Life cycle assessment of buildings: an end-of-life perspective

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Chapter

Life Cycle Assessment of Buildings: An End-of-Life Perspective

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Abstract

Building demolition waste represents a huge environmental challenge worldwide. 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 chapter evaluates the various stages of the life cycle of demolished waste materials, the potential carbon emission reduction associated with different demolished wastes and waste treatment strategy options. An assessment framework was developed and exemplified by a case study of a supermarket building. The results showed that the processing or treatment stage generate the largest amount of carbon emission (81%) in the life cycle of demolished waste materials, whilst the transportation stage contributed the least (1%). It was further found that steel waste recycling has the greatest environmental benefits (more than 90%) compared to concrete (less than 1%). Additionally, the study revealed that landfilling waste generated the largest amount of carbon emissions compared to recycling. The findings can contribute to mitigating the environmental building demolition projects. Furthermore, the detailed assessment approach provides theoretical and methodological guidance which can be adopted to guide the quantitative analysis of other types of demolition projects globally.

Keywords: embodied carbon emissions, end-of-life, building waste materials, life cycle assessment, recycling, landfilling

1. Introduction

The construction sector is a mainstay of many economies around the world. It has inherent value through the creation of distinctive economic and social products. However, the sector also generates a huge impact on the environment, which raises sustainability concerns. One of the environmental concerns is the generation of large volumes of construction and demolition (C&D) waste, along with the carbon embodied in them. For example, the industry is responsible for nearly 50% of the solid waste sent to landfills [1]. In the European Union (EU), C&D waste is around 20–30% (Ding, 2018). Waste Statistics compiled by Defra [2] indicate that in 2016, 63% of the total waste stream in England (189 million tonnes) was attributed to construction, demolition and excavation waste. Of this figure, an estimated 50% was attributed to C&D waste. C&D waste is described as a mixture of different waste streams, including inert waste, non-hazardous waste and hazardous waste, generated from construction, renovation, and demolition activities of buildings, roads, bridges and other structures [3]. As a result of its impact on the environment, the EU has classified C&D waste as a priority for its members to reduce [4].

In contrast with construction projects, however, demolition projects generate a greater volume of waste [5]. Consequently, the environmental concern of demolition waste does not only relate to the amount generated, but also its treatment. The commonly used treatment methods in dealing with demolition waste include reuse, recycling and landfill [6, 7]. These treatment methods require waste collection, sorting, transportation, recycling and final disposal. These treatment processes are referred to as the demolition waste life cycle [7–9]. Throughout the steps of treating demolished waste, a significant amount of carbon emissions is emitted as a result of energy utilisation associated with transportation and machine operations [7, 10, 11]. Nevertheless, recycling as an end-of-life treatment strategy bears positive and negative environmental impacts [12], since recycling demolished waste can reduce the extraction of virgin building materials [13]. Since the increase in end-of-life waste considerably impacts the overall construction industry's carbon emissions performance, the industry and practitioners need a low-carbon emission treatment strategy for demolished waste. Therefore, the evaluation of environmental effects associated with end-of-life waste management along with the selection of a low-carbon emission management approach is the response of the building and construction sector to environmental challenges. This evaluation and selection should start with an appropriate quantification method for the life cycle carbon emission of the building demolition waste [4, 14].

Life cycle assessment (LCA) is a widely recognised tool used in the evaluation of the environmental performance of a product or procedure over its entire life cycle [15]. Many previous studies relating to a building's life cycle considered one or some specific phases of the life cycle of a building such as material manufacture, construction or use [16, 17]. Other researchers focussed on the assessment of the entire life cycle of a building [18, 19]. Few studies, however, place emphasis on end-of-life carbon emission assessment of the life cycle of a building [20–22]. The quantification of carbon emissions resulting from building demolition waste treatment is mostly ignored [7, 20, 23]. For a clear understanding of the life cycle carbon emission associated with building demolition waste, an in-depth consideration of the processes and activities involved in demolition and treatment of waste is needed.

One of the challenges of conducting an LCA is accurate data acquisition. However, the use of building information modelling (BIM) directly provides data including geometric information, physical attributes and material quantities [24, 25]. The integration of LCA and BIM not only overcomes the need to enter information manually but also combines the strengths of both tools [26, 27]. Thus, BIM provides efficient means of acquiring essential data for carrying out life cycle assessment of buildings, while streamlining the process of data collection [28, 29]. Yet, few studies adopt a BIM-LCA integrated approach in the evaluation of end-of-life carbon emissions [7]. Meanwhile, various past studies have suggested that the building and construction sector can play a vital role in the mitigation of climate change by properly controlling and minimising carbon emissions from construction and demolition activities [30, 31].

