value [11]. Nonetheless, the building industry only manages to exploit a small percentage off this inherent value, as the elements are crushed for recycling at EoL [11], even though prefabricated building elements can potentially enable deconstruction for reuse [8].

The economic benefit of reuse are only realised upon retrieving materials and components from the building. For long-lived materials and components this could potentially be decades into the future which misfits the industries interest in generating short-term profit. This indicates that successful implementation of CE in the building industry has to come from a balance between short-term profit in the interest of the industry stakeholders and long-term sustainability goals. This could potentially be achieved by purposely combining short- and long-term CE strategies that target specific building types and their investors. E.g. reuse of building components and modules may be more suitable for short-

and medium-lived buildings, whereas social housing projects that have a frequent change in users over time may be looking for CE strategies such as DfD to facilitate easy adaptability and maintenance.

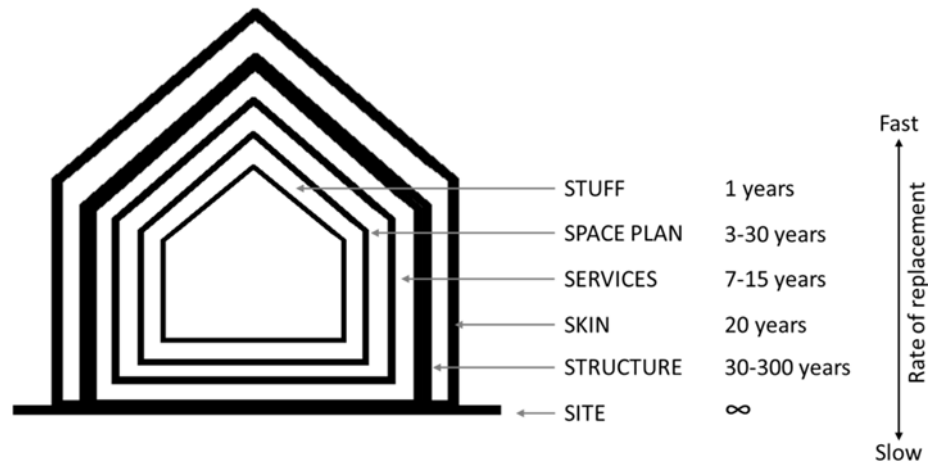


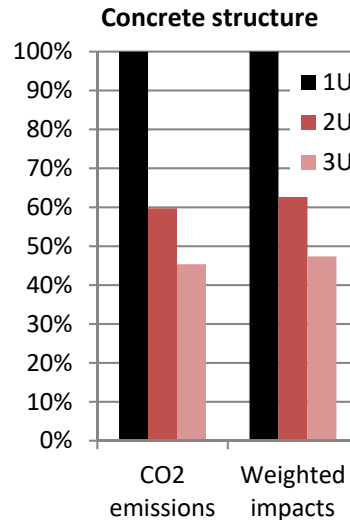
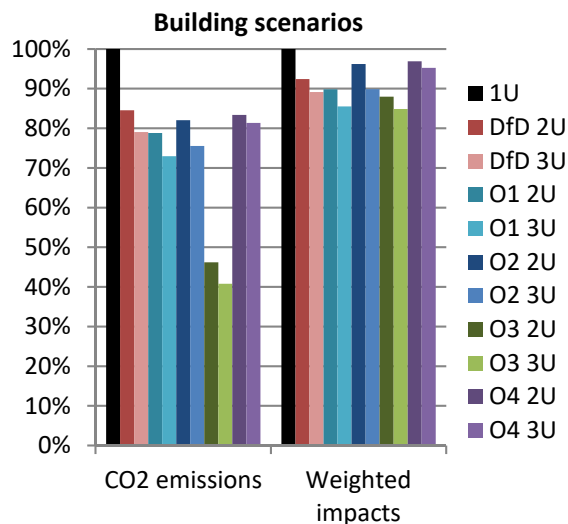
Figure 2. Building elements in relation to lifespan adapted from [24].

