Using BIM and LCA to evaluate material circularity: Contributions to building design improvements

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Abstract –

The construction sector has suffered from low productivity and considerable waste due to the fragmentation of its value chain and inefficient design and material usage processes. The circular economy (CE) principles have gained significant attention among researchers and practitioners to help overcome these challenges. Construction materials such as timber and steel elements will lend themselves more easily to reuse and recycle for new construction to reduce carbon emissions. The BIM-based LCA method could be explored and expanded to evaluate design options for circular construction to advance the knowledge about implementing circular economy principles in construction projects. However, this is relatively new and requires proof of concepts to demonstrate precisely how BIM-based LCA could be implemented to help stakeholders decide on optimal design options and material choices. To address this need, this study proposes a BIM-based LCA process for comparing the carbon impact of two design model options considering different material choices, including the possibilities of using virgin materials and recycled and reused materials. Findings show that the timber structure was favored over the precast concrete structure because timber materials entailed less carbon emission; however, the precast concrete structure has great potential of being reused for future new construction projects. Findings also show that Module A (with timber and steel materials) has a slightly higher circularity (39%) than Module B (with concrete materials) with 37% circularity.

Keywords –

BIM; LCA; Circular economy; Design options; Secondary materials; Embodied carbon

1 Introduction

Construction projects and buildings typically use many concrete and steel materials with high embodied carbon values. According to the Intergovernmental Panel on Climate Change (IPCC, 2014), buildings are expected to account for 52% of worldwide energy-related carbon emissions by 2050. A solution to reducing embodied and total carbon emissions is using by-products and waste materials for producing building materials, as advocated by the Ellen McArthur Foundation (2021). Circular economy (CE) in the built environment was defined as the strategic programming of a building to quickly change its configuration for longevity and potentially be susceptible to the loop of reducing, reusing, and recycling for resource efficiency (Pomponi & Moncaster, 2017). Associated is the concept of circular construction, which was understood as an approach to achieving CE targets (slowing, closing, and narrowing the construction resource loops) considering the local or regional capacity to supply and transport (re-)used materials through prioritizing the extension of building service life and recycling, reusing, recovering materials when building functionalities are lost (Stahel, 2016; Chen et al., 2021). By adopting the circular economy principles in the built environment, the resources can be used more efficiently, and therefore material waste and carbon impacts in construction projects could be reduced. Projects guided by CE principles can potentially alter traditional building design processes. For example, many researchers investigated design with reused materials (Brütting et al., 2019), design with recycled materials (Borg et al., 2021), and design for disassembly (Sanchez et al., 2020) methods to ensure optimal design options could be generated to minimize carbon emissions and reduce the exploitation of raw virgin materials.

Building information modeling (BIM) and lifecycle assessment (LCA) methods have been widely studied and accepted as "business-as-usual" in current design practices (Hollberg et al., 2020). The potential of integrating BIM and LCA is sufficient information about building geometry and functionality for building sustainability assessment purposes (e.g., to achieve a high rating in sustainable building certification systems such as BREEAM or LEED). For assessing the environmental impact of building design options, LCA covers the entire life cycle of buildings from raw materials extraction and processing, manufacturing of building components and transportation to use and end-of-life (Safari & AzariJafari, 2021). Researchers have developed various tools, plug-in functions and software to enable BIM-based LCA by linking the quantity take-off and standard material libraries from a BIM authoring software with the local LCA database to measure the environmental impact during different phases of the project life cycle (Röck et al., 2018; Hollberg et al., 2020). With the development of CE principles, BIM-based LCA could be further explored to evaluate circular design options. However, the research in this direction is relatively new and requires proof of concepts to demonstrate exactly how BIM-based LCA is implemented to help stakeholders make decisions on optimal design options and material choices.