The chapter aims to propose an integrated analytical framework based on the LCA model for assessing the impact of the life cycle stages of demolished waste materials, waste material type and waste treatment options on carbon emission reduction. In contrast with other studies, this chapter contributes to mitigating the environmental impact of a demolished supermarket building and exemplifies this with a case study. In addition, it contributes to the theoretical frameworks for quantifying the environmental impact of demolished waste materials by clearly addressing the following questions: (i) "which stage of the life cycle demolished waste critically influence carbon emissions reduction?" (ii) "What type of demolished waste material greatly impacts end-of-life carbon emission reduction?" (iii) "which waste treatment strategy significantly affect end-of-life carbon emissions reduction?" Comprehensive and detailed analyses were performed to better understand the research trends and knowledge gaps in this discipline.

2. Materials and methods

2.1 Case study

This research employed a case to conduct detailed calculations of carbon emission during the end-of-life. A case study is recognised to be appropriate in investigating complex research particularly, where there is a lack of data available to understand the effect of demolished building waste and the treatment strategies on carbon emissions [10]. The selected case study was a current UK supermarket building. The case building was a single-storey with an average area of 2500 m^2. 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 case building simulation is shown in **Figure 1**. The height of the front elevation was 7.02 m while the back was 5.10 m.

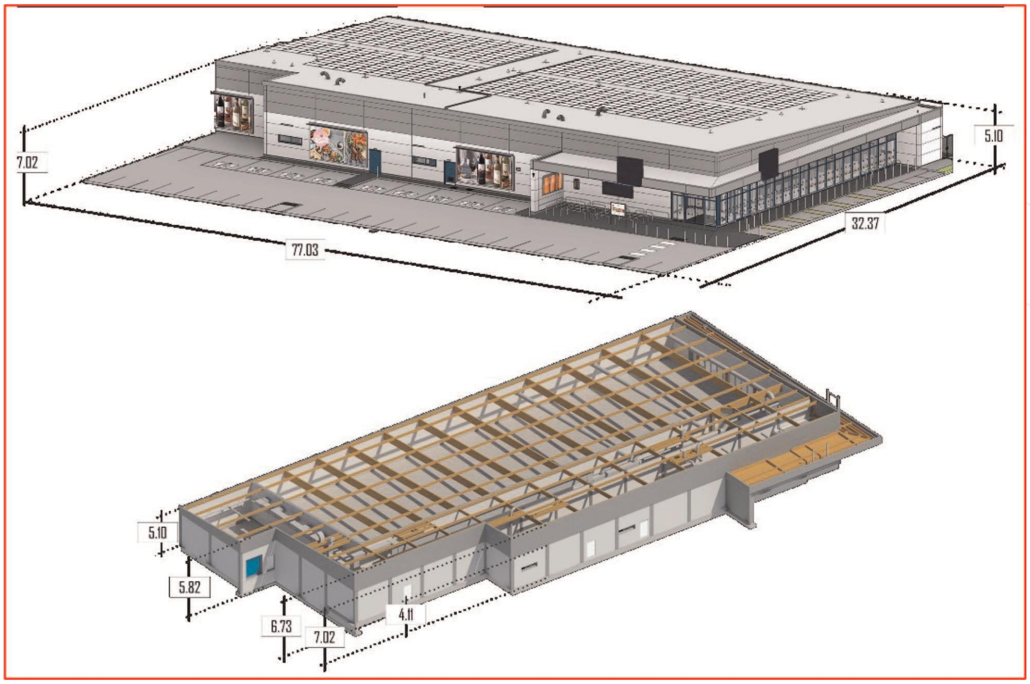

Figure 1.
The simulated model of the case building.

Waste material type	Building component	Weight (kg)
	Category A	
Aluminium	Windows; Doors; Roof; Curtain walls	9618.60
Concrete		1,881,559.12
Steel	Iron pieces; Steel in concrete	240,875.19
Plastic	Pipes and other plastic materials	135.91
Glass	Windows; Doors; Curtain walls	7190.75
Timber	Structural columns; Roof frames	66,921.64
	Category B	
Gypsum	Walls; Ceilings	46,746.45
Mortar	Wall plaster	2765.08
Tiles	Floor; Ceiling	61,639.23
Mixed materials		44,622.31
Total		2,362,074.29

Table 1.
Inventory of main waste materials in the case building.

