End-of-life management strategies to mitigate the impacts of building components on climate change: a case study

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Abstract. The reduction of embodied carbon emissions in buildings has a significant impact on mitigating climate change. Current studies suggest that circular economy principles have the potential to reduce environmental impacts. Recycling and reuse of deconstructed building materials during the end of the useful lifespan of a building can help reduce carbon emissions. A process-based life cycle assessment was performed for the end-of-life phase of a steel frame and precast concrete supermarket building in the UK. The amount of potential carbon emissions reduction through the adoption of a specific end-of-life management strategy was quantified. The results indicate that reusing building components provides the greatest reduction of 72% compared to landfill, whilst recycling achieves a 41% reduction. Additionally, a comparison between reuse and recycling reveals a reduction of about 33%, indicating reuse should be considered a priority in minimising embodied carbon emissions of buildings.

Keywords: embodied carbon; end-of-life; circular economy; reuse; recycling; landfill; life cycle assessment

1. Introduction

The threat of global warming to human existence and economic well-being because of the increase in global mean temperature has been documented (Intergovernmental Panel on Climate Change (IPCC), 2021). The rise in carbon emissions is seen as the main cause of global warming. The building and construction sector is responsible for about 40% of the global emissions of greenhouse gases (GHG), uses up to 36% of the world's energy and natural resources, and accounts for approximately 50% of the solid waste sent to landfills (UN-Habitat, 2015; Hossain, Wu and Poon, 2017; GlobalABC, 2019). With the increasing recognition of climate change's impact, the built environment is under immense pressure to reduce its adverse environmental impacts. The end-of-life of the building is increasingly involved to enhance waste management and the adverse environmental impact of the built environment. The application of the life cycle assessment (LCA) has been successful in the built environment to help assess the effects of buildings on the environment and align towards solutions that are environmentally friendly (Ingrao et al., 2018; Hao et al., 2020; Roberts, Allen and Coley, 2020). As a best practice, an LCA focuses on the systematic evaluation and quantification of carbon emissions throughout the whole building's lifespan (RICS, 2017; Mendoza Beltran et al., 2018), however, a partial LCA can also be performed (Gibbon et al., 2022).

The concept of circular economy (CE) and deconstruction (design for disassembly) has been suggested as one of the best approaches to managing buildings' end-of-life and closing the material loops in the built environment (Akinade et al., 2017; Chau et al., 2017; Kirchherr, Reike and Hekkert, 2017). Yet, the conventional approach to disposing of building materials still dominates the construction sector (Guy, Shell and Esherick, 2006; Knoth, Fufa and Seilskjær, 2022).

Numerous advantages of CE and deconstruction are suggested in the literature. It can enhance material efficiency and reduce the consumption of raw materials along with carbon emissions, whilst diverting demolition waste from landfills (Akinade et al., 2017; Rakhshan et al., 2020). Furthermore, deconstruction and design for disassembly practices help useful building materials and components to fulfil their estimated useful service life by reintroducing them into the market value chain (Akbarieh et al., 2020). It also helps in minimising the burden of the landfill at the end of a building's useful life by making it possible for dismantled building elements and components to become feedstock thereby keeping them within the production process or cycle, and thus, ensuring the built environment becomes more circular and sustainable (Chini and Bruening, 2003; Ohms et al., 2019; Akbarieh et al., 2020). Additionally, with the application of suitable waste management methodologies for dismantled building materials, deconstruction can result in energy savings during the end-of-life stage (Begum et al., 2007; Chau et al., 2017).

Even though not specific to supermarkets, numerous studies have been widely published in recent years on the waste management strategies of buildings. For instance, Di Maria, Eyckmans and Van Acker (2018) conducted a detailed life cycle study to compare the environmental impact of landfilling and recycling building materials. The results show landfilling has the highest environmental impact while recycling after selective demolition reduced about 59% of the total environmental impacts. In China, Dong et al. (2018) calculated the energy saving and carbon reduction potential of recycling wastes, it was established that there were greater advantages to recycling waste steel and nonferrous metals of about 44% and 42% of energy saving, and 60% and 33% of carbon emission reduction, respectively. Brown and Buranakarn (2003) compared energy in materials to energy used to recycle them. Although focusing on energy saving only, Huysman et al. (2015), Kim and Song (2014) and Faraca, Tonini and Astrup (2019) have all carried out studies to determine the benefits of recycling materials from deconstruction, incineration of wastes arising from timber-based products and plastics to simulate energy production options and carbon reduction potentials. However, the principles of CE particularly reusing recovered construction materials were not considered by these studies.

