Energy & Buildings 296 (2023) 113387

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Variations in whole-life carbon emissions of similar buildings in proximity: An analysis of 145 residential properties in Cornwall, UK

Lin Zheng [a,b], Markus Mueller [b,c,d], Chunbo Luo [d,e], Tamaryn Menneer [b,f], Xiaoyu Yan [a,b,*]

[a] Renewable Energy Group, Engineering Department, Faculty of Environment, Science and Economy, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
[b] Environment and Sustainability Institute, Faculty of Environment, Science and Economy, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
[c] Department of Earth and Environmental Sciences, Faculty of Environment, Science and Economy, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
[d] Institute for Data Science and Artificial Intelligence, University of Exeter, Exeter EX4 4RN, UK
[e] Department of Computer Science, Faculty of Environment, Science and Economy, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
[f] European Centre for Environment and Human Health, University of Exeter Medical School, Knowledge Spa, Royal Cornwall Hospital, Truro, Cornwall TR1 3HD, UK

ARTICLE INFO

Keywords:
Whole Life carbon emissions
Building life cycle
Residential property
Sustainable building design

ABSTRACT

Assessing and reducing the whole-life carbon emissions (WLCE) of buildings is essential to achieving global climate targets. Although many studies have examined building WLCE, there is a lack of understanding of the variability of WLCE for a large number of similar buildings in proximity and the key influencing factors. We fill these knowledge gaps by quantifying the WLCE of 145 residential properties in Cornwall, UK, following methods recommended in official standards and guidelines for building WLCE and using actual electricity consumption recorded by sensors, and then analysing correlations between the WLCE and a range of factors related to the properties and their occupants. We found significant variations in the WLCE among these 145 properties, ranging from 21 to 193 t CO_2eq, with the WLCE intensity ranging from 0.5 to 2.6 t CO_2eq/m^2. There are strong correlations between WLCE and two factors: floor area and number of occupants, followed by number of bedrooms, type of property, window frame material, type of heating system, age of the main occupant, type of glazing, and loft insulation thickness. This suggests that both building attributes and occupant characteristics can result in significant variations in the WLCE of similar buildings in proximity. Therefore, both building design and occupant lifestyle need to be considered when developing strategies to reduce building WLCE.

1. Introduction

Buildings are responsible for approximately 40% of global carbon emissions. Thus, decarbonizing the building sector is crucial in achieving the Paris Agreement's objective of limiting the increase in average global temperature to below 2 °C, which is necessary to mitigate the significant risks associated with climate change [1–3].

Life cycle analysis or life cycle assessment (LCA) plays a crucial role in informing carbon reduction strategies [4,5]. It is a method for holistically evaluating the environmental impacts of a product throughout its whole life (e.g., creation, use, and end-of-life) [6]. ISO 14040:2006 [7] defines LCA as "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle". It was first conceptualised in the 1970 s and then gradually refined and standardised, and it is currently considered the most appropriate and reliable tool for assessing the environmental impacts and supporting decision-making for sustainable development [8–12].

Life cycle thinking plays a fundamental role in Whole Life Carbon Emission (WLCE) studies [13]. Given that the building sector is a significant contributor to global carbon emissions, there has been a growing interest in quantifying WLCE in buildings at both global and national levels, as well as for individual buildings. WLCE studies in the building sector can help architects understand the lifetime consequences of building design decisions by quantifying emissions throughout the different stages of the building life cycle [14–17]. This promotes durability, resource efficiency, and future adaptability, all of which contribute to lifetime carbon reductions for buildings [18]. Understanding building WLCE is also the basis for sustainable net-zero building design [19–23].

The concept of the life cycle stages of buildings including the product stage, construction stage, use stage, and end-of-life stage, was presented around the 2000 s and formalised by a set of standards from the

---

* Corresponding author.
E-mail address: Xiaoyu.Yan@exeter.ac.uk (X. Yan).

https://doi.org/10.1016/j.enbuild.2023.113387
Received 8 February 2023; Received in revised form 13 July 2023; Accepted 17 July 2023

European Committee for Standardisation in recent years. A modular concept for the definition of the system boundaries and scope of life cycle stages of buildings was introduced by The British Standard BS EN 15978:2011 (Sustainability of construction works) standard [24]. It was updated in The EN 15804 + A2 (Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products) standard [25] to refer to the full life cycle stages of buildings. The diagram (see Fig. 1) encompasses the building life cycle stages, scope, and typical system boundaries adapted from BS 19578, EN 15804, and ISO 21930:2017 [26]. The initial phase of a product's life cycle is commonly referred to as the "cradle" stage. When analysing the product stage specifically, it is often termed "cradle-to-gate," where the "gate" signifies the point at which the product is ready for shipment from the factory. On the other hand, the final stage of the life cycle is known as the "grave." Therefore, an analysis that encompasses the entire life cycle of a building is often referred to as "cradle-to-grave" [27]. Carbon emissions from buildings can also be broadly categorised into operational emissions resulting from energy use during the use stage and embodied emissions of building materials and components that make up the structure [28], which also include the lifetime emissions from maintenance, repair, replacement, and ultimately demolition and disposal [29].

