Measuring and Mitigating Embodied Carbon in Educational buildings: A case study in the UK

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Abstract. Embodied carbon is a significant contributor to a building's greenhouse gas (GHG) emissions. Thus, decarbonizing the building industry is a necessary response to national and global carbon reduction objectives. During the design stage, architects have the opportunity to reduce a building's embodied carbon. However, minimizing embodied carbon requires evaluating embodied carbon emissions during various life cycle phases. Recently, researchers have shown increased interest in the Life Cycle Assessment (LCA) of buildings, a methodology for assessing environmental impacts at all stages of a building's life. This research aims to determine the impact of using 'low-carbon materials' strategy on the total embodied carbon of an educational building using LCA and three different data sources: EPDs, the ICE database, and RICS guidelines. The analysis of the building indicated that metal and concrete materials generate the most embodied carbon, approximately 1038 and 552 tonCO_2e, respectively. It was also determined that the Product Stage accounts for over 80% of total emissions. Moreover, using recycled metal material, low-carbon concrete, light-coloured brick, and Rockwool can reduce embodied carbon by 47%, 43%, 10%, and 43%, respectively. Consequently, the embodied carbon of the building has the potential to be reduced by 37% overall.

Keywords: Embodied Carbon, Life Cycle Assessment, Embodied carbon reduction strategy, data sources, GHG emissions

1. Introduction

The Paris Agreement, which was ratified during the Paris climate conference (COP21) in 2015, is the world's first universal, legally binding agreement to address global climate change and stipulated that the global average temperature must be maintained "well below 2 ^{0}C & pursuing efforts to limit it to 1.5°C" (United Nations, 2015).

After the Paris Agreement in 2015, the European Union (EU) established its own plan and released the European Green Deal in December 2019, which involves a thorough and far-reaching transformation for both EU members and nations that engage in trade with the EU. The EU has set its sights on lowering carbon emissions in Europe by 55% from 1990 levels by the year 2030. The ultimate objective of the EU is to become the world's first carbon-neutral continent by the year 2050, as demonstrated by the "Fit for 55" program, which was introduced in July 2021 in accordance with this objective. In the long run, the target is to achieve net zero greenhouse gas emissions by the year 2050 (European Commission, 2019). The UK's Sixth Carbon Budget necessitates a 78 percent reduction in carbon emissions by 2035, compared to 1990 levels, in order to reach net zero emissions by 2050. At COP26, the UK Government pledged to reduce carbon emissions by 68% by 2030, compared to 1990 levels (Building to net zero: costing carbon in construction, 2022).

COP 27 saw countries present a resolution package that reaffirmed their commitment to limit global temperature rise to no more than 1.5°C above pre-industrial levels. The decision package strengthens countries' actions to reduce greenhouse gas emissions and adapt to the unavoidable impacts of climate change, as well as increase the financial, technological, and capacity-building assistance that developing nations require (COP 27: Delivering for people and the planet, 2022).

Buildings have a crucial role in implementing the Paris Agreement (Rockström et al., 2017) as they account for 39% of all global energy-related carbon emissions (Adams, Burrows and Richardson, 2019) Carbon emissions divide into two categories: operational carbon and embodied carbon. In more detail, 28% of carbon emissions come from operational carbon (carbon emitted during the heating, cooling, lighting, etc.) and 11% belong to embodied carbon (CO_2 emitted throughout the extraction, manufacture, transportation, construction, and demolition of a building).

Recent studies contend that the focus has shifted from operational carbon to embodied carbon as low/zero carbon building design and renewable energies have become increasingly popular (Kayaçetin and Tanyer, 2020; Malmqvist et al., 2018). According to the findings by (Salem et al., 2020), the nearly-zero energy buildings standard is possible and could be applied to existing UK structures. The highlighted outcomes illustrated that the standard is reachable through well-considered design decisions and careful consideration of a building's resilience to a changing climate, which can result in long-term energy savings.

In other words, with improved energy efficiency, decarbonization of grid electricity, and the use of more materials in buildings (i.e. thicker insulation, double-glazing, additional technologies, etc), embodied carbon is now seen as a major contributor to the ongoing environmental impacts of the built environment (Vickers et al., 2021; Teng and Pan, 2020; Schmidt et al., 2020). This means that embodied carbon can represent a higher proportion of whole life carbon than it used to. Thus, embodied carbon has become significant and can represent 40-70% of Whole Life Carbon in a new building (LETI Embodied Carbon Primer, 2020). Unlike operational carbon which only relates to energy used to keep the building running when in-use, embodied carbon is associated with different phases of the building's life (Ekundayo et al., 2019). Also, embodied carbon is released in a short time, which can have annual impacts compared with operational carbon (Sandanayake et al., 2017).

Increasing building constructions have become one of the fastest-growing drivers of carbon emissions. Energy conservation and carbon reduction in buildings is crucial in the context of global carbon neutrality (Chen et al., 2022).

According to the World Green Building Council (World GBC), embodied carbon is expected to account for 50% of all carbon emissions from new construction projects. A new vision released in 2019 called for a reduction in embodied carbon of at least 40% by 2030 and a goal of net-zero embodied carbon by 2050 for all new structures, infrastructure, and renovations (United Nations, 2015). There are three primary categories of low-embodied-carbon solutions for buildings: whole-building design, one-for-one material substitution, and specification. In general, whole-building design solutions can result in the highest reductions in embodied carbon. Yet, material substitution can also result in significant reductions in embodied carbon, particularly when applied to carbon-intensive materials such as concrete and steel (Esau et al., 2021). Ref. (United Nations, 2015) concluded the use of cement replacements such as pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) can have a significant effect in reducing the embodied carbon for concrete. It was noted that steel accounted for a minor portion of the total consumption of building materials but was the largest user of energy and carbon emitter (Chen et al., 2022). For energy-intensive building materials like steel, improving steel recycling and using low carbon energy sources in manufacturing are effective strategies. Also, by transforming the currently dominated Basic Oxygen Furnace to Electric Arc Furnace, significant carbon reductions in steel production can be achieved (Chen et al., 2022). Depending on the building type, strategies for reducing embodied carbon can vary. According to (Robati and Oldfield, 2022) the embodied carbon profile of concrete and timber buildings requires different strategies to minimize their environmental impact. In concrete structures, the majority of embodied carbon emissions occur in stage A of the lifecycle. This indicates that initiatives to dematerialize concrete in structural design, reduce emissions through cement replacement materials, or decarbonize the supply chain would be the most effective at reducing embodied carbon. In contrast, timber structures would benefit from end-of-life emission reduction techniques. In general, mass timber buildings have the potential to have lower embodied carbon emissions than concrete buildings, even when cement replacement materials are considered.