The structural form determines the main materials. The main materials in the case building are displayed in **Table 1** along with the quantities. The waste materials were derived from two categories. The waste materials in category **A** are considered waste with a high recyclable value. Category **B**, on the other hand, is considered waste with a very low recyclable value and is therefore landfilled. This is because large-scale demolition is usually carried out using mechanised techniques. Consequently, the generated demolished waste is in small volumes, difficult to sort and is generally generated in a mixed form [32].

2.2 Carbon emission factors of the main waste materials and end-of-life stages

The life cycle of demolished waste materials involved various stages and a series of processes (see Section 2.3.3 for a full explanation). Carbon emission factors (CEFs) are vitally important as they affect the accuracy of the life cycle calculation results. CEFs can be derived from numerous sources. More localised CEFs enhance the accuracy of the assessment results [33]. Consequently, the choice CEFs was based on the principle of regional priority. CEFs of the main waste materials are listed in **Table 2**.

2.3 Life cycle assessment

The life cycle of waste materials involves various processes and activities. In this study, the assessment used is consistent with the four ISO standards for LCA: definition of scope and goal; life cycle inventory (LCI) which quantifies the inputs; inventory analysis (LCIA) which converts the inputs to emissions; and interpretation of results.

Based on the above breakdowns, the LCA estimation model was developed to evaluate the life cycle carbon emission of demolished waste materials. To generate

Stages	Carbon emission factor ($kgCO_2eq.$)
Demolition & deconstruction stage	
Demolishing by machine	3.400[b,c]
Transportation stage	
Transporting waste to processing plant & disposal site:	
Aluminium	1.31E-02[a]
Concrete, steel, plastics, glass, timber, mortar & mixed materials	0.1065[b,c]
Tiles	1.01E-1[a]
Processing of waste – recycling	
Aluminium	1.07E-02[a]
Steel, plastics, glass & concrete	0.013[b,c]
Timber	1.67[b,c]
Roof	9.54E+01[a]
Disposal – Landfill	
Aluminium	0.00E+01[a]
Concrete, steel, plastics, glass, mortar & mixed materials	0.013[b,c]
Timber	2.15[b,c]
Tiles	4.63E+01[a]
Material recovery	
Aluminium	−3.98[a]
Concrete	−0.000989[d]
Steel	−1.6[b,c]
Timber	−0.524[b,c]
Roof	−17.43[a]

[a] *Environmental Product Declaration (EPD).* [b] *Royal Institute of Chartered Surveyors (RICS) [34]* [c] *The Institute of Structural Engineers (IStructE) [35]* [d] *The Department for Business, Energy and Industrial Strategy (BEIS) [36].*

Table 2.
Waste materials and carbon emission factors.

data for the estimation, BIM was used, while data from other sources were used to complement the estimation.

2.3.1 Scope, goal and system boundaries definitions

This LCA examines the carbon emissions of demolished building waste materials under two end-of-life treatment strategies (see Section 2.3.4). Data was taken from a UK supermarket building. As noted above, an assessment framework that incorporates BIM with an LCA was used to provide data on demolition waste generation. The assessment framework comprises various elements as illustrated in **Figure 2**. The scope and goal phase covers all activities and resources involved in the process of demolished waste from generation to final disposal.

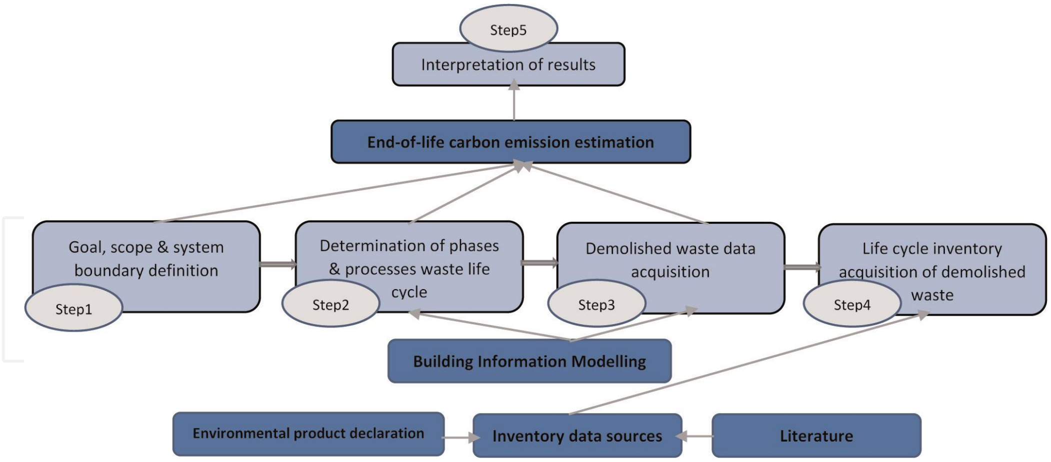

Figure 2.
Framework of carbon emission assessment of demolished waste [7].

