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Blay-Armah, Augustine, Bahadori-Jahromi, Ali ORCID: https://orcid.org/0000-0003-0405-7146, Mylona, Anastasia and Barthorpe, Mark (2024) A life cycle assessmen of building demolition waste: a comparison study. Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 177 (3). pp. 100-113. ISSN 1747-6526

http://dx.doi.org/10.1680/jwarm.22.00012

Cite this article
Blay-Armah A, Bahadori-Jahromi A, Mylona A and Barthorpe M
A life cycle assessment of building demolition waste: a comparison study.
Proceedings of the Institution of Civil Engineers – Waste and Resource Management,
https://doi.org/10.1680/jwarm.22.00012

Research Article
Paper 2200012
Received 09/05/2022;
Accepted 26/10/2023;
First published online 24/11/2023

Waste and Resource Management

A life cycle assessment of building demolition waste: a comparison study

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Globally, building demolition waste constitutes a considerable environmental problem. The environmental implications are not only associated with volume but also with carbon embodied in the waste. These adverse environmental impacts associated with the generated waste can be minimised through appropriate waste management strategies. This study proposed a mathematical model from the end-of-life perspective to examine two waste treatment methods. The model was illustrated by a case study of three approved building construction systems by a current UK supermarket referred to as construction methods CM1, CM2 and CM3 to assess the construction system with the least carbon dioxide emission. Landfilling and recycling were assumed as waste treatment methods to examine the preferable waste treatment method. Results showed that recycling is the most preferred method of waste treatment method of the supermarket. This was revealed by the amount of demolition waste material recycled (more than 90%) from each of the CM compared with the volume of waste materials landfilled (<10%) and the associated carbon dioxide emissions. Steel has the highest carbon reduction potential contributing ~80% in each case study compared with concrete ~1%. Finally, CM1 has the lowest carbon dioxide emission, with both CM2 and CM3 emitting ~3% more.

Keywords: life cycle assessment/waste materials

Notation

A	total carbon dioxide emission of the building compared with the baseline building
B	total carbon dioxide emission of the baseline building
CEFw	carbon dioxide emission factor of waste material
*Dem	carbon dioxide emission associated with the machine during demolition
EC_{equip}	carbon dioxide emission associated with plant
EC_{rec}	carbon dioxide emission from the recycling plant
$EC_{tot,landfill}$	total carbon dioxide emission from landfilling waste material
$EC_{tot,recycling}$	total carbon dioxide emission from recycling waste material
EC_{transp}	carbon dioxide emission linked to distance covered by truck
$EQEC_i$	carbon intensity per unit consumption of fuel
EQF_i	energy consumption by the demolition plant
EQ_i	number of hours plant/equipment (hour)
P	proportion of carbon dioxide emission from a construction method to the baseline building's total carbon dioxide emission
Qw	quantity of waste material being processed
TD_i	total distance
$TECF_i$	carbon dioxide emission coefficient per fuel unit used
$TECF_r$	carbon dioxide emission coefficient per fuel unit used
TF_i	fuel used per load of a truck
TF_r	fuel used per return journey
TL_i	number of loads of trucks
TL_r	number of the return journey to the demolition site

1. Introduction

It is generally recognised that the building sector considerably impacts the environment. The sector is responsible for 36% of global energy consumption, up to 40% of all raw materials, and accounts for almost 40% of embodied carbon dioxide emissions [Hossain *et al.*, 2017; United Nations Environmental Programme (UNEP, 2021)]. The industry is also responsible for ~50% of the solid waste sent to landfills (Crowther, 2018). In the European Union (EU), construction and demolition waste (C&DW) generation forms ~20–30% of the total solid waste (Ding, 2018). Waste statistics compiled by Defra (2018) indicate that in 2016, 63% of the total waste stream in England (189 Mt) was attributed to construction, demolition and excavation waste. Of this figure, an estimated 50% was attributed to C&DW. Due to waste production's major impact on the environment worldwide, it has been labelled by the EU as a priority for its members to reduce it (Gálvez-Martos *et al*., 2018). Additionally, the 'Global Status Report for Buildings and Construction Sector' (UNEP, 2021) acknowledged that embodied carbon dioxide emissions will continue to rise unless a concerted effort is taken to mitigate the emissions. Thus, even though the sector contributes immensely to the creation of national wealth and growth globally, its impact on the climate cannot be ignored. Reducing embodied carbon dioxide emissions within the building sector is, therefore, a fundamental feature of mitigating climate change.

Besides, effective and efficient building demolition waste management is essential in a sustainable building sector. Globally, landfilling has been the main method of disposing of demolition waste (Ding, 2018). However, if wastes are untreated and illegally dumped in open spaces and waterways can lead to environmental problems including land depletion and deterioration, freshwater pollution and global warming through carbon dioxide emissions (Swarna *et al*., 2022; Yeheyis *et al*., 2013). Furthermore, the depletion of natural resources (Kolaventi *et al*., 2018) requires the implementation of effective waste management during the end-of-life of buildings to prevent waste generation, while turning waste into resources (Zhang *et al*., 2022). For instance, Wang *et al*. (2022) observe that in China, ∼0.3 t of construction waste is produced per square meter of a building during the construction phase, while ∼1.3 t is generated per square meter of a building at the end-of-life phase. Consequently, the management of demolition waste generated due to end-of-life activities is crucial in C&DW management.