Studies have shown that structural materials can be responsible for up to 50% of initial embodied carbon, and up to 20% of whole lifecycle carbon (Robati et al., 2021; Robati et al., 2018; Robati et al., 2017; De Wolf et al., 2017; Akbarnezhad and Xiao, 2017).

Ref. (Chen et al., 2022) showed that cement, steel, brick, lime, and linoleum were five major materials with high embodied energy and carbon. Approximately 93.1% of the total embodied energy and about 95.7% of the total embodied carbon were associated with the five materials.

In recent years, the LCA of buildings has received a growing amount of attention from the academic community. However, since many professionals in the building business are unfamiliar with the LCA, very few new construction projects utilize it (Pai and Elzarka, 2021). The LCA methodology, which was widely standardized in the 1990s, aims to measure the environmental impacts of products and processes throughout their whole life cycle, i.e., "from cradle to grave" (Hellweg and Milà i Canals, 2014). The LCA approach, a crucial tool mandated by the International Organization for Standardization (ISO) 14040/14044 (Pai and Elzarka, 2021; Hellweg and Milà i Canals, 2014) for calculating and assessing the embodied carbon of buildings, has been widely utilised.

Over the last few years, considerable work has been conducted into developing formal standards and recognized industry reports for practitioners conducting an embodied carbon assessment (Teng et al., 2018). In compliance with EN 15804 (Esau et al., 2021), the Environmental Product Declarations (EPDs) were established in 2014 to explain the environmental implications of various building materials. These EPDs were a significant step towards regulating the embodied carbon assessment of buildings (BS EN 15804, 2021). EPDs are a growing source of environmental data in the construction products market and are increasingly being used for (1) environmental performance assessment of buildings and (2) product comparison for procurement decisions during the later stages of building design (Waldman, Huang and Simonen, 2020).

Also, institutions issued reports on the methodology of embodied carbon analysis. The Royal Institute of Chartered Surveyors (RICS) published Whole life carbon assessment for the built environment,' which provides information for conducting embodied carbon assessment and is widely accepted methodology (Papakosta, 2017).

In terms of the database, the Inventory of Carbon and Energy (ICE) is a popular database developed by the University of Bath, UK (Papakosta, 2017), which provides emission factors of materials based on references collected from a range of public sources, such as journal papers, reports, books, and conference papers. Other well-known databases are Ecoinvent, Gabi, and the UK Department for Business, Energy, and Industrial Strategy (BEIS) database (Hammond and Jones, 2008).

Moreover, there are some software programs for embodied carbon assessment; the most famous ones are OpenLCA, and SimaPro. Ref. (Li, 2021) found that some LCA tools are not adequate enough to provide full life cycle carbon emission results and also nearly all of the tools are region-specific data and are subject to regional building norms; thus, applicability needs to be further discussed when applying to areas rather than the country of origin.

Ref. (Hart, D'Amico and Pomponi, 2021) compared the mass and whole-life embodied carbon (WLEC) emissions of building superstructures. The cradle-to-gate modules A1–A3 have been assessed through SimaPro 9, Freight transport to the construction site (module A4) is modeled using UK BEIS database and values for emissions associated with other stages of the building's life are derived from literature benchmarks. Normalised results showed clear differences, with the concrete frame having approximately five times the mass of the timber frame and 50% higher than the steel frame, with median values of 119, 185, and 228 $kgCO_2e/m^2$ for the timber, concrete, and steel frame, respectively.

A Whole Life Carbon Assessment was conducted in a residential structure, and the results showed that metal and concrete components had the greatest embodied carbon at 40.56 and 31.03 $tonCO_2e$, respectively. Also, it showed how utilising recycled metal, less carbon-intensive concrete, and recyclable aluminum can each cut CO_2 emissions by 18.57, 2.07, and 2.3 $tonCO_2e$, respectively (Keyhani et al., 2023).

This research intends to determine the impact of using 'low-carbon materials' strategy on the total amount of embodied carbon. Following this introduction, the available methodology and databases for carbon assessment are described. The exact quantity of materials is determined by simulating an actual case study building. Then, hot zones of the building are detected, and embodied carbon reduction strategy is employed.

2. Research Methods

2.1. Life Cycle Assessment

The LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (BS EN ISO 14040, 2020). The LCA studies comprise four phases. These are: 1. the goal and scope definition; 2. the inventory analysis; 3. the impact assessment; and 4. the interpretation (BS EN ISO 14040, 2020). In the goal and scope phase, the boundary, assumptions, and purpose of the research are mentioned, and during inventory analysis, all the database needed for assessment is collected. Impact assessment involves evaluation of the size and significance of the environmental impacts of a product throughout its life cycle, and during interpretation, the results of inventory analysis and impact assessment within the goal and scope are analysed.

To help describe the environmental impact of an asset, its life cycle is split into stages and modules as defined by BS EN 159785 for buildings (Fig 1) and PAS 208010 for infrastructure (Gibbons et al., 2022).

The EN 15978 standard defines the different life cycle stages including A1-3 ('Cradle to Gate'), A1-3 + A4-5 ('Upfront Carbon / Cradle to Site'), B1-5 ('Use'), B6-7 ('Operational Carbon'), C1-4 ('End of Life'), and A1-C4 ('Whole Life Carbon / Cradle to Grave') (Schmidt et al., 2020). The system boundary of this project is Cradle to Site as well as End of Life stages.

The life cycle stage modules enable transparency and flexibility in the assessment. They also provide a standardised structure for comprehensive reporting, with clusters that can be looked at individually as well as in conjunction with one another (Hammond and Jones, 2008).

2.2. Calculation methods and processes

This method is mainly divided into five stages. Specifically, (1) the quantity of materials used in the case study should be identified. Material quantities from the following sources must be used and clearly stated in the LCA, in the following order of preference and subject to availability at the different project stages: 1. Materials delivery records, 2. BIM model, 3. Bill of quantities (BoQ) or cost plan, 4. Estimations from consultants' drawings (Hammond and Jones, 2008).