Meanwhile, it has been established that the carbon emission of a building comprises operational and embodied carbon (Roberts, Allen and Coley, 2020). Previously, substantial attention has been focused on the reduction of operational carbon due to its higher proportion (Sturgis, 2017). Nevertheless, with the advancement in technology coupled with stringent building regulations for energy efficiency in building, the share of operational carbon emissions in the whole lifecycle emission of buildings in new projects is on the decline (Ajayi, Oyedele and Ilori, 2019; Röck et al., 2020). With the decreasing importance of operational carbon to the entire life cycle emissions of buildings, embodied carbon should accordingly become the main concern for reduction (Pomponi, De Wolf and Moncaster, 2018). Whilst there have been studies that highlight embodied carbon, most of these studies consider upfront emissions with few discussing end-of-life of buildings (Wu, Xia and Zhao, 2014). Besides not examining the reuse of recovered building materials, none of the above findings was related to supermarket buildings with sufficient application of precast concrete frames.

Therefore, this study aims to evaluate the embodied carbon emissions reduction arising from implementing different management strategies for a building's end-of-life for different building materials and components in a supermarket building and provide associated data through an actual project. Besides, it seeks to compare the benefits of reuse over recycling and landfill during the end-of-life of a building and identify the strategy that can provide the largest reduction in embodied carbon during deconstruction through the application of CE principles.

To realise the aim of this study the following research questions were pursued: (a) which end-of-life management strategy offers the greatest reduction in embodied carbon? (b) to what extent can the reduction be achieved?

It is believed that the results of this study could augment and enhance carbon emission research and guide the development of supermarket buildings to low carbon intensive, by including the end-of-life stage. This can help designers and engineers fully understand whole-life embodied carbon and make informed decisions by adopting reduction strategies at an early stage of the project. The quantification of the end-of-life embodied carbon is underpinned by the principles of LCA.

2. literature review

2.1 Building end-of-life and Circular Economy

The end-of-life of a building refers to the period in which the building is in its final phase of service life. As buildings approach their end-of-life the material stock and as-sociated embodied carbon will be released, and therefore, it is crucial to select appropriate strategies to manage different materials and components (Akbarnezhad and Xiao, 2017; Chau et al., 2017). Addressing the challenge of minimising carbon emissions, CE and deconstruction frameworks offered hope (Blomsma and Brennan, 2017; Stephan and Athanassiadis, 2018; Ghaffar, Burman and Braimah, 2020). These frameworks progressively seek to extend building material life through the promotion of material efficiency. Building materials maintain their value since built assets act as banks of valuable materials and products. Regarding end-of-life management strategies, there have been some vital developments within CE and de-construction packages, such as reuse and recycle (European Commission, 2020; Ghaffar, Burman and Braimah, 2020). Meanwhile, de-construction requires design for disassembly measures to allow the durability and adaptability of built assets in conformity with the CE principles. This is crucial not only in terms of reducing the sector's waste but also the amount of virgin raw material used, and the associated carbon emissions. Consequently, the linear economy model and its end-of-life perception need to change to reusing and recycling building materials in production as well as consumption processes (Kabirifar et al., 2020).

2.2 Reusing and recycling

Reuse in construction mainly refers to the process of using recovered building components or materials for the same purpose or to satisfy a similar application or a new function (Huang et al., 2018). In general, reuse involves minimal treatment prior to reapplication in a similar function. On the other hand, recycling is the process of converting or breaking down recovered building materials to make a new homogeneous material (Kabirifar et al., 2020). Unlike reuse, recycling results in a lesser value material for re-application or as re-placement feedstock for the reproduction of components (Blengini and Garbarino, 2010; Hahladakis, Purnell and Aljabri, 2020). Notwithstanding, according to Ghaffar, Burman and Braimah (2020), the knowledge and experience on the reuse opportunities of building materials within the construction sector are very limited. Therefore, this paper intends to

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promote reuse and recycling as end-of-life management strategies, which can be crucial towards transitioning the sector to a more circularity by linking design to end-of-life management where output flows can be re-integrated as secondary raw material.

2.2 Life cycle assessment of building

The whole lifecycle of building materials is usually divided into five phases, from raw material extraction to final disposal as illustrated in Figure 1.

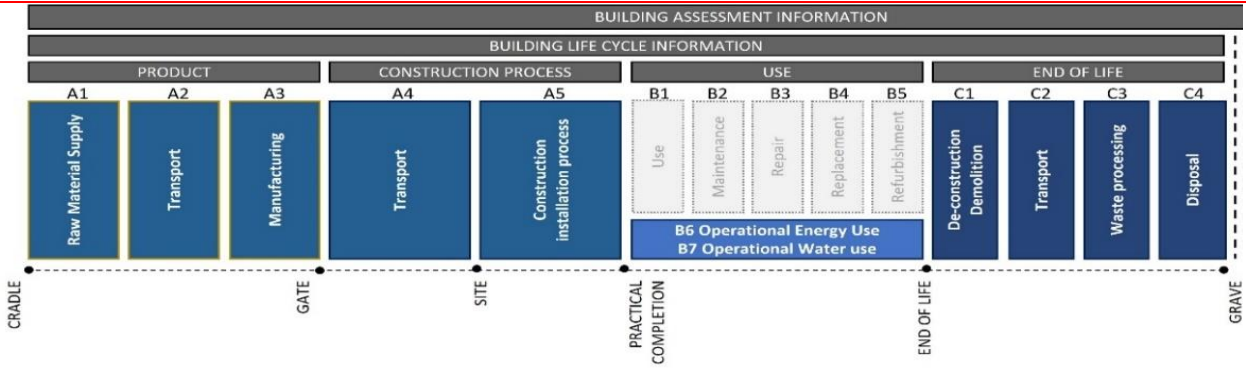

Figure 1: Life cycle phases reproduced from (BS EN 15978:2011, 2012)

