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Evaluation of Embodied Carbon Emissions in UK Supermarket Constructions: A Study on Steel, Brick, and Timber Frameworks with Consideration of End-of-Life Processes

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Abstract: Buildings and the construction sector as a whole are among the chief emitters of carbon, and the structural system of a building contributes substantially to its embodied carbon emissions. Whereas extensive studies exist into carbon missions, a detailed evaluation of real multipart building systems in brick, steel, and timber (glulam) substitutes is lacking. This paper employs whole-life-embedded carbon as a sustainability metric to compare a current UK supermarket building system of steel, brick, and timber. Four construction systems by the supermarket, referred to as CS1, CS2, CS3, and CS4, are used in the investigation. Comparisons are also made between two end-of-life treatment methods (recycle and landfill) along with the benefits that can be realised in future construction projects. The outcome from the comparative assessment reveals that there are minor variations in the embodied carbon of building systems used by the supermarket. CS4, while currently presenting marginal gains (approximately 148,960.68 kgCO_2eq.) compared to CS1, loses its advantages when recycled contents for future construction projects are considered. The result indicates that CS4 generates about 18% less carbon emission reduction potential than CS1, whilst CS3 generates approximately 16% less than CS1. The findings of this article can enhance the knowledge of embodied carbon estimation and reduction capabilities of timber, steel, and brick buildings. Also, the detailed method for quantifying embodied carbon used in this article can be adopted in similar projects around the world.

Keywords: building systems; embodied carbon emissions; life-cycle assessment (LCA); material selection

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1. Introduction

It is well known that buildings contribute immensely to global carbon emissions and are a major consumer of resources over their entire life cycle [1,2]. Recent studies suggest that buildings consume approximately 30% of global energy and are associated with greenhouse gas emissions [3,4]. These statistics are suggested to rise at an increasing rate, which raises sustainability concerns [5]. Consequently, numerous researchers have made frequent attempts to minimise the effects of buildings on the environment [6,7].

Meanwhile, the carbon emissions associated with buildings' life cycles are commonly categorised into two broad groups—embodied and operational carbon [8,9]. The operational carbon results from various activities relating to energy use during the lifespan of a building. These include lighting, ventilation, heating, and cooling [10,11]. On the other hand, embodied carbon is attributed to emissions resulting from operations, such as building element production, installation, and construction, and demolition during the end-of-life [12,13]. With the operational stage of the life cycle of buildings attracting much attention, resulting in the development of advanced technologies, policies, and measures to drive down carbon emissions, embodied carbon has become the main focus of the current research in an attempt to address the environmental effects during the construction and end-of-life phases of buildings [13,14]. A key part of addressing the environmental impacts of these phases of the building life cycle has been the choice of building materials. The structure of the building is a prime contributor to the overall embodied carbon [15,16]. Additionally, it has been observed that a building's carbon footprint may significantly be influenced by the structural system that is selected [17,18].

Numerous past studies have made material and structural system selection and their impact on lifecycle carbon emissions the main focus [19,20]. Akbarnezhad and Xiao [10] studied the current strategies for embodied energy and carbon reduction in structures by considering each strategy's benefits and disbenefits. Likewise, the impact of the material selection on the operational and embodied carbon of buildings was the main focus of a study by Thormark [17], which found that up to 23% of the carbon emission reduction can be realised through the appropriate material selection. Nadoushani and Akbarnezhad [20] examined the carbon emission savings related to structural system substitution and showed that an appropriate structural system selection may greatly impact the life cycle energy consumption of a building along with the associated carbon emissions.

Concrete and steel are the most popular building materials generally used not only because of their strength to remain high-quality for a long period of time but also because they are readily available, flexible, and reasonably priced compared with their counterparts [21,22]. In recent years, the use of timber as a replacement for concrete and steel has gained popularity in research focus. Owing to progress in innovation and engineering, a new class of potentially low-energy structural systems, such as laminated veneer lumber (LVL), cross-laminated timber (CLT), and glue-laminated timber (glulam) has been developed. These building materials are widely promoted because of their sustainability benefits in construction techniques, energy savings, life-cycle cost, recyclability, and reusability [23,24]. Despite the highlighted sustainability advantages, there is limited detailed research to analyse and compare the embodied carbon emissions of timber, brick, and steel structural systems of supermarket buildings, particularly the end-of-life processes.

Thus, this paper seeks to perform a comprehensive life-cycle analysis of the carbon emissions associated with the construction and end-of-life phases of a precast concrete and steel-frame building and compare it to brick and glulam structures. To achieve this, a case study of four building construction systems approved by a current UK supermarket is used. The study was chosen to compare the typical structural materials—concrete, steel, brick, and glulam—because these are commonly used in construction projects, such as supermarkets. Each material has its own unique properties that make it suitable for certain applications, but their selection often depends on a variety of factors. These factors include the cost, speed of construction, design requirements, local building regulations, and sustainability objectives. By comparing these specific materials, this paper seeks to offer a detailed understanding of the impacts of the material or structural-system selection on embodied carbon emissions, along with a building's overall sustainability. The findings of the study are expected to enhance the knowledge of embodied carbon estimation and reduction capabilities at the construction and end-of-life stages of glulam, steel, and brick structures. The research question underpinned in this article is: "Which structural system generates the least carbon emission and to what extent?" Related to the main question is a sub-research question listed as follows:

- "Which structural system has the greatest potential to reduce carbon emissions during the end-of-life?"

2. Materials and Methods

2.1. Construction Materials—A Review of the Literature

In the realm of construction, various materials have been utilised over the years to create structures that withstand the test of time. Among these materials, concrete, brick, steel, and glulam have emerged as popular choices owing to their unique properties and advantages.

Concrete is undoubtedly one of the most widely used construction materials. Concrete possesses exceptional compressive strength, making it a suitable choice for constructing foundations, walls, and pavements [21]. Its versatility enables it to be poured into moulds of varying shapes and sizes, allowing for flexible and creative architectural designs [21,22]. Additionally, concrete exhibits excellent fire resistance, providing a robust barrier against flames and high temperatures [25]. However, concrete is relatively heavy, making it necessary to reinforce structures with steel bars to enhance their tensile strength [26]. Furthermore, concrete requires time to cure, which can extend construction timelines.

