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Comparative analysis of the whole life carbon of three construction methods of a UK-based supermarket

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# Comparative analysis of the whole life carbon of three construction methods of a UK-based supermarket

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## Abstract

The built environment has been a significant contributor to global carbon emissions. It, therefore, has a vital role to play in the reduction efforts of future climate change. While the design of buildings may determine future energy use for cooling, heating, and lighting during the operational stage of the building, this study aims to observe the effect of the building design on the operational as well as the whole-life carbon emissions. Past studies have focused on either the operational carbon or the embodied carbon of a building. Using a cradle-to-grave assessment of a typical UK supermarket, this study explores the relationship between embodied carbon and operational carbon. Additionally, it examines the effects of the variables between three approved construction methods of the same design on the whole life of carbon. These methods are a steel structural frame and cladding panel external wall, steel frame and perforated walls, precast concrete and glulam frame and precast concrete walls. The findings of this research will contribute to mitigation strategies for the environmental impacts of supermarket building construction whilst providing a framework for future assessment of the whole-life carbon of supermarket buildings.

**Practical Application:** Employing the life cycle assessment methodology, this paper examines the potential of minimising both embodied and operational carbon by observing the whole life carbon. Highlighting the influence of the GHG emission contributing factors in each stage on each other. Additionally, the recommended methodology for the supermarket building types of this case study, could be adapted for other types of buildings. The findings could also augment carbon emission research and guide the development of supermarket buildings to low carbon intensive. Furthermore, collaboration with the industry in carrying out this research aids in adopting the findings as practical and theoretical guides for engineers and designers in reducing the building sector's harmful environmental impact.

## Keywords

Climate change, embodied carbon, operational carbon, whole life carbon, supermarket building

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## Introduction

### *Background & whole life carbon*

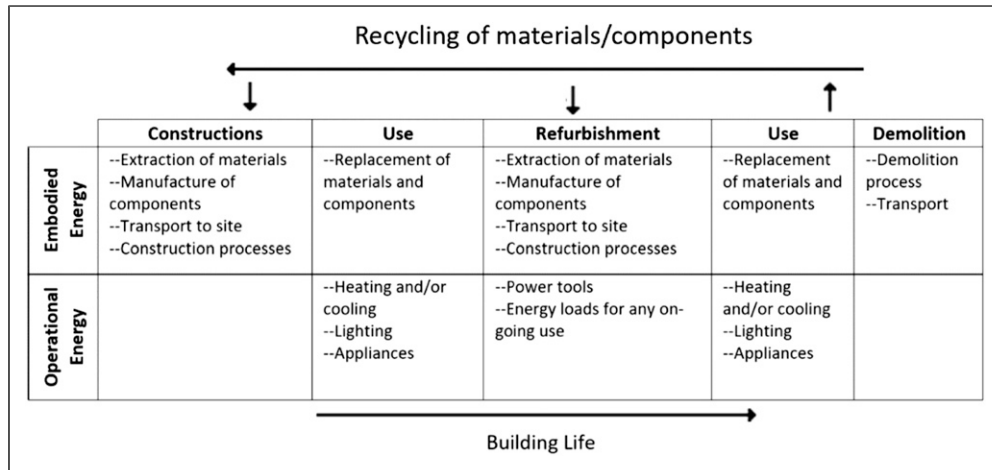
The rise of global warming and climate change has resulted in many actions by different bodies. The UK government has approved the Climate Change Act 2008, which sets legally binding targets for greenhouse gas (GHG) emission reduction, with the Committee on Climate Change (CCC) mandated regular government progress reports on reaching the target of net-zero emissions by 2050.<sup>1</sup> The building sector is one of the most energy-intensive and prominent contributors to GHG emissions. According to the International Energy Agency (IEA) based in Paris, the building and construction sectors are responsible for approximately one-third of total global final energy consumption and nearly 15% of direct CO<sub>2</sub> emissions.<sup>2</sup> Data published in 2019 shows the sector accounts for 39 and 11% of global energy-based emissions, respectively.<sup>3</sup> The 2020 CCC Sixth Carbon Budget reported that UK buildings are responsible for 59% of the UK electricity consumption and 87 MtCO<sub>2</sub>e of direct GHG emissions. In contrast, when including the indirect emissions, the total percentage rises to 23% of total UK emissions.<sup>4</sup> According to the “Global Status Report”,<sup>4</sup> 28% of the global carbon emissions are related to the operation of buildings compared to 11% attributed to embodied emissions which involve emissions associated with the construction industry. This report equally highlights the importance of reducing embodied energy and carbon emissions as a primary concern for action. However, the report gave no action plan to reduce carbon emissions and mitigate climate change. Additionally, the construction sector uses up to 36% of the world’s natural resources and accounts for approximately 50% of the solid waste sent to landfills.<sup>5,6</sup> Therefore, there is immense pressure on the building and construction sector to reduce emissions.<sup>3,6</sup>

Carbon emissions are generally categorised into 2 types: embodied carbon and operational carbon. Embodied carbon are the emissions produced during the material extraction, processing, manufacturing, transportation, construction, demolition and final disposal of construction material, also called “capital

carbon”.<sup>7</sup> Conversely, operational carbon are the emissions produced from energy used for heating and cooling, lighting, equipment load, and energy loads for any ongoing use. The Whole Life Carbon (WLC) refers to both the operational and embodied carbon of a building.

Whole life carbon reduction faces significant challenges, partially due to the emissions occurring at different stages of the life cycle. Reduction of WLC emissions and optimising building design, it is vital to study both the operational and embodied emissions of all the available alternate design options, which would involve the inputs, processes, and outputs of the building at each stage. As demonstrated in [Figure 1](#), the embodied carbon emissions can be examined in two stages. The emissions produced during the building’s construction (including emissions emitted from material production, transport of material, and on-site activities) are termed upfront carbon. And the emissions produced during the demolition or deconstruction of the building (including the transportation of demolished materials, processing of waste and final disposal of waste materials) are termed end-of-life carbon.<sup>8</sup> This distinction is vital as, juxtaposed to the end-of-life emissions, the upfront emissions occur before the building is in use. Operational energy or operational carbon in buildings arises from the building’s lighting, heating, ventilation, air conditioning (HVAC), and appliances. Whilst, these emissions occur at different stages of the lifespan of the building and varying magnitudes, they all significantly contribute to the WLC emissions of a building.<sup>7,8</sup> In the past the majority of the focus of the industry has been on reducing operational carbon. This has partially been due to the importance assigned to operational carbon and energy consumption.

A study by Moncaster and Symons<sup>10</sup> investigating the carbon impact of each stage of the life cycle in residential buildings, showed that the proportion of the end-of-life stage ranges between 5 and 21% of total carbon emissions. Peng<sup>11</sup> notes that in a comparison study examining the whole life carbon emissions of the domestic sector operational carbon accounts for nearly 85.4% of the WLC. Likewise, a study by Iddon and Firth,<sup>12</sup> focused on the embodied and operational carbon of new-build housing in the UK, concluded that operational carbon accounts for



**Figure 1.** Indicative components of embodied and operational energy over an illustrative building life cycle recreated from.<sup>9</sup>

approximately 74–80% of WLC over a 60 years period. Additionally, several studies have revealed that the operational phase is responsible for 80–85% of the life cycle carbon emissions in buildings,<sup>13,14</sup> while the remaining stages of a building’s life cycle account for 15–20%.<sup>15</sup>

In contrast, a study by Röck et al.<sup>16</sup> conducted a systematic review to ascertain the global trends of carbon emissions occurring throughout the life cycle of buildings, analysing over 650 LCA case studies. The review categorised different energy performance classes based on a final sample of 238 cases. The study found that while the average embodied carbon emissions from buildings is about 20–25%, the share of embodied carbon rises to about 45–50% in highly energy-efficient buildings and can exceed 90% in extreme instances. Likewise, Andersen et al.<sup>17</sup> carried out a systematic review of 226 different scenarios to investigate embodied carbon emission results reported in Life Cycle Assessment (LCA) studies. The analysis concluded that, in general, the average reported values of timber buildings to range between 33 and 50% of embodied carbon emissions of buildings. Nevertheless, the findings showed that the importance of operational carbon is reducing. In contrast, the significance of embodied carbon becomes greater due to advances in energy efficiency and stricter regulations for energy efficiency in

buildings. These reviews highlight an increasing need and significance to optimise both operational and embodied carbon emissions of buildings.