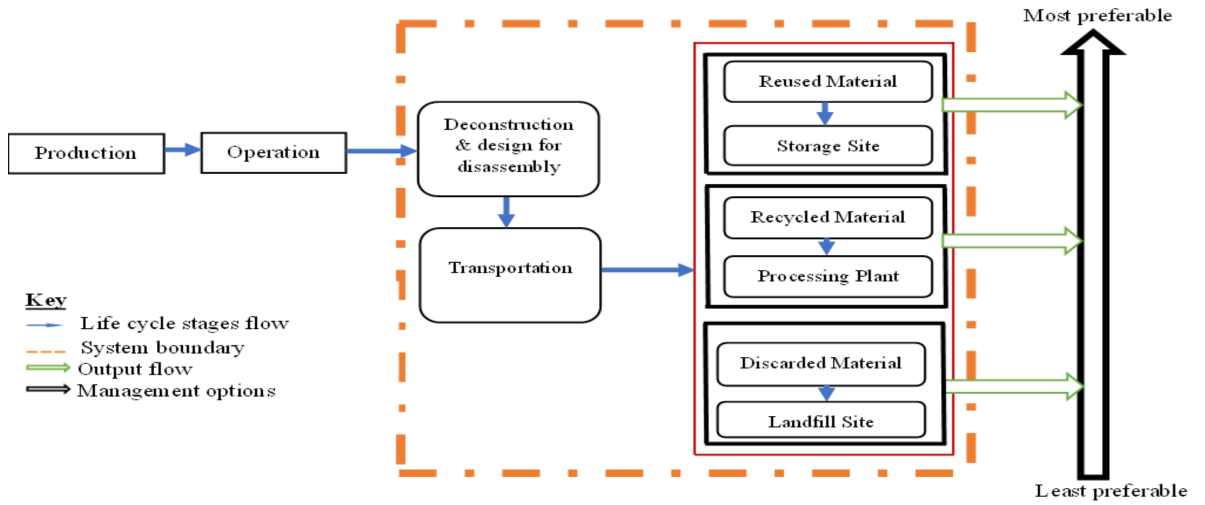

Figure 2: Life cycle assessment phase and flow of material of the study

The first phase also referred to as 'cradle-to-gate' comprises the extraction of raw materials for their manufacturing. The second phase termed 'cradle-to-site' coincides with the transportation of construction materials from the manufacturing point to the building site. The third is also known as 'cradle-to-completion' and corresponds to the construction and installation processes. The fourth phase is the 'use' of the building over the entire useful lifespan, while the fifth phase correlates with the end-of-life management of building materials. A system boundary that involves all five phases is termed 'cradle-to-grave.' However, embodied carbon may be considered using any of the life cycle phases (Akbarnezhad and Xiao, 2017; Gibbon et al., 2022). Accordingly, the system boundary of this study is end-of-life as illustrated in figure 2.

2.2.1 Goal and scope definition

The goal of this study is to calculate the potential carbon emissions reduction of a supermarket building by adopting the principles of CE along with deconstruction and design for disassembly. A comparison is then made between reuse and recycle on one hand and landfill the traditional disposal of building material on the other. The scope only consists of carbon emissions related to building deconstruction, transportation of building materials from the deconstruction site to the storage site for future reuse, transportation to a recycling plant and disposal site.

2.2.2 Functional unit

The functional unit states the function of the analysed materials and is used in LCAs as the foundation for estimating the quantities of materials under consideration (Minunno et al., 2020). The functional unit of this study is 2500 m^2 consisting of the whole building as shown in Figure 3.

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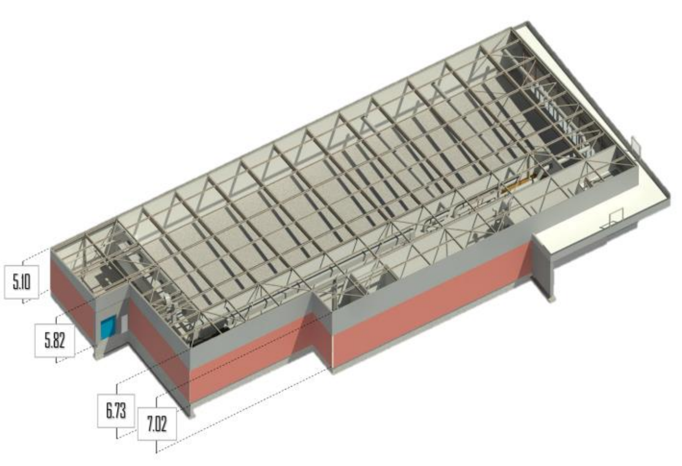

Figure 3: simulated case building

3. Methodology

The strategy developed to minimise the environmental impact of building waste includes the 3Rs (reduce, reuse and recycle) (Ding, 2018). Hence, the 3Rs can be deemed as a hierarchy of best practices for achieving carbon reduction. The emphasis of this study is the application of reuse and recycling practices. It investigates the unexplored area of reusing building materials and components and applies an LCA to a real supermarket building. Comparisons are made between reuse, recycling and landfill to determine which strategy produces greater carbon emission reduction.