In LCA, functional units are used to ensure like-to-like comparisons. In this study, the functional unit of demolished waste considers two variables – materials weight (kg) and carbon emission (kgCO_2eq). In order to scale up the results to any weight of demolished waste material, the functional unit will consider 1 kg of waste materials. The functional unit is therefore kgCO_2eq of per 1 kg demolished waste.

2.3.2 Life cycle inventory

The main type of life cycle inventory (LCI) and data used was the process LCI (primary and secondary environmental data). The process LCI was used to systematically quantify the physical inputs and outputs of the waste materials within the process LCA system boundary. The process LCI of each component and activity was derived using the breakdown approach, which gives carbon emissions per kg of waste material generated. The LCA quantification formulas were developed to estimate the life cycle carbon emission during the end-of-life (see **Figure 2**). As stated earlier, the LCA was integrated with BIM to provide data imported into the calculation of end-of-life carbon emissions. During these end-of-life activities and processes, records of energy consumption by machines were sought through multiple data sources including EPDs from manufacturers/suppliers and site surveys. To complement the robustness of these data, additional carbon emission factors for each phase and activity were gathered from other literature. Where data was not available from EPD and recognised eco-data source the mean value of the other literature searches was used.

2.3.3 Life cycle impact assessment of demolished building material

As noted in Section 2.1.2, the life cycle impact assessment (LCIA) approach employed in this study was the process-based LCA inventories (where the physical flow of all aspects of building materials can be identified and traced) to establish the carbon emission embodied in building demolished waste. As an LCA technique, the process-based has the strength to reveal carbon emissions from the specific demolition process and activity, along with its accuracy and detailed processes [17, 37, 38]. The rationale of this method is straightforward and clear, carbon emissions from individual activities can be estimated and analysed separately [17]. This method is frequently adopted in the quantification of carbon emissions of construction processes [17, 39, 40]. Finally, the results of the LCIA were then analysed and the conclusions were drawn.

Meanwhile, there are four stages of the life cycle the waste materials and a series of activities are involved. The analysis of these activities is fundamental to identifying carbon emission factors (CEFs). The first stage covers all the processes in the demolition of the building at the end of its useful life. During the demolition, several machines can be used and energy/fuel consumed through the use of these machines or equipment as well as related emissions serve as a source of CEF. Carbon emissions at this phase also include the projected operating time for machines or equipment used in carrying out the demolition of the building multiplied by the average electric power used and/or fuel per unit of time and the related carbon intensity per litre of fuel used. The second stage covers the transportation of the demolished waste materials to treatment plants, recycling plants or landfill sites. CEFs are also derived from the environmental impacts associated with these activities. The third stage covers all the processes in the waste treatment plant, while the fourth and final stage covers the processes associated with the final disposal of demolished building materials.

The conceptual LCA framework focuses on the demolished building materials for which waste treatment is expected, and therefore, the environmental impacts were calculated. However, two aspects of carbon emission are associated with recycling waste materials - the adverse environmental effects and the environmental benefits [7]. The net environmental impact is equal to the difference between the impacts due to the recycling process that replaces the production of virgin materials and the impacts due to the production of the avoided virgin material. The net benefits associated with material replacement and energy consumption, or carbon emission is the difference between the input and output of the secondary material.

Using life cycle inventories, the process LCA for the use of machine/equipment can be defined by Eq. (1) as:

$$\mathrm{EC}_{\mathrm{equip}} = \sum \mathrm{EQ}i * \mathrm{EQF}i * \mathrm{EQEC}i \tag{1}$$

Where:

$\mathrm{EC}_{\mathrm{equip}}$ refers to carbon emission associated with plant or equipment used in dismantling or demolishing a building at the end-of-life ($\mathrm{kgCO_2eq}$); $\mathrm{EQ_i}$ refers to the number of hours plant/equipment $_i$ is used for the dismantling or demolition process (hour); $\mathrm{EQF_i}$ refers to the type of fuel used by the demolition plant/equipment $_i$ (kWh or litre per hour); and $\mathrm{EQEC_i}$ refers to carbon intensity per unit consumption of fuel $_i$ ($\mathrm{kgCO_2eq}$ per litre).