This study proposes a BIM-based LCA process for comparing the carbon impact of two design model options considering different material choices, including the possibilities of using virgin materials and recycled and reused materials. Tekla Structures software and the One-Click LCA platform are used to implement the BIM-based LCA process to perform the carbon emission calculations. The two design model options include 1) Model A: a timber building structure, and 2) Model B: a precast concrete building structure, both of which represent the prevalent building types in the view of sustainable construction. The BIM-based LCA process outputs the carbon emissions for different building life cycle stages when certain building materials are chosen for the building design and when they are again circulated in the next project life cycle. The focus is on understanding how the CE principles support the carbon reductions in buildings through optimal material considerations.

The rest of this paper is structured as follows. Section 2 provides a literature review on circular construction and material circularity as well as the BIM-based sustainable design. Section 3 describes the BIM-based LCA process for comparing the material circularity of two design model options. Section 4 illustrates the findings of the carbon emissions from the two design model options considering different materials choices. Section 5 discusses the potential and limitations of this study, followed by conclusions and future work in Section 6.

2 Literature review

2.1 Circular construction and material circularity

The construction sector is characterized as extremely resource-intensive due to the significant energy consumption, greenhouse gas emissions, and waste generation. The emissions in the construction industry can be reduced by increasing practices of reusing, recycling and recovering materials, in particular the CE model. By adopting the CE principle, the construction sector could play a strategic role in achieving Net Zero by 2050 (Pomponi & Moncaster, 2017). Stahel (2016) suggested that the CE should emphasize reducing product environmental impact, extending the useful life of the products used and employing sustainable resources, all of which are critical for developing climate change mitigation strategies. Circular construction models have been developed around utilizing the embedded economic and environmental value in products and materials as long as possible, such as substituting primary materials with secondary materials (Safari & AzariJafari, 2021). To overcome the resource depletion challenges, there has been a drastic shift towards a CE paradigm in the built environment to reduce the pressure on non-renewable resources (Chen et al., 2021). CE principles seek to maintain building components and resources at their highest intrinsic value for as long as possible. Building components are kept in a continuous loop of use, reuse, repair and then recycled, thereby reducing waste and preventing negative externalities of CO2 emissions.

Various studies have shown the advantages of adaptive reuse of building materials and the possibility of using the existing built environment as a source of reused components (Brütting et al., 2019; Sanchez et al., 2020). Building components can be reused and circulated in three ways: 1) reusing the existing components on-site through improving them or extending them, 2) relocating the majority or even all of the existing components to a new location, and 3) individual components obtained from the destruction of a building being reused directly in another building (Nußholz et al., 2020). Stahel (2016) states that the prefabrication of components and their modularization could create building products designed for reuse. Strategies for re-entering construction and demolition waste into the production chain concentrate primarily on the recycling process, whereas studies focusing on reuse are less frequent. It has been a challenging task for construction practitioners to understand what and how building materials could be reused as well as how much carbon impact could be reduced through these new design and construction strategies such as design for future reuse or design with reused materials.

2.2 BIM-based sustainable design

BIM has been widely adopted in current construction practices that facilitate the coordination of design and construction information. By adding a sustainability dimension, BIM-based sustainable design centered around design considering the LCA when using the material information and parametric building design information from BIM authoring software.

The BIM-based LCA method is a well-established technique for sustainability studies in the built environment which could be extended to the CE-driven research (Pomponi & Moncaster, 2017). For example, Röck et al. (2018) and Hollberg et al. (2020) have designed BIM-LCA applications to support the design process of real buildings, which allowed the designers to track design decisions on the continuously evolving BIM model. However, studies in this direction have not supported circular concepts in building design processes.