Brick, on the other hand, is a traditional construction material that has been used for centuries. Usually manufactured from clay or shale, bricks offer durability, low maintenance, and resistance to pests and weathering [27]. Additionally, their aesthetic appeal adds a unique charm to buildings, making them a popular choice for both residential and commercial construction [28]. However, bricks are not as versatile as concrete, which limits the range of architectural designs that can be achieved [27]. They are also time-consuming to install, as each brick must be carefully laid and mortared into place.

Steel is renowned for its exceptional strength and durability, therefore making it an ideal material for constructing high-rise buildings, bridges, and industrial structures. Unlike concrete, steel possesses superior tensile strength, allowing it to withstand heavy loads without deformation [29]. Its relatively lightweight nature facilitates faster construction, reducing overall time and labour costs [30]. Moreover, steel frameworks can be prefabricated off-site and assembled on-site, enhancing efficiency and precision during construction [29]. However, steel is susceptible to corrosion, necessitating protective coatings or the use of stainless steel in corrosive environments. Additionally, steel structures are more vulnerable to fire, which requires appropriate fireproofing measures.

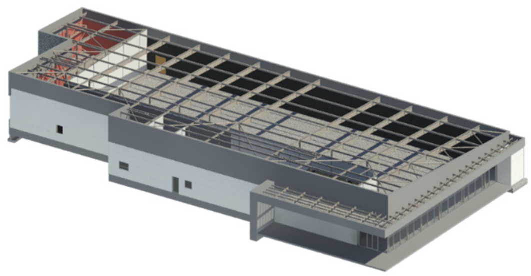
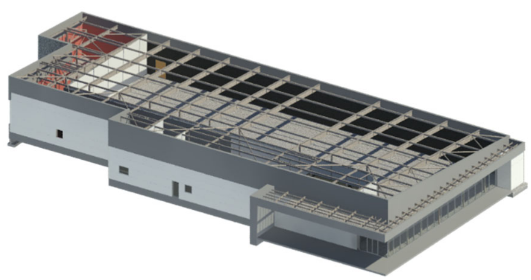
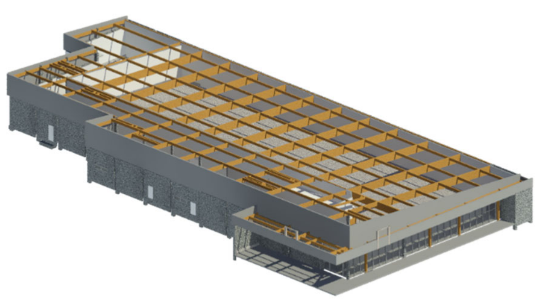
Glulam, short for "glued laminated timber", is an environmentally friendly alternative to traditional construction materials. Made by bonding multiple layers of timber using adhesives, glulam combines the natural strength and beauty of wood with enhanced load-bearing capabilities. Its exceptional dimensional stability, resistance to warping and shrinking, and excellent insulating properties make it suitable for a variety of applications, including beams, columns, and roof trusses [24]. Moreover, glulam provides a warm and inviting aesthetic, creating a soothing ambience within the built environment [23]. However, glulam has a limited span and may require additional support in large-scale structures. It is also prone to moisture damage if not appropriately protected [23].

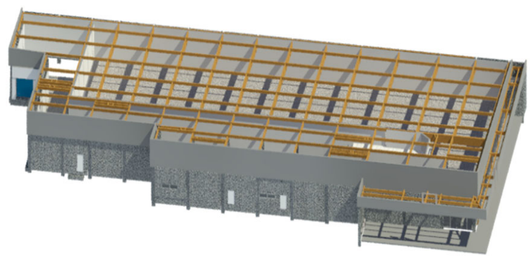
Meanwhile, past investigations have suggested that steel and concrete have higher embodied carbon emissions than their timber-based building counterparts [31,32]. However, in many instances, studies were based on hypothetical scenarios. Therefore, the adoption of real case studies could provide an important level of information for decision-making regarding timber-based materials and other building-material alternatives.

2.2. Description of Case Study and Justification

A supermarket building is investigated in this research. The buildings are the approved construction systems of a current UK supermarket. Autodesk® Revit® Building Information Modelling (BIM) software (2 0 2 1 0 8 0 5 _ 1 4 0 0 (x 6 4)) was used for modelling the buildings in the case study to aid the embodied carbon assessment [33], as displayed in Table 1.

Table 1. Description of building models, material specifications, and physical parameters.

Model	Building Component	Material	Material Details	Material Density (kN/m³)
CS1				
	External Walls	Cladding Panels	Sandwiched Cladding Panels with Mineral Wool Insulation	12.55
	Columns	Steel	Metal—Steel 50-355/43-275	77.01
	Beams	Steel	Metal—Steel 50-355/43-275	77.01
	Foundation	Concrete Slab	Cast-in-Place Concrete with RC25/30 and RC28/35 Strengths	23.61
CS2				
	External Walls	Poroton Brick	Clay Block—Poroton Block	0.59
		Cladding Panels	Sandwiched Cladding Panels with Mineral Wool Insulation	12.55
	Columns	Steel	Metal—Steel 50-355/43-275	77.01
	Beams	Steel	Metal—Steel 50-355/43-275	77.01
	Foundation	Concrete Slab	Cast-in-Place Concrete with RC25/30 and RC28/35 Strengths	23.61
CS3				
	External Walls	Precast Concrete	100 mm Thick Walls, Single-Skin Concrete Blocks	23.61

		Cladding Panels	Sandwiched Cladding Panels with Mineral Wool Insulation	12.55
	Columns	Precast Concrete	Reinforced Concrete—Precast	23.61
	Beams	Glulam	Glue-Laminated Timber	4.41
	Foundation	Concrete Slab	Cast-in-Place Concrete with RC25/30 and RC28/35 Strengths	23.61
CS4				
	External Walls	Precast Concrete	100 mm Thick Walls, Single-Skin Concrete Blocks	23.61
		Cladding Panels	Sandwiched Cladding Panels with Mineral Wool Insulation	12.55
	Columns	Glulam	Glue-Laminated Timber	4.41
	Beams	Glulam	Glue-Laminated Timber	4.41
	Foundation	Concrete Slab	Cast-in-Place Concrete with RC25/30 and RC28/35 Strengths	23.61

The buildings are a standard design of the supermarket. The four buildings in the case study are referred to as CS1, CS2, CS3, and CS4, as illustrated in Table 1. They are all single-storey, with an average area of 2500 m^2. The height of the front elevation of each building is 7.02 m, while the back elevation is 5.10 m. For CS2, Poroton brick (with outstanding fire-resistance and exceptional thermal features) external walls extend up to a height of 4.109 m, and cladding panel external walls extend from 4.109 m to 5 and 104—7.02 m. The precast concrete external walls of CS3 and CS4 extend to a height of 4.109 m, whilst the cladding panel external walls start from 4.109 m and 5.104 m extending to and go to 7.02 m. The finishes from CS1, CS2, CS3, and CS4 to the internal walls include paint and plasterboard. The floor coverings are ceramic tiles, vinyl, and paint. The windows are glazed and aluminium-framed with steel external doors.