However, the beneficial impact of recycling C&DW is significant when it is compared with the landfill approach (Huang *et al*., 2018). For example, in connection with global warming potential, Ortiz *et al*. (2010) and Marzouk and Azab (2014) assessed three different scenarios (landfilling, incineration and recycling) and observed that the most sustainable way of treating C&DW is recycling due to its ability to make the most of the resources that have already been extracted, followed by incineration and the least preferred is landfilling. Similarly, Wu *et al*. (2016) explored the impact of C&DW treatment using two scenarios – landfilling and recycling using private or state-owned facilities. The authors concluded that more priority should be given to state-owned recycling centres due to their positive environmental impact. On the contrary, other researchers have attempted to give suggestions for improving C&DW reuse and recycling. In China, Duan and Li (2016) recommended that greater emphasis should be put on enhancing the waste management of concrete, masonry, mortar and ceramic waste, because these four types of C&DW account for ∼90% of the volume of the country's C&DW while having the greatest potential for recycling. Huang *et al*. (2018) revealed that C&DW recycling is currently limited to certain materials such as concrete brick. In Portugal, for instance, Coelho and de Brito (2013a, 2013b) assessed the energy consumption and carbon dioxide emissions of recycling C&DW. The authors found that recycling demolished waste materials could provide environmental benefits of at least a factor of three due to the potential to substitute virgin resources. Similarly, in a study to develop a model to evaluate the cradle-to-grave environmental impacts of a building in Italy, Blengini (2009) discovered that recycling steel and aggregate can lead to a reduction of up to 18% in carbon dioxide emissions and 29% in energy consumption. Although the aforementioned reviews consider the environmental benefits of recycling due to the substitution effects of raw materials, some demolition waste materials with great environmental performance have not been considered. In addition, the assessments in these studies are based on a single demolition project.

To fill this knowledge gap, this study proposes a mathematical model for carbon dioxide emissions quantification from the end-of-life perspective. The model is illustrated by a case study of three approved building construction systems by a current UK supermarket to evaluate the construction system that generates the lowest carbon dioxide emission. Two waste treatment approaches were considered to assess the environmental impact of demolition waste materials on carbon dioxide emission reduction. Autodesk® Revit® BIM software was used in modelling the buildings in the case study to aid the end-of-life assessment. This paper contributes to the quantification and reduction of carbon dioxide emissions of buildings by clearly addressing the following questions: 'What is the preferred method of waste treatment by the supermarket?' 'Which recycled waste material has the greatest substitution effects on raw materials?' 'Which construction method generates the least carbon dioxide emission and to what extent?' Comprehensive and detailed analyses were performed to better understand the research trends and knowledge gaps in this discipline.

2. Literature review

2.1 Life-cycle assessment

The growing awareness to mitigate climate change has resulted in the need to assess the demolished waste of buildings and the carbon embodied in them. The life-cycle assessment (LCA) is one of the primary tools that enable the evaluation and comparison of the potential environmental impacts of waste materials throughout their entire life cycle – from the demolition of the building to the final disposal of demolished waste ISO 14040 (ISO, 2006a). As an internationally standardised tool, LCA is extensively used in many industries including construction (Malmqvist, 2011; Robati *et al*., 2021; Roberts *et al*., 2020) to quantify the environmental performance of demolished waste materials. It is used for the quantitative evaluation of a material used, energy flows and environmental impacts of products. It systematically assesses the potential impact of each material and process. The use of the LCA method allows various phases associated with the development of products and their potential impact throughout the life cycle from cradle to grave to be assessed ISO 14044 (ISO, 2006b; Rebitzer *et al*., 2004). It is a valuable tool for evaluating building material options to select the lowest environmental impact choice, while allowing different phases of life cycle of a system to be assessed (Buyle *et al*., 2013; Fu *et al*., 2014; Malmqvist, 2011). The increased use of LCA in the construction sector has been attributed to several factors. For example, Finnveden *et al*. (2009) explored recent developments in LCA and ascribed the growth of life cycle thinking and the increasing confidence in its application to authoritative organisations such as International Standards Organisation (ISO) and European Commission initiatives and supplemented by a series of guidelines. Similarly, Asdrubali *et al*. (2013) asserted that the adoption of LCA facilitates the reporting of environmental performance.

Furthermore, the growing importance of LCA and its application in the construction sector is also evidenced in the development of environmental product declarations (EPDs). An EPD is a collection of quantified environmental information for a product with predetermined classifications of parameters based on ISO standards. EPDs are supplied by producers and manufacturers and externally validated to certify the environmental impact of the product per the requirements of BS EN 15804 (CEN, 2019). Additionally, the EPD production process must meet the standard of ISO 14044. Waldman *et al*. (2020) observed that the goal of EPDs is to share building materials or environmental impacts of products with their users. This view is supported by Gelowitz and McArthur (2017), who revealed that EPDs provide freely available environmental data. In the same vein, Ibáñez-Forés *et al*. (2016) revealed that one of the important features of EPDs is to act as a valuable source of transparency to understand the environmental impacts of construction materials and processes. A broader perspective has been adopted by Andersen *et al*. (2019) who argued that the availability of EPDs affords assessors more certainty in their findings. Thus, EPD makes it simple for designers to select sustainable construction materials and serves as a data source for carbon embodied factors (CEFs) in environmental performance assessment.

2.2 Significance of embodied carbon in life-cycle emissions of buildings

Embodied carbon is related to the amount of greenhouse gas emissions from the extraction, transporting and refining of raw materials, manufacturing of building components and construction, maintenance and renovation, and demolition of buildings (Ajayi *et al*., 2019; Azari, 2019; UK GBC, 2017; Waldman *et al*., 2020). On the basis of the boundary of the study, however, embodied carbon can be assessed for different phases of life cycle of a system (Ekundayo *et al*., 2019; Trinh *et al*., 2017), as shown in Figure 1. This study considers the end-of-life carbon dioxide emissions along with the benefits and loads.