In this research, the materials' quantity is identified using Revit®, in which a 3D model of the building is simulated to give us the quantity of materials. (2) The carbon factors of the building's materials should be compiled. EPDs, the ICE database, and the RICS guideline are utilised in this research. (3) The embodied carbon factor should be applied to the software to calculate the embodied carbon of each material. This step is applied to materials during the product stage; the embodied carbon of the other stages is calculated manually. (4) Calculate the total embodied carbon of the building by summing the embodied carbon of each material. (5) Finding materials with the greatest amount of embodied carbon and using carbon reduction strategy to mitigate these emissions.

2.3. Case Introduction

As a case study, this investigation used The London College which is a large, detached educational building. This building is coated in red bricks and has double glazed windows of a dark brown colour. The total floor area of the building is around 2500 m^2 and it is constructed in three levels, where the ground floor level accommodates areas such as the kitchen, cafe, library, offices and reception. The first floor accommodates staff rooms and classrooms, and the second floor includes labs, classrooms and offices. The building has been surveyed and simulated in Autodesk® Revit®, version 2023 which is a Building Information Modelling (BIM) software. This software accurately calculates the amount of building materials utilised. Table 1 shows the quantity of materials applied in this building.

Table 1 Material quantity in the residential building

Building Element	Structural Element	Component	Volume (m^3)	Weight (kg)
Substructure	Pad Foundation	Concrete	302.60	695970.80
		Rebar	9.08	71261.36
Superstructure	Structural Framing	Concrete Column	43.15	99254.20
		Rebar	1.29	10162.77
	Floor	Concrete (Cast In Situ)	583.64	1342369.70
		Concrete (Sand/Cement Screed)	39.39	90601.60
		Rebar	18.69	146724.07
	Roof	Concrete (Cast In Situ)	194.25	446775
		Rebar	5.83	45745.88
		Rock Mineral Wool	39.00	1988.75
		Steel - Areco - Metallic Graphite RR45	0.24	1676.74
		Expanded Polystyrene (EPS)	21.29	638.58
	Ceiling	Acoustic Ceiling Tile 24 x 48	22.79	6608.94
		Aluminium	3.69	10147.51
	Stair	Concrete (in situ)	11.68	26864
		Rebar	0.35	2750.64
	External Walls	Aerated Concrete Block	107.88	64729.80
		Brick (strong-coloured)	121.48	236886
		Plasterboard	13.47	10529.63
		Steel - Areco - Metallic Graphite RR45	15.12	102161.90
		Expanded Polystyrene (EPS)	28.57	857.13
	Internal Walls and Partitions	Aerated Concrete Block	68.16	40897.20
		Aluminium	7.94	21850.56
		Door - Frame/Mullion	0.20	98.21
		Glass	2.76	6895
		Paint - White Lining	2.73	3542.50
		Plasterboard	42.07	32901.87
		Softwood	27.13	13454.99
	Windows	Glass	4.93	12320
		Window Frame	7.67	20714.40
	Doors	Door - Panel	3.51	2654.32
		Door - Frame/Mullion	0.90	681.91
		Door - Architrave	0.77	583.63
		Door – Glazing	0.77	1927.50
		Aluminium	0.28	781.85
		Door - Handle	0.54	4561.65

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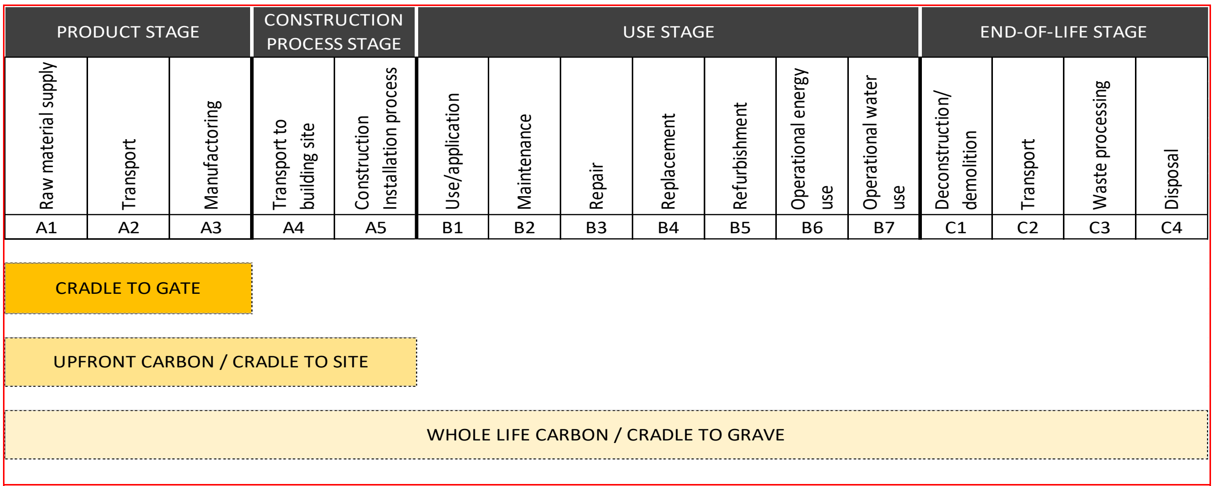

Fig. 1 Life cycle stages reproduced from IStructE 'How to Calculate Embodied Carbon' (Gibbons et al., 2022).

2.4. Embodied Carbon Calculation

Determining embodied carbon means identifying the amount of carbon emissions associated with the production, transportation, manufacturing and disposal of a product or material over its entire lifespan.

2.4.1. Product stage (A1-A3)

The A1-A3 phases relate to the manufacture of raw materials (A1), production and assembly (A2), and transportation to the manufacturer's site (A3). Calculating embodied carbon emissions during the A1-A3 phases of a product's life cycle requires the following formula:

$$EC_{A13} = \sum_{i=1}^{n} [Q_i(ECF_{A13,i})] \quad (1)$$

Where Q_i is the weight of ith material, $ECF_{A13,i}$ is the embodied carbon factor (ECF) associated with i th material.

2.4.2. Transportation (A4/C2)

The carbon factors for transportation of each material to site and transportation of waste materials from site to the landfills or recycling plants are calculated by multiplying the transportation distances (Table 2) by the respective transportation modes' emissions factors (Table 3). The formula for the embodied carbon factor calculation is shown below.

$$\mathrm{ECF}_{\mathrm{A4/C2,j}} = \sum_{\mathrm{j}} (\mathrm{TD}_{\mathrm{mode}} \times \mathrm{TEF}_{\mathrm{mode}}) \quad (2)$$

Where ECFA4/C2,j is embodied carbon factor of transport to/from site for j th material, $\mathrm{TD}_{\mathrm{mode}}$ is transport distance for each transport mode and $\mathrm{TEF}_{\mathrm{mode}}$ is transport emission factor for each transport mode considered.