In relation to the aforementioned CE strategies, buildings are complex products that consists of a multitude of other products that delivers different functions with different characteristics and rates of replacement resulting in different potential retrieval for reuse or recycling over the building's life cycle as well as different economic and environmental value, as illustrated in Figure 2. Buildings can thus be viewed as a system of temporary storage and constant flow of resources that needs to be managed individually. This indicates that such CE strategies should not only focus on entire buildings but also differentiate between the flow of different building materials and component groups, potentially exploiting the replacement rates of these to facilitate short-, medium- and long-term benefits throughout the buildings lifespan. A study found different potentials for embodied energy and green house emission reductions from combining different design and construction strategies that relate both to the life cycle stages they impact as well as the stakeholder who have the principle responsibility for each [23]. Among others the use of alternative materials for the building structure such as timber, as well as use of recycled or recovered materials is recommended [23]. Development of such strategies for individual building materials and component groups in terms of CE [9] will help answer when and what to recycle or reuse within a building, narrowing the CE scope for the stakeholders to specific building elements with both a high functional, environmental and economic value, potentially facilitating a simpler CE decision support approach useful in the design phase. Furthermore, more research is required to determine what the optimal life cycle scenario is for these materials and component and how long the function should and could be provided as the most circular solution may not be the most beneficial in terms of the environment and economy [25][22]. There may also be limiting factors for continuous recycling or reuse presenting themselves at the material, component or building level [15]. The environmental performance strategies can be estimated trough life-cycle assessment (LCA), which is a scientifically based and ISO standardized method for assessing resource consumptions and environmental impacts of a given product, system or service over its entire life cycle [26]. Use of LCA is increasing within the construction industry and the methodology has been used in some recently published CE studies [3], [27].

4. Results and discussions

The combination of different material choices for the component groups within each building scenario, shown in Table 1, results in different environmental impacts of the overall building, as shown in Figure 3a, indicating that the combination of different material choices has a noteworthy influence on the buildings embodied CO₂ emissions. In addition, the weighted impacts of both the building in

Figure 3a, the concrete structure in Figure 3b and component groups in Table 1 deviates from the CO₂ emission indicating that the different material choices performs unequally across the impact categories with the risk of trade-offs.



Scenarios
 1U: one use cycle,
 2U: two use cycles,
 3U: three use cycles,
 DfD: design for disassembly of the prefabricated concrete structure
 O1: glass façade with concrete columns
 O2: glass façade with steel columns,
 O3: glass façade with wooden columns,
 O4: glass façade with concrete columns and plastic embedded concrete bubble floor slabs.

Figure 3a. The building scenario’s percentage environmental impacts resulting from different structural component group material choice combinations and their respective number of use cycles of different building scenarios.

Figure 3b. The prefabricated concrete structure’s percentage environmental impacts of one, two and three use cycles.

Figure 3c. Explanation of the building scenarios tested.

Table 1. Different component groups’ percentage embodied environmental impact savings resulting from different component group material choice combinations and their respective number of use cycles compared to the conventional building design.

Component group	Use cycles	CO ₂ emissions savings [%]					Weighted impact savings [%]				
		DfD	O1	O2	O3	O4	DfD	O1	O2	O3	O4
Floor slabs	1			-		22			-		-46
	2			45		-			45		-
	3			60		-			60		-
Core walls	1			-					-		
	2			36					23		
	3			50					40		
Roof	1			-		23			-		-45
	2			31		-			37		-
	3			41		-			47		-
Columns	1			-					-		
	2	41	-181	-370	73	-181	34	-147	-1164	69	-147
	3	57	-101	-239	80	-101	53	-77	-812	77	-77
Beams	1			-					-		
	2			25		90			35		94
	3			33		92			47		96

Due to material and component characteristics it is observed from Figure 3a, that change of the load-bearing concrete sandwich façade for a lighter non-load-bearing glass façade in all O scenarios,

which requires additional load bearing columns, results in overall environmental impact savings on an overall building level but can potentially exhibit burdens on the component level of the columns as seen in Table 1 for O2, O3 and O4. The same concrete columns are used in O1 and O4 resulting in the same environmental impact savings. Figure 3a shows that the best performing scenario on building level in both in terms of CO₂ emission and weighted impacts is O3, due to substitution of the concrete columns with timber. The use of plastic embedded concrete bubble floor slabs in O4 decrease the amount of concrete in the slabs resulting in the need for additional steel which again results in increased impacts as the slabs are also not suitable for reuse. However, since the concrete bubble floor slabs are double spanned, there is no need for beams which results in major savings of the component level of the beams in O4. The floor slabs in the remaining scenarios account for 35% of the building's total mass, and also represent the largest CO₂ emission savings as well as weighted impact savings compared to the other component groups.