Compared with operational carbon, embodied carbon had not received much attention from earlier researchers due to its share of the whole life cycle emission. In recent years, however, various studies have reported an upward trend in the share of embodied carbon in life cycle emissions (Panagiotidou and Fuller, 2013). For instance, Röck *et al*. (2020) carried out a systematic review to ascertain the global trends of carbon dioxide emissions occurring throughout the life cycle of buildings by analysing over 650 LCA case studies. The review categorised different energy performance classes based on a final sample of 238 cases. The study found that while the average embodied carbon dioxide emissions from buildings are ~20–25% compared with operational carbon dioxide emissions, the share of embodied carbon rises to ~45–50% with highly energy-efficient buildings and can exceed 90% in extreme instances. In a study to examine embodied carbon share in offices, warehouses, supermarkets and houses, Sturgis and Roberts (2010) reported 45, 60, 20 and 30% respectively in comparison with operational carbon dioxide emissions. The authors further suggested that with improvements in technologies and stricter legislation, the shares for all the abovementioned building types could rise to ~95% in the 2020s. The aforementioned reviews point to the fact that there is a strong indication that the embodied impacts of buildings are a significant contributor to total emissions due to efficient building services and increased use of legislation. Additionally, it highlights the growing importance of managing embodied carbon.

2.3 Significance of LCA and building information modelling integration

Building information modelling (BIM) is described as a 'digital representation of a building' (Teng *et al*., 2022). Using the building components as the basic elements, BIM software directly offers data including the geometric information, physical attributes and material pictorial features for a digital model to create a prototype building that broadly displays parts of the characteristics of the actual building (Nizam *et al*., 2018; Wang *et al*., 2022). The integration of BIM and LCA holds huge potential for sustainable construction because BIM supports the implementation of integrated design (Díaz and Antön, 2014; Zimmermann *et al*., 2021). The application of BIM not only provides a platform for information management but also supports the collaboration of the various stakeholders involved in

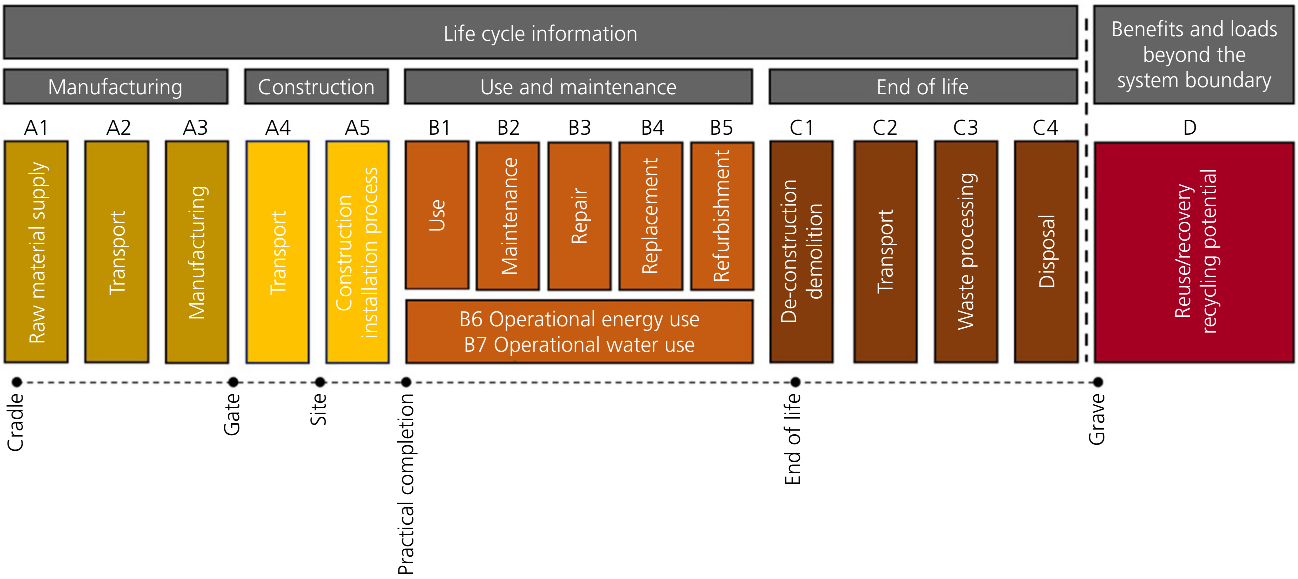


Figure 1. LCA framework reproduced (source: BSI (2012))

the project from the early design phases onward (Díaz and Antön, 2014; Zimmermann *et al.*, 2021). BIM integration also enhances efficiency of a project and improves coordination, thereby reducing energy and materials waste (Röck *et al.*, 2018; Teng *et al.*, 2022). Successful integration allows the automatic extraction of the building data directly from the BIM model to support the performance of LCA (Chen *et al.*, 2021; Teng *et al.*, 2022). Thus, BIM is a tool with great potential for supporting and improving environmental impact assessments, along with decision-making (Han and Leite, 2022; Santos *et al.*, 2020; Tecchio *et al.*, 2019).

3. Methodology

This study aims to assess end-of-life carbon dioxide emissions reduction by examining the impact of different waste materials on carbon dioxide emission reduction. This is illustrated by a case study of three approved building construction systems by a current UK supermarket. The finding is intended to assist designers and other stakeholders to make a sustainable choice of materials and construction system alternatives. The scope of this study is the LCA system boundary of module C in addition to benefits and loads due to possible reuse and/or recycling (see Figure 1). The life cycle inventory includes the compilation and quantification of materials and energy inputs and carbon dioxide emissions output during the stage C of the building life cycle along with module D.

The study adopts a process-based LCA methodology (where the physical flow of all aspects of building materials can be identified and traced) to establish the influence on end-of-life carbon dioxide emissions by examining the three buildings in the case study. The BIM is utilised to provide data on waste generation for all buildings in the case study. These data are then used in the quantification of end-of-life carbon dioxide emissions.