3.1 Embodied carbon calculation

A process-based LCA method is adopted in this study due to its strength to reveal carbon emissions from the specific construction process, along with its accuracy and detailed processes (Suh and Huppes, 2005; Zhu et al., 2020; Liu and Leng, 2022). The rationale of this method is straightforward and clear, carbon emissions from individual activities can be estimated and analysed separately (Liu and Leng, 2022). Process-based is frequently adopted to identify and calculate the carbon emissions of construction processes (Luo et al., 2019; Zhang et al., 2019; Liu and Leng, 2022). It describes the estimation of carbon emissions by multiplying the quantity of the product with the corresponding emission coefficient. Accordingly, the embodied carbon for each material quantity herein can be calculated by the formula (1):

$$\text{Embodied carbon } (EC_u) = \textstyle\sum_u (Q_{mat,u} \times ECF_u) \qquad (1)$$

The amount of end-of-life carbon emission is estimated by the sum of emissions of each subdivision as shown in equation (2):

$$EC_{eol} = EC_1 + EC_2 + EC_3 + EC_4 \qquad (2)$$

Carbon emission related to deconstruction, transportation, processing and disposal is estimated by equations (3) to (6):

ECC1=∑u (Accordingly, the embodied carbon for each material quantity herein can be calculated by the formula (3):

$$\text{Embodied carbon } (EC_u) = \textstyle\sum_u (Qmat_{,u} \times ECF_u)\times EC_{mach,u}) + \sum v\, (Q_{ene,v} \times ECF_{ene,v}) \qquad (3)$$

$$EC_{C2} = \textstyle\sum w (Q_{trans,w} \times ECF_{C2,w}) \qquad (4)$$

$$EC_{C3} = \textstyle\sum y (Q_{comp,y} \times ECF_{C3,y}) \qquad (5)$$

$$EC_{C4} = \textstyle\sum z (Q_{disp,z} \times ECF_{C4,z}) \qquad (6)$$

where u refers to the type of machinery, v refers to the type of energy, w, y, and z refer to the type of material in subdivisions [C2], [C3], and [C4], respectively. EC_{C1} represents the carbon emissions associated with machinery used and energy consumed for deconstruction. EC_{C2} is the emission associated with the transportation of deconstructed materials while EC_{C3} and EC_{C4} represent emissions associated with building component processing and disposal respectively.

To enable effective comparison, it is assumed that building materials and components are either maximum reused, recycled or landfilled. Table 1 displays the end-of-life management scenarios considered in this study.

Table 1: End-of-life management scenarios

Strategy	Reuse [C1 + C2]	Recycle [C1+C2 +C3]	Landfill [C1+C2 + C4]

Consequently, the benefits of CE principles of reuse over recycling and landfill during the end-of-life are calculated by equations (7) to (9):

$$ECRP_{land} = \textstyle\sum u\, (EC_{C4} + EC_{C2} + EC_{C1}) - (EC_{C1} + EC_{C2}) \qquad (7)$$

$$ECRP_{rec} = \textstyle\sum u\, (EC_{C3} + EC_{C2} + EC_{C1}) - (EC_{C1} + EC_{C2}) \qquad (8)$$

$$ECRP_{use} = \textstyle\sum u\, (EC_{C1} + EC_{C2}) - (EC_{C1} + EC_{C2} + EC_{C3}) \qquad (9)$$

where $ECRP_{land}$, $ECRP_{rec}$ and $ECRP_{use}$ refer to the embodied carbon reduction potential of landfilling, recycling and reusing building components or materials, while ($EC_{C4} + EC_{C2} + EC_{C1}$), ($EC_{C3} + EC_{C2} + EC_{C1}$) and ($EC_{C1} + EC_{C2}$) represent emissions associated with landfill, recycling and reuse respectively.

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3.2 Case study building

A case study is acknowledged to be desirable in investigating complex research particularly, where there is a lack of data available to understand the effect of carbon emissions from building materials and components (Ding, 2018). The current case building is a single-storey supermarket structure in the UK (Figure 3). The total construction area of the building is approximately 2500 m^2 with a height of 7.02m which reduces to 5.10m in front and back elevations respectively. The building comprises steel columns and beams structural frame, cladding panel external walls and a concrete slab foundation. The internal wall finishes consist of paint to plasterboard. The floor coverings are ceramic tiles, vinyl, and paint. The windows are glazed and aluminium-framed with steel external doors.