Whereas the four standard designs of the supermarket buildings are similar in many ways, the key differences between them are the quantities of concrete, brick, steel, and glulam. For instance, the external walls of CS1 are mainly made of aluminium cladding panels with steel columns and beams. On the other hand, the external walls of CS2 are chiefly made up of brick with steel columns and beams, whilst the external walls of CS3 and CS4 are primarily made up of concrete. However, whereas CS3 has glulam beams and concrete columns, CS4 has glulam for both the beams and columns. Each material—concrete, brick, steel, and glulam—offers unique properties and advantages during construction; hence, their impacts on the embodied carbon emissions are assessed.

2.3. Life-Cycle Assessment

The embodied carbon life cycle of buildings involves numerous processes and activities. In this research paper, the adopted evaluation approach is in harmony with the four International Standard Organisation (ISO) standards for the LCA [34,35]: (i) goal and scope definition; (ii) life-cycle inventory (LCI); (iii) life-cycle inventory analysis (LCIA); (iv) interpretation of results.

2.3.1. Goal and Scope Definition and System Boundary

This study aims to assess the environmental performance of building materials and the carbon embodied in them. Three interrelated stages, namely, the product phase (extraction of raw materials, transportation, and production); the construction-process phase (transportation of materials to the site, installation, and erection); and the end-of-life phase (demolition, transportation of waste, processing/treating waste, and final disposal of waste), are determined as the system boundaries of this research, as illustrated in Figure 1. The benefits as well as loads associated with material recovery are also considered.

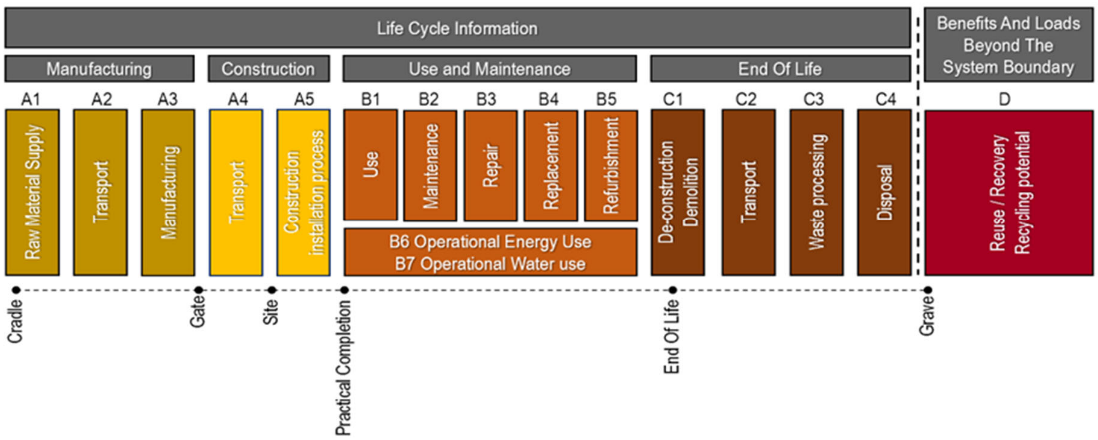


Figure 1. Life-cycle assessment framework, reproduced from reference BS EN 15978:2011 [36].

2.3.2. Analysis of Life-Cycle Inventory

To assess the environmental performance associated with individual materials at a particular stage, it was necessary to consider the contributions of the associated parameters, such as energy use and carbon emissions, to the overall activities of the building process, including construction, installation, transportation, and disposal processes. The primary input of the LCI and data used during this LCA phase was the process LCI. The process-based LCI was adopted to ensure the systematic estimation of the building materials (input and output attributes) within the study's boundary system. Using the systematic breakdown method, the carbon emissions of individual building materials and processes are derived per kilogram of material used. The formulae for the calculations were developed based on the LCA standards to quantify the carbon emissions embodied in the case-study building. The consumption of fuel and related carbon emissions associated with the manufacture of raw materials and transportation and installation processes, along with the demolition and waste-processing activity records were pursued from numerous data sources, including the Environmental Product Declarations (EPDs) from manufacturers/suppliers and site surveys. To strengthen the reliability of the results, carbon emission factors from EPDs were chosen as the preferred source. If data were unavailable from EPDs and reliable data sources, carbon emission factors were adopted from the literature.

2.3.3. Building Material Life-Cycle Impact Assessment

As stated above, one of the most frequently used and effective methods to assess and determine a building project's environmental impacts is the process-based quantification method. The method involves determining the sum of the environmental impacts of one or more activities needed to construct a particular building [37,38]. This method not only quantifies carbon emissions from individual activities and analyses them separately but also uses data to express the environmental impact of the respective component or material.

2.4. Quantification of the Life-Cycle Embodied Carbon

The estimation of the total life-cycle embodied carbon of each building was achieved by determining and summing the emissions during material extraction and production (EC_{ExtMat}), transportation (EC_{Tra}), construction (EC_{Con}), and demolition (EC_{Dem}) stages, as illustrated in Figure 1 and Equation (1).

$$EC_{Total} = EC_{MatExt} + EC_{Tra} + EC_{Con} + EC_{Dem} \quad (1)$$

2.4.1. Cradle-to-Practical Completion Estimation

The carbon emissions relating to the extraction of building materials and production stages are EC_{ExtMat}, usually described as cradle-to-gate carbon emissions, and are responsible for a substantial percentage of the entire embodied carbon in buildings. To calculate the cradle-to-gate carbon emissions of the various building materials, quantity take-offs for all the building materials were taken using Autodesk Revit BIM software. The amounts of the individual building materials were then multiplied by their corresponding carbon emission factors (CEFs), as sourced from the Bath Inventory of Carbon and Energy (ICE) database [39] and publicly available EPDs. Table 2 presents the cradle-to-practical completion CEFs used in this study.