Both Figure 3a and Figure 3b shows that the more use cycles the higher the potential impact savings of both the building and the concrete structure. Use of the prefabricated concrete structure two and three times revealed potential savings of 40% and 55% respectively of the structures embodied CO₂ emissions. The business case found that the cost of traditional decommissioning by demolition of the prefabricated concrete structure, where the concrete is crushed to substitute natural resources such as stone and gravel and the reinforcement steel sold as scrap metal for recycling, would cost the client 16 mio. DDK [16]. However, resale of the prefabricated concrete elements for reuse in a subsequent building would profit the client 35 mio DDK. As price levels of resources are expected to increase over time, the economic return of such a CE model could potentially also increase over time [16]. A sensitivity analysis shows that despite uncertainty related to retrieval percentages and retrieval values of the concrete elements the value of the CE model still provides a reasonable future profit worth pursuing [16].

The high degree of reuse i.e. reusing the prefabricated concrete elements, results in both a higher environmental and economic benefit compared to recycling and disposal of these elements at final EoL, which aligns with the concept of Figure 1. On the other hand, to seize these inherent benefits, reuse of building materials at this scale requires major changes to the industry practices [9]. i.e. the building methods and management of construction waste. DfD suggest production standardization, modularization, storage and relocation of building materials and components, which may be difficult to achieve since current building practices reflect projects that unlike and non-repeated. As a consequence here-off, it is likely that application of CE will vary depending on the context of the project and the diverse nature of its supply chain [15]. Furthermore, the potential economic profit and second use of the prefabricated concrete elements does not occur before 80 years into the future and then again another 80 years for the third use. This increases the uncertainty regarding material resource prices and waste management systems in the future making it difficult to predict the potential value and use of long lived products such as these [15]. The discontinuity of stakeholders over such a long lifespan also questions who will ensure reuse of these prefabricated concrete elements in the future.

Combining different life cycle design and construction strategies for material and components groups could emerge as a simple way to gauge the performance of CE in the design stage of a project and may decrease the complexity of applying CE to the built environment, making it more comprehensible for the different stakeholders of the supply chain. It may also help facilitate an alignment of a more commonly agreed CE definition within the built environment, that takes into account both short- and long-term goals and benefits, which may motivate collaboration between industry stakeholders of the complex supply chain.

Taking into account the magnitude of the environmental implication stemming from the building industry, long-term DfD demonstrated in the case study as a CE principle will most likely not be able to solve these burden issues entirely. However, focusing on life cycle design strategies, such as DfD, that balances a combination of impact reductions up front with potential reductions in the future as suggested in this study may help mitigate the problems [23]. On the other hand, substantial future

environmental impact and resource consumption reductions resulting from such strategies can only be realized through particular scenarios for which the present designer and the future building owners should take responsibility [23].

5. Conclusions

A literature study found that the main challenges preventing the industry from seizing CE potentials are: the high complexity of the supply chain as well as focus on short-term goals such as short-term profit that misfit the long-term goals of sustainability. Focus on short-term profit creates competition among the stakeholders resulting in insufficient collaboration between these. Additionally the absence of a commonly agreed definition of CE results in lack of knowledge on how to practice impactful CE within the building industry. The literature study also found that potential environmental impact saving as well as economic benefits could be further increased through a higher degree of reuse, which was confirmed through a case study designed for disassembly. Furthermore, the buildings overall environmental impact savings could potentially be improved through optimized materials choice combinations e.g. wood, steel and glass, thereby enabling easier disassembly for both reuse and recycling. It is suggested that there might be certain CE principles that fit better together with certain building types, materials and components, advocating combination of different life cycle design and construction strategies specific for different material and component groups and their inherent characteristics. This heuristic method can potentially mitigate the main challenges identified in the literature review by approaching CE in the built environment on a more comprehensible level for its stakeholders and support decision making in the design stage of new buildings to seize inherent CE potentials.

The potential economic and environmental impact saving found for the case study are only applicable to this specific case. Next step of this research will involve developing this approach building on quantitative sustainability assessments employing LCA to assess what the optimal life cycle scenario is for key building materials and component and how long the function of these materials and components should and could be provided to categorise which CE principles fit with different building types, materials and component groups.