3.2.1 Acquisition and determination of building materials and data sources

In this study, Autodesk® Revit® BIM software was used to aid the end-of-life assessment. The main building materials used in the estimation of embodied carbon are displayed in Table 2 along with their adjusted embodied carbon factors (ECFs). It should be noted that the adjusted ECFs are for the worst-case scenario considered in this study.

Table 2: Main building materials and embodied carbon factors

Material Type	Adjusted ECF
Aluminium	13.2[c]
Bricks	1.28[c]
Ceiling tiles	5.64[c]
Concrete	3.42[b]
Floor tiles	26.10[a]
Glass	4.32c
Insulated Roof	11.44[a]
Paint	0.01[c]
Plasterboard	0.12[c]
Plastics	7.59[c]
Mineral wool	10.89[c]
Steel	5.67[c]
Timber	2.15[b]
Vinyl	7.59[c]

[a]- EPD
[b]- RICS
[c]- Literature

The material quantities necessary to calculate the embodied carbon were derived through the simulation. The main building materials are therefore grouped into different categories as shown in Table 3 (RICS, 2017; Carbon Leadership Forum, 2018).

Table 3: Material quantities

Category	Material Quantity (kg)
Ceiling	5,971.23
Doors	971.37
Floors	484,360.93
Roofs	56,585.31
Framing	89,894.55
Foundation	1,029,571.93
Walls	359,107.78
Windows	9,465.25
MEP*	4,584.95
Total	**2,040,513.31**

*(Mechanical, Electrical and Plumbing)

On the other hand, the accuracy of calculation results is affected by the reliability of carbon emission factors. Although most of the building materials are produced in the UK, there is a lack of a database that has comprehensive carbon emission factors for end-of-life (Blay-Armah et al., 2022). A more careful selection of carbon factors enhances the authenticity of the assessment results (Ge, Luo and Lu, 2017). Therefore, in this study, the first preference or choice of carbon emission factors for individual building materials is obtained from the manufacturer's environmental product declaration (EPD). Where there is no EPD for a material, carbon emission factors are sought from localised national databases (Ge, Luo and Lu, 2017). Finally, the literature is considered a last resort if the carbon emission factor cannot be obtained from the first two preferences. Deconstruction materials and components were assumed to be transported to a storage site, recycled plant and landfill site by heavy-duty, fully laden diesel wagon. The related transportation emission is 0.07524gCO_2e/kg/km and an average default transport distance of 50 km is assumed for all management strategies or scenarios (RICS, 2017; Gibbon et al., 2022). It is further assumed that the emission associated with deconstructing the entire structure is 3.4kgCO_2e/m^2. In accordance with the chosen supermarket practice, the average service lifespan of the building is assumed to be 20 years.

4. Results and Discussions

Three end-of-life management scenarios (landfill, recycling and reuse) were simulated within the parameters of the study (see Figures 1-3). The embodied carbon emissions of all three scenarios were calculated using the process-based method. The results for each management scenario are presented in table 4.

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Table 4: Total carbon emissions of each end-of-life management scenario

Category	Landfill ($kgCO_2e$)	Recycle ($kgCO_2e$)	Reuse ($kgCO_2e$)
Ceiling	253.90	208.48	170.81
Doors & Windows	38,643.07	8,857.18	5,372.87
Floors	11,071.07	9,518.66	9,484.19
Roofs	95,413.62	29,237.82	14,049.07
Framing	20,190.75	10,502.68	7069.67
Foundation	8,045.41	8,045.41	8,045.41
Walls	37734.10	18,298.05	12,978.42
MEP	22,171.35	11,432.00	7,695.23
Total	**233,523.27**	**96,100.29**	**64,865.67**

4.1 Landfill

As shown in table 4, the landfill scenario simulated the worse possible end-of-life treatment for deconstructed building materials and components. This strategy accounted for a total of about 233,523.27 kgCO2e embodied carbon emissions. In terms of the proportion of building components to the total embodied carbon emissions of this scenario, figure 4 shows that the top three were roofs (40.89%), doors and windows (17%) and walls (16%).

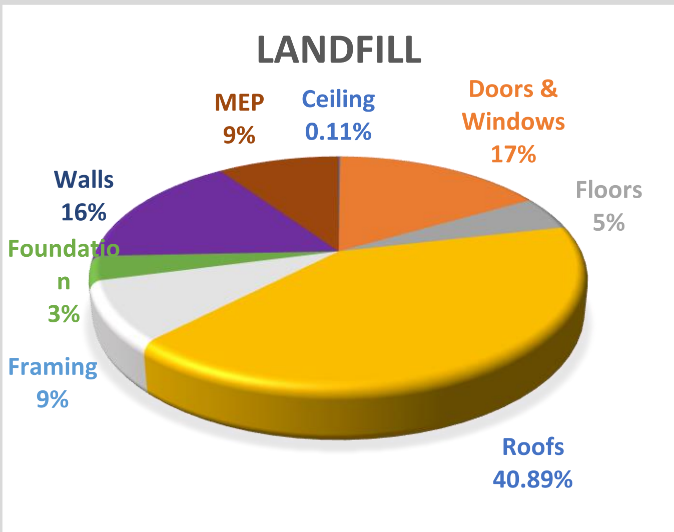

Fig. 4: Proportion of each building component to the total landfill carbon emissions

4.2 Recycling

From Table 4, the results obtained from the primary carbon emission analysis show that the recycled scenario was the second-greatest carbon emissions reduction end-of-life strategy, with a total of 96,100.29 $kgCO_2e$. Similar to the landfilled scenario, the roof contributed the highest in terms of building components, accounting for up to 31% of the total embodied carbon emissions under this scenario. This was followed by the wall which contributed about 19% of the total emission as displayed in figure 5.