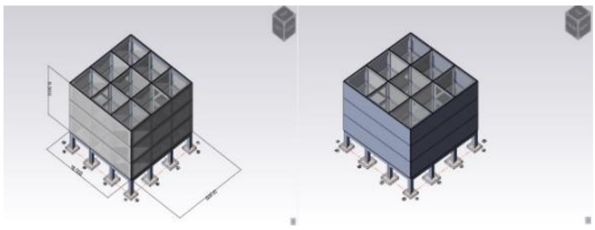
One way to promote CE is to design through material circularity assessment using BIM-based LCA to embed sustainable building regulations and environmental product declaration (EPD) in the BIM authoring software. However, the related research has been missing from the current body of knowledge on CE in the built environment. Considering the benefits of CE, as claimed by many scholars (e.g., Joensuu et al., 2021), there is a need to prove the concept of using BIM and LCA tools to realize new design processes guided by CE. This study investigates a case study of two design model options by using BIM and LCA to evaluate material circularity. The comparative results would help stakeholders understand material choices in optimal design to reduce carbon by maximizing the reusing and recycling of building materials.

3 Methodology

The study proposes a BIM-based LCA process to calculate carbon emissions for buildings with different design options and material choices. Tekla Structural Designer was used for developing the building model. The structural elements such as beams, columns, footings, etc., were designed in this software and applied the required materials and loads for the building. It was also used to calculate the bill of quantities of the materials required based on the building design. The One-Click LCA software was used for performing the life cycle assessment concerning carbon emissions for the building. One-Click LCA provides embedded algorithms for measuring building circularity. The detailed information on building circularity calculations is provided through the One-Click LCA online help center.

Two elemental building models, Model A and Model B (Figure 1) were designed at LOD 300 using the same dimensions according to the British Standards (BS 1192, 2018). Different materials were applied to the same geometrical components of the building. Model B used more concrete than Model A. The internal walls of Model B were applied with ready mix concrete, whereas Model A has timber wall panels. Also, precast concrete elements were used in Model B for slabs and external walls. The total area of the building is 324 m^2 (18 m x 18 m). The 3-story buildings have a total height of 9 m with a 3 m floor-to-floor spacing. The two design model options were used to perform life cycle assessments to investigate the amount of carbon these buildings emit from manufacturing to demolition. The total material quantities and the material compositions with the design options for Model A and Model B are summarized in Table 1 and Table 2, respectively. It is noted that parts of the ready-mix concrete are used in different locations and for different purposes in Model A and B. For example, Model A uses ready-mix concrete for flooring, while Model B uses pre-casted holly-core concrete slabs. Another slight difference is that Model B uses ready-mix concrete for interior walls but instead, Model A uses timber walls. Despite the differences, the total usage quantities of ready-mix concrete are almost equal in Model A and Model B, as shown in Table 1.

The electricity consumption for each building is set to 25 kWh/m^{2,} and the heating consumption to 68 kWh/m^2. The water consumption and wastewater are set to 25 m^3 per annum. It is noted that these values are not chosen according to specific real-world cases but are considered for comparison purposes only based on the average consumption of the household in the UK.



(a) (b)

Figure 1. Structural models for Model A (a) and Model B (b) using Tekla Structural Designer

The standard EN 15978:2011 is chosen in this study to specify the LCA framework in the built environment. It divides the life cycle of buildings and infrastructures into the product stage (A1-A3), construction stage (A4-A5), use stage (B1–B7), end-of-life stage (C1–C4), and benefits or loads beyond the system boundary (D) (British Standards Institution, 2011). The product stage (A1-A3) is represented as materials that include the impacts caused due to the extraction of raw materials, transportation and emissions that are caused due to manufacturing. The construction stage is divided into transportation to site (A4) and installation process (A5). A4 covers the effects of transporting materials from the production site to the construction site. A5 covers the impacts of energy and water consumption during the construction stage, material waste and other environmental implications. Use stage (B1-B7) includes the use phase (B1-B3), material replacement & refurbishment (B4-B5), energy use (B6) and water use (B7). B1-B3 covers the emissions from the use of materials. B4-B5 covers the replacements of entire construction elements bringing them back to their pre-existing performance levels. B6 includes the usage of both electricity and district heating. B7 includes the environmental consequences of water throughout the life cycle, including manufacturing, transportation, and wastewater treatment. End-of-life (C1-C4) covers the process of recyclable construction depending on the kind of material, impacts of pre-processing and landfilling for waste streams that cannot be recycled. Benefits or loads beyond system boundary (D) are about the external impacts, including the advantages and loads beyond the building's life cycle. It provides various environmental advantages from reusable, recycled and secondary materials.