Table 2 Transport emissions factors for the UK reproduced from IStructE 'How to Calculate Embodied Carbon' (Gibbons et al., 2022).

Mode	**$\mathrm{TEF}_{\mathrm{mode}}$ ($\mathrm{gCO_2e/kg/km}$)**
Road transport emissions, average laden	0.10749
Road transport emissions, fully laden	0.07375
Sea transport emissions	0.01614
Freight flight emissions	0.53867
Rail transport emission	0.02782

Table 3 ECF for Module A4 for the UK reproduced fro m IStructE 'How to Calculate Embodied Carbon' (Gibbon s et al., 2022).

A4/C2 transport scenario	**km by road**	**km by sea**	**ECFA4,i ($\mathrm{kgCO_2e/kg}$)**
Locally manufactured	50	-	0.005
Nationally manufactured	300	-	0.032
European manufactured	1500	-	0.161
Globally manufactured	200	10000	0.183

2.4.3. Construction Installation Process (A5)

Module A5 emissions are broken down into two subsets. Emissions associated with the volume of each material that is wasted on site are identified as A5w emissions and emissions due to general construction activities e.g. energy use from machinery and temporary site offices, are identified separately as A5a emissions.

The carbon factor for material wastage on site (A5w) is calculated by multiplying a waste factor by the sum of the carbon factors associated with the product's production (A1–A3), transportation to site for construction (A4),

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transportation away from site for waste processing (C2), and waste processing or disposal (C3–C4).

$$ECF_{A5} = ECF_{A5w} + EC_{A5a} \quad (3)$$

$$ECF_{A5w,k} = WF_k \times (ECF_{A13,k} + ECF_{A4,k} + ECF_{C2,k} + ECF_{C34,k}) \quad (4)$$

Where $ECFA5_{w,k}$ is construction waste embodied carbon factor for kth material, WF_k is waste factor for kth material, ECFA13,k is embodied carbon factor for A1–A3 for kth material, $ECF_{A4,k}$ is embodied carbon factor for transport to site for k th material, $ECF_{C2,k}$ is transportation away from site carbon factor, $ECF_{C34,k}$ is waste processing and disposal embodied carbon factor.

$$EC_{A5a} = CAEF \times PC/100{,}000 \quad (5)$$

Where EC_{A5a} is embodied carbon from construction site activities (A5a), CAEF is construction activities emission factor of 700kgCO_2e/£100,000 for superstructure and substructure only, or 1,400kgCO_2e/£100,000 for whole building, and PC is project cost.

2.4.4. Demolition or deconstruction stage (C1)

Determining the embodied carbon of the demolition or deconstruction stage requires calculating the quantity of carbon emissions produced during the demolition or deconstruction of a building.

$$EC_{C1} = \sum_j (Q_{mac,k} \times ECF_{mac,k}) + (Q_{energy,e} \times ECF_{energy,e}) \quad (6)$$

Where EC_{C1} is the carbon emissions associated with on-site machinery operation and energy consumption for demolition, $Q_{mac,k}$ is the duration of type k machinery operation and Q (energy,e) is the amount of type 'e' energy.

2.4.5. Waste Processing Stage (C3)

The embodied carbon (C3) of the waste processing stage refers to the quantity of carbon dioxide emissions connected with the manufacturing and installation of waste processing equipment, as well as the energy consumed during the process. This includes emissions from the production of machinery, equipment, and construction materials used in waste processing facilities, as well as the energy used to power these facilities.

$$EC_{C3} = \sum_l (Q_{wap,l} \times ECF_{C3,l}) \quad (7)$$

Where $Q_{wap,l}$ is the quantity of type 'l' material for waste processing.

2.4.6. Disposal stage (C4)

The embodied carbon (C4) of the waste disposal stage is the quantity of carbon emissions resulting from the final disposal of waste. This includes emissions resulting from the transportation of waste to landfills or other disposal sites, the construction and operation of landfills, and the decomposition of waste. The scenarios for site waste disposal are shown in Table 4. It displays three different options for the embodied carbon produced over the product's life cycle.

$$EC_{C4} = \sum_m (Q_{dis,m} \times ECF_{C4,m}) \quad (8)$$

Where $Q_{dis,m}$ is the quantity of type 'm' material for disposal.

2.5. Assumptions

- biogenic carbon sequestered is assumed as −1.67kgCO_2e per kg of timber (Gibbons et al., 2022).
- In embodied carbon calculations, transport distances should be estimated based on project-specific scenarios. A default road transport distance of 50 km on average laden was assumed in this research (Hammond and Jones, 2008).
- According to the RICS guideline, carbon factors for waste processing for reuse, recovery, or recycling (C3) and disposal (C4) are frequently combined in embodied carbon assessments because the two scenarios are mutually incompatible. Since materials and/or components are meant to be recycled beyond the end of the useful life of the built asset, C3 and C4 were estimated to be 0.013 kgCO_2e/kg for all materials in accordance with RICS guidance (Gibbons et al., 2022).
- Due to the lack of information from the contractor, the following could be assumed about the average rate:

  $$EC_{C1} = 3.4\ \text{kgCO}_2\text{e/m}^2\ \text{GIA} \quad (9)$$

  where EC_{C1} is embodied carbon due to demolition and deconstruction, GIA is gross internal area (i.e., the area of a building measured to the internal face of the perimeter walls at each floor level) (Gibbons et al., 2022).

Table 4 Site waste disposal scenarios reproduced from RICS 'Whole life carbon assessment for the built environment' (Hammond and Jones, 2008)

Site Waste Disposal Scenarios		
Disposal to landfill/incineration	Reuse or recycling on-site	Reuse or recycling off-site
(A1–A3) +(A4) + (C2) + (C4)	(A1–A3) +(A4) + (C3)	(A1–A3) +(A4) + (C2) + (C3)

2.6. Carbon Reduction Strategy

There are numerous strategies for reducing a building's embodied carbon, including the following:

1. Reducing the amount of materials utilised is one of the simplest methods to reduce embodied carbon. This can be accomplished by optimising design, prefabrication, and assembly off-site.
2. Choose low-carbon materials, such as recycled materials, or low-carbon concrete.
3. Minimise waste during construction. It can be accomplished by precisely calculating the amount of materials needed during the design phase.
4. Prioritise local sourcing: Sourcing materials locally reduces emissions from transportation.