Table 2. Cradle-to-practical completion-assigned embodied carbon factors.

Building Material	**CEF Detail**	**CEF ($kgCO_2eq./kg$)**
Aluminium	Aluminium Extruded Profile, European Mix, Inc. Imports	1.7063
	Aluminium Sheet, European Mix, Inc. Imports	3.2906
Brick	Clay, Brick	0.213
Cement	Mortar or Screed (1:3 cement and sand mix) (CEM 1)	0.2002
Concrete	100 mm Thick Walls, Single-Skin Concrete Blocks, Solid, High Density, Average Strength, Inc. Mortar	0.0966
	150 mm Thick Walls, Single-Skin AAC Concrete Blocks, Average Strength, Inc. Mortar	0.2569
	Concrete, RC25/30 with CEM 1 Cement	0.1286
	Concrete, RC28/35 with CEM 1 Cement	0.1362
	Precast Concrete Beams and Columns—Steel Reinforced with World-Average Steel	0.247
	Precast Hollow-Core Concrete Flooring, 150 mm, Prestressed Steel Reinforced with European Recycled Steel	0.1711
Floor Paint	Paint, General	2.91
Glass	Glass Toughened 3 mm, Ex Frame	1.6672
Glulam	Timber, Glulam No Carbon Storage	0.5121
	Timber, Laminated Veneer Lumber (No Carbon Storage)	0.3898
Gypsum Wall Board	Plasterboard	0.39
Insulation	Mineral Wool	1.28
Paint	Paint, General	2.91
Plaster	General (Gypsum)	0.13
Plastic	PVC pipe	3.23
Plywood	Plywood	1.1
Poroton	Clay, Brick	0.213
Steel	Steel Pipe	2.87

	Steel, Organic Coated Sheet	3.06
	Steel, Section (Primary)	3.03
	Steel, Sheet Hot-Rolled Coil	2.28
	Steel, Sheet Hot-Dip Galvanised Steel	2.76
Vinyl		2.85
Building Material		CEF ($kgCO_2eq./m^2$)
Sandwiched Panels		44.5284
Roof panels		35.616
Tiles (Ceiling)		17.2
Tiles (Floor)		10.5

The embodied carbon from the material extraction is calculated by Equation (2):

$$EC_{MatExt} = (1 + \ _i) * Q_i * ff_i \quad (2)$$

where EC_{MatExt} represents the total carbon emission of material i (in $kgCO_2eq.$), $_i$ refers to the ith material's waste factor, Q_i corresponds to the quantity of the ith material that is consumed (measured in kg), while ff_i corresponds to the fuel-consumption (energy) factor for the ith material (measured in $kgCO_2eq./kg/km$).

The construction of a building also involves a lot of carbon emissions resulting from transport activities (EC_{Tra}). The mode of transport along with the type and capacity of the truck used for the transportation of the materials were employed to decide their fuel consumption and the resulting carbon emissions. Table 3 shows the values assumed for these calculations.

Table 3. Transport modes, emission factors, and distances.

Building Component		**TEF (Mode)**	**TEF ($kgCO_2eq./kg/km$)**
Basic Roofs Ceilings Curtain Walls	Internal Walls and Partitions Roof Fittings Windows	Road Transport Emissions, Average Laden	0.0001065
Basic Roofs Ceilings Electrical Cabling System External Doors External Wall Finishes External Walls Floor Finishes Floors/Slab	Ground-Bearing Slab Internal Doors Mechanical Duct System Plumbing and Piping System Screed Structural Columns Structural Foundations Structural Framing	Road Transport Emissions, Fully Laden	0.00007524
Building Component		TD (Mode)	TD (km) by Road
Basic Roofs Ceilings Electrical Cabling System External Walls Floors/Slab Ground-Bearing Slab Internal Walls and Partitions	Mechanical Duct System Plumbing and Piping System Roof Fittings Screed Structural Columns Structural Foundations Structural Framing	Local Manufacturing	50
Ceilings External Wall Finishes	Floors/Slab Internal Walls and Partitions	National Manufacturing	300

External Walls Floor Finishes	Roof Fittings Screed		
Basic Roofs Curtain Walls External Doors	External Walls Internal Doors Windows	European Manufacturing	1500

In addition to the mass of materials to be conveyed, the distance of the journey can significantly impact the amount of carbon emissions associated with transportation. Hence, the carbon emissions associated with transportation are estimated using Equation (3) as follows:

$$EC_{Tra} = [FEy * f_T * dm\ (w_i + w_T)]/1000 \quad (3)$$

where EC_{Tra} denotes the total carbon emissions resulting from transportation; FEy refers to the carbon emission factor for the type of energy/fuel that is used (y) (in $kgCO_2eq./MY$), while f_T stands for the fuel content factor of the conveying truck (T) (in MY/tonne-km); dm denotes the travelling distance of the transporting truck (in km); w_i represents the material weight of i; w_T, the weight of the conveying truck (T), respectively, (in kg).

The carbon emissions due to construction and installation operations (EC_{Con}) were calculated by multiplying the carbon emissions for the duration that the machinery was used and the rates of fuel consumption. The fuel-based equation was used because carbon emissions are related to the consumption of fuel. Thus, EC_{Con} was quantified using Equation (4) as follows:

$$EC_{Con} = (FEz * f_z * qz)/1000 \quad (4)$$

where FEz denotes the content factor for the type of fuel that is consumed (y) (in GY/kL), whilst fz represents the carbon emission factor (in $kgCO_2eq./GY$), and qz refers to the fuel that is consumed (in kL).

2.4.2. End-of-Life Estimation

The total carbon emissions related to end-of-life activities, such as the demolition of the building, transportation of demolition waste materials to recycling plants, and/or disposal at the landfill (EC_{Dem}), are determined by the treatment options that are adopted. In this study, recycling and disposal (landfilling) were adopted because the initial design for the construction of the building did not adopt the design for disassembly principles. The carbon emissions associated with various activities at each stage are paramount to the end-of-life carbon emission estimation, as they serve as key parameters or inventory data. Among the key parameters are the rates of fuel/energy used by machines, the total distance covered by trucks, the rates of fuel/energy consumed by trucks, the CEF per unit of energy, and the CEF of demolition waste materials. Table 4 presents the CEFs for the waste materials at various stages.

Table 4. End-of-life stages and carbon emission factors.