During the use phase (B1-B3), carbon will be reduced. When exposed to air, materials such as concrete, cement, and mortar absorb carbon dioxide and reverse the calcination step during the cement manufacturing process. The amount of carbon absorbed is determined by the material exposure duration and the original amount of cement. During stage D, carbon emissions have been reduced again because of the environmental benefits of using reused and recycled materials.

Table 1. Total material quantities for the two design model options

Material choices	**Model A (units)**	**Model B (units)**		**Material Wastage (%)**	**Transport (km)**
Ready-mix Concrete (m^3)	455.7	456.0		4.0	60.0
Precast Concrete (m^3)	0.0	139.9		0	60.0
Timber (m^3)	194.4	0.0		17.9	130.0
Steel (ton)	35.5	18.2		4.9	110.0
Hollow-core concrete for slabs (m^2)	0	1296.0		0.0	60.0

Table 2. The material compositions of the two design model options

Component	**Dimensions**	**Materials used (Model A)**	**Materials Used (Model B)**
Slab	18 m x 18 m D = 0.15 m	Ready Mix Concrete C28/35, Cut & bent steel rebar (104.5 m^3)	Ready Mix Concrete C28/35, Cut & bent steel rebar (104.5 m^3)
Floorings	18 m x 18 m D = 0.15 m	Ready Mix Concrete C28/35, Cut & bent steel rebar (194.3 m^3)	Hollow-core concrete slabs C30/37 (1296 m^2)
Columns	0.8 m x 0.8 m H = 12 m	Ready Mix Concrete C40/50, Reinforcement steel for concrete (60 m^3)	Ready Mix Concrete C40/50, Reinforcement steel for concrete (60 m^3)
Beams	0.25 m x 0.5 m (internal) 0.45 m x 0.7 m (external)	Ready Mix Concrete C28/35, Carbon steel reinforcing bar (62.9 m^3)	Ready Mix Concrete C28/35, Carbon steel reinforcing bar (62.9 m^3)
Footings/Pad Bases	2.1 m x 2.1 m 2.44 m x 2.45m	Ready Mix Concrete C25/30, Reinforcement steel for concrete (34 m^3)	Ready Mix Concrete C25/30, Reinforcement steel for concrete (34 m^3)
Exterior Wall	9 m x 18 m T = 0.23 m	Insulated masonry wall with brick slips and aircrete block (298.1 m^2)	Precast concrete wall elements (139.9 m^3)
Interior Wall	9 m x 18 m T = 0.23 m	Timber wall – structural sawn timber panels (194.4 m^3)	Ready Mix concrete – low strength C12/15 (194.4 m^3)
Roof	18m x 18 m D = 100 mm	Roof panels with QuaCore hybrid insulation core (12.6 kg/m^2)	Roof panels with QuaCore hybrid insulation core (12.6 kg/m^2)

4 Findings

4.1 Comparing carbon emissions from two design model options

After performing the calculations using One-Click LCA, Model A showed a total carbon emission of 1461 Tons CO2e with an average of 71.15 kg CO2e/m2 per year. Model B showed a total carbon emission of 1533 Tons of CO2e with an average of 78.87 kg CO2e /m2 per year. The results represent the carbon emitted from the raw material stage to the building's end-of-life stage with an assumed lifespan of 60 years, covering carbon emission from the construction stage along with heat and electricity distribution systems.