Carbon emission is also calculated for waste generation during the demolition of the building. It is assumed that waste from the demolished building during the end-of-life of the case building is equal to the mass of material in the constructed building excluding the waste factor and has the same building component category breakdown. Consequently, the process LCA of building demolition can be represented by Eq. (2) as:

$$\mathrm{EC}_{\mathrm{struct}} = \sum \mathrm{S}i * \mathrm{SCEF}i \tag{2}$$

Where:

$\mathrm{EC}_{\mathrm{struct}}$ refers to carbon emission associated with the demolished building; $\mathrm{S_i}$ refers to the quantity of material $_i$ resulting from the demolished structure or building (m^2, m^3 or kg); and $\mathrm{SCEF_i}$ denotes the carbon emission coefficient per unit of material $_i$ ($\mathrm{kgCO_2eq}$ per kg, m^3 or m^2).

Using life cycle inventories, the process LCA for transporting demolished materials can be defined by Eq. (3) as:

$$\mathrm{EC_{transp}} = \sum \mathrm{TD}i * \mathrm{TL}i * \mathrm{TF}i * \mathrm{TCEF}i \tag{3}$$

Where:

$\mathrm{TD_i}$ denotes the total distance covered for material $_\mathrm{i}$ (km); $\mathrm{TL_i}$ refers to the number of loads of trucks for the transportation of material $_\mathrm{i}$ (No.); TFi represents the fuel used per load of truck (litre per km); and $\mathrm{TECF_i}$ refers to the carbon emission coefficient per fuel unit used $_\mathrm{i}$ ($\mathrm{kgCO_2eq}$ per litre).

In this study, two waste treatment approaches - recycling and landfilling were assumed. As noted above, recycling demolished waste materials has both adverse environmental impacts and environmental benefits. Therefore, the environmental benefits of substituting virgin materials with recycled (secondary) materials are subtracted. Subsequently, the process LCA for recycling demolition waste can be defined by Eq. (4) as:

$$\mathrm{EC_{rec}} = \sum \mathrm{EC_{rec-qe}}i - \mathrm{EC_{rec-(-ben)}}i \tag{4}$$

Where:

$\mathrm{EC_{rec}}$ is the carbon emission from the recycling plant ($\mathrm{kgCO_2eq.}$); $\mathrm{EC_{rec\text{-}qe}}$ is the emission resulting from machine operation during recycling ($\mathrm{kgCO_2eq}$); and $\mathrm{EC_{rec\text{-}(-ben)}}$ is the carbon emission reduction through the replacement of raw materials ($\mathrm{kgCO_2eq}$).

Accordingly, using life cycle inventories, the process LCA for the total carbon emissions of the demolished waste over the life cycle for recycling and landfill treatment options can be represented by Eq. (5) and (6) respectively.

$$\mathrm{EC_{TOTALREC}} = \sum \mathrm{EC_{de}} + \mathrm{EC_{tp}} + \mathrm{EC_{pr}} \tag{5}$$

$$\mathrm{EC_{TOTALLAN}} = \sum \mathrm{EC_{de}} + \mathrm{EC_{tp}} + \mathrm{EC_{dp}} \tag{6}$$

Where:

$\mathrm{EC_{TOTALREC}}$ and $\mathrm{EC_{TOTALLAN}}$ refer to the total carbon emission of the life cycle of building demolition waste for recycling and landfilling respectively ($\mathrm{kgCO_2eq}$); $\mathrm{EC_{de}}$ is the carbon emission at the demolition phase ($\mathrm{kgCO_2eq}$); $\mathrm{EC_{tp}}$ is the carbon emission during transportation phase ($\mathrm{kgCO_2eq}$); and $\mathrm{EC_{pr}}$ refers to the carbon emission during recycling (kg $\mathrm{CO_2eq.}$), while $\mathrm{EC_{dp}}$ is the carbon emission during disposal.

Results analysis is a key aspect of a life cycle assessment study. Therefore, through the scenario analysis, the stage of the end-of-life with greater carbon emission can be identified. Also, the type of waste material and treatment strategy with the largest carbon emission potential can be identified. Hence, low-carbon waste materials can be proposed to manage the end-of-life carbon emission and associated substantial amounts of building waste. Accordingly, the process LCA for the comparison waste can be defined by Eq. (7) as:

$$\mathrm{P_{eol}} = \mathrm{B_{eol}} / \sum \mathrm{B_{eol}} \tag{7}$$

Where:

$\mathrm{P_{eol}}$ is the proportion of carbon emission from a stage of demolition waste life cycle, treatment strategy and type of waste material the case building (%).