Stages	CEF ($kgCO_2eq.$)
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, Timber (Glulam), and Tiles	3.400 [bc]
Transportation Stage (C2)	
Transportation of Waste Materials to Treatment Facilities and Landfill Sites:	
Aluminium	0.0131 [a]
Bricks	0.0015 [d]

Concrete	0.0017 [d]
Steel	0.040 [d]
Plastics, Glass, Plaster, Paint, Gypsum, Mineral Wool, Timber (Glulam), and Roof	0.0054 [bc]
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 [bc]
Timber (Glulam)	1.67 [bc]
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 [bc]
Timber (Glulam)	2.15 [bc]
Tiles	4.63 [a]
Material Recovery and Benefit (D)	
Aluminium	−3.98 [a]
Bricks	−0.0207 [d]
Concrete	−0.0053 [d]
Glass	−0.39 [d]
Steel	−1.45 [d]
Timber (Glulam)	−0.524 [bc]
Roof	−17.43 [a]

[a] Environmental Product Declaration (EPD) from manufacturers/suppliers; [b] [40]; [c] [41]; [d] [42].

The equations used for the carbon emission calculations for the end-of-life stages are discussed below in detail.

The carbon emissions for the estimated operation times of plants and machines during the demolition can be represented by Equation (5) [43,44] as follows:

$$EC_{equip} = \sum EQi * EQFi * EQECi \quad (5)$$

where EC_{equip} is the carbon emissions resulting from the use of plants and machines to demolish or dismantle the building at the end of its service life ($kgCO_2eq.$), EQ_i denotes the number of hours required using machine i to demolish or dismantle the building, EQF_i represents the type of fuel used by machine i in the building demolition (L/h), and $EQEC_i$ is the CEF of the rate of fuel consumed per machine i ($kgCO_2eq./L$).

The demolished building waste needs to be transported to a recycling facility and/or landfill site. The carbon emission linked to the loads of trucks, distance covered, along with the fuel that is used can be estimated using Equation (6) as follows:

$$ECtranspW = \sum_{i}^{n} TDi * TLi * TFi * TCEFi \quad (6)$$

where $EC_{transpW}$ is the emissions associated with transporting waste materials, TD_i denotes the total distance covered for transporting material i to the processing facilities and landfill sites from the demolition site (km), TL_i is the number of truck loads required for conveying material i in (tonnes), TF_i is the rate of fuel consumption per truckload per kilometre

(L/km), and $TECF_i$ represents the CEF of a unit of fuel consumed in transporting material i ($kgCO_2eq./L$).

Additionally, the return journeys of the empty trucks are considered in this study. Therefore, the carbon emissions associated with the return journey can be estimated using Equation (7) as follows:

$$\mathrm{ECtranspR} = \sum_{i}^{n} \mathrm{TD}r * \mathrm{TFr} * \mathrm{TCEFr} \quad (7)$$

where $EC_{transpR}$ is the emissions associated with the return journeys, TD_r denotes the total distance covered for the return journeys from the recycling facilities and disposal sites to the demolition site (km), TF_r refers to the unit of fuel consumed per return journey (L/km), whilst $TECF_r$ represents the CEF per unit of fuel consumed for the return journey ($kgCO_2eq./L$).

The overall emissions associated with the distances covered in transporting waste materials are estimated by totalling all the journeys for the corresponding number of truckloads using Equation (8) as follows:

$$\mathrm{ECtransp} = \sum_{i}^{n} \mathrm{ECtranspW} + \mathrm{ECtranspR} \quad (8)$$

where EC_{transp} is the overall carbon emissions related to transporting the demolition waste materials.

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

$$EC_{rec} = Q_{wi} * CEF_{wi} \quad (9)$$

where EC_{rec} denotes the carbon emissions associated with waste treatment during recycling ($kgCO_2eq.$), Q_w represents the quantity of waste material i that is being processed, while CEF_w is the carbon emission coefficient of waste material i.

Accordingly, the overall carbon emissions resulting from the processing (recycling) and disposal (landfilling) of demolition waste materials can be estimated using Equation (10) and (11), respectively, as follows:

$$EC_{tot,landfill} = \sum D_{em} + T_{ransp} + D_{is} \quad (10)$$

where $EC_{tot,landfill}$ represents the total carbon emissions resulting from landfilling waste material i; D_{em} denotes the carbon emissions associated with the machine during demolition; T_{ransp} refers to the carbon emissions from transporting waste material i to the disposal site, including return journey; and D_{is} represents the carbon emissions that may occur due to decay associated with the disposal of waste material i.

$$EC_{tot,recycling} = \sum D_{em} + T_{ransp} + P_{ro} \quad (11)$$

where $EC_{tot,recycling}$ represents the total carbon emissions resulting from recycling waste material i; D_{em} denotes the carbon emissions associated with the machine during demolition; T_{ransp} refers to the carbon emissions from transporting waste material i to the recycling plant, including return journey; and P_{ro} represents the carbon emissions associated with processing waste material i.

One of the key objectives of this paper is to perform a comparative analysis of the embodied carbon emissions of four buildings constructed with various material components. Hence, Equation (12) is proposed for comparing the total carbon emissions of the buildings as follows:

$$PcD = \{(X\text{-}Y)/Y{*}100\} \quad (12)$$

where PcD is the proportion of comparative differences (%), X is the carbon emissions calculated for the building compared with those calculated for the baseline building, and Y is the sum of the carbon emissions calculated for the baseline building.

2.5. Assumptions

Numerous sources can provide CEF data, including EDPs from manufacturers or suppliers, eco-databases, the literature, and many others. As noted by Ge, Luo, and Lu [45], to improve the accuracy of the assessment outcomes, CEFs should be chosen carefully. Consequently, in this paper, EPDs were the first preferable source of CEF data. Where EPDs were unattainable, CEFs were sought from databases, while the literature was the least preferred data source.

Meanwhile, demolition waste materials are classified based on previous studies [46] and data from demolition contractors, as listed in Table 5. Type A includes aluminium, bricks, concrete, steel, glass, and timber; and Type B includes gypsum, mineral wool, paint, plaster, plastics, and tiles. In Type A, a percentage of the materials is recycled, and the remaining is landfilled; while in Type B, 100% of the materials is landfilled.

Table 5. Waste material groups for end-of-life treatment.