Comparing all the life cycle stages in Model A, energy use has the highest carbon emission, followed by the raw material stage. However, in Model B, the raw material stage has the highest carbon emission when compared to the other life cycle stages. Table 3 shows the detailed comparison of embodied carbon emissions (Tons CO2e) from the two design model options when sourcing virgin materials (Stages A1-A3). During stages B4-B5 and C1-C4, Model B has emitted less carbon than Model A, attributed to the use of precast concrete panels. Model B used ready mix concrete and reinforcement steel for slabs, beams and columns and brick masonry for external walls, which requires less refurbishment during the use stage compared with timber materials. The precast elements can be easily reused, which is why Model B has less carbon emission during the C1-C4 stage. Whereas ready mix concrete needs to be crushed, and they can be recycled as additives or aggregates or for landfilling but cannot be reused as a direct material.

To compare the impact of design with reused materials for the two model options, reused materials were assigned to the models in One-Click LCA to reveal how much carbon can be reduced. It is noted that the CE concept of reuse in this study means the reuse of the product or component as is or through direct remanufacturing of materials without being recycled. The results from One-Click LCA show that approximately 31% of carbon was reduced for Model A, and nearly 35% of carbon was reduced for Model B in the total carbon emissions (operational plus embodied carbon emission). Confirming that using reused materials helps reduce carbon emissions due to various factors such as manufacturing, transportation, etc. As a result, it helps reduce total carbon emissions. The remaining carbon emissions are due to the building's operational use and end-of-life stages.

The recycling factors were applied for material settings in One-Click LCA to compare the impact of design with recycled materials for the two models. Materials such as concrete and steel were used as virgin materials mixed with recycled binders. For example, concrete was added with 50% of fly ash content or ground granulated blast-furnace slag (GGBS), and steel was produced from secondary scrap. Table 4 shows the details of recycled binders added to the materials along with the carbon emissions those materials produced.

By adding recycled binders to the virgin materials, around 6% of carbon was reduced for Model A, and 6.5% of carbon was reduced for Model B from the total carbon emissions. Another assessment was performed using the same but reused materials to reveal how much additional carbon can be reduced using the reused products along with recycled binders. Results show that a total of 33% of carbon was reduced for Model A, and 36% was reduced for Model B. The total carbon emission of Model A dropped to 991 Tons of CO2e with an average of 50.98 kg CO2e/m^2 per year. For Model B, the emission was reduced to 985 Tons of CO2e with an average of 50.65 kg CO2e/m^2 per year.

Table 3. Comparison of embodied carbon emissions (Tons CO2e) from the two design model options when sourcing virgin materials (Stages A1-A3)

Material choices (sourcing virgin materials)	**Model A**	**Model B**
Ready-Mix concrete		
C28/35	75	26
C40/50	48	48
C25/30	8.4	56
Steel Reinforcement		
Cut & Bent steel rebar	12	N.A
Reinforcement (Rebar)	10.1	10.1
Carbon steel reinforcement bar	4.9	4.9
Precast concrete		
Hollow-core concrete slabs	N.A	64
Concrete wall elements	N.A	47
Other construction materials		
Structural sawn timber	21	N.A
Emulsion for exterior masonry	0.23	N.A
Emulsion matt paint for outdoor	N.A	0.49
Anti-corrosive paints	0.31	0.31

Note: N.A indicates that the field is not applicable.

Table 4. Comparison of embodied carbon emissions (Tons CO2e) from the two design model options when sourcing recycled materials (Stages A1-A3)

Material choices (sourcing recycled materials)	**Model A**	**Model B**
Ready-Mix concrete (Adding 50% GGBS content)		
C28/35	40	14
C40/50	29	29
C25/30	4.7	32
Steel Reinforcement		
Cut & Bent steel rebar	12	N.A
Reinforcement (Rebar, 90% recycled content)	8.1	8.1
Carbon steel reinforcement bar (using secondary production, 97.07% recycled content)	5.2	5.2
Precast concrete (Added 40% recycled binders in cement)		
Hollow-core concrete slabs	N.A	53
Concrete wall elements	N.A	34

Note: N.A indicates that the field is not applicable.