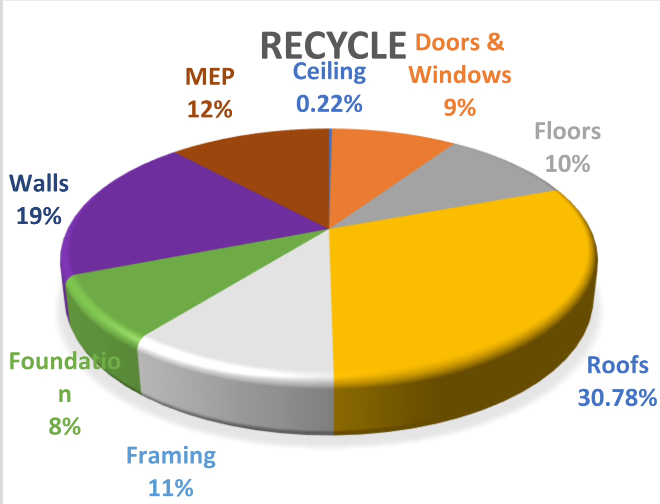

Fig. 5: Proportion of each building component to the total recycled carbon emissions

4.3 Reuse

The analysis of the third scenario was carried out by calculating the equivalent emissions from reusing the building components. The reuse scenario simulation presents the best possible end-of-life strategy in which all deconstructed building materials were assumed to be reused in future projects to satisfy similar applications or a new function. The embodied carbon emissions of this strategy amounted to 64,835.07 $kgCO_2e$.

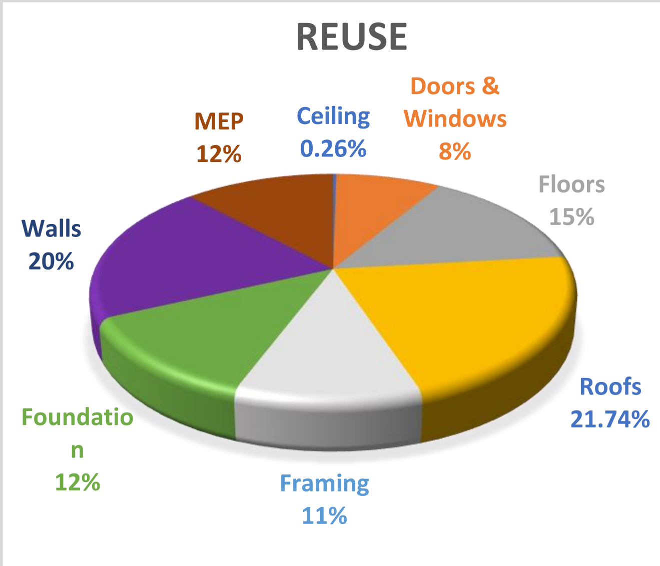

Fig. 6: Proportion of each building component to the total reuse carbon emissions

The carbon emissions of the main building components at the end of life were calculated with the roof representing about 21.74% of the total emissions as indicated in figure 6. This was followed by wall and floor contributing 20% and 15% respectively.

One main observation can be drawn from Figures 4-6 and Table 4. The carbon emissions of different building components vary considerably and are affected by factors such as carbon intensity unit and coefficient. As can be seen, the roof consistently contributed the highest carbon emission in all scenarios. This can be attributed to the fact that steel and aluminium are two materials that made up the roofs, which require much more energy in their production, and thus, high carbon intensive materials. More importantly, the manufacturer's EPD was used in the calculation as compared to national averages and literature.

4.4 Comparison of management strategies

To explore what can be realised through the application of CE principles to the case study, the conventional buildings' end-of-life management (landfilling) and the CE 2Rs (reuse and recycle) were compared. For a fair, judicious comparison, landfill (scenario 1) was used as the baseline strategy. The results are discussed below.