Waste Material	Building Components
Type A	
Aluminium	Doors, Roof, Windows
Bricks	Walls
Concrete	Floors, Foundations, Walls
Glass	Doors, Windows, Curtain Walls
Steel	Structural Frames, Steel in Concrete, Iron Pieces, Roof
Timber	Ceilings, Structural Frames, Roof, Walls
Type B	
Gypsum	Ceilings, Walls
Mineral Wool	Walls, Roofs
Paint	Floors, Walls
Plaster	Walls
Plastics	Pipes, Other Plastic Materials
Tiles	Ceilings Floors, Walls

Furthermore, Table 6 presents the waste material weight proportions for each treatment option. Demolition waste materials are assumed to be transported by a heavy-duty diesel truck to a maximum distance of 50 km for processing and/or to disposal facilities [40,47]. In addition, the processing of recyclable waste materials is accounted for in C3 and has a minor effect on C4, which is ascribable to the unrecyclable small portion sent to landfills with other demolition waste materials.

Table 6. Waste distribution for treatment.

Waste Material	Demolition/ Dismantling	Treatment Option (%)	
		Recycle	Landfill
Aluminium	Demolition	80 [c]	20
Bricks	Demolition	90 [de]	10
Concrete	Demolition	90 [e]	10
Paint	Demolition		100
Glass	Demolition	50 [e]	50

Timber	Demolition	90 [e]	10
Gypsum	Demolition		100
Mineral Wool	Demolition		100
Plaster	Demolition		100
Plastics	Demolition		100
Steel	Demolition	92 [ab]	8
Tiles	Demolition		100

[a] [40]; [b] [41]; [c] [48]; [d] [49]; [e] Contractor's confirmation.

3. Results

3.1. Material Quantities

Table 7 summarises the quantity take-off scores from the comprehensive design analysis of the four different buildings in the case study. The main differences between the material quantities of the four construction methods are concrete, bricks, steel, and glulam. As shown in Table 7, CS1 (the baseline building) has the lowest material quantity. In comparison to CS1, CS2 has approximately 19% more; CS3, roughly 25% more; and CS4, nearly 18% more materials than CS1. Additionally, concrete comprises most of the material quantity among the four building systems. For example, concrete accounts for around 80% in CS1, 67% in CS2, 89% in CS3, and 87% in CS4.

Table 7. Building material quantities and weights.

Building Material	Weight (t) CS1	Weight (t) CS2	Weight (t) CS3	Weight (t) CS4
Aluminium	16.69	16.77	10.24	10.24
Bricks/Poroton	26.95	403.74	-	-
Concrete	1476.30	1463.47	2045.25	1904.27
Glass	8.11	8.11	8.11	8.11
Steel	151.64	139.29	46.83	46.83
Timber (Glulam)	1.67	1.67	49.34	66.84
Gypsum	43.54	67.37	38.72	38.82
Mineral Wool	52.40	28.87	46.21	46.21
Paint	0.29	0.28	0.15	0.15
Plaster	0.32	0.31	2.55	2.55
Plastics	0.12	0.12	0.12	0.12
Tiles	60.30	60.30	61.64	61.64
Total	1838.33	2190.30	2309.16	2185.78

In contrast with concrete, steel accounts for about 8% in CS1, 6% in CS2, and approximately 2% in both CS3 and CS4. Timber-based materials account for nearly 3% in CS4, 2% in CS3, and approximately 0.08% in both CS1 and CS2. On the other hand, aluminium represents less than 1% of the total mass of building materials in all the building systems. The differences in the material quantities may be due to the specific site location requirements and the design adopted to construct the buildings.

3.2. Comparative Analysis of Embodied Carbon Emissions

Figure 2 displays the total life-cycle embodied carbon emissions of the four building systems. The assessment results demonstrate that CS4 generates the least embodied carbon emissions compared to the other three buildings. Compared to CS1, CS4 generates approximately 17% less embodied carbon emissions, CS3 creates about 13% less and CS2 generates up to 10% more.

The assessment results further indicate that in comparison with the end-of-life phase, the construction phase contributes much more to the overall embodied carbon emissions of the buildings' life cycle. In comparison with the end-of-life phase, the construction phase generated almost 11 times more carbon emissions in both CS1 and CS2, whilst it generated about 10 times more carbon emissions than the end-of-life phase in CS3 and CS4.

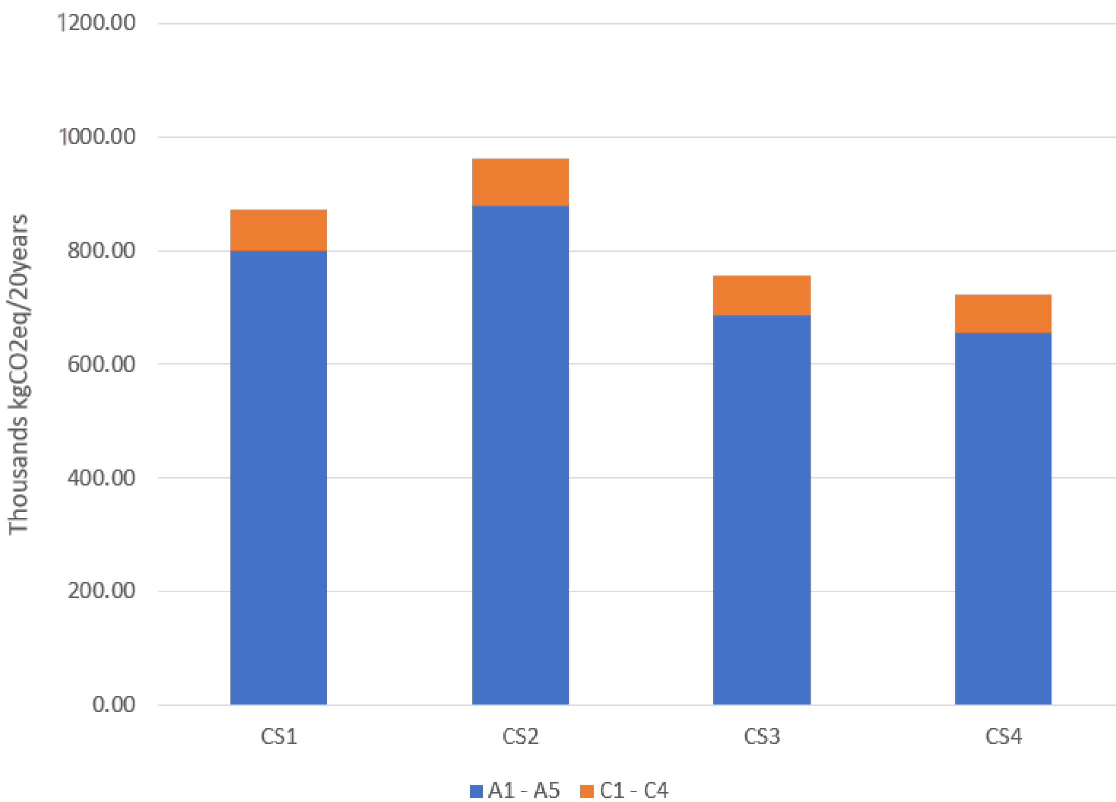


Figure 2. Comparison of embodied carbon emissions over 20-year lifespan.