### Whole life carbon in supermarket buildings

Additionally, there is limited research available focusing on UK supermarket’s operational carbon emissions and less attention has been placed on quantifying and reducing the impacts of the other phases of the building’s life cycle.<sup>18</sup> Several studies have focused on calculating and lowering the emissions of the commercial buildings and specifically supermarkets. Such as a study in 2018 conducted on Spanish supermarkets with sale areas of 400–2500 m<sup>2</sup>, which focused on reducing the final energy consumption of its building services such as lighting, cooling, air conditioning, ventilation, and bakery ovens. Reducing it by an average of 25% using natural light, installing presence detectors, time programmers for light, replacing old air conditioning systems with a better efficient system,<sup>19</sup> On the other hand, the adoption of a circular economy (CE), which addresses issues of resource scarcity and climate change,<sup>20</sup> is considered an appropriate solution for managing waste from electrical and electronic equipment (WEEE).

As it seeks to close the loop of the product life cycle, reduce emissions and retain the highest value of the product.<sup>21</sup> The use of refrigerators and other appliances makes the supermarket an ideal field for the potential implementation of CE.<sup>22,23</sup> A study conducted in 2015 analysed energy consumption data of 565 supermarkets in the UK and revealed a 3.30% annual reduction in energy consumption between the years 2013 and 2017 where in over the 5 years, the total energy consumption reductions achieved were a 32% reduction in lighting, 20% in refrigeration and 8% in HVAC systems.<sup>24</sup>

Typical supermarkets in the UK are described as high energy usage intensity (EUI) buildings due to their increased refrigeration and lighting needs. By examining the breakdown of the energy use in these buildings (Figure 2), it can be observed that small power demands (referring to energy used by small appliances, equipment and CCTV) represent a significant proportion of total emissions and that lighting is the greatest regulated energy use.<sup>23</sup> Considering this,

structural and building fabric differences could affect the emissions of each stage of the building's life cycle differently.

Additionally, there is no specific agreed single value for the whole life carbon emissions for supermarket buildings in the UK, and this is due to several reasons such as unavailability of Environmental Product Declarations (EPDs), unavailable or missing information regarding the raw materials used, varying use of building services equipment and specific technical details regarding equipment.

Numerous studies have attempted to explain the comparative ecological advantages of concrete, steel and timber structural systems.<sup>26–28</sup> Although extensive research has been carried out on structural systems, no single study exists that analyses supermarkets' construction developments. Therefore, it is vital to have a fresh insight into the environmental impacts of such construction developments. This paper seeks to provide a holistic view of supermarkets' material components and construction

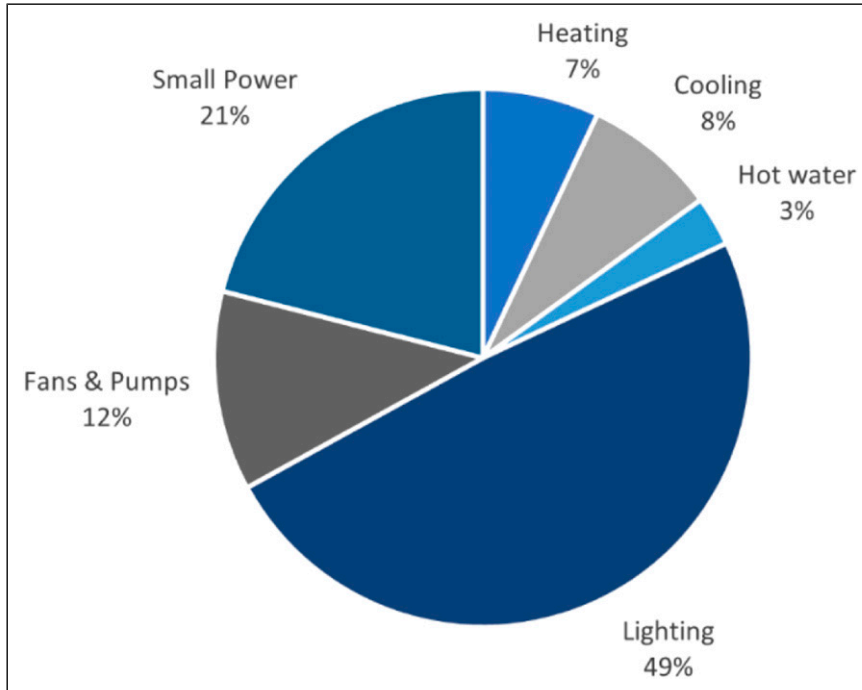


Figure 2. Breakdown of energy use in a typical supermarket.<sup>25</sup>

developments. Comparing the embodied carbon with the operational carbon and whole life carbon of three construction approaches of a supermarket in the UK.

### Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is an internationally accepted systematic and holistic methodological technique used to evaluate the environmental impacts of any product or procedure, including building materials and construction developments. An LCA can be used to assess the environmental effects of a product throughout its life span - from raw materials extraction to final disposal. Not only does an LCA quantify the impacts of the construction of a building at different phases, but it also provides a better understanding overview of an extensive variety of building components. The literature on life-cycle analysis has highlighted the importance of building materials and embodied energy in a whole life-cycle carbon emissions assessment of buildings.<sup>29–31</sup>

An LCA is primarily performed in four stages (Figure 3). In the first stage, the Goal and Scope, based on the goal of the assessment, the scope and the stages included are determined. In the second stage, the Life Cycle Inventory (LCI), all data

required for the assessment are identified and collected. In the third stage, Life Cycle Impact Assessment (LCIA), the potential environmental impact of the stages included in the scope are calculated. The final stage is the Life Cycle Interpretation stage, in which the results from the LCI and LCIA stages are evaluated.

This research aims to estimate and evaluate the embodied and operational GHG emissions of supermarket buildings in the UK. This is achieved by calculating the life cycle carbon emissions. The results can offer quantifiable and comparable carbon emissions for further carbon reduction in similar buildings in the UK.

**Goal & scope.** The goal of this research is to compare the WLC of three variations of a typical Lidl supermarket. These three structures follow the same design and HVAC systems and the variations (Table 1) are the materials of the external walls, internal walls, column, and beams. Therefore, the components included in the embodied carbon calculations are confined to the known variables. For the operational carbon, considering the building type, pattern of use and relevant technical and functional requirements, based on the ISO15686-1: 2011 guideline<sup>33</sup> an average service life of 20 years is assumed for this study. According to CIBSE guide

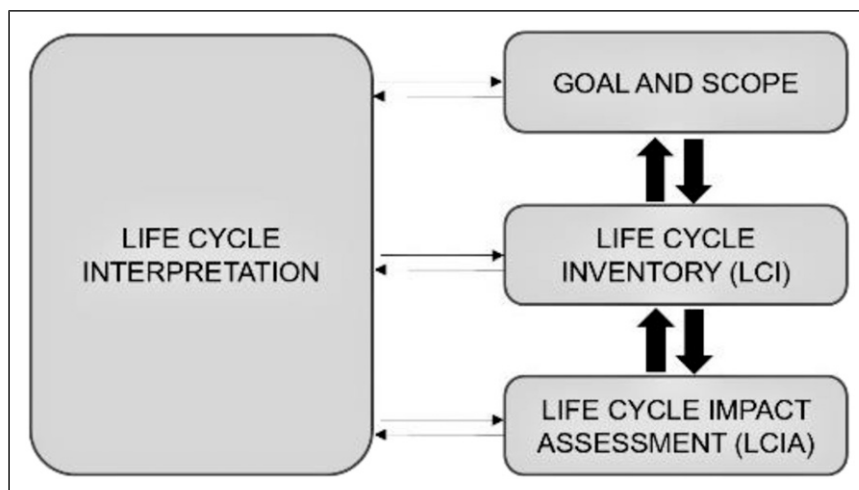


Figure 3. LCA stages reproduced from ISO 14040.<sup>32</sup>

to the replacement rates of building services<sup>34</sup> the components included in the study with Reference Service Life (RSL) under 20 years would be identical in all three designs. This would similarly apply to the emissions from refrigerant types and leakage rates.

The life cycle of a building has been conventionally divided into four stages including, A (product and construction); B (in use and operation), C (end of life), and D (beyond the life cycle) (Figure 4). The scope of this research consists of the embodied and operational carbon emissions of the three defined buildings, including A1 – A3 phases termed as “extraction of material”, “transportation” and “manufacturing”, A4 – A5’ construction’, B6–B7’ use’ and C1 – C4’ end of life phases. These four stages as illustrated in Figure 4, are considered the system boundary of this study.