$\mathrm{B_{eol}}$ is the total carbon emission from the case building ($\mathrm{kgCO_2eq}$).

2.3.4 End-of-life scenarios and assumptions

In this study, two waste treatment options were considered. Based on the recovery rates of the UK from localised literature and other sources, the percentage of each material was determined. **Table 3** shows the assumed end-of-life treatment options for the waste materials along with the percentages A heavy-duty diesel truck (17 tonnes load) was assumed as a transportation mode for the demolished waste materials [34, 35]. In addition, a maximum distance of 50 km by road for both treatment options was assumed.

3. Results

3.1 Carbon emission impact of life cycle stages of demolished waste material

According to the analytical assessment model, the total carbon emission of different stages in the lifecycle of the waste materials was calculated (see **Table 4**). The value of the treatment stage was the largest representing about 81% of the total end-of-life carbon emission. This includes the environmental impact of input/output of treating and recycling demolished waste, carbon emission reduction of waste replacement as well as landfilling unrecyclable waste. The carbon emission values of demolition and transportation stages accounted for 18% and 1% respectively. The carbon emission of the treatment stage is influenced by different carbon emission values compared to the demolition stage (see **Table 2**). Despite being the major carbon emission contributor, if recycling is selected, where possible, for waste treatment, the reuse of recycled materials could result in environmental benefits. This suggests that the choice of waste material treatment option should be given priority in order to reduce carbon embodied in them.

Waste Material	Demolition/Dismantling	Treatment Option		Weight	
		Recycle (%)	Landfill (%)	Recycle (kg)	Landfill (kg)
Aluminium	Demolition	92	8	8849.11	769.59
Concrete	Demolition	90	10	1,693,403.21	188,155.91
Steel	Demolition	92	8	221,605.17	19,270.02
Plastic	Demolition	50	50	67.95	67.95
Glass	Demolition	50	50	3595.38	3595.38
Insulation	Demolition	—	100		66,921.64
Timber	Demolition	55	45	25,710.55	21,035.90
Gypsum	Demolition	—	100		2765.08
Tiles	Demolition	—	100		61,639.23
Mortar	Demolition	—	100		2765.08
Mixed materials	Demolition	—	100		44,622.31
Total				1,953,231.37	411,608.00

Table 3.
End-of-life options for common building elements.

Stage	Carbon emission (kgCO$_2$eq)
Demolition	114,388.47
Transportation	9323.49
Treatment	530,322.71
Total	654,034.67

Table 4.
Carbon emission of life cycle stages of demolished waste materials.

Table 4 indicates that transportation is by far the least carbon emission end-of-life stage. This is because the distance of transporting waste materials to the processing plant or disposal site is located locally. This result emphasises the need for selecting local processing facilities as long distance defeats the goal of carbon emission reduction.

3.2 Carbon emission reduction potential of waste materials replacement

The total carbon emission reduction that can be achieved through replacement was −797,147.34 kgCO$_2$eq. Steel accounted for the majority of the environmental benefits and was much higher than other materials in the case building even though it represents only 10% of the total waste materials (see **Figure 3**). Aluminium was the second largest contributor, followed by timber and concrete. As illustrated in **Figure 3**, the environmental benefit of concrete contributes to as low as 0.16%, although it accounts for nearly 80% of the weight of all generated waste. This is because the value of the environmental benefit of concrete in terms of carbon emission reduction potential is much smaller than that of steel and aluminium. For example, the environmental benefit of recovering one kg of aluminium (in the roof) for reuse can contribute to 17.43 kg CO$_2$eq of carbon emission reduction, while this value is only 0.000989 for