This research intends to determine the impact of using ‘low-carbon materials’ strategy on the total amount of embodied carbon using LCA and the three data sources listed. According to (Sandanayake, 2017), top categories for reducing embodied carbon are Concrete, Rebar, Insulation and Glazing. In this research, the first three categories are considered as embodied carbon reduction solutions. The following paragraph explains why glazing should not be considered.

In our case study, the glazing type is double-glazed units with 12 mm of glass; to reduce its embodied carbon, it should be changed to single panels. Since this is an educational building that requires a quiet environment and is close to Heathrow Airport, it is not a good idea to replace the windows.

2.7. Data Collection

There are a few ECF available and some of them are not readily available because they form part of comprehensive LCA software or are for internal use within a particular organization (Gibbons et al., 2022).

EPDs are always our first preference because they are the most reliable database available. They are produced by manufacturers and are the most accurate database for calculating embodied carbon. However, there are a limited number of them available and cannot be used for a whole project.

In addition, an open and freely available database is the ICE database developed by the University of Bath. This contains cradle to gate data for embodied carbon and has been largely assembled from published information and LCA provided by a variety of sources (Gibbons et al., 2022).This database is our second choice during (A1-A3) and is applied when EPDs are unavailable.

For the other stages of the building’s life RICS guideline is used to calculate the embodied carbon. The RICS has released a guideline note titled "Whole-life carbon Assessment for the built environment" that gives guidance for evaluating the carbon effects of building materials and construction processes. This guideline is used whenever EPDs are not available.

2.8. Revit® Building Information Modelling (BIM)

Revit® is Autodesk's Building Information Modelling (BIM) software that architects, engineers, and construction professionals use to design, plan, and manage buildings and infrastructure. In this research Site visits and Cad drawings are used to gather the data required for simulation in Revit. During site visits, architectural drawings of the case study, such as plans and sections, are compared with the current state of the building to see if it has been altered. When all site data has been acquired, drawings are usually modified in AutoCAD format, if necessary. The updated AutoCAD drawings are then used to create a 3D Revit model of the building that includes all the existing zones such as the library, offices, reception, labs, classrooms, and staff rooms, among others, etc (Fig 2). Lastly, the Schedules of the building elements are exported to provide information on the quantities of all materials. These Schedules can be exported to Excel or other software. Fig. 3 shows part of Wall material Schedule of the building in Revit.