3.3. Assessment of End-of-Life Treatment Options

The amount of carbon emissions that occur during the end of a building's lifespan is largely determined by the treatment option that is adopted. Generally, three options are available to deal with demolition waste materials, namely: reuse, recycling, and disposal. In this study, however, recycling and disposal (at landfills) were used, owing to the method that was adopted in the initial construction of the buildings, to examine the most preferable method for treating the supermarket waste materials.

The LCA results from the two end-of-life treatment strategies and the detailed contributions of each option are presented in Figure 3. According to the results, the recycling treatment method generates the highest amount of carbon emissions among all the buildings in the case study. In comparison with the landfilling treatment method, recycling creates almost six times more carbon emissions in both CS1 and CS2, seven times more in CS3, and eight times more in CS4.

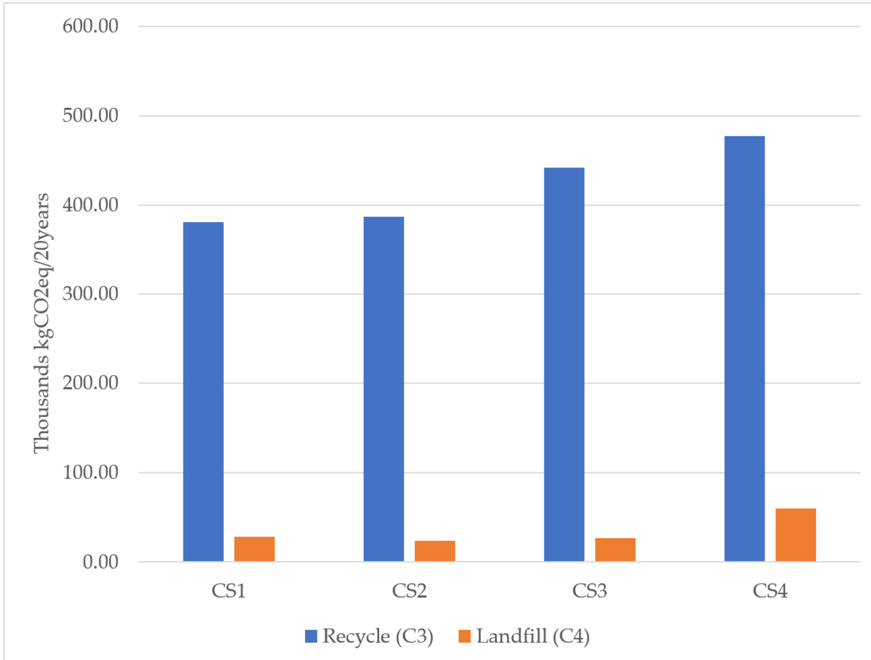


Figure 3. End-of-life treatment options over 20-year lifespan.

3.4. Material Recovery and Carbon Emission Reduction Potential

Figure 4 presents the material recovery and carbon emission reduction potential associated with each of the building systems that was considered. The negative values indicate the amount of carbon emissions that can be avoided in future projects owing to the substitution of steel, aluminium, concrete, bricks, glass, and timber during construction. As exhibited in Figure 4, CS2 generates the greatest substitution impacts or the potential for reducing carbon emissions in future construction projects. In contrast with CS1, CS2 generates slightly more (about 0.2%), CS3 creates approximately 18% less, while CS4 produces roughly 16% less than CS1.

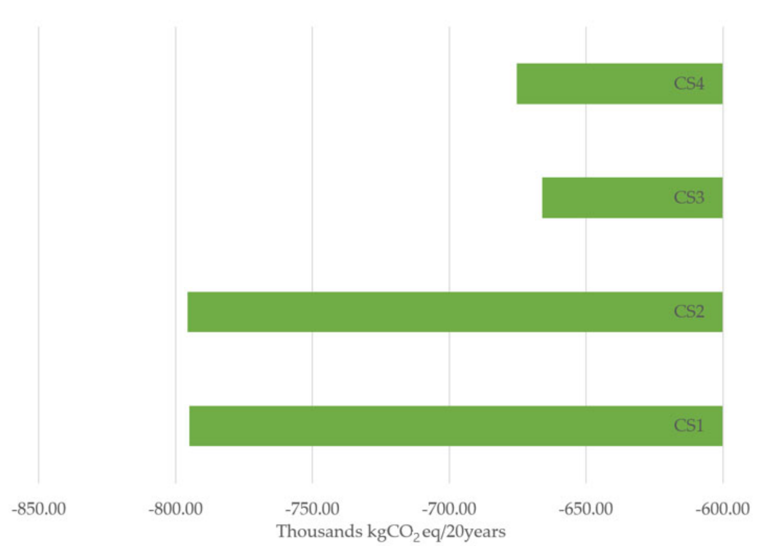


Figure 4. Distribution of material recoveries and carbon emission reduction potentials over 20-year lifespan.

4. Discussion

This paper seeks to perform a full life-cycle analysis of the carbon emissions associated with the end-of-life and construction phases of a precast concrete and steel-frame building and compare them with those associated with the end-of-life and construction phases of full glulam, Poroton brick and steel-frame, and half-glulam structures. It also aims to offer detailed insight into the impacts of the choice of building materials on the embodied carbon emissions and overall building sustainability. Two end-of-life treatment methods were adopted to examine the most preferable method for treating the supermarket waste materials.