## Methodology

### Case study

The building chosen for this case study, was the standard design of a LIDL supermarket. The standard design comprises a 2500 m<sup>2</sup> single-story building. For this standard design there are three approved methods of construction as depicted in Table 1. The first method of construction (referred to as P1) is composed of a steel column and beam structural frame, cladding panel external walls and a concrete slab foundation. The second method of construction (referred to as P2) is composed of a steel column and beam structural frame, proton external walls up to Height(H) = 4.109 m and cladding panel external walls from H = 4.109 m to H = 5.104–7.02 m, with a concrete slab foundation. The third method of construction (referred to as P3) is composed of a pre-cast concrete column and glulam beam structural frame, pre-cast concrete external walls up to H = 4.109 m and cladding panel external walls from H = 4.109 m to H = 5.104–7.02 m, with a concrete slab foundation. The internal wall finishes for P1, P2 and P3 include paint to plasterboard. The floor coverings are ceramic tiles, vinyl, and paint. The windows are glazed and aluminium-framed with steel external doors.

A Whole Life Carbon (WLC) assessment was carried out within the previously defined boundaries for each of the three construction methods (P1, P2, P3).

*Life Cycle Inventory (LCI)*. In this study, two different software tools have been utilised to aid the WLC assessment. The Autodesk® Revit® BIM software and the TAS (Thermal Analysis software) by EDSL.

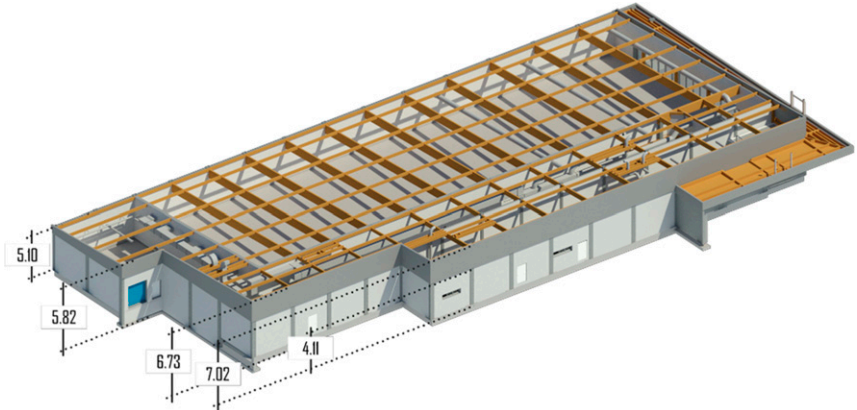
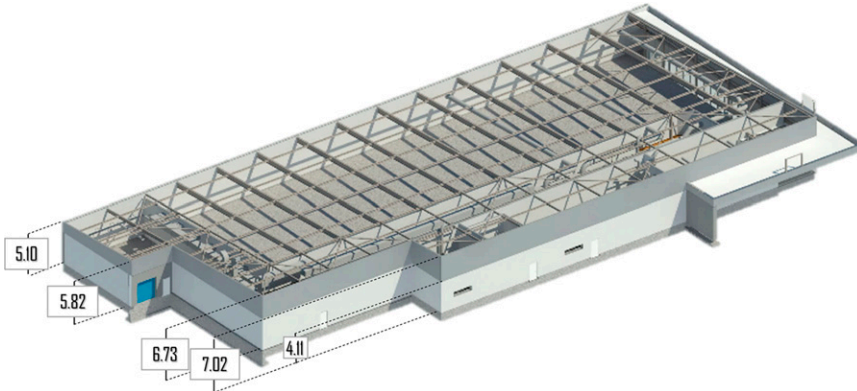
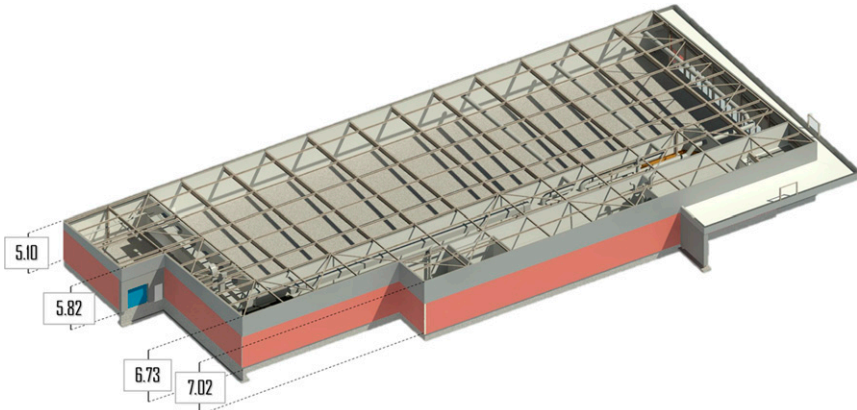
The material quantities necessary to calculate the embodied carbon were derived by simulating a 3D model for P1, P2 and P3 using Autodesk® Revit® BIM software (Table 1). The model was designed with the closest accuracy to the plans. The Revit® material library was used to assign materials to the simulation and modified to match the plan physical attribute specifications. The material quantities for each model are illustrated in Table 2. As mentioned, one of the main barriers to performing a WLC assessment is the lack of specific EPDs. Therefore, considering that all three models follow the same HVAC system design, in this research, the embodied carbon of the ducts, pipes and electrical cabling has been included while the building service units (AHU, HVAC, DHW) have been omitted.

Additionally, in order to keep the findings of this study in line with the goal of the research certain limitations were placed on the consideration of different factors which could be explored in future studies. Such as the use of refrigerants in the supermarket store, and refrigerant leakage. However, this omission does allow for the methodology for calculating the WLC to be further adapted to other building types such as offices, retail buildings and warehouses.

The TAS software which incorporates CIBSE weather files and complies with the building regulations guidance 2010: Part L2 for England and Wales.<sup>36</sup> was used to calculate the energy use and emission of the three models. As the software allows for changes to the building fabric and given that P1, P2 and P3 do not differ in floor plan design, a 3D model of the building was simulated (Figure 5). As these building plans are specific to the UK, the construction methodology is done according to the Building Regulations 2010.<sup>30</sup> A further explanation

**Table 1.** Simulated standard design model for three construction methods of LIDL supermarket buildings using Autodesk® Revit® BIM software: Isometric view of the model.

PI	External wall Cladding panel	Columns Steel	Beams Steel
P2	External wall Poroton block + cladding panel	Columns Steel	Beams Steel
P3	External wall Pre-cast concrete + cladding panel	Columns Pre-cast concrete	Beams Glulam



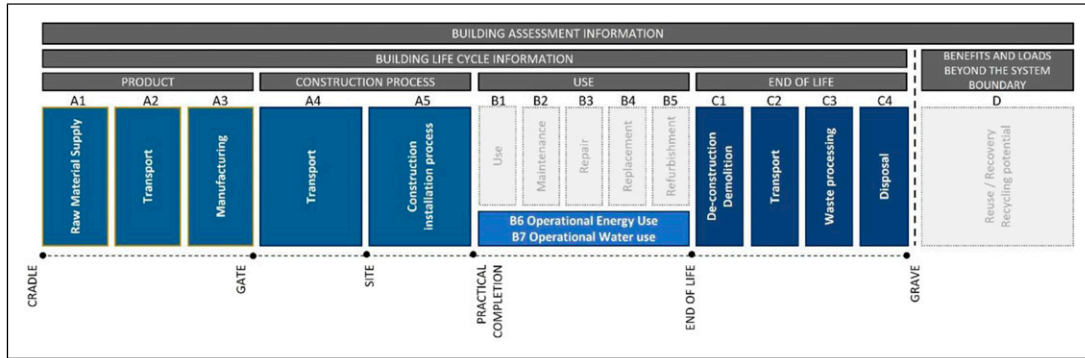


Figure 4. Life cycle stages reproduced from BS EN 15,978-2011.<sup>35</sup>

Table 2. Summary of material quantities.

Category	Material weight (tonne)		
	P1	P2	P3
Ceilings	5.97	5.97	5.90
Floors	365.41	365.42	371.94
Foundations	1148.53	1141.88	1148.53
Framing	89.89	89.89	240.74
MEP (Mechanical, Electrical, Plumbing)	4.58	4.58	4.58
Roofs	56.59	56.59	55.93
Walls	359.11	637.14	698.87
Windows + doors	10.44	10.44	10.44
Total	2040.51	2311.92	2536.93

and detailed description of TAS have been outlined in previous papers.<sup>37,38</sup>

#### Calculation

**Embodied carbon (A1-A5, C1-C4).** The embodied carbon of the cladding panels, roof panels, floor tiles and ceiling tiles was calculated by using the LIDL approved supplier's manufacturer EPDs for the available embodied carbon stages of the corresponding materials (Table 3).