References

- [1] K. N. Brejnrod, P. Kalbar, S. Petersen, and M. Birkved, "The absolute environmental performance of buildings," *Build. Environ.*, vol. 119, pp. 87–98, 2017.
- [2] S. Farzin Faezi, "Construction Waste Management for Sustainable Environmental Education," *MAGNT Res. Rep.*, vol. 2, no. 4, pp. 1444–8939, 2014.
- [3] P. Ghisellini, C. Cialani, and S. Ulgiati, "A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems," *Journal of Cleaner Production*. pp. 1–22, 2015.
- [4] F. Nemry *et al.*, "Environmental Improvement Potentials of Residential Buildings (IMPRO-Building)," *European Commission, Joint Research Centre*, 2008.
- [5] The United Nations, "Proposal for Sustainable Development Goals - Sustainable Development Knowledge Platform," 2015. [Internet]. Available: <https://sustainabledevelopment.un.org/focussdgs.html>. [Accessed: 08-Nov-2017].
- [6] H. Kharas, "The Unexpected Expansion of the Global Middle Class an Update," *Global Economy and Development program at the Brookings Institution*, 2017.
- [7] D. Biello, "Can Smarter Growth Guide China's Urban Building Boom?," 2012. [Internet]. Available: http://e360.yale.edu/features/can_smarter_growth_guide_chinas_urban_building_boom. [Accessed: 08-Nov-2017].
- [8] A. Kylili and P. A. Fokaides, "Policy trends for the sustainability assessment of construction materials: A review," *Sustain. Cities Soc.*, vol. 35, no. April, pp. 280–288, 2017.
- [9] L. A. Akanbi *et al.*, "Salvaging building materials in a circular economy: A BIM-based whole-

- life performance estimator,” *Resour. Conserv. Recycl.*, vol. 129, no. May 2017, pp. 175–186, 2018.
- [10] Ellen MacArthur Foundation, “Circularity in the Built Environment: Case Studies,” 2016.
- [11] F. Pomponi and A. Moncaster, “Circular economy for the built environment : A research framework,” *J. Clean. Prod.*, vol. 143, pp. 710–718, 2017.
- [12] S. Pauliuk, “Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations,” *Resour. Conserv. Recycl.*, 2018.
- [13] M. Niero and M. Z. Hauschild, “Closing the Loop for Packaging: Finding a Framework to Operationalize Circular Economy Strategies,” in *Procedia CIRP*, 2017, pp. 685–690.
- [14] A. Urbinati, D. Chiaroni, and V. Chiesa, “Towards a new taxonomy of circular economy business models,” *J. Clean. Prod.*, vol. 168, pp. 487–498, 2017.
- [15] K. T. Adams, M. Osmani, T. Thorpe, and J. Thornback, “Circular economy in construction: current awareness, challenges and enablers,” *Proc. Inst. Civ. Eng. - Waste Resour. Manag.*, vol. 170, no. 1, pp. 15–24, 2017.
- [16] J. Sommer and K. Guldager, “*Building A Circular Future*”. The Danish Environmental Protection Agency, 2016.
- [17] Ellen MacArthur Foundation, “Growth within: a circular economy vision for a competitive europe,” *Ellen MacArthur Found.*, p. 100, 2015.
- [18] M. H. A. Nasir, A. Genovese, A. A. Acquaye, S. C. L. Koh, and F. Yamoah, “Comparing linear and circular supply chains: A case study from the construction industry,” *Int. J. Prod. Econ.*, vol. 183, pp. 443–457, 2017.
- [19] H. Winkler, “Closed-loop production systems-A sustainable supply chain approach,” *CIRP J. Manuf. Sci. Technol.*, vol. 4, pp. 243–246, 2011.
- [20] J. A. Bekier and M. Vedel-jørgensen, “Circular Economy: Where Sustainability Means Business?,” Copenhagen Business School, 2017.
- [21] J. Kirchherr, D. Reike, and M. Hekkert, “Conceptualizing the circular economy: An analysis of 114 definitions,” *Resources, Conservation and Recycling*. pp. 221–232, 2017.
- [22] M. Niero, “Circular Economy in corporate sustainability strategies: a review of corporate sustainability reports in the Fast-Moving Consumer Goods sector,” Manuscript submitted for publication, 2018.
- [23] T. Malmqvist, M. Nehasilova, A. Moncaster, H. Birgisdottir, and F. Nygaard, “Energy & Buildings Design and construction strategies for reducing embodied impacts from buildings – Case study analysis,” *Energy Build.*, vol. 166, pp. 35–47, 2018.
- [24] S. Brand, *How Buildings Learn: What Happens After They’re Built*. Viking Press, Indiana, 1994.
- [25] A. E. Scheepens, J. G. Vogtländer, and J. C. Brezet, “Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable,” *J. Clean. Prod.*, vol. 114, pp. 257–268, 2016.
- [26] European Committee for Standardization, Standard EN 15978, “*Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*,” 2012.
- [27] A. Genovese, A. A. Acquaye, A. Figueroa, and S. C. L. Koh, “Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications,” *Omega*, vol. 66, pp. 344–357, 2016.