3.1 Life cycle of waste material

The life cycle of waste materials involves various processes and activities. The first stage is C1, where the demolition/dismantling of the building with a machine or equipment takes place. This stage involves energy consumed in the use of equipment, fuel consumption and associated emissions. C2 is the second stage, where the generated demolished waste is transported away from the site to processing facilities. The third stage referred to as C3 is where processing of the waste materials for reuse, recovery and/or recycling occurs. The final stage known as C4 is the disposal of the waste material. Also, the assessment included module D that is an additional module that allows supplementary information (benefits and loads) beyond the system boundary (reuse, recovery and recycling potential) to be considered.

3.2 Case study

This research employed three types of cases to carry out detailed calculations of carbon dioxide emission during the end-of-life phase of buildings in a comparative study. The selected case studies are three approved building construction systems by a current UK supermarket. Autodesk® Revit® BIM software was used to provide the data on demolition waste generation. Design drawings were obtained and validated with a site survey. The three buildings in the case study are referred to as construction methods CM1, CM2 and CM3. The three CMs are all single-storey with an average area of 2500 m^2. The height of the front elevation is 7.02 m whereas the back elevation is 5.10 m.

In this study, CM1 was selected as the baseline building because most of the supermarket buildings adopted this construction development. The other two construction systems (CM2 and CM3) are compared with the baseline because they have slightly different materials composition.

Although all three buildings in the case study have a similar roofing system and materials along with internal partition walls, there are crucial structural characteristics differences in the foundation, framing and external facades that affect the material used in each CM. Table 1 displays the structural components of each CM alongside their building information model.

Based on earlier studies (Wang *et al*., 2018) and data from demolition contractor, waste materials are grouped into two types. Type A includes aluminium, brick, concrete, steel, glass and timber. Type B includes gypsum, mineral wool, paint, plaster, plastic and tile. Waste materials of type A were sent to recycling facilities whereas type B waste materials were landfilled. Table 2 provides the weights of the main components and waste materials of each building.

3.3 Scenarios and assumptions

The estimation of carbon dioxide emission reduction potential arising from different waste materials requires several pieces of information including background scenarios and assumptions. Table 3 presents the end-of-life treatment options and waste material weight proportions. A heavy-duty diesel truck (17 t load) was assumed as a transportation mode for the demolished waste materials (Gibbon and Orr, 2020; RICS, 2017). In addition, waste materials were assumed to be transported by diesel trucks for a maximum distance of 50 km by road including the return journey. Meanwhile, based on the information provided by the demolition contractor, two types of building demolition waste are considered in this study (see Table 2). In some cases, a percentage of some waste materials are recycled and the remaining landfilled, whereas others are 100% landfilled (see Table 3).

3.4 Acquisition of inventory data

A series of activities are involved in the demolition and processing of waste materials. These activities are fundamental to the quantification of carbon dioxide emissions at the end of life. As noted in Figure 1, the life cycle of building demolition waste materials involves four stages. Demolition of the building is the first stage where wastes are generated using machines. Consequently, the emission resulting from operating the machine should be estimated (Wang *et al*., 2018). Transportation is the second stage. In this stage, generated building demolition waste materials are transported to the processing plant or disposal site. Therefore, the associated carbon dioxide emissions should be quantified (Zhang *et al*., 2013). The third stage involves the processing of generated demolition waste. The carbon dioxide emissions from sorting and separating as well as processing are accounted for during estimation (Ding, 2018). The final stage comprises the disposal of wasted materials. Waste materials sent to landfill sites can generate carbon dioxide emissions due to decay and thus be considered in the quantification (Wang *et al*., 2018).

Table 1. Structural details and building information models of the three study cases

Structural description	CM1	CM2	CM3
			
Substructure	Slab foundation	Slab foundation	Pile cap foundation
Superstructure	Framing: steel Roof: metal insulation sandwich panel roofing system.	Framing: steel Roof: metal insulation sandwich panel roofing system.	Framing: precast concrete columns and glulam beams. Roof: metal insulation sandwich panel roofing system.
External envelope	Walls: steel frame insulated cladding panels, concrete and glazed curtain wall panels. Glazed windows and metal doors.	Walls: poroton bricks, steel frame insulated cladding panels, concrete and glazed curtain wall panels. Glazed windows and metal doors.	Walls: precast concrete, steel frame insulated cladding panels and glazed curtain wall panels. Glazed windows and metal doors.
Interiors	Walls: metal studs, plasterboard, insulation and timber. Floorings: tiles, vinyl and paint.	Walls: metal studs, plasterboard, insulation and timber. Floorings: tiles, vinyl and paint.	Walls: metal studs, plasterboard, insulation and timber. Floorings: tiles, vinyl and paint.

Table 2. Weights of the main components and waste materials of the case study

Waste material	Building component	Weight (t) CM1	Weight (t) CM2	Weight (t) CM3
Type A: %		91.00	9.00	94.00
Aluminium	Doors; roof; windows	16.69	16.77	10.24
Brick	Walls	26.95	403.74	
Concrete	Floor; foundations; walls	1476.30	1463.47	2045.25
Glass	Doors; windows; curtain walls	8.12	8.11	8.11
Steel	Structural frames; steel in concrete; iron pieces; roof	151.64	139.29	46.83
Timber	Ceiling; structural frames; roof; walls	1.67	1.67	49.34
Type B: %		9.00	7.00	6.00
Gypsum	Ceiling; walls	43.54	67.37	38.72
Mineral wool	Walls; roofs	52.40	28.87	46.21
Paint	Floors; walls	0.29	0.29	0.15
Plaster	Walls	0.32	0.32	2.55
Plastic	Pipes; other plastic materials	0.12	0.12	0.12
Tiles	Ceiling; floors; walls	60.30	60.31	61.64
Total		1838.34	2190.31	2309.16