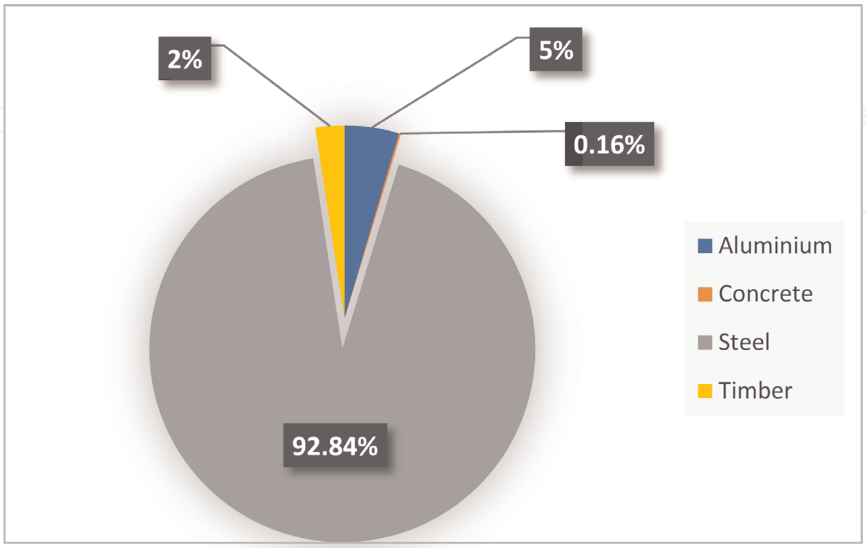

Figure 3.
Proportion of carbon emission reduction potential by waste materials.

recovering one kg of concrete. This result indicates that the recovery and the subsequent processing of metal should be given priority in terms of material potential to reduce carbon emissions during end-of-life.

3.3 Carbon emission of treatment options

As noted in Section 2.3.4, two waste treatment options (recycling and landfill) were considered to explore the best waste treatment strategy. The net environmental impacts or benefits due to recycling were also accounted for. **Figure 4** shows the contribution of each waste material to the two treatment options' carbon emissions. In all, 2,364,839.37 kg of waste was generated from the demolition of the case building. Out of this total, 83% were recycled accounting for 595,330.41 kgCO$_2$eq of the overall carbon emissions, whereas landfilling waste contributed 150,945.83 kgCO$_2$eq. Recycling the waste materials, however, has huge environmental gains as indicated in **Figure 4**. The result reveals that recycling contributes a net environmental benefit of up to −201,816.93 kgCO$_2$eq when the environmental gain is combined with the carbon emission. This suggests that the most significant end-of-life management option is recycling compared with landfilling demolished waste. Additionally, by comparing the two end-of-life management options, recycling contributed to a potential reduction of approximately 7% in overall carbon emissions.

4. Discussion of results

The management of the end-of-life of a building involves a series of processes and activities as well as diverse carbon-intensive waste materials. However, only limited studies have focused on combining the various stages of demolished waste materials, carbon emission reduction along with treatment strategies. This study aimed to develop an integrated analytical framework based on the LCA model to assess the impact of the life cycle stages of demolished waste materials on carbon emission in order to provide guidance for carbon emission reduction and raw materials conservation.

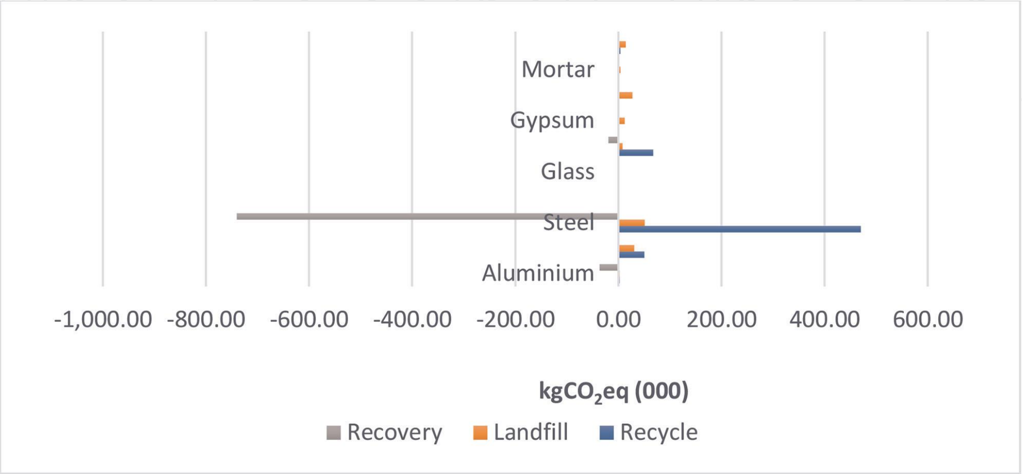

Figure 4.
Analysis of treatment options.

The results from the breakdown of the life cycle stages (demolition, transportation, processing and disposal) indicated that the processing or treatment stage generated the largest amount of carbon emission (81%) during end-of-life. On the other hand, the transportation of demolished waste material contributed the least (1%) to the total life cycle of carbon emission. The insignificant impact of the transportation stage on end-of-life carbon emissions has also been highlighted by previous studies. Coelho and de Brito [41, 42] assessed the carbon emission embodied in construction and demolition waste materials and suggested that the overall transportation distance should be always reduced because of the related energy consumption and carbon emissions.