Upfront embodied carbon involves A1-A3 – the emissions from the production process of the building materials. In lieu of the availability of an EPD for the materials, these values were calculated via equation (1). Which ECF represents the embodied carbon factor which is the potential

environmental impact of each material or process per unit weight. The best resource for ECFs in the UK has been shown to be the ICE database,<sup>39</sup> which has been utilized this research.

Equation 1 – Embodied carbon for material production (A1-A3)<sup>40</sup>

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

$EC_{A13}$  = A1 – A3 embodied carbon

$Q_i$  = quantity of  $i$ th material

$ECF_{A13,i}$  = embodied carbon factor of  $i$ th material

In line with industry standard practice, an assumption of steel with 59% recycled content for the steel frame, and precast concrete beams and columns



**Table 4.** Default value assumed for material transport distance for A4 and C2 stages.

Stage	TD (Km) by road		Assumption
A4 transport scenario	Local manufacturing	50	<ul style="list-style-type: none"> <li>• Default ceiling</li> <li>• Concrete</li> <li>• Steel beams and columns</li> <li>• Plaster board</li> <li>• Pipe and pipe fittings</li> <li>• Duct and duct fittings</li> </ul>
	National manufacturing	300	<ul style="list-style-type: none"> <li>• Default flooring</li> <li>• Gutter and roof flushing</li> <li>• Metal stud internal walls</li> <li>• Timber walls</li> </ul>
	European manufacturing	1,500	<ul style="list-style-type: none"> <li>• Schueco windows</li> <li>• Assa Abloy doors</li> <li>• Arcelor Mittal roof panel</li> <li>• Arcelor Mittal cladding panel</li> </ul>
C2 transport scenario	Local manufacturing	50	<ul style="list-style-type: none"> <li>• All material</li> </ul>

Equation 2 - Carbon factor for transportation (A4,C2)<sup>40</sup>

$$ECF_{A4/C2,i} = \sum_{mode} (TD_{mode} \times TEF_{mode})$$

$ECF_{A4/C2,i}$  = embodied carbon factor of transport to/ from site for  $i$ th material

$TD_{mode}$  = transport distance for each transport mode considered

$TEF_{mode}$  = transport emission factor for each transport mode considered

The emissions from on-site waste ( $EC_{A5w}$ ) were calculated using equation (3), where  $WF$  represents the waste factor. Where applicable, the  $WF$  chart from the WRAP Net Waste Tool data was used and where not applicable based on the guidelines a default value of 1% was assigned.<sup>40</sup>

Equation 3 - Embodied carbon for construction waste (A5w)<sup>40</sup>

$$EC_{A5w,i} = WF_i \times (ECF_{A13,i} + ECF_{A4,i} + ECF_{C2,i} + ECF_{C34,i})$$

$ECF_{A5w,i}$  = construction waste embodied carbon factor  $i$ th material

$WF_i$  = waste factor for  $i$ th material given by equation 4

$ECF_{C2,i}$  = transportation away from the site, calculated in the same way as  $ECF_{A4,i}$  but transport distance is assumed to be 50 km by road if taken for reuse or recycling

$ECF_{C34,i}$  = waste processing and disposal emissions associated with construction waste material

$ECF_{A13,i}$  = carbon sequestration for any timber products wasted during construction

The embodied carbon associated with deconstruction/ demolition ( $EC_{C1}$ ) was estimated using equation (4). Where  $m$  is the type of machinery for on-site operation, and  $e$  is the type of energy used. And the carbon emission associated with the processing of demolished waste ( $EC_{C3}$ ) was calculated using equation (5).

Equation 4 - Embodied carbon for deconstruction/ demolition (C1)<sup>34</sup>

$$EC_{C1} = Q_{machinery,m} \times (Q_{energy,m} \times ECF_{energy})$$

$EC_{C1}$  = carbon emission associated with dismantling or demolishing the building

$Q_{machinery,mi}$  = the type of plant/equipment used in the demolition of the buildings

$Q_{energy,mi}$  = the type of fuel used by the demolition plant/equipment

$ECF_{energy,m}$  = carbon emissions per unit consumption of fuel

Equation 5 - Embodied carbon for demolished waste (C3)<sup>40</sup>

$$EC_{C3} = \sum_i (Q_{wp,i} \times ECF_{C3,i})$$

$EC_{c3,i}$  = carbon emissions associated with processing waste the  $i$ th material

$Q_{wp,i}$  = quantity of  $i$ th material for waste processing

$ECF_{c3,i}$  = waste processing embodied carbon factor of  $i$ th material

The carbon emission associated with the treatment of demolished waste disposal ( $EC_{C4}$ ) was calculated using equation (6). At the end of the building's useful life, the structure is assumed to be demolished, and materials are recycled according to the current UK recovery rate and the remaining are sent to landfill. As there is no current regulation an end-of-life scenario of reuse or recycling cannot be determined or guaranteed for the glulam timber material, the captured carbon for the glulam frame is assumed to be released during this stage.

Equation 6 - Embodied carbon for material disposal (C4)<sup>40</sup>

$$EC_{C4} = \sum_i (Q_{wd,i} \times ECF_{C4,i})$$

$EC_{c4,i}$  = total carbon emissions associated with waste disposal of the  $i$ th material.

$Q_{wd,i}$  = quantity of  $i$ th material for waste disposal

$ECF_{c4,i}$  = waste disposal embodied carbon factor of  $i$ th material

The total amount of the embodied carbon of the building was calculated using equation 7.

Equation 7 – Total embodied carbon

$$EC = EC_{A1-A3} + EC_{A4} + EC_{A5} + EC_{C1} + EC_{C2} + EC_{C3} + EC_{C4}$$

**Operational carbon (B6–B7).** The operational energy consumption and the associated emissions of P1, P2 and P3 were calculated using TAS software in which the building services were kept identical, and the fabric of the building was changed accordingly. The simulation of the LIDL supermarket building was

**Table 5.** Simulation assumptions: building summary specification.

Simulation parameter	Assumption set
Calendar	NCM standard
Air permeability	5.0 m <sup>3</sup> /h.m <sup>2</sup> @ 50 Pa
Infiltration	0.125 (ACH)
Fuel source	Grid supplied electricity
CO <sub>2</sub> factor	0.21107 kg/kWh

taken as a typical UK supermarket building. The model was designed with the closest accuracy to the plan's measurements. The sales area, entrance lobby, bakery, warehouse, toilets, and other offices including IT room, cash room, utility, meeting room, cloakroom, and welfare canteen were defined in the model.

Crucially, other parameters set in the TAS software package included using the National Calculation Methodology (NCM) standard calendar to reflect the operational hours of the supermarket and the floor area size fixed to be 2500 m<sup>2</sup> as per the actual building (Table 5). The internal conditions of the individual spaces such as the entrance lobby, corridor, water closet (WC), welfare and other rooms were assigned according to the NCM.

The construction materials were assigned to the build elements. The thermophysical characteristics of the building materials, specifically walls, frames, floor, and doors (Table 6) were defined in order to generate the BRUK-L report. Further data regarding 3D Modelling, modelling process, simulation building/process and data collection can be found in Hasan et al.<sup>42</sup>

The HVAC systems applied in the operation of the building include the heating, cooling, and domestic hot water circuits as prescribed for each individual zone of the supermarket building. The systems are equipped with plantrooms consisting of 3-pipe variable refrigerant flow circuits (VRF), sales air handling unit (AHU) VRF circuits, and local electric DHW circuits with grid-supplied electricity as a fuel source. The VRF HVAC systems consists of outdoor units connected to multiple indoor units via refrigerant piping providing cooling and heating to individual zones. A natural vent is used for the entrance lobby with no heating or cooling. The sales area uses a VRF with mechanical ventilation. The

**Table 6.** Simulation assumptions: building fabric specification.

Building element	Calculated area-weighted average U-values (W/m <sup>2</sup> K)
Wall (average)	0.24
Wall (poroton block)	0.18
Wall (precast concrete)	0.69
Floor	0.21
Roof	0.13
Windows	3.08
Personnel doors	1.32
Vehicle access doors	1.78
High-usage entrance doors	3.34

welfare and storage airside configuration consists of mechanical ventilation with heat recovery (MVHR) with direct/storage electric heater or heat pump (electric) for heating and air conditioning (AC) for cooling. Furthermore, an AC only VRF for extract only with no heating or cooling is applied to the storage/delivery warehouse, bakery, and customer WC.