4.2 Evaluation of material circularity

Building circularity is calculated through One-Click LCA based on the end-of-life process for each material. Throughout all the phases of the life cycle, the entire material flow will be treated utilizing the specified processing chain, which defines the implications for life cycle stages C & D. The reason for performing circularity assessment is to reveal the amount of material recovery and reuse capability after the building's end-of-life stage. The end-of-life process for each material was set before performing the circularity assessment for the building. For concrete, the end-of-life process was crushing concrete for aggregate usage in cement, or it can be used for landfilling for concrete blocks. Steel was recycled or reused as a direct material. Materials like emulsion and paints can be used as landfilling inert materials. Timber panels will be reused as material, or they can also be used for wood incineration or landfilling.

According to the embedded definition in One-Click LCA, material circularity refers to the percentages of materials quantities that could be "recovered" and "returned" at the building's end-of-life phase. The term "materials recovered" means the utilization of circular materials. It is indicated by the percentage of total materials used, made up of recycled, reused, and renewable materials. The term "materials returned" is represented by the end-of-life circular treatment of used materials. It is the total sum of recycled or utilized materials, together with 50% of materials downcycled or used as energy. Both materials returned and materials recovered are calculated based on the embedded default factors used for the project in One-Click LCA, such as material wastage on the construction site and other factors, including material replacement and refurbishment. The circularity score is the average of the sum of the materials recovered and the materials returned.

To illustrate the circularity score for both models, including the percentage for each CE path, the scenario with recycled materials sourced to replace virgin materials (Table 4) was used. The results are shown in Figure 2. Results show that 7.5% (5% + 2.5%) of the total quantities of materials could be recovered as is in Model A, and 69.5% (26.9% + 16.6% + 52%/2) of the total quantities could be returned either through reusing, recycling, or downcycling for other projects. The results are similar in Model B; however, its recovery rate is relatively lower than that in Model A, very likely due to the difficulties of recovering precast concrete than timber materials. Model A showed a building circularity of 39% (≈ (7.5% + 69.5)/2), and Model B showed a circularity of 37% (≈ (1.8% + 71.4%)/2). The results indicate that timber and metals (mainly timber and steel used in Model A) showed the highest circularity score, as they can be easily recycled or reused in contrast to concrete which usually needs to be crushed for recycling. This could also be the primary reason why concrete and other materials such as bricks and gypsum have the least percent of material recovery. Also, these materials have a high downcycling rate, which only indicates a single recycling process due to low quality.

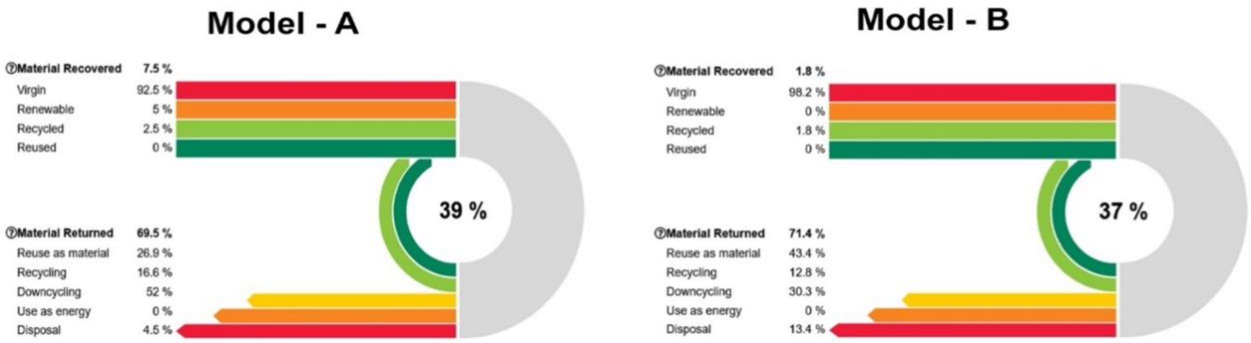


Figure 2. Circularity scores output from One-Click LCA

Behind these numbers, the implications of material choices are critical. Reused and recycled materials can reduce transportation, manufacturing, installation, other construction works, and waste disposals. When reused, precast concrete produced less carbon than ready mix concrete because the precast panels could be easily transported and reused directly without crushing them. As previously shown, adding recycled binders to virgin materials could reduce carbon emissions. Concrete added with fly ash or GGBS could be used as the recycled binder, and steel obtained from secondary scrap can be used for reinforcement.