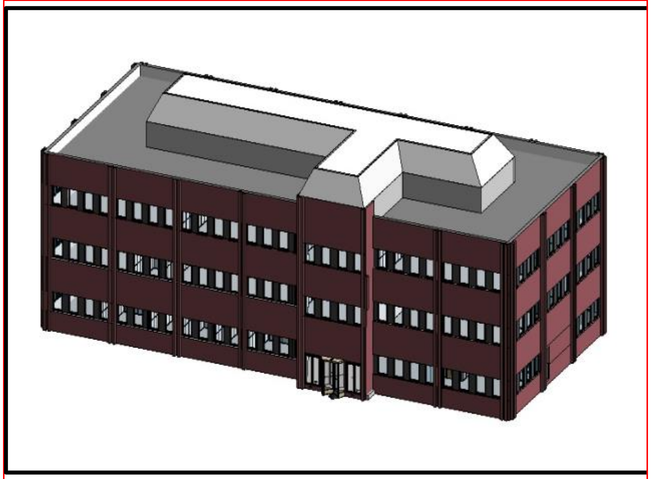

Fig. 2 3D model of The London College

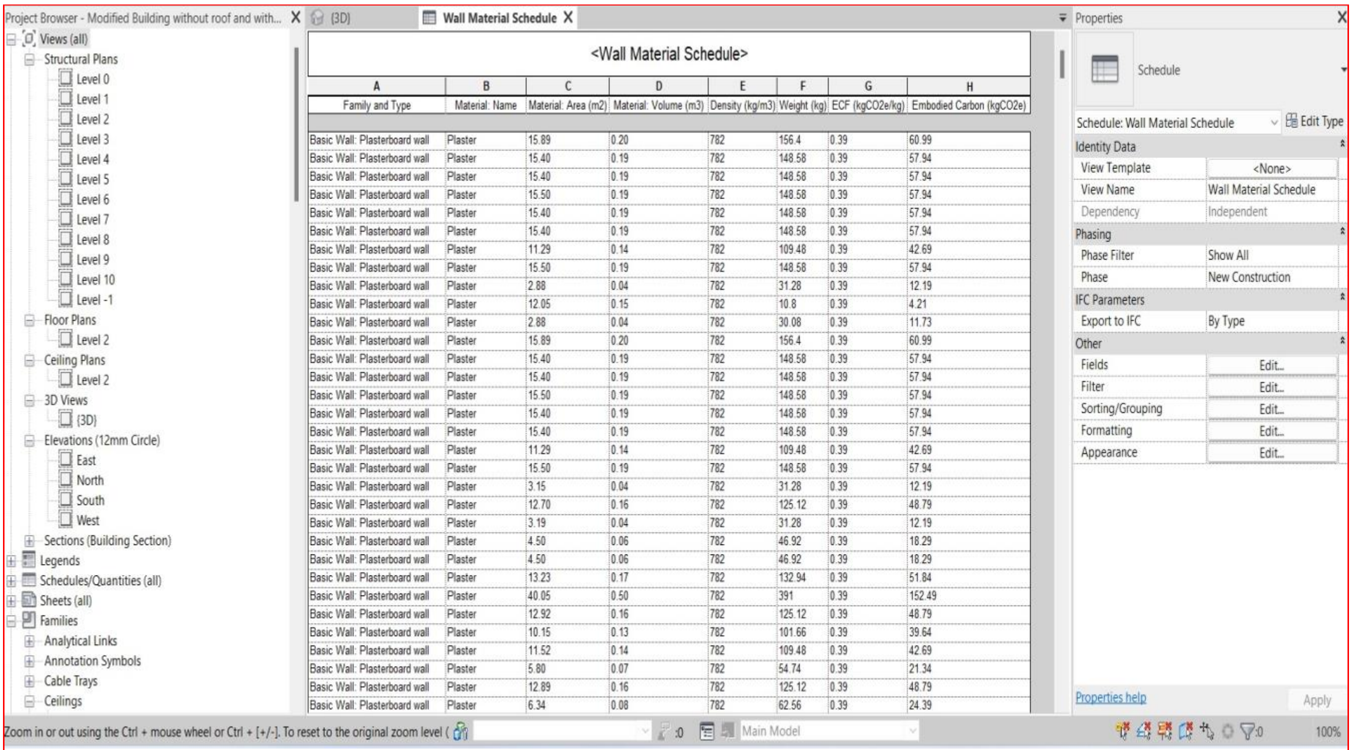

Fig. 3 Wall material Schedule in Revit

3. Results and Discussion

3.1. Initial Embodied Carbon

Table 5 represents the whole embodied carbon of the building and also mentions biogenic sequestration. The term "biogenic sequestration" describes a natural process wherein organisms, such as plants, trees, and other living things, absorb and store atmospheric carbon dioxide (CO_2) through biological processes like photosynthesis. During the growth of plants and other photosynthetic organisms, which turn the CO_2 into biomass through photosynthesis, CO_2 is absorbed from the atmosphere. Until the end of the building's life, the stored carbon can be locked. A portion of this emission will be released since the materials used in this research will be recycled at the end of their useful lives. In addition, Biogenic Sequestration is calculated by multiplying the quantity of materials by their embodied carbon factor.
According to Table 5 the Biogenic Sequestration and Whole embodied carbon of the building are 29.18 and 2040.69 $tonCO_2e$, respectively.

Table 5 Total embodied carbon based on different stages of the building's life

Upfront Carbon (A1-A5w) ($kgCO_2e$)	1823194.30
A5a ($kgCO_2e$)	140000
C1 ($kgCO_2e$)	8670
C2-C4 ($kgCO_2e$)	97487.63
Biogenic Sequestration ($kgCO_2e$)	-29180.0102
Whole embodied carbon ($kgCO_2e$)	2,040,696.11

The Fig. 4 and Table 6 display the proportion of embodied carbon in the building components of our case study. The major contributors to embodied carbon emissions are walls and floors, which account for 35% and 30% of the total carbon, respectively, and emit 667.58 and 570.37 $tonCO_2e$. To determine the cause of their high embodied carbon level, these components were analysed to identify which materials contain the most embodied carbon.

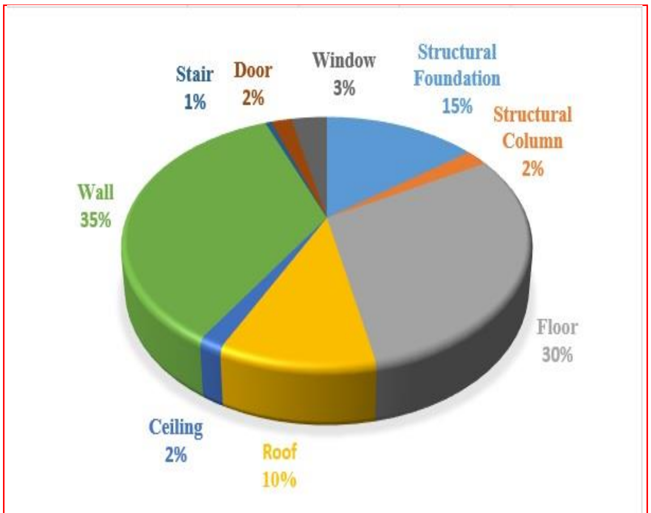

Fig. 4 Percentage of embodied carbon based on building's components

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Table 6 Share of embodied carbon based on building's components

Material	A1-A5$_w$ ($kgCO_2e$)	C2-C4 ($kgCO_2e$)	Total ($kgCO_2e$)
Ceiling	30,536.48	307.06	30,843.54
Door	30,135.52	6,700.28	36,835.80
Floor	541,427.67	28,947.92	570,375.58
Roof	189,031.22	9,591.90	198,623.12
Stair	10,186.66	542.69	10,729.35
Structural Column	37,334.10	3,580.77	40,914.87
Structural Foundation	261,786.85	14,059.53	275,846.38
Wall	634,672.53	32,912.40	667,584.93
Window	63,915.32	605.36	64,520.67

Fig. 5 represents the embodied carbon of materials in Wall (1) and Floor (2) categories. Clearly, the high quantity of embodied carbon in these components is attributable to metal and concrete, which are the largest contributors to embodied carbon. It is important to note that metal materials have a lighter weight than concrete but much higher carbon content. It implies that we should be extremely cautious when determining the amount of metal required for our project, as even a slight overestimation imposes a substantial environmental cost.

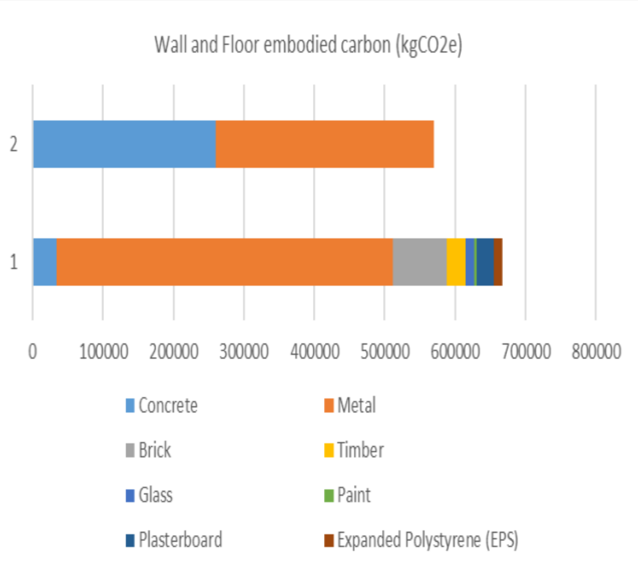

Fig. 5 Embodied carbon of materials in floor and wall

In this research, the embodied carbon of the London College building materials during their life cycle is calculated (Table 7), and stages with the highest embodied carbon are determined. The Product Stage (A1-A3) accounted for approximately 80% of the total embodied carbon, as shown in Fig. 6. This stage describes the total quantity of greenhouse gas emissions associated with a product's production and manufacturing. This includes all emissions produced during the extraction and processing of raw materials, the production of the product, and its transportation.