Additionally, in order to keep the findings of this study in line with the goal of the research certain limitations were placed on the consideration of different factors, such as the application of on-site renewable energy sources, such as photovoltaics (PV), wind turbines, combined heat, and power (CHP). However, exploring these options would go beyond listing the magnitude and direction of random and systematic errors, affecting the validity process of this study. Further studies could investigate various on-site renewable energy sources, quantifying their impact on energy and cost savings over a fixed period. Similarly investigating the EC calculation of HVAC systems being used in the supermarket building, as well as consideration of various refrigerant systems (e.g., R404a/R448) and refrigerant leakage.

Previous studies have been carried out observing the supermarket buildings' performance in other major cities such as London, Manchester, and South Hampton. As Norwich is located in a different part of the climatic region of the UK than the other major cities, the city of Norwich is selected as it lies in the specific climatic region of Eastern England, about 100 miles North-East of London and is the largest city in East Anglia.

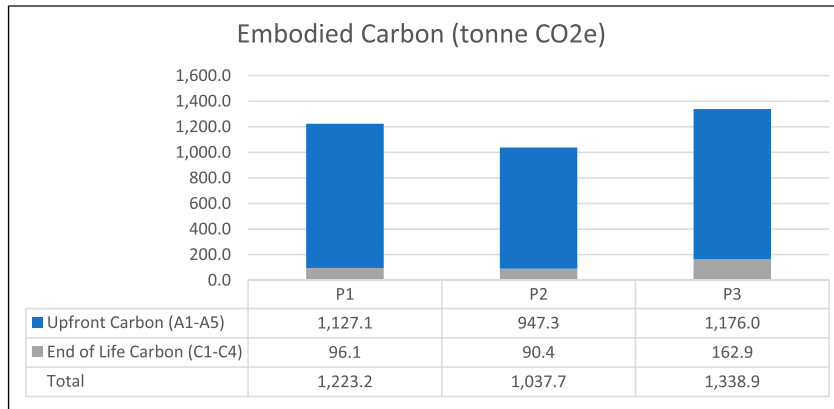
For energy use analysis, CIBSE provides two datasets, namely Test Reference Year (TRY) files for energy assessments and Design Summer Year (DSY) files for overheating analysis. As the model is designed in Norwich, this study will be making use of current, and future CIBSE Norwich TRY weather files for evaluation purposes<sup>43</sup> The CIBSE future TRYs are based on the UKCP09 projections.<sup>44</sup> Furthermore, the TRY files are used for predicting average energy consumption and compliance with the UK building regulations, which is a requirement while planning a new building.<sup>45</sup> Due to the limited literature available focusing on energy consumption and carbon emissions analysis in building this paper focuses on the supermarket building located in the city of Norwich.

## Results and discussion

### Embodied carbon

The embodied carbon of P1, P2 and P3 which were calculated within the defined parameters (Figure 6). The results obtained from the preliminary carbon emission analysis show that the P2 model contributed the least carbon emissions, with a total EC of 1037.7 tCO<sub>2</sub>e. Followed by the P1 model with a total EC of about 1223.2 tCO<sub>2</sub>e, while the P3 model contributes the highest carbon emissions with a total EC of 1338.9 tCO<sub>2</sub>e.

It could be assumed that a glulam frame would contain a lower embodied carbon due to timbers' intrinsic capability of absorbing CO<sub>2</sub>.<sup>46</sup> Many studies



**Figure 6.** Calculated embodied carbon contribution of models P1, P2, P3.

such as Hafner and Schäfer,<sup>47</sup> Spear et al.<sup>48</sup> and Hart, D'Amico and Pomponi<sup>28</sup> have respectively observed a potential 9–56% EC reduction in timber-based materials compared to mineral substitutes, a possible 20% EC reduction by substituting masonry with timber frames and a potential 43% EC reduction by use of timber frames compared to concrete and steel frames; the reduction or potential reduction is achieved by the inclusion of sequestered carbon in the results. Although it might appear that the findings of this study do not align with such studies, in order to avoid the risk of misleading results, a carbon-neutral calculation approach is assumed for wood-based materials.<sup>49</sup>

The embodied carbon of the different components between the three models, as depicted in Table 7, highlights the contribution of each component to the EC. As demonstrated the inclusion of the sequestered carbon can make a significant impact on the total EC. However, the sequestered carbon could only be considered as a carbon-saving measure if the retention of the sequestered carbon can be guaranteed. The reuse of the material which would guarantee the retention of the captured carbon falls under the D stage (beyond the system) (Figure 4) and beyond the scope of WLC assessments and this study. Additionally, the inclusion of the negative carbon value, with the assumption of reuse, in this assessment, would mean that the carbon saving attribute could not be applied in the material's future life cycles.<sup>50</sup> Considering the

carbon storage of the glulam timber frame reduces the EC of P3 by 67.2 tCO<sub>2</sub>e to 1271.7tCO<sub>2</sub>e. As seen in Figure 7 this model still contributes the highest carbon emissions.

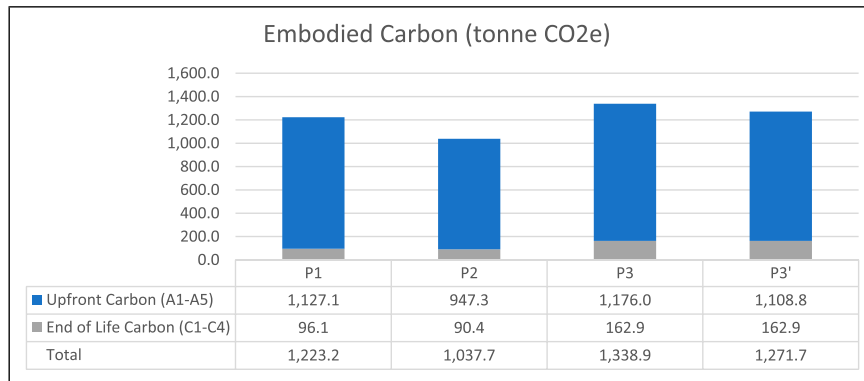
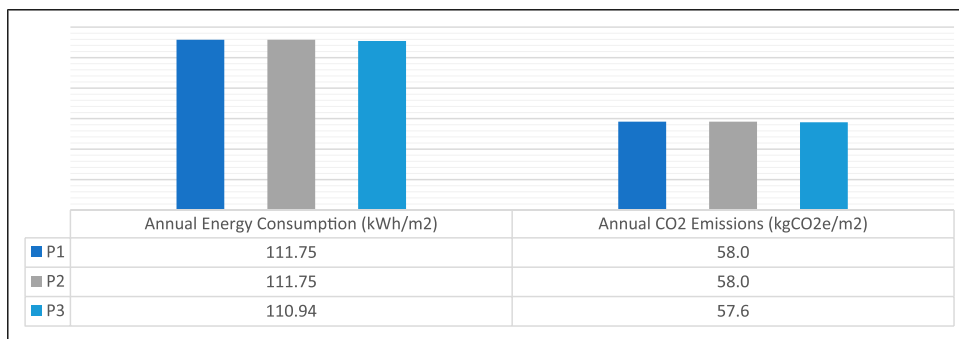
### Operational energy/carbon

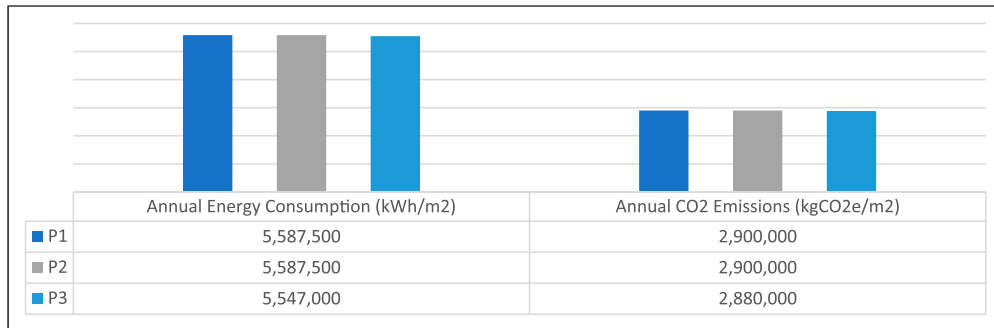
**Current scenario.** To calculate the operational energy and carbon emissions of the supermarket building located in Norwich, the CIBSE Test Reference Year (TRY) for Norwich, has been used. The annual energy consumption (kWh/m<sup>2</sup>) and annual CO<sub>2</sub> emissions (kg/m<sup>2</sup>) of P1, P2 and P3 were calculated within the defined parameters (Figure 8) using the Norwich current TRY files. Showing that the operational phase of models P1, P2 and P3 are nearly identical; however, model P3 consumes slightly less energy as well as produces fewer emissions.