Existing studies on the quantification of WLCE in the building sector often have different objectives. Some studies evaluate the carbon footprint of the building stock and built environment at a national level, for example, in China [30], Australia [31], and Ireland [32,33]. These studies have employed diverse approaches, including input–output and process-based models [30] and innovative methodologies such as the Commodity Accounting Method and Sectoral Summation Method [32], to quantify the embodied carbon emissions of building materials. A model for forecasting the WLCE of the whole residential building sector was developed based on key drivers effecting the performance of the entire building stock [33]. They have also taken into account factors such as population growth, economic growth, and policy rather than solely focusing on technologies [31]. Although these studies offer useful information at a strategic level for policymakers and stakeholders in specific regions, they often lack detailed insights at a building level.

Some studies analysed the WLCE of specific buildings to understand the emission characteristics of their building types. Examples include studies on a three-floor office building in the UK [34], a residential building in Spain [35], a timber-frame low energy use house in the UK [36], a typical large-scale office building [37] in China, a typical residential building in Ghana [38], a wood-based flat [39], a wood-based domestic house [40], hotels [41], and a traditional Korean building [42]. Their results show that the retrofitting approach that combines both passive and active measures, such as biomass boilers and solar panels, can considerably reduce the WLCE for refurbishing office buildings. Local low-carbon materials, renewable energies, and recycling value chains are essential for reducing the WLCE of residential properties. Operational carbon emissions account for the largest share of buildings WLCE. The monitoring and management of energy systems is the key factor affecting the WLCE of the large-scale office building. The stabilised earth block facade proved to be the most sustainable facade as it reduces cumulative energy demand. The type of heating system strongly influences wooden-based residential properties' primary energy use and carbon emissions. However, such studies often use a single building as a case study to provide emission characteristics for different types of buildings. Although these studies offer valuable insights into the unique challenges and opportunities for reducing carbon emissions in specific types of buildings, they rely on individual buildings as case studies and therefore may not provide generalizable findings for similar buildings. Moreover, WLCE calculations may be less accurate when using estimated or simulated building energy consumption data in some of these studies [35–38,41,42] rather than actual consumption.

In addition, some studies calculated and compared the WLCE of several different buildings to show the variations and investigate the factors that influence the WLCE. For example, a glued laminated bamboo-based rural residential building has a lower WLCE than a reinforced concrete building [43], with the main reduction in carbon emissions in the use stage and the product stage. This is mainly because the bamboo material has better insulation performance compared to concrete, resulting in lower emissions during the use stage, and bamboo has the ability to sequester carbon, resulting in lower emissions during the production phase. An urban residential building has a higher WLCE than a rural one in Turkey [16]. A steel-bamboo structure is more carbon-friendly than a reinforced concrete frame structure mainly