Table 3. End-of-life treatment options and waste material weight proportions

		Treatment option: %		Material weight: %	
Waste material	Demolition/dismantling	Recycle	Landfill	Rec weight: t	Land weight: t
Aluminium	Demolition	80[a]	20	13.35	3.34
Brick	Demolition	50[b,c]	50	13.47	13.47
Concrete	Demolition	90[c]	10	1328.67	147.63
Paint	Demolition		100		0.29
Glass	Demolition	50[c]	50	4.05	4.05
Timber	Demolition	90[c]	10	1.50	0.17
Gypsum	Demolition		100		43.54
Mineral wool	Demolition		100		52.40
Plaster	Demolition		100		0.32
Plastic	Demolition		100		0.12
Steel	Demolition	92[d,e]	8	139.51	12.13
Tile	Demolition		100		60.30
Total				1500.55	337.76

[a]Cousins (2021)
[b]Hopkinson *et al*. (2019)
[c]Contractor's confirmation
[d]RICS (2017)
[e]Gibbon and Orr (2020)

The carbon dioxide emission associated with various activities at each stage is paramount to end-of-life carbon dioxide emission estimation as they serve as key parameters or inventory data. These inventory data include energy consumption rates of machines, the CEF of unit energy, transportation distance, energy consumption rates of transportation and CEF of demolition waste materials. Table 4 presents the CEFs for the waste materials at various stages. Meanwhile, numerous sources can provide data including EDP manufacturers or suppliers, eco-databases, literature and many others. As noted by Ge *et al*. (2017), a more careful selection of CEFs enhances the authenticity of the assessment results. Consequently, in this paper EPDs were the first preferable source of CEF. Where EPD was unattainable, CEFs were sought from databases and literature was the least preferred data source.

Based on the preceding two paragraphs, carbon dioxide emissions for the projected operating time for plants and equipment during demolition can be represented by the following equation (Zhang *et al*., 2013; Ding, 2018; Wang *et al*., 2018):

1. $$EC_{equip} = \sum EQ_i \cdot EQF_i \cdot EQEC_i$$

Table 4. Carbon dioxide emissions factors of demolition waste materials

Stages	Carbon dioxide emission factor: kg CO_2eq/kg
Demolition and deconstruction stage (C1)	
Bricks	0.0048[d]
Concrete	0.0056[d]
Steel	0.020[d]
Plastics, glass, plaster, paint, gypsum, mineral wool, roof and tiles	3.400[b,c]
Transportation stage (C2)	
Transporting waste to processing plant and disposal site	
Aluminium	0.0131[a]
Bricks	0.0015[d]
Concrete	0.0017[d]
Steel	0.040[d]
Plastics, glass, plaster, paint, gypsum, mineral wool and roof	0.0054[b,c]
Tiles	1.01[a]
Processing of waste – recycling (C3)	
Aluminium	1.07[a]
Bricks	0.0021[d]
Concrete	0.0024[d]
Glass	0.432[a]
Steel and plastics, glass, plaster, paint, gypsum and mineral wool	0.013[b,c]
Timber	1.67[b,c]
Roof	9.54[a]
Disposal – landfill (C4)	
Aluminium	0.0034[a]
Bricks	0.0016[d]
Concrete	0.0014[d]
Glass	0.279[a]
Steel, plastics, glass, plaster, paint, gypsum, mineral wool and roof	0.013[b,c]
Timber	2.15[b,c]
Tiles	4.63[a]
Material recovery benefit (D)	
Aluminium	−3.98[a]
Bricks	−0.0207[d]
Concrete	−0.0053[d]
Glass	−0.39[d]
Steel	−1.45[d]
Timber	−0.524[b,c]
Roof	−17.43[a]

[a]EPD from manufacturers/suppliers
[b]RICS (2017)
[c]Gibbon and Orr (2020)
[d]SteelConstruction.info (2021)

where EC_{equip} refers to carbon dioxide emission associated with plant or equipment used in dismantling or demolishing a building at the end-of-life (kg CO_2eq.); EQ_i refers to the number of hours plant/equipment i is used for the dismantling or demolition process (hour); EQF_i refers to the energy consumption by the demolition plant/equipment i (kWh or litre/h) and $EQEC_i$ refers to carbon intensity per unit consumption of fuel i (kg CO_2eq./l).

The demolished building waste needs to be transported to a recycling facility or landfill site. The carbon dioxide emission linked to loads of trucks, distance covered along with the fuel used can be estimated using the following equation:

2. $$EC_{transp} = \sum TD_i \cdot TL_i \cdot TF_i \cdot TCEF_i$$

where TD_i denotes the total distance covered for material i (km); TL_i refers to the number of loads of trucks for the transportation of material i (t); TF_i represents the fuel used per load of truck (l/km) and $TECF_i$ refers to the carbon dioxide emission coefficient per fuel unit used i (kg CO_2eq./l).

Trucks may make a return journey to the demolition site empty. Therefore, carbon dioxide emissions associated with the return journey can be estimated by the below equation:

3. $$EC_{transp} = \sum TD_r \cdot TL_r \cdot TF_r \cdot TCEF_r$$

where TD_r denotes the total distance covered for the return journey to the demolition site (km); TL_r refers to the number of the return journey to the demolition site (dimensionless); TF_r represents the fuel used per return journey (l/km) and $TECF_r$ refers to the carbon dioxide emission coefficient per fuel unit used (kg CO_2eq./l).

Two waste treatment approaches (recycling and landfill) are assumed in this study. Demolition waste processed at the recycling plant generates carbon dioxide emissions and therefore must be considered. On the other hand, recycled materials can substitute for the use of natural resources. However, the benefits of replacing raw materials are considered in future projects.

4. $$EC_{rec} = \sum Q_{wi} \cdot CEF_{wi}$$

where EC_{rec} is the carbon dioxide emission from the recycling plant (kg CO_2eq.); Q_w represents the quantity of waste material i being processed, whereas CEF_w refers to the carbon dioxide emission factor of waste material i.