As presented in the results section, carbon emission reduction can be achieved through the substitution effects of reusing recycled waste materials. While some past studies have indicated that the recycling of construction and demolition waste has environmental benefits due to the potential to replace virgin materials, the environmental performance of some demolished waste materials has been ignored. For example, a study to evaluate embodied carbon, [17] only considered the recycling of steel and aluminium. Similarly, a study to develop a model to evaluate the cradle-to-grave environmental impacts of a building in Italy, [43] only considered the recycling of steel and aggregate. The current study, however, considered at least four major waste materials. The analysis of the results revealed that steel has a significant impact on demolished waste life cycle carbon emission reduction. Despite representing only 10% of the total mass of generated waste materials, the result analysis indicates that steel has a carbon emission reduction potential of more than 90% of the case building. This result indicates that the recovery and the subsequent processing of metal should be given priority in terms of material potential to reduce carbon emissions during end-of-life.

Furthermore, by investigating the two waste treatment strategies (recycling and landfill) currently viable to the supermarket, this study revealed that landfilling generated the largest amount of carbon and the largest contributor to life cycle carbon emission during the end-of-life phase. In contrast, the analysis of the results emphasises that overall recycling building waste can lead to significant environmental benefits rather than adverse environmental impacts, particularly for materials with a high-value recyclable potential such as steel, aluminium and timber. This is due to the carbon emission reduction potential associated with material recovery. For instance, the results indicate that recycling instead of landfilling could achieve an overall 7% environmental benefit. The significant impact of recycling demolished waste materials has also been highlighted by previous studies. In a study to develop a model to evaluate the cradle-to-grave environmental impacts of a building in Italy, [43] stated that recycling steel and aggregate can lead to environmental gain. Similar findings were reported by [12, 41, 42], who found that recycling demolished waste materials could provide environmental benefits because of the potential to substitute raw materials. Conversely, [10] pointed out that the carbon emission associated with demolished waste materials can be considered lost if landfilled, since virgin materials would be required to replace them. Therefore, careful consideration should be given to the treatment strategies of demolished waste materials.

5. Conclusion

Building demolition waste represents a huge environmental challenge worldwide. 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 chapter evaluates the various stages of the life cycle of demolished waste materials, the potential carbon emission reduction associated with different demolished wastes and waste treatment strategy options. This was exemplified by a case study of a supermarket building. The analytical framework and the detailed method of quantifying the environmental impact have the potential to be adopted in other building demolition projects.

The results of this study show that the processing or treatment stage might generate the largest amount of carbon emission (81%) in the life cycle of demolished waste materials. In contrast, the transportation of stage contributed the least (1%) to the total life cycle of carbon emission.

Likewise, this study revealed that carbon emission reduction can be achieved through the substitution effects of reusing recycled waste materials. The analysis indicates there are environmental benefits to substituting virgin resources with recycled building-demolished waste, which compensates for the environmental impacts associated with the processing of waste materials. The environmental gain differs considerably from one waste material to another. For example, despite representing only 10% of the total mass of generated waste materials, steel has a carbon emission reduction potential of more than 90% of the case building. The recycling of metal (steel and aluminium) and timber-based materials should be given priority in terms of material potential to reduce carbon emissions during end-of-life.

Additionally, this study revealed that landfilling generated the largest amount of carbon and the largest contributor to life cycle carbon emission during the end-of-life phase. On the other hand, recycling demolished waste materials can lead to significant environmental, particularly for materials with a high-value recyclable potential such as steel, aluminium and timber. For instance, the results indicate that recycling over 80% of the total mass of generated waste materials could achieve an overall 7% environmental benefit.

This study offers some useful implications and guidance for designers, engineers and other stakeholders regarding the treatment of construction and demolition waste. For instance, where reuse is less viable, recycling waste should be considered an integral part of the demolished waste treatment strategy for each building's end-of-life project. The development of the waste treatment strategy should give major priority to metal waste such as steel and aluminium as well as wood-based materials because of their positive environmental performance during end-of-life treatment. Also, the findings reported in this study can contribute to mitigating the environmental impact of building demolition projects. Furthermore, the detailed assessment approach provides theoretical and methodological guidance which can be adopted to guide the quantitative analysis of other types of demolition projects globally. Finally, the findings complement the existing literature, which mainly addresses the environmental performances of demolished waste by means of the life cycle assessment methodology.

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