First, the outcome of the comparative assessment of the research showed that the usage of timber-based materials, such as glulam, can reduce embodied carbon emissions. Compared with CS1, CS4 can save approximately 148,960.68 kgCO_2eq. of carbon emissions. This result is comparable to the findings revealed by a past study in Australia by Li, Rismanchi, and Ngo [31]. Using three hypothetical scenarios, the authors found that 15,397 tonnes of carbon emissions could be saved if all the slabs, beams, and columns in scenario 1 (reinforced concrete) were substituted with timber in a high-rise building. Similarly, in a scenario-based study to examine and compare the carbon emissions from the use of timber and concrete materials in the construction of structures, Sandanayake et al. [32] found that a total of 523.6 kgCO_2eq./m^2 was emitted for concrete buildings and 508.8 kgCO_2eq./m^2 was emitted for timber structures. The total embodied carbon emissions in CS3 are also lower than those in CS1 (115,929.72 kgCO_2eq.). Consequently, with regard to embodied carbon emissions, buildings constructed with glulam perform better than their steel and Poroton brick counterparts. This suggests that replacing as much steel and Poroton brick as possible with glulam to construct buildings can achieve the most significant reduction in embodied carbon emissions.

Although the embodied carbon emission reduction benefits resulting from substituting timber-based materials have been suggested in some previously published studies, most of the analyses are not based on real scenarios. For example, both studies by Li, Rismanchi, and Ngo [31] and Sandanayake et al. [32] were based on hypothetical scenarios. Therefore, the adoption of real case studies could provide an important level of information for decision-making regarding timber-based materials and other building-material alternatives.

Furthermore, the results from both end-of-life treatment strategies revealed that recycling was the most preferred method for treating the supermarket waste materials. This was shown by the volume of carbon emissions produced by both treatment options. In contrast with landfilling, recycling generated the greatest carbon emissions. In all four building systems that were considered, the carbon emissions from landfilling (disposal) are at least six times lower than those from recycling. This could be partly because at most, only 10% of the waste materials from each building were treated and disposed of in landfills during the end-of-life stage. This finding supports the conclusion drawn in previously published research [50], which proposes that landfilling or disposal should always be avoided whenever possible. Thus, by recycling more demolition waste materials, the end-of-life management strategy is aligned with the principles of sustainability and the waste hierarchy framework.

Finally, the amount of carbon emissions that can be avoided owing to material recovery and subsequent substitution in future projects was evaluated. The results indicated that CS2 has the highest carbon emission reduction potential. Compared with CS1, CS2 has a relatively higher carbon emission reduction potential by nearly 0.2%. On the other hand, compared with CS1, CS3 and CS4 have lower carbon emission reduction potentials by approximately 18% and 16%, respectively. The main materials responsible for the carbon emission reduction potential are steel, aluminium, timber (glulam), and concrete. For example, steel represents about 8% of the total material quantity in CS1, 6% in CS2, and approximately 2% in both CS3 and CS4. However, it contributes the greatest total substitution effects or potential to reduce carbon emissions in future construction projects in comparison with concrete, which accounts for almost 80% in CS1, 67% in CS2, 89% in CS3, and 87% in CS4. This finding supports past research by Wang et al. [46]. In their investigation, an LCA was performed on building demolition waste materials to explore the effective reuse/recycling potential of an entire building. The authors found that whereas aluminium represents almost 1% of the total mass of generated building waste, it contributes nearly 45% of the substitution impacts. This is vital because the use of recycled demolition waste materials in future construction projects can assist not only in minimising the demand for virgin building materials but also reduce the embodied carbon emissions from and building waste materials disposed of in landfill sites.

Although previously published research has hinted at the environmental benefits of recycling and subsequently reusing building waste materials in future projects, other waste materials with equally significant environmental performances have been disregarded. For example, Blengini [51] only evaluated steel and aggregates but did not evaluate building materials, such as timber and aluminium. This research, on the other hand, has demonstrated that by recycling different building waste materials, an even greater percentage of carbon emissions can be reduced through material substitution. Consequently, the inclusion and subsequent utilisation of recycled demolition waste materials in the design phase of projects can be a fundamental way to maximise the potential of recovered waste materials while reducing the amount of waste to dispose of at landfill sites.

5. Conclusions

In this article, a full evaluation has been conducted for the carbon emissions associated with the construction life-cycle phases and end-of-life of buildings. A case study of four buildings with the same dimensions was employed. The four buildings were designed using Autodesk® Revit® BIM software, each with different proportions of steel, bricks, timber, and concrete, to facilitate the comparison. Two end-of-life treatment methods were considered to evaluate the carbon emissions along with the environmental benefits that can offset the environmental impacts of future projects.

The study results show that in comparison with the other three structures, CS4 currently presents marginal gains in embodied carbon emissions. Compared with CS1 (the baseline building), CS4 generates nearly 17% less embodied carbon emissions, whereas CS3 creates about 13% less. Conversely, in comparison with CS1, CS2 (Poroton brick) generates up to 10% more. This suggests that replacing as much steel and Poroton brick as possible with glulam to construct buildings can achieve the most significant reduction in the total embodied carbon emissions.

The results further revealed that of the two end-of-life treatment strategies, recycling generated the highest carbon emissions in contrast with landfilling. In all four buildings that were considered, the carbon emissions from landfilling (disposal) were at least six times lower than those from recycling. This indicates that more end-of-life waste materials were recycled instead of landfilled and suggests that the main strategy that was adopted to treat demolition waste at the end-of-life stage is aligned with the principles of the waste hierarchy framework.

In addition, this study showed the environmental benefits of the substitution of raw materials through recycling and subsequent reuse in future projects. Overall, compared with CS1, CS2 (precast concrete and Poroton brick) had a relatively higher carbon emission reduction potential by almost 0.2%. In contrast, compared with CS1, CS3 and CS4 had lower carbon emission reduction potentials by about 18% and 16% respectively.

In summary, the outcome of the comparative assessment reveals that there are minor variations in the embodied carbon emissions of the building systems used by the supermarket. CS4, although currently presenting marginal gains in embodied carbon emissions, loses its advantages when recycled building material contents are considered for future projects.

This study recommends some helpful suggestions for designers and other construction stakeholders. First and foremost, the study findings can enhance the knowledge required for estimating the embodied carbon emissions and reduction capabilities of timber, steel, and brick buildings. By evaluating the two most used treatment approaches (recycling and landfilling) at the end of a building's lifespan, the study offers indicators that facilitate the selection of the most sustainable waste treatment strategy for a particular building whilst guiding the process of decision-making. Finally, the proposed detailed method for quantifying embodied carbon emissions can be adopted in similar projects around the world.

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