Table 7 Share of embodied carbon based on building's materials categories

Material	A1-A5w ($kgCO_2e$)	C2-C4 ($kgCO_2e$)	Total ($kgCO_2e$)
Insulation	100688.47	1315.08	102003.55
Metal	1028130.21	9611.93	1037742.15
Wood	7711.22	29273.05	36984.27
Glass	97195.60	387.44	97583.04
Concrete	501959.89	50143.53	552103.41
Brick (strong-coloured)	57193.71	4340.94	61534.65
Plaster	27182.38	2350.74	29533.12
Paint	3132.82	64.92	3197.73

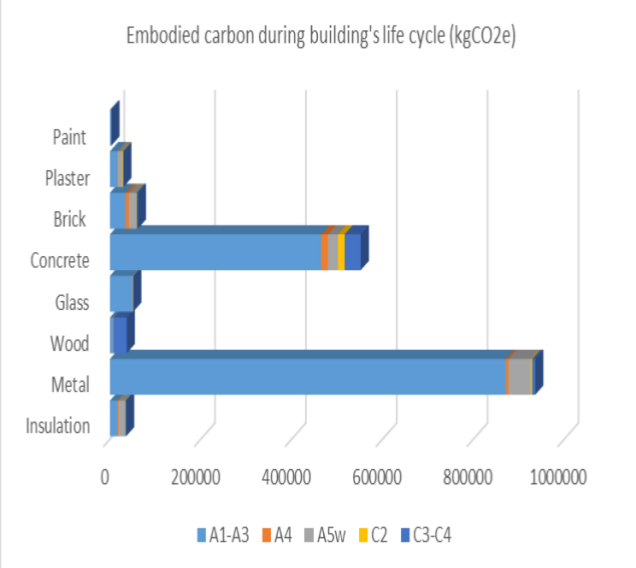

Fig. 6 Embodied carbon produced during different stages of the building's life

3.2. Embodied Carbon Reduction

Utilizing recycled materials rather than virgin materials is one of the most effective methods to reduce embodied carbon in our case study. The use of recycled metals reduces embodied carbon by 47%, given that 55% of total emissions in the London College come from virgin metals. This means that by using recycled metals, we can cut the embodied carbon by 441.8 $tonCO_2e$.

In addition, as concrete materials with 552 $tonCO_2e$ are the second greatest contributor and account for about 78% of the overall quantity in our case study, the use of less carbon-intensive materials can significantly reduce the total embodied carbon.

Fly Ash and GGBS are selected as partial cement

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replacements to determine their impact on embodied carbon reduction. There are various advantages to using Fly Ash as a partial replacement for cement in concrete. Because of its environmental benefits and cost-effectiveness, Fly Ash, a by-product of coal-fired power plants, is considered a sustainable alternative to cement.

When used as a partial replacement for cement, Fly Ash can increase the workability and durability of concrete, reduce the heat of hydration, and reduce the amount of cement required for building construction. This can result in financial savings as well as environmental benefits, as cement manufacturing contributes significantly to greenhouse gas emissions.

Additionally, Ground Granulated Blast Furnace Slag (GGBS) can be used as a partial cement substitute. According to (Rana and Rughooputh, 2014), partial substitution of GGBS for cement enhances the workability of the mixture. With increasing GGBS content, the compressive and tensile fracture strengths, flexure, and modulus of elasticity increase. It was also determined that the optimal mixture consists of 50 percent cement and 50 percent GGBS.

Various scenarios for embodied carbon reduction in concrete materials of our case study were analysed using Fly Ash and GGBS as cement replacements. In more detail, 15%, 30%, and 40% Fly Ash replacement, as well as 25% and 50% GGBS replacement, were examined. Our case study utilized RC 32/40 In-Situ Concrete for superstructure and structural purposes. According to Fig. 7, the 50% cement and 50% GGBS mixture reduces the embodied carbon of our case study by 43%, which is more than the other compositions.

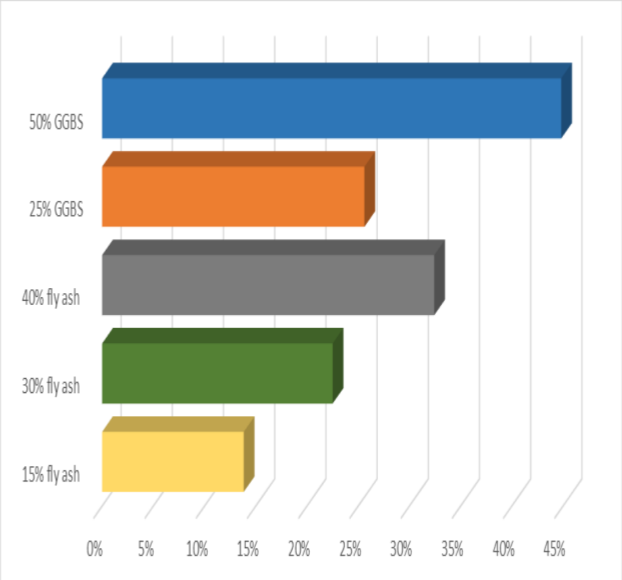

Fig. 7 Different scenarios for cement replacement

Moreover, Bricks rank third in terms of embodied carbon production, following concrete and metal materials. The standard brick format used in our case study is a rectangular cuboid with a declared size of 215x100x65mm; 3 slotted perforations and 2 voids to the rear pass through the bed face of the brick. The brick consists of limestone aggregates with Portland cements with various proportions of oxide pigment. There are three types of this form of brick: white bricks, light-coloured bricks, and strong-coloured bricks. In our case study, strong-coloured brick is utilised. By substituting this brick with light-coloured bricks, the embodied carbon is reduced by nearly 10 percent.

Finally, insulation materials have the potential to reduce embodied carbon even further. Replacing Expanded Polystyrene (EPS) with Rock Wool has some benefits. Rock wool has better thermal insulation, fire resistance, and sound insulation, and it also has less embodied carbon. Rock wool can reduce the embodied carbon by almost 43%, making it more eco-friendly than EPS.

The embodied carbon of building materials initially (1) and after utilising embodied carbon reduction strategy (2) is shown in Fig. 8. In addition, the effect of using 'low-carbon materials' strategy in different construction components is shown in Fig. 9. The greatest reductions occur in the floor, roof, and structural foundation at 50.1%, 23.7%, and 17.2%, respectively.