4.4.1 Landfill vs recycle

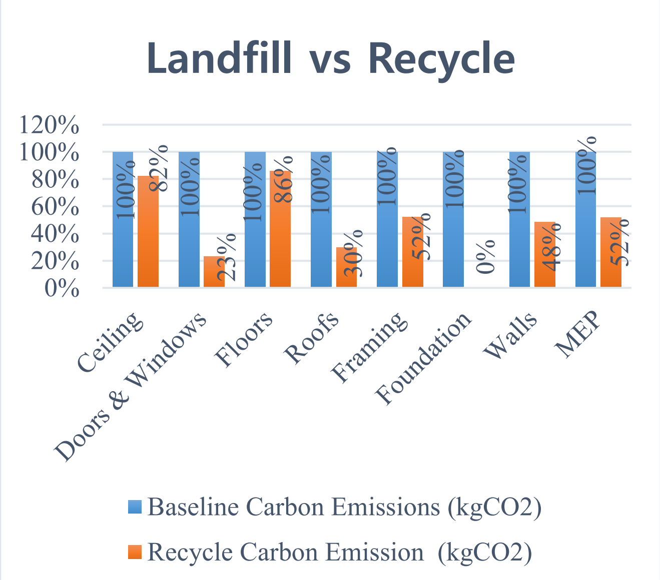

Fig. 7: Embodied carbon reduction potential of landfill vs recycle

Figure 7 shows the carbon emissions reduction potential of recycling the building components and materials in comparison to traditional landfilling during end-of-life. At the end of its service lifespan, the building is assumed to be dismantled, and its components recycled or landfilled. The reduction potential can be deduced by calculating the difference between landfill and recycling. The overall impact of carbon emission from recycling is 96,100.29 $kgCO_2e$ versus 233,523.27 $kgCO_2e$ emitted by the landfill.

The carbon reduction potential of CE and deconstruction because of recycling is apparent from this comparative LCA. The avoidance of landfilling resulted in a reduction in embodied carbon emissions of up to 41%. Indeed, figure 7 shows that across all considered categories it is possible to reduce carbon emission by at least 14% except for foundation if CE principles are adopted.

4.4.2 Landfill vs reuse

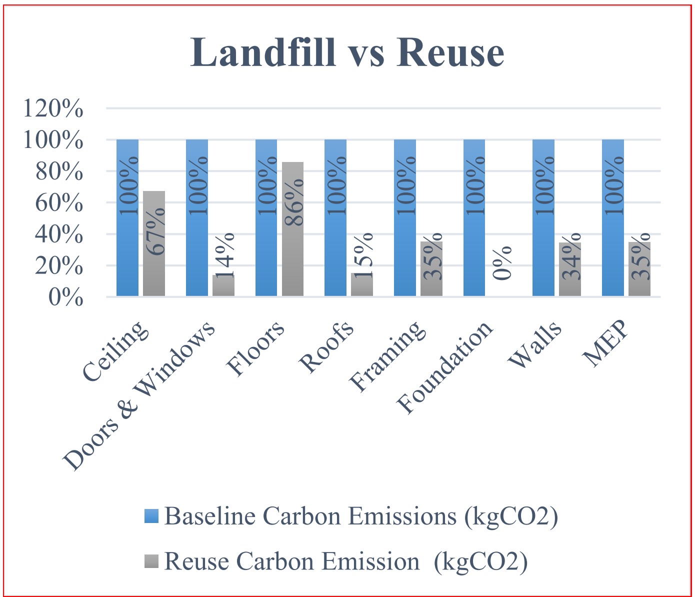

Fig. 8: Embodied carbon reduction potential of landfill vs reuse

Figure 8 displays the carbon emissions reduction potential due to the adoption of the CE end-of-life management strategy of reuse. Adopting reuse instead of landfill results in a potential reduction of 168,657.60 $kgCO_2e$ from 233,523.27 $kgCO_2e$ (see table 3). In total, reusing the building components allows a reduction of about 72% in terms of embodied carbon emissions at the end of the building service life, when compared with the landfill approach of end-of-life treatment.

4.4.2 Recycle vs reuse

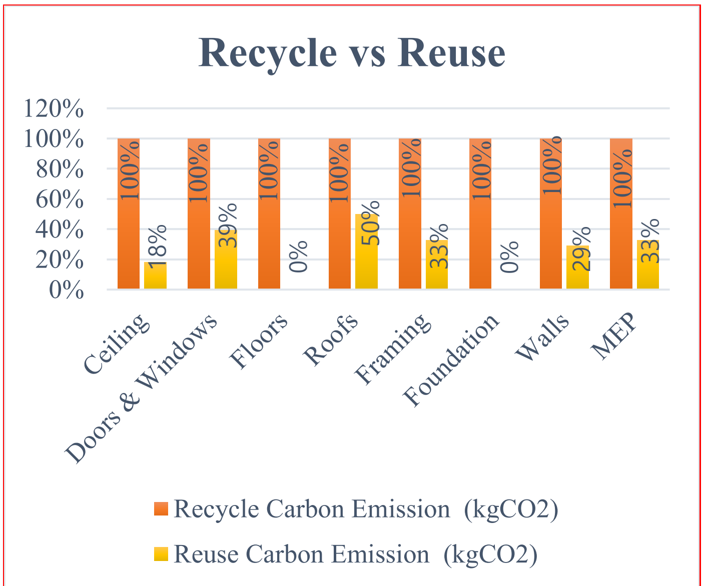

Fig. 9: Embodied carbon reduction potential of recycling vs reuse

The end-of-life carbon emissions attributed to recycling and reuse are presented in figure 9. By comparing the two strategies, it is possible to evaluate and separate the