These results indicate the energy consumption and subsequent carbon emissions from controlled, fixed building services and fittings, including space heating and cooling, hot water, ventilation and lighting. However, energy consumption from processes that are not controlled, which TAS categorises as equipment use, cannot be considered towards the total energy consumption. Given that these processes such as IT equipment, lift, escalators, refrigeration systems, external lighting, and small power equipment, are dependent on user/customer actions, which cannot be predicted and can vary throughout the buildings lifecycle.

**Table 7.** Calculated embodied carbon contribution of the external wall, roof frame and column components of models P1, P2, P3.

Model	Building component	Embodied carbon (kgCO <sub>2</sub> e)		
		A1–A5	C1–C4	Total
P1, P2	Steel roof frame	36,935.17	5100.46	42,035.63
P3	Glulam roof frame (without carbon storage)	35,567.46	77,090.24	112,657.70
P3	Glulam roof frame (with carbon storage)	–31,563.84	77,090.24	45,526.40
P1, P2	Steel columns	8986.13	16,904.48	25,890.61
P3	Pre-cast concrete columns	29,280.04	2284.65	31,564.69
P1	Cladding panel walls	702,514.48	18,298.05	720,812.53
P2	Poroton walls	523,475.48	12,431.26	535,906.74
P3	Precast concrete walls	736,606.64	14,525.38	751,132.02

**Figure 7.** Calculated embodied carbon comparison of models P1, P2, P3, P3' (including timber sequestered carbon).**Figure 8.** Operational energy and carbon emissions of models P1, P2 and P3 under the current scenario.



**Figure 9.** Operational energy and carbon emissions of models P1, P2, P3 under future scenario.

*Future scenario (20-year period).* As mentioned, the observed service life for this study is 20 years. Assuming that the energy consumption and associated carbon emissions of the supermarket building remain the same for the next 20 years, the results based on the use of the current TRY obtained in calculated for the current scenario are then multiplied by 20, to obtain projections of future energy usage. Retaining the remaining factors, the annual energy consumption and carbon emissions of the next two decades of P1, P2 and P3 were calculated. While this assumption creates some limitations and uncertainty it does provide a valid benchmark comparison for all three models. Adjusting for future changes using CIBSE emission scenarios of 2050s (low, medium, and high each with 10th, 50th and 90th percentile) would produce unclear and confusing results for any given model under investigation and would not provide results for this study's purposes.

The results presented in Figure 9 showing, as expected, the near identical annual energy consumption and carbon emissions of all three models for the next two decades. With P1 and P2 consuming 5,587,500 kWh energy and P3 consuming 5,547,000 kWh. And P1 and P2 producing 2,900,000 kgCO<sub>2</sub>, and P3 producing 2,880,000 kgCO<sub>2</sub> of carbon emissions. Highlighting that due to the quantity of operational emissions, even small differences could make a significant difference. As seen in the 20 tonnes of carbon emissions difference between models P1 and P2 with P3.

As supermarket stores are primarily powered by the national grid, it is also important to understand the decarbonisation of this energy system which means moving from a centralised, fossil fuel-dependent system to a green and renewable energy system.<sup>51</sup> In 2021 a landmark commitment to decarbonise the UK's electricity system by 2035 was confirmed by the UK government by introducing a ten point plan for a Green Industrial Revolution via home-grown, green technologies.<sup>52</sup> However, at this moment there are no further explanatory notes or details available from the official sources.

*Verifying simulation results.* There are distinct possibilities of differences between simulation results and actual building performance due to use of different assessors, different tools, unknown data, or uncertain information such as user activity. With certain studies suggesting a possibility of energy performance gap as high as 30%.<sup>53</sup> Therefore, it is important to investigate the reliability of the simulation results. The reliability of the TAS simulation results was tested by validating the results against measured energy consumption of a LIDL supermarket building of similar proportions and building performance operation in the UK. According to survey and real-time annual energy measurements recorded over five consecutive years, a consumption range of 137.31 kWh/m<sup>2</sup> to 150.53 kWh/m<sup>2</sup> was observed. These values are slightly higher compared to the 111.75 kWh/m<sup>2</sup> calculated using TAS. However, these differences are affected by various factors such as the exact location of the building, weather database difference and historical climate change, dissimilar

HVAC systems, air infiltration systems, as well as use of TAS instead of Simplified Building Energy Model (SBEM) methodology carried out by independent commercial assessors.

### Benchmarking results

For the purposes of benchmarking the results against the nominal values of a notional building of a similar size, it is important to have the exact corresponding values. A notional building is a theoretical design of a compliant specification and is intended to be an aid to designers, showing how compliance might be achieved using certain technologies or u-values. The operational carbon energy and emissions of a notional building would approximately consume 109 KWh/m<sup>2</sup> and produce 53 KgCO<sub>2</sub>/m<sup>2</sup> depending upon the model type used.

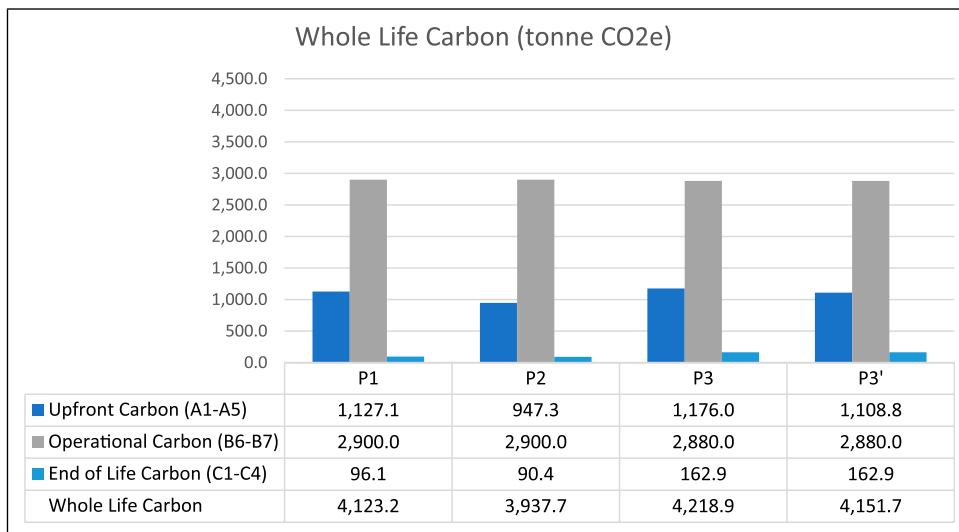
As previously mentioned, the lack of regulation and significantly less case studies for embodied carbon, prohibits the ability to create a benchmark comparison value. The London Energy Transformation Initiative (LETI) published a design guide in 2020 providing some data for residential, commercial office and school buildings suggesting a that the latter would produce approximately 1000 kgCO<sub>2</sub>e/m<sup>2</sup> in the A1-A5 stages, with a reduction goal of 600 kgCO<sub>2</sub>e/m<sup>2</sup>.<sup>54</sup> The case

studies in this research produced between 378.92 kgCO<sub>2</sub>e/m<sup>2</sup> and 470.39 kgCO<sub>2</sub>e/m<sup>2</sup>. Although, a Built Environment Carbon Database (BECD) is being developed by several bodies including RIBA, the RICS, CIBSE, BRE, CIOB, IStructE, and ICE which will soft launch in 2023, which could be a vital tool for future research.<sup>55</sup>

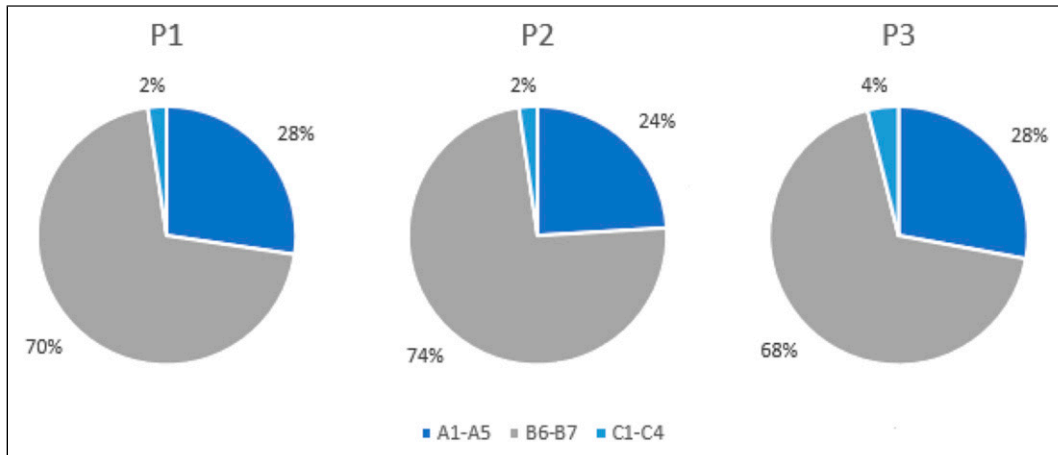
### Whole life carbon

In order to examine the whole life carbon of the three models, the operational carbon, adjusted for the 2,500 m<sup>2</sup> floor area of the building, and the embodied carbon were consolidated. It can be observed that the Whole Life Carbon (WLC), as depicted in Figure 10, follow the same trend as the embodied and operational carbon individually. With model P2 having the lowest WLC of 3937.7 tonneCO<sub>2</sub>e, followed by model P1 with a 4123.2 tonneCO<sub>2</sub>e WLC impact and P3 having the highest impact, with a WLC of 4218.9 tonneCO<sub>2</sub>e. Moreover, even considering the sequestered carbon, the WLC of P3' is still higher than the WLC of P1 and P2, with a value of 4151.7 tonneCO<sub>2</sub>e.