Accordingly, the total carbon dioxide emissions of the demolished waste over the life cycle for landfill and recycling treatment options can be estimated by the below equations, respectively.

5. $$EC_{tot,landfill} = \sum Dem + Transp + Dis$$

where $EC_{tot,landfill}$ represents total carbon dioxide emission resulting from landfilling waste material i; Dem denotes carbon dioxide emission associated with the machine during demolition; Transp refers to carbon dioxide emission from transporting waste material i to the disposal site including return journey and Dis represents carbon dioxide emission associated with disposing of waste material i that may occur due to decay.

6. $$EC_{tot,recycling} = \sum Dem + Transp + Pro$$

where $EC_{tot,recycling}$ represents total carbon dioxide emission resulting from recycling waste material i; Dem denotes carbon dioxide emission associated with the machine during demolition; Transp refers to carbon dioxide emission from transporting waste material i to the recycling plant including return journey and Pro represents carbon dioxide emission associated with processing waste material i.

Estimation and analysis of results are key aspects of an LCA study. Through the scenario analysis, the building or CM with low end-of-life emission is identified. Hence, a low carbon dioxide emission building type can be proposed. Consequently, Equation 7 is used to compare the carbon dioxide emission of each CM during the end-of-life stage of the building life cycle.

7. $$P = [(A - B)/B] \times 100$$

where P represents the proportion of carbon dioxide emission from a CM to the total carbon dioxide emission (%) of the baseline building; A refers to the total carbon dioxide emission of the building compared with the baseline building and B is the total carbon dioxide emission of the baseline building.

4. Results

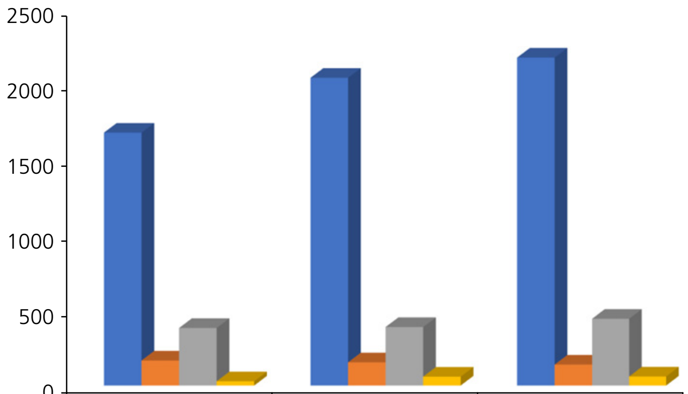
4.1 Assessment of preferred waste treatment method and associated carbon dioxide emission

Figure 2 presents the amount of demolition waste materials recycled and landfilled, along with the associated carbon dioxide emissions from each CM. In contrast with landfill, the results show more than 90% of the total generated waste from each CM was recycled accounting for ~0.23CO_2eq/t, 0.18CO_2eq/t and 0.20CO_2eq/t for CM1, CM2 and CM3, respectively, while less than 10% of the waste from each CM was sent to landfill sites after the necessary processing.

The results further reveal in Table 2 that concrete is the main component of demolition waste recycled accounting for ~88% of the weight in CM1, 72% in CM2 and 95% in CM3. On the other hand, the composition of the landfilled waste materials shows that tiles account for the highest weight in both CM1 and CM3, whereas gypsum accounts for the highest weight in CM2.

4.2 Carbon dioxide emission reduction or substitution effect analysis

Carbon dioxide emission reduction is the potential of using waste recycled materials in other construction projects and its



	CM1	CM2	CM3
Recycle: Material weight (t)	1673	2037	2171
Landfill: Material weight (t)	165	153	139
Recycle: Carbon emissions (kg CO_2eq/t)	381	387	442
Landfill: Carbon emissions (kg CO_2eq/t)	28	58	59

Figure 2. Assessment of preferred waste treatment method and carbon dioxide emission

impact on reducing carbon dioxide emissions. As shown in Figure 3, steel generates the largest carbon dioxide emission reduction at least 80% across all construction systems even though it accounted for ~8% of the total mass of generated waste in CM1, 6% in CM2 and 2% in CM3 compared with the other waste recycled materials. Aluminium creates the second largest carbon dioxide emission reduction potential (6.6%) in both CM1 and CM2, while it is third (4.6%) in CM3.

Looking at end-of-life carbon dioxide emission reduction, timber is the second largest contributor after steel in CM3. In contrast to steel and timber, concrete has the lowest contribution to carbon dioxide emission reduction ~1% across all buildings despite generating the largest mass of demolition waste material (see Figure 3 and Table 2).

Figure 4 presents the substitution effects or carbon dioxide emissions reduction potential associated with each building in the case study. The negative values on the *y*-axis indicate the amount of emissions that can be avoided in future projects due to the substitution of steel, aluminium, concrete, brick, glass and timber during construction. From Figure 4, CM3 generates the lowest whereas both CM1 and CM2 generate ~14% more.

4.3 Comparison of carbon dioxide emission of the buildings in the case study

Table 5 presents the total carbon dioxide emission from the perspective of the demolition waste material life cycle. The result reveals that CM3 generates slightly more carbon dioxide emissions compared with CM2 at the end of life. Overall, the results demonstrate that CM1 emits the lowest carbon dioxide emission when summing up all emissions from the two treatment approaches, whereas both CM2 and CM3 emit ~3% more.

5. Discussion

This study develops a mathematical model to assess carbon dioxide emission from the end-of-life perspective. The model is illustrated by a case study of three approved building construction systems by a current UK supermarket to assess the construction system with the least carbon dioxide emission at the end-of-life stage. Two waste treatment approaches were considered to evaluate the environmental impact of demolition waste materials.