5 Discussions

The circular economy concept has received significant attention to be restorative and regenerative and aims to keep products, components, and materials at their highest utility and value at all times. Using reused materials to replace virgin materials showed an apparent reduction of nearly 35% for both studied models. Model B showed higher carbon emissions when compared to Model A, whereas when using the reused materials, Model B showed an apparent reduction in carbon emissions compared to Model A. In addition, LCA has been performed for materials containing recycled binders or other recycled products. Recycling involves using a considerable amount of water and energy and the formation of carbon emissions, which may have a more significant environmental impact than reusing materials. The reuse of building components is a potential alternative for reducing construction and demolition waste. Many studies suggest that reused materials are considered environmentally and economically beneficial compared with recycled materials. This study also showed that reused materials entailed fewer carbon impacts than recycled materials because of less reprocessing efforts.

The use of precast elements opens up the possibility of designing the materials to be readily installed, deconstructed, and reused in the future. Materials such as ready-mix concrete can be crushed as aggregate by downcycling when demolished at their end-of-life stage. From the findings, the precast panels and timber walls have shown the highest reuse factor to reduce carbon emissions.

In addition, there are a few limitations of this study:

- Real-world examples and case studies could have been used; however, there is a lack of evidence of CE-oriented projects in the UK construction industry.
- The developed models targeted the concept designs. Similar studies should be carried out on more detailed model designs in the future.
- Evaluating the difference between the expected and actual service life of the entire building may impact the findings from the One-Click LCA analysis. Although a certain lifetime has been provided for each material in the study, however, in reality, this can be completely different.
- The factors of Design for Disassembly (DfD) and Design for Adaptability (DfA) in One-Click LCA may play a critical role in computing the circularity score, which should be studied further as part of the CE implementation.

Despite the limitations and potential barriers to implementing design for CE solutions in construction (such as difficulties of implementing new business models), the findings from this study indicate that design for material circularity and design with material circularity could help reduce carbon emissions in construction projects and therefore would have an impact to achieve the United Nations' Net Zero Carbon program targets.

6 Conclusions and future work

Circular economy in the built environment is an important solution to overcoming resource depletion and reducing environmental impact. Using a BIM-based LCA process, this study investigated two building design options by applying the recycled and reused materials to reveal how much carbon could be reduced using virgin materials.

Results showed that adaptive reuse of precast concrete and timber elements could reduce carbon emissions through reduced needs for transportation, energy usage and material manufacturing. Comparing the two model design options suggested that the secondary materials should be used to replace the virgin materials to reduce carbon emissions and increase the circularity of materials. Reusing materials could reduce more carbon emissions when compared to recycled materials. As expected, materials such as precast elements have a high reuse capability compared to cast-in-situ and ready-mix concrete.

The circularity score was calculated to reveal the percentage of materials recovered and materials returned. The results indicate that timber and metals (timber and steel in Model A) yield a high circularity score since they can be easily recycled or reused in contrast to concrete, which usually needs to be crushed for recycling. Maximizing the reuse of materials could be considered a major strategy for the designers to choose between material resources.

The carbon emissions factors used for the resources of the two models in this study were based on the average values of water usage, fuel consumption, district heating and cooling consumption, and exported energy for UK households. This study will be extended into a real-life project using specific real-world project values. Other environmental impacts such as acidification, ozone depletion, eutrophication, and other factors will be investigated in future research work.

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