Examining the embodied and operational carbon separately provided an insight into the reasons regarding the issues of performing a WLC assessment.



**Figure 10.** The upfront, operational and end-of-life emissions contribution of models P1, P2, P3, P3'.



**Figure 11.** Contributions of the upfront, operational, and end-of-life emissions of models P1, P2, P3 to the Whole life carbon.

The percentage breakdown as depicted in Figure 11 show that the presentation of WLC within this format could be misleading without providing the vital context of the results. Whilst the results of this study present a comparison where the Operational Carbon (OC) has minimal difference between the three models, in other studies this may result in misplaced focused of reduction efforts.

The factors contributing to the largest portions of the OC, such as lighting, are considered negligible when calculating the EC. Consequently, while it might be expected that the building fabric, the largest single contributor to the EC in all three models, contributing 30% of P1, 26% of P2 and 32% of P3's EC, would affect the OC of the buildings. The nature of the building use and the subsequent energy use breakdown, and where all 3 models are designed with the same HVAC system as presented in this study, factors such as building fabric which significantly affect the difference in EC do not affect the OC as substantially. It could be concluded that the ability to observe the effects of each factor on the emissions of each stage separately would provide more accurate information which would be ideal for future environmental impact reduction efforts. However, adopting this conclusion outside the parameters of this case study would not be practical. As mentioned, one of the possible factors of this result is

the specific design and use of the building. Additionally, these results can inform future WLC reduction strategies which could be implemented. As the variable factors in this study affecting the environmental impact of each stage are observable, changes to any factor to reduce the impact of any particular stage can be considered with the knowledge of the effect on the WLC. Furthermore, this study provides a framework for the future study of the non-variable factors between the three models, such as the building design, HVAC system, and the effects on the whole life carbon and further reduction efforts.

## Conclusions

This research aimed to examine the material components and construction developments of buildings by comparing embodied (EC) and operational carbon (OC) emissions of three construction approaches. The life cycle phases included in the analysis were production, construction, operation, and disposal (A1-A5, B6-B7, C1-C4). A case study of a typical UK supermarket building LCA was performed to evaluate three construction approaches with different building materials. The whole life carbon (WLC) emissions were shown to be 4123 tonneCO<sub>2</sub>e for the P1 model, of which the EC accounted for 30%.

Showing a 3938 tonneCO<sub>2</sub>e WLC emission for the P2 model, of which the EC contributed 26%. The three construction approaches were analysed, considering the potential to reduce embodied carbon emissions over the whole life span of the building. Relevant findings from the preliminary calculations using Revit and TAS tools for the models revealed that P3 has the largest WLC of 4219 tonneCO<sub>2</sub>e representing an EC contribution increase of 32% increase without considering the biogenic carbon. The findings of this investigation observe that the carbon emissions of supermarket buildings could be reduced (approximately 6.6% reduction), by carefully making material choices without the need of extreme redesigns or reconfigurations to building systems. Additionally, as the three structures were designed with identical building services, the results showed that this method of embodied carbon reduction in these structures has limited influence on the operational carbon. Future studies could also explore the influence reduction of OC via the implementation of alternative building structures and examining the influence of those reduction strategies on the EC. These insights may assist designers and engineers in making the right design decisions for buildings regarding a comprehensive carbon emissions reduction strategy. These findings could also provide foundational information in the development of further WLC reduction strategies such as design changes in the plan, size, and layout of similar buildings.

Additionally, highlighting that it is imperative to consider the WLC when making design decisions. Unless the processes of all stages can be controlled, considering the lack of legislations for many processes, in particular end of life, carbon savings in one stage may be negated in other stages. And consideration of carbon savings from captured carbon to inform design decisions should be examined beyond the lifecycle. It is, therefore, crucial to develop this further knowledge along with the enrichment of relevant information.

This study contributes to our understanding of embodied and operational carbon emissions. Additionally, the method employed in this study assessing the WLC of UK supermarket buildings, could assist in providing a framework for the calculation of future

cradle to grave impact assessments of other building types. Allowing for and encouraging more informed design decisions by investors, developers and institutions to lower carbon emissions associated with their building stock. Furthermore, given the need to provide futureproofing of buildings against the changing climate whilst reducing future harm, it is vital that the introduction of passive design technologies and incorporation of high-efficiency HVAC systems could provide a realistic plan to secure the built environment ahead of the expected change in the climate.

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### References

1. Muinzer TL. Is the climate change act 2008 a constitutional statute? *EURO* 2018 Dec 1; 24(4): 733–753.
2. IEA. *Buildings - A source of enormous untapped efficiency potential [Internet]*. Paris: IEA; 2022 Aug [cited 2022 Apr 22]. Available from: <https://www.iea.org/reports/buildings>
3. Environment UN. 2019 Global Status report for buildings and construction sector, 2019 [Internet]. UNEP - UN Environment Programme [cited 2021 Dec 18]. Available from: <http://www.unep.org/resources/publication/2019-global-status-report-buildings-and-construction-sector>
4. CCC. The sixth carbon budget - the UK's path to net zero; 2020 Dec [Internet]. Committee on Climate Change [cited 2022 Apr 25] p. 448. Available from: <https://www.theccc.org.uk/publication/sixth-carbon-budget/>