First, the study reveals that the most preferred method of waste treatment by the supermarket is recycling. This was illustrated by the mass of demolition waste recycled in comparison with landfilled and the associated carbon dioxide emissions generated during treatment. Although more than 90% of each CM's generated waste was processed by way of the recycle option, <10% of the waste materials from each CM were landfilled. This shows that landfilling is the least preferable waste treatment option by the supermarket as suggested by the waste hierarchy frameworks. This finding agrees with some earlier studies (Zhang *et al.*, 2022) which recommend that landfill disposal should always be avoided whenever possible.

However, even though, the recycling treatment method generates the majority of the carbon dioxide emission at the end-of-life stage, the findings from all buildings in the case study show that it is the better treatment option compared with landfill as it can effectively and efficiently reduce carbon dioxide emissions in the long term. For example, steel accounts for not more than 8% of the total weight of generated waste in each case study. However, it

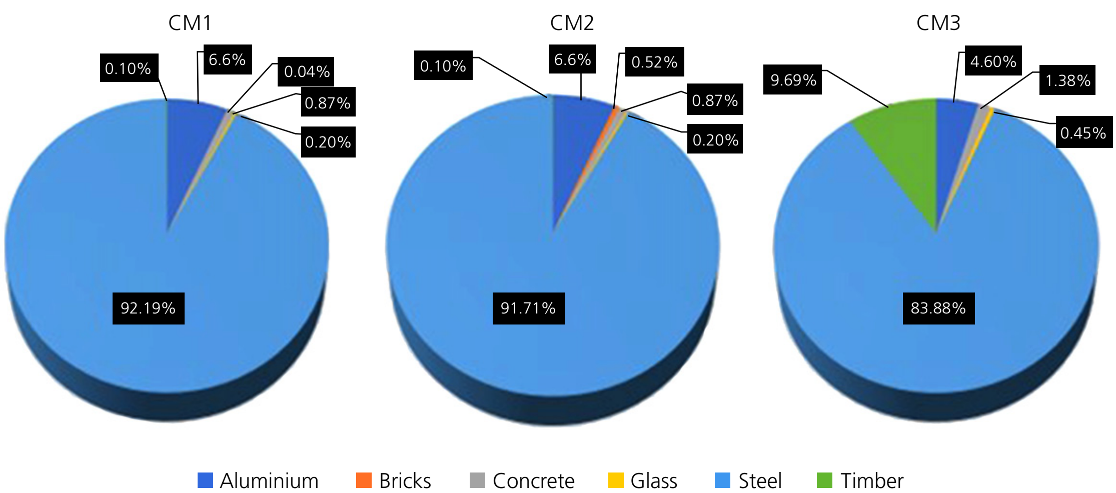


Figure 3. Distribution of carbon dioxide emission reduction potential by waste materials

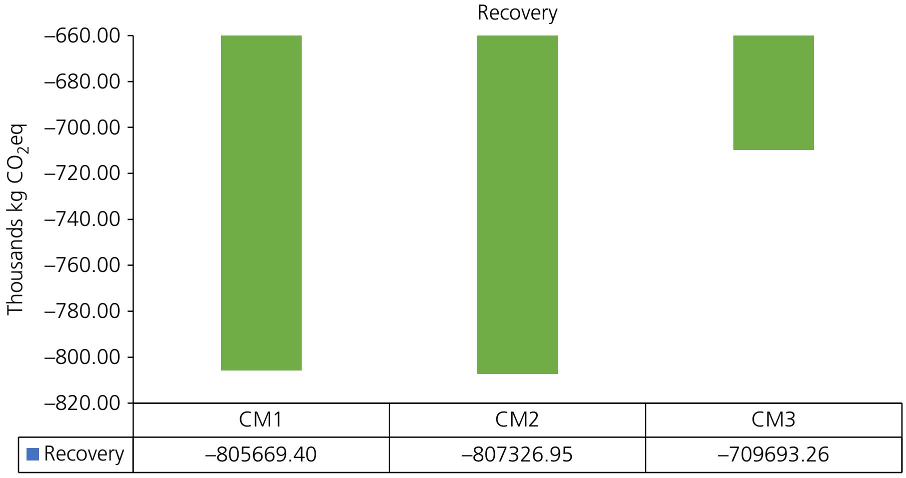


Figure 4. Distribution of carbon dioxide emission reduction potential by buildings in the case study

Table 5. Comparison of carbon dioxide emission

Building	Total carbon dioxide emission: kg CO_2eq
CM1	415 830.44
CM2	427 311.40
CM3	427 850.49

contributes to at least 80% of the carbon dioxide emission reduction. This is because both steel and aluminium are almost infinitely recyclable. For instance, it is suggested that ∼80% of aluminium is taken back into production worldwide (Cousins, 2021). These findings confirm results from earlier published research (Coelho and de Brito, 2013a, 2013b) which concluded that energy consumption and carbon dioxide emissions can be minimised through the reuse and recovery of demolition waste materials. Similarly, Wang *et al.* (2018) found that aluminium contributes ∼45% of the carbon dioxide emission reduction whereas it accounts for ∼1% of the weight of the total generated demolition waste. This is crucial because the use of recycled demolition waste materials in future projects could partly offset the environmental impacts from the inputs and outputs treatment of the waste materials. These are valuable construction materials that can help to reduce the demand for virgin building materials, minimise embodied carbon and waste on landfill sites.