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potential emissions reduction of recycling and reuse of building components resulting from the adoption of CE and deconstruction. The total impact of carbon emission of reuse is 64,835.07 kgCO_2e whilst 96, 100.29 kgCO_2e are emitted by the recycling strategy. From figure 9, it can be seen that across all considered categories it is possible to reduce carbon emission by at least 48% except for floor and foundation if reuse is adopted instead of recycling. This can be attributed to the fact that concrete which is the major material for both floor and foundation is assumed to only recycle in this study. The carbon reduction potential of CE and deconstruction as a result of reuse is evident from this comparative LCA. Resorting to reuse as the main end-of-life management strategy rather than recycling resulted in a further reduction of up to a third (33%) in embodied carbon emission.

The analysis showed that reusing building components where possible is the best end-of-life strategy. This is because the components are used as a whole or part for the same function or purpose as opposed to disposal to landfill. This strategy not only preserves raw materials but also reduces the adverse environmental impact as well as the cost of disposing of waste (Mália et al., 2013). On the other hand, the landfill scenario was the worse end-of-life treatment strategy. This is because this strategy offers no opportunity to extend the life of building materials after the deconstruction or demolition. Additionally, when building components or materials are landfilled, embodied carbon can be considered emitted as the replacements may be virgin or new materials (Ding, 2018). The findings are also reflected in previous studies conducted by Blengini and Di Carlo (2010), Gálvez-Martos et al. (2018), Hahladakis, Purnell and Aljabri (2020) and Kabirifar et al., (2020) who found that the greater environmental benefits come from reusing building components or materials not only in terms of helping to reduce the use of virgin materials but also a potential reduction in operating costs and carbon emissions.

However, the reuse strategy requires rethinking the design to maximise the potential of components or material recovery at the end-of-life (Tingley and Davison, 2015; Rakhshan, et al., 2020). Life cycle thinking also plays a crucial role in enabling component reuse. Hence, end-of-life treatment should be an integral part of planning and designing the building.

5. Conclusions

In this paper, the aim was to assess the embodied carbon emissions reduction potential arising from implementing different management strategies for a building's end-of-life. This research has successfully quantified the potential embodied carbon emissions reduction that can be realised through the implementation of different end-of-life management strategies for a typical steel frame and precast concrete supermarket building in the UK. The findings of the study indicated that a significant amount of reduction in the entire embodied carbon emissions could be realised if an appropriate end-of-life management strategy was adopted. This study has found that generally, maximum reuse and maximum recycle scenarios could provide the greatest carbon emissions reduction, whereas maximum landfill could result in high carbon emissions. The relevance of deconstruction and reuse is supported by the current findings. The findings from the study showed that adopting the CE principles of design for disassembly and reuse is the most effective strategy to reduce embodied carbon emissions. Increasing the adoption of reusing building components and materials could result in a 72% reduction in carbon emissions, while recycling could achieve a 41% emission reduction. The potential reduction rate between the two strategies was about 33%. Accordingly, a reasonable approach to tackle embodied carbon minimisation during the building's end-of-life could be to reuse building materials and components. Consequently, more attention should be given to deconstruction and design for disassembly during the planning phase of the project.

Given that, globally, there are different recovery rates for construction materials, the generalisability of these results should proceed with caution. For instance, the UK has recovery rates of over 90% for most construction materials, and thus, the study assumed maximum reuse, recycling or landfilling. Therefore, the carbon reduction potential estimations provided in this research for the end-of-life management strategies must be interpreted as the maximum possible values. Additionally, the choice of end-of-life management strategies is influenced by various factors including current government legislation on waste management and the level of technological advancement in treating waste materials.

Notwithstanding, the results from this study make several contributions to the current knowledge. First and foremost, it can serve as a guide for designers, engineers, policymakers and other stakeholders to the best end-of-life management practices by facilitating decision-making regarding optimal end-of-life strategy in terms of carbon emission minimisation. This can allow not only the inclusion of CE principles of design for disassembly and deconstruction at the initial phase of the project but also encourage the reuse and recycling of construction materials. In addition, the findings of this investigation can be considered as the scientific basis for developing effective and efficient strategies for prolonging the building materials thereby maintaining building components in the material loop. This can help in reducing carbon emissions of the built environment and mitigating climate change. Furthermore, the assessment approach can provide theoretical and methodological guidance for analysing the environmental impact of similar types of civil construction projects around the globe. The CE practice of reuse to optimise carbon reduction worth promoting and should be considered a priority in minimising embodied carbon emissions of buildings. Thus, the contribution of this paper is considerable – providing real data on embodied carbon in the context of supermarket buildings.

Although this study evaluated the potential embodied carbon emissions reduction of reusing building materials, it did not consider the whole embodied carbon life cycle phases. Further experimental investigations are, therefore, needed to determine the whole life cycle and fully understand the implications of CE principles of design for disassembly and deconstruction.

Acknowledgments

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