5. Hossain MU, Wu Z and Poon CS. Comparative environmental evaluation of construction waste management through different waste sorting systems in Hong Kong. *Waste Manag* 2017 Nov; 69: 325–335.
6. UN Habitat. Buildings day proves a hit at COP21|UN-Habitat [Internet]. UN Habitat - A Better Urban Future. [cited 2022 Jan 20]. Available from: <https://unhabitat.org/buildings-day-proves-a-hit-at-cop21>
7. Richard McPartland. UK green building council. Embodied carbon: developing a client brief; 2017 [Internet]. UK Green Building Council [cited 2022 Apr 29]. Available from: <https://www.thenbs.com/knowledge/developing-an-embodied-carbon-brief-for-clients>
8. Adams M, Burrows V and Richardson S. *Bringing embodied carbon upfront - coordinated action for the building and construction sector to tackle embodied carbon* [Internet]. World Green Building Council; 2019 [cited 2022 Jan 19]. Available from: <https://worldgbc.org/article/bringing-embodied-carbon-upfront/>
9. Yohanis YG and Norton B. Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy* 2002 Jan 1; 27(1): 77–92.
10. Moncaster AM and Symons KE. A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energ Build* 2013 Nov; 66: 514–523.
11. Peng C. Calculation of a building’s life cycle carbon emissions based on Ecotect and building information modeling. *J Clean Prod* 2016 Jan; 112: 453–465.
12. Iddon CR and Firth SK. Embodied and operational energy for new-build housing: a case study of construction methods in the UK. *Energ Build* 2013 Dec; 67: 479–488.
13. Sharma A, Saxena A, Sethi M, et al. Life cycle assessment of buildings: a review. *Renew Sustain Energy Rev* 2011 Jan; 15(1): 871–875.
14. Robati M, Oldfield P, Nezhad AA, et al. Carbon value engineering: a framework for integrating embodied carbon and cost reduction strategies in building design. *Build Environ* 2021 Apr; 192: 107620.
15. Asdrubali F, Baldinelli G, Bianchi F, et al. A comparison between environmental sustainability rating systems LEED and ITACA for residential buildings. *Build Environ* 2015; 86: 98–108.
16. Röck M, Saade MRM, Balouktsi M, et al. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Appl Energy* 2020 Jan; 258: 114107.
17. Andersen CE, Rasmussen FN, Habert G, et al. Embodied GHG emissions of wooden buildings—challenges of biogenic carbon accounting in current LCA methods. *Front Built Environ* 2021 Aug 31; 7: 729096.
18. Hasan A, Bahadori-Jahromi A, Mylona A, et al. Investigating the potential impact of future climate change on UK supermarket building performance. *Sustainability* 2020 Dec 22; 13(1): 33.
19. Ríos Fernández JC and Roqueñi N. Analysis of the potential of Spanish supermarkets to contribute to the mitigation of climate change. *Sustain Prod Consumpt* 2018 Apr; 14: 122–128.
20. Ellen MacArthur Foundation (last). *Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition* [Internet]. Isle of Wight, UK: Ellen MacArthur Foundation Publication; 2013 [cited 2022 Nov 17] p. 1–98. Available from: <https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an>
21. Geissdoerfer M, Savaget P, Bocken NMP, et al. The circular economy – A new sustainability paradigm? *J Clean Prod* 2017 Feb; 143: 757–768.
22. Bressanelli G, Saccani N, Pigosso DCA, et al. Circular Economy in the WEEE industry: a systematic literature review and a research agenda. *Sustain Prod Consumpt* 2020 Jul; 23: 174–188.
23. Bressanelli G, Saccani N, Perona M, et al. Towards circular economy in the household appliance industry: an overview of cases. *Resources* 2020 Nov 3; 9(11): 128.
24. Foster A, Evans J and Maidment G. *Benchmarking of supermarket energy consumption*. [Internet]. International Institute of Refrigeration (IIR); 2018 [cited 2022 Dec 27]. Available from: <https://openresearch.lsbu.ac.uk/item/86v68>
25. Target Zero Information Line. Guidance on the design and construction of sustainable, low carbon supermarket buildings [Internet]. 2011 Jun p. 16. Available from: [https://www.steelconstruction.info/images/8/82/Supermarket\\_guidance\\_doc\\_v2.pdf](https://www.steelconstruction.info/images/8/82/Supermarket_guidance_doc_v2.pdf)
26. Skullestad JL, Bohne RA and Lohne J. High-rise timber buildings as a climate change mitigation measure – a comparative LCA of structural system alternatives. *Energy Procedia* 2016 Sep; 96: 112–123.

27. Teshnizi Z, Pilon A, Storey S, et al. Lessons learned from life cycle assessment and life cycle costing of two residential towers at the university of British Columbia. *Procedia CIRP* 2018; 69: 172–177.
28. Hart J, D'Amico B and Pomponi F. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *J Ind Ecol* 2021 Apr; 25(2): 403–418.
29. De Wolf C, Yang F, Cox D, et al. Material quantities and embodied carbon dioxide in structures. *Proc Inst Civ Eng Eng Sustain.* 2015 Sep 29; jensu.15.00033
30. Akbarnezhad A and Xiao J. Estimation and minimization of embodied carbon of buildings: a review. *Buildings* 2017 Jan 4; 7(4): 5.
31. Tecchio P, Gregory J, Ghattas R, et al. Structured under-specification of life cycle impact assessment data for building assemblies. *J Ind Ecol* 2019 Apr; 23(2): 319–334.
32. British standards institution, Technical Committee B/558 S of construction works, British Standards Institution, European Committee for Standardization. *Environmental management - life cycle assessment - principles and framework (BS EN ISO 14040:2006+A1:2020)*. BSI Standards Publication; 2006.
33. British Standards Institution. *Buildings and constructed assets, service life planning, Part 1, General principles and framework*. 2nd ed. Genève: BSI Standards Publication, 2011.
34. Prudence G and Green A. *Guide M Maintenance engineering and management* [Internet]. London: The Chartered Institution of Building Services Engineers; 2014 [cited 2022 Jun 6]. 164 p. Available from: <https://www.cibse.org/knowledge-research/knowledge-portal/guide-m-maintenance-engineering-and-management-2014-pdf>
35. British Standards Institution. *Environmental management - life cycle assessment - principles and framework (BS EN ISO 14044:2006)*. London: BSI Standards Publication, 2021.
36. Pan W and Garmston H. Building regulations in energy efficiency: compliance in England and Wales. *Energy Policy* 2012 Jun; 45: 594–605.
37. Amirkhani S, Bahadori-Jahromi A, Mylona A, et al. Impact of low-E window films on energy consumption and CO2 emissions of an existing UK hotel building. *Sustainability* 2019 Aug 7; 11(16): 4265.
38. Bahadori-Jahromi A, Salem R, Mylona A, et al. The effect of occupants' behaviour on the building performance gap: UK residential case studies. *Sustainability* 2022 Jan 25; 14(3): 1362.
39. Mohebbi G, Bahadori-Jahromi A, Ferri M, et al. The role of embodied carbon databases in the accuracy of Life Cycle Assessment (LCA) calculations for the embodied carbon of buildings. *Sustainability* 2021 Jul 16; 13(14): 7988.
40. Gibbons OP and Orr JJ. *How to calculate embodied carbon*. [Internet]. Institution of Structural Engineers (Great Britain); 2020 [cited 2021 Dec 18]. Available from: <https://www.istructe.org/1StructE/media/Public/Resources/istructe-how-to-calculate-embodied-carbon.pdf>
41. RICS. *Whole life carbon assessment for the built environment* [Internet]. 1st ed. London: Royal Institution of Chartered Engineers, 2017, p. 41. Available from: [www.rics.org](http://www.rics.org)
42. Hasan AU, Bahadori-Jahromi A, Mylona A, et al. Comparing building performance of supermarkets under future climate change: UK case study. *Techno-Press J* 2022; 8(1): 73–93.
43. CIBSE. *Guide J Weather, solar and illuminance data* [Internet]. London: The Chartered Institution of Building Services Engineers; 2002 [cited 2022 Jun 6]. 456 p. Available from: <https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000Hj0hmQAB>
44. Eames M, Kershaw T and Coley D. On the creation of future probabilistic design weather years from UKCP09. *Building Serv Eng Res Tech* 2011 May; 32(2): 127–142.
45. Eames M, Ramallo-Gonzalez A and Wood M. An update of the UK's test reference year: the implications of a revised climate on building design. *Build Serv Eng Res Technol* 2016 May; 37(3): 316–333.
46. Prentice I, Farquhar G, Fasham M, et al. The carbon cycle and atmospheric carbon dioxide. In: JT Houghton, Y Ding, DJ Griggs, et al. (eds) *Climate change 2001: the scientific basis*. Cambridge University Press, 2001, pp. 183–237.
47. Hafner A and Schäfer S. Environmental aspects of material efficiency versus carbon storage in timber buildings. *Eur J Wood Prod* 2018 May; 76(3): 1045–1059.
48. Spear M, Hill C, Norton A, et al. *Wood in construction in the UK: an analysis of carbon abatement potential* [internet]. UK: The BioComposites Centre, 2019. [cited

- 2022 Jun 23] p. 38. Report No.: BC-1383-2018-ES. Available from: <https://www.theccc.org.uk/publication/wood-in-construction-in-the-uk-an-analysis-of-carbon-abatement-potential-biocomposites-centre/>
49. Hoxha E, Passer A, Saade MRM, et al. Biogenic carbon in buildings: a critical overview of LCA methods. *Build Cities* 2020 Aug 12; 1(1): 504–524.
  50. Jones C and Hammond G. ICE embodied carbon database [Internet]. 2019 [cited 2021 Dec 21]. Available from: <https://circularecology.com/embodied-carbon-footprint-database.html>
  51. Groves C, Henwood K, Pidgeon N, et al. The future is flexible? Exploring expert visions of energy system decarbonisation. *Futures* 2021 Jun; 130: 102753.
  52. Vella H. Ten steps to net zero [energy decarbonisation]. *Eng Techn* 2021 Feb 1; 16(1): 20–24.
  53. Tronchin L and Fabbri K. A round robin test for buildings energy performance in Italy. *Energ Build* 2010 Oct; 42(10): 1862–1877.
  54. LETI. *LETI Embodied carbon primer - supplementary guidance to the climate emergency design guide* [Internet]. CB George, editor. LETI; 2020 [cited 2021 Dec 20]. Available from: <https://www.leti.uk/ecp>
  55. Fiske J. *Built environment carbon database - philosophy and programme* [Internet]. BECD; 2022 [cited 2022 Dec 30]. Available from: <https://www.becd.co.uk/documents>