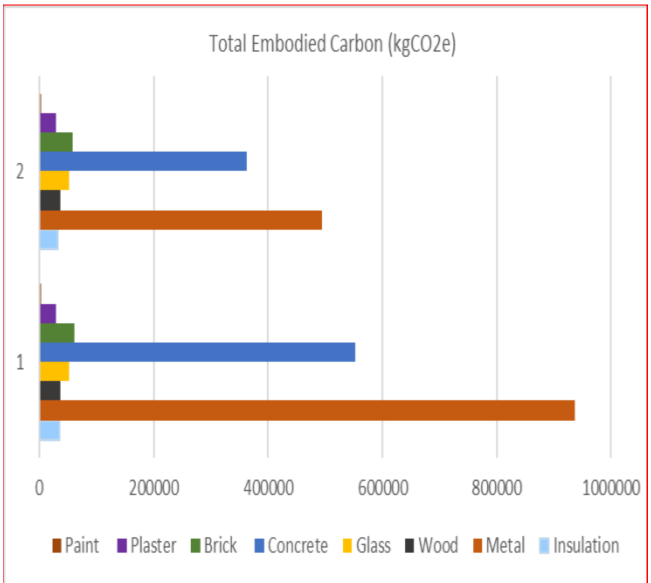

Fig. 8 Total embodied carbon before and after reduction

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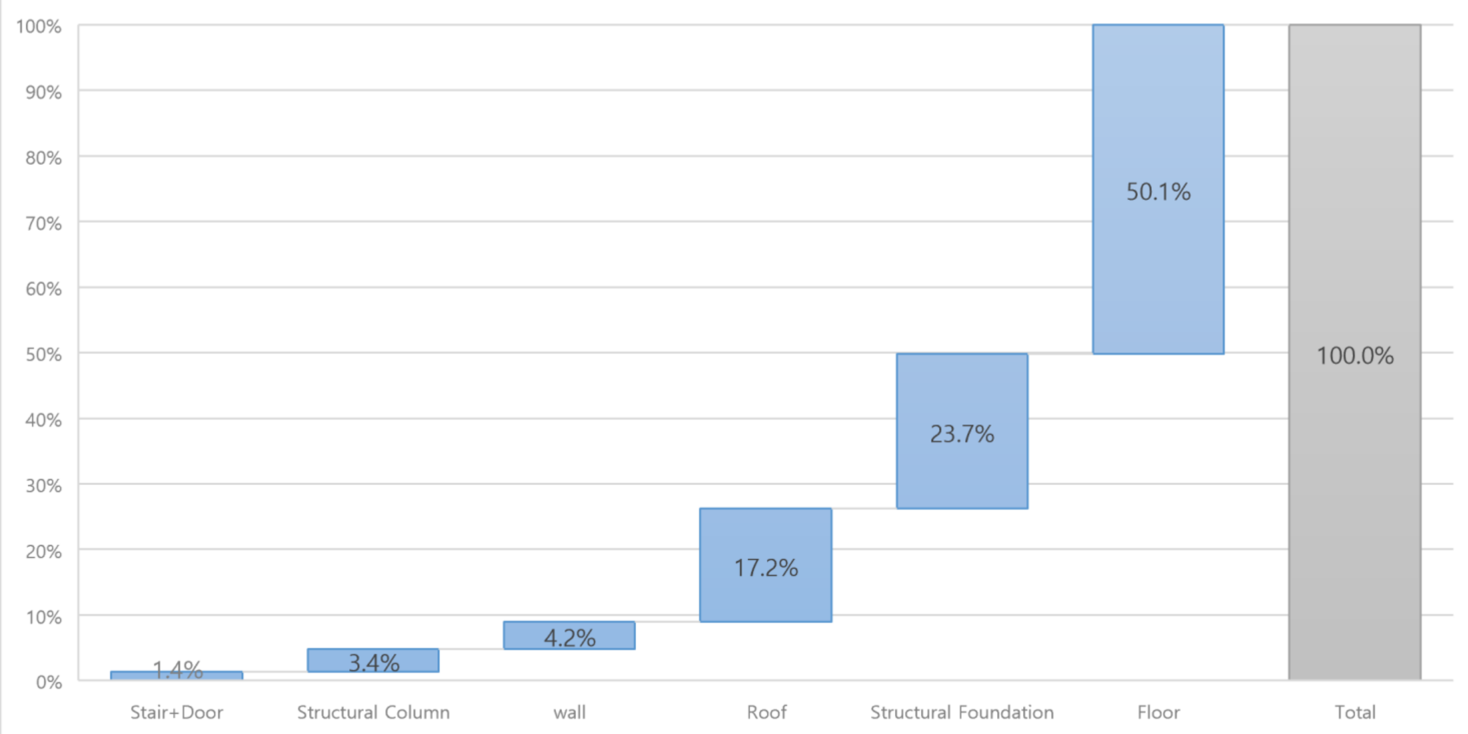

Fig. 9 Embodied carbon reduction in building components

4. Conclusion

Reducing the embodied carbon dioxide of buildings is crucial to achieving national and global carbon reduction goals. This research employs the LCA methodology with EPDs, the ICE database, and the RICS guideline for assessing the impact of using 'low-carbon materials' strategy on the total embodied carbon. EPDs are always our first choice, but when they are unavailable, we use the ICE database and RICS guideline. There are various strategies to reduce the embodied carbon of buildings, and this study investigates the impact of the low-carbon materials strategy on the total embodied carbon of the building. The results revealed that the major contributors to embodied carbon emissions are walls and floors, which account for 35% and 30% of total emissions, respectively. The high value of embodied carbon in walls and floors is due to the use of metal and concrete materials containing 1038 $tonCO_2e$ and 552 $tonCO_2e$, respectively. The embodied carbon assessment of the building's materials throughout their life cycle showed that the Product Stage is the major contributor to embodied carbon compared to other phases of the building's life, producing more than 80% of the total emissions. To reduce the embodied carbon of the building, recycled metals were used in place of virgin metals, which reduced the embodied carbon by 47%. In addition, various scenarios for the partial replacement of cement with Fly Ash and GGBS revealed that the combination of 50% cement and 50% GGBS has the greatest potential to reduce embodied carbon by 43%.

Also, Brick, the third-largest contributor to embodied carbon, could be 10% less carbon-intensive if strong-colored bricks were replaced with light-colored bricks. Moreover, replacing Expanded Polystyrene with Rockwool in insulation materials reduced its embodied carbon by 43%. Finally, considering all the material replacements, the embodied carbon of the whole building could be reduced by 37% overall.

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