Additionally, in comparison with steel, aluminium and timber, concrete generates the least amount of substitution effects ∼1% despite generating at least 70% of the mass of demolition waste in each of the case study buildings. This may be partly explained by the fact that concrete has the least negative carbon dioxide emission factor compared with steel, aluminium and timber (see Table 4). Notwithstanding, recycling concrete demolition waste can be highly significant in carbon dioxide emission reduction. This is because there is a lot of concrete used in the case study buildings and if not recycled may be sent to landfill sites to occupy land. Besides, if concrete waste is recycled or landfilled after the demolition process, the carbonation reaction within the concrete occurs on a larger scale due to the surface area exposed and the diffusion rate of carbon through the material. This leads to a higher rate of carbon dioxide emission sequestration out of the atmosphere (Kamal *et al.*, 2020; Pomponi *et al.*, 2020).

Although the environmental benefits resulting from recycling and subsequent reuse in future projects have been suggested by some earlier published studies, some waste materials with great environmental performance have been ignored. Blengini (2009), for instance, only examined steel and aggregate without considering other materials such as timber and aluminium. This study has shown that an even larger proportion of carbon dioxide emissions can be minimised by substituting raw material aluminium that accounted for <1% in each of the case studies. Therefore, adopting recycling and/or reusing demolition waste materials at the design phase of the project can be a fundamental way to maximise the potential of recovery while reducing the amount of waste to landfill sites.

Finally, the investigation revealed that CM1 generates the lowest carbon dioxide emissions at the end-of-life stage of the building's life cycle when summing up all emissions from the two treatment approaches compared with CM2 and CM3.

Surprisingly, CM3 that has more timber-based materials than any other building studied performed no better than other construction systems, prompting further investigation into likely causes. The probable cause might be the amount of mass of concrete (∼88% of the total waste) involved in the construction that is evident in the building typology, thus diminishing the amount of carbon dioxide emission reduction findings compared with the other construction systems.

Additionally, a mass of timber-based material is often regarded as more sustainable in direct comparison with equivalent weights of other materials. Such assessments become difficult because there is not a single building that completely consists of a single construction material. This is specifically apparent in the case of the CM3 used for this study wherein the mass of demolition concrete waste material is ∼41.5 times greater than the weight of the timber. This inclusion of other materials as a requirement of modern design and construction may limit the direct impact of using timber-based materials with respect to reduction in overall embodied carbon.

The relatively high embodied carbon value for CM3 (Glulam building) in relation to CM1, the baseline building revealed in this study does align with earlier research by Zeitz *et al.* (2019). In this study, an LCA was carried out on parking garages built of precast concrete, cellular steel, post-tension and timber to compare the embodied carbon and energy reduction potential of different structural systems. Their comparison found the embodied carbon reduction of the cellular steel structural system is greater than timber structure (by almost 15%) and greater than the precast concrete structure (∼26%). On the hand, in a comparative cradle-to-gate study between laminated timber and reinforced concrete of mid-rise office buildings, Robertson *et al.* (2012) concluded that the embodied energy of the timber structure is considerably greater than the concrete structure (by ∼80%) if both feedstock and process energy is considered. The authors further suggest that the embodied energy of timber is mainly feedstock-based, suggesting a combustible energy source can be effortlessly obtained at the end of the material lifespan. This indicates that the slightly higher carbon dioxide emission value of CM3 does not necessarily suggest timber is an environmentally inferior structural material.

6. Conclusion

Globally, building demolition waste constitutes a considerable environmental problem. The environmental implications are not only associated with volume but also with carbon embodied in the waste. These adverse environmental impacts associated with the generated waste can be minimised through appropriate waste treatment strategies. This study proposed a mathematical model to assess the life cycle carbon dioxide emission from the end-of-life perspective. The model is illustrated by a case study of three approved building construction systems by a current UK supermarket to assess the construction system with the least carbon dioxide emission. Landfilling and recycling were assumed as waste treatment methods to evaluate the environmental impact of demolition waste materials.

The results from the two waste treatment methods (recycle and landfill) currently viable to the supermarket show that recycling is the most preferable treatment approach. This was revealed by the amount of demolition waste material recycled (more than 90%) from each CM and the associated carbon dioxide emissions compared with waste materials landfilled. Compared with landfill, ∼9 t out of every 10 t were recycled, which accounted for ∼0.23 CO_2eq/t from CM1, 0.18 CO_2eq/t from CM2 and 0.20 CO_2eq/t from CM3. This demonstrates that landfilling demolition waste materials was the least preferable treatment method by the supermarket.

Furthermore, this study revealed that there are environmental benefits to the substitution of raw materials through recycling and subsequent use in future construction projects that use recycled waste materials. This could comparatively offset the environmental impacts associated with demolition building waste processing. However, the carbon reduction potential differs considerably depending on the type of waste material. For example, steel accounts for ∼8% of the total weight of generated waste in each of the buildings studied. However, it contributes as much as ten times its weight to carbon dioxide emission reduction potential. By contrast, the weight of concrete accounts for at least 70% of the demolition waste in each case study. However, it contributes to ∼1% of the carbon dioxide emission reduction in each of the case studies. Yet, waste generated through the demolition process can be valuable resources for the construction industry if they are efficiently collected, treated and reprocessed. Demolition waste can be an important resource not only to substitute virgin material but also can help reduce embodied carbon as well as demand for landfill sites.

Additionally, the study suggests that CM1 has the lowest carbon dioxide emission, whereas both CM2 and CM3 emit ∼3% more.

This study offers some useful implications for designers, engineers and other stakeholders. First, recycling demolition waste such as steel, aluminium and timber was shown to be vital to carbon dioxide emission reduction in future projects. Consequently, where reuse is less viable, recycling waste should be considered an integral part of the demolished waste management strategy because small variations in the reuse of these demolition waste materials might have a profound impact on the carbon dioxide emissions for future construction projects that use recycled waste materials. Moreover, the development of the waste management strategy should give major priority to metal waste such as steel and aluminium as well as wood-based materials and concrete due to their positive environmental performance during end-of-life treatment. Besides, the mathematical model for carbon dioxide emissions quantification has the potential to be adopted in other end-of-life building projects globally.

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