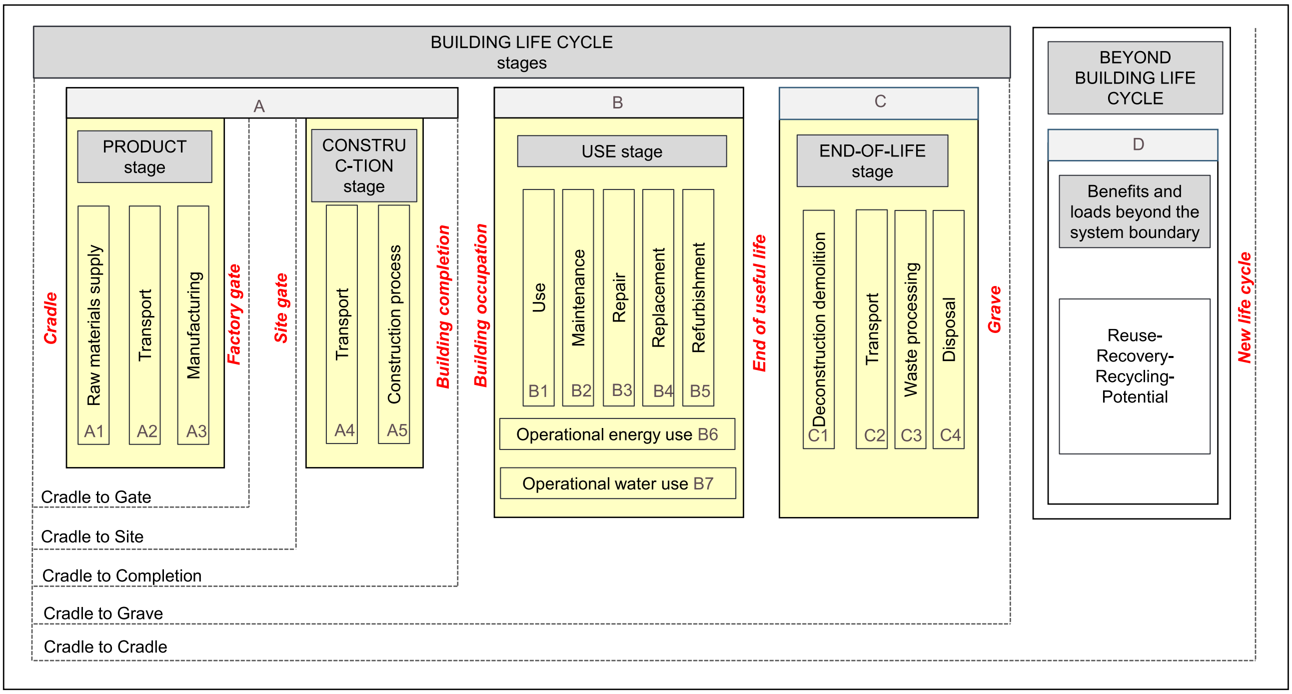


Fig. 1. Building life cycle stages (adapted from the BS EN 15978:2011, EN15804 and ISO 21930), and the scope and typical system boundaries.

because: (1) it has a lower energy need for space heating in the use stage, resulting in lower operational emissions; (2) it has a lower self-weight (quantity of materials), resulting in lower emissions from the foundation in the product stage, from transportation in the construction stage, and from waste transportation in end-of-life stage; and (3) it has lower on-site energy demand for processing steel products compared with casting concrete members in the construction stage, resulting in lower total embodied emissions. [44]. Energy efficient buildings with better building performance could be assessed as green buildings according to the Evaluation Standard for Green Building (GB/T 50378–2006) in China. The average WLCE of green buildings is lower than non-green buildings in China, mainly because of their energy-saving technologies, which resulting in lower operational carbon emissions [45]. The average WLCE of buildings with district heating systems is lower than that of buildings with central heating systems [46]. The retrofit of office buildings' roofs with the white roof or sedum-tray garden roof depends on the climate and various environmental benefits in China [47]. In these studies, the type of building structure, type of heating system, and number of stories were found to be key factors that influence the building's WLCE. However, when comparing different kinds of buildings, using only one specific building as a representative may not be sufficiently generalisable, e.g. one building in an urban area to represent the urban residential building and another building in a rural area to represent the rural residential building [16], one bamboo-based structure building and one reinforced concrete frame structure building [43,44], one white roof and sedum-tray garden roof office buildings. Meanwhile, some of these studies used simulated energy consumption data rather than actual data for the WLCE calculation (e.g., simulated by software [43,43,44] or assumed from energy audits and statistics [46]). As a result, some factors that impact operational carbon emissions may be overlooked, further affecting the WLCE results for different buildings and the investigation of the influencing factors.

Other studies aimed to contribute to the early design of sustainable buildings by developing and evaluating WLCE estimation or prediction models using WLCE calculation results from a case study as a baseline. Examples include establishing an online program based on a flat [48], developing an automated estimation program based on a residential property [49], and building different prediction models based on 207 residential properties [50]. However, estimated or simulated energy consumption data were used in these studies to calculate the WLCE (e.g., estimated using building energy efficiency rating certification [48], estimated based on national agency reports [49], simulated by software [50]). As building energy consumption can be strongly influenced by a wide range of factors (e.g., actual weather conditions and occupant behaviour), using estimated or simulated energy consumption data could affect the accuracy of the baseline WLCE results, leading to potential inaccuracy in the programs and models developed. Some studies on building WLCE did not follow the official standards, and others did not cover a building's whole life cycle stages [51–55]. For example, some studies classify the process of material transportation from the manufacturing factory to the site into the production stage [46,56], while others classify this process into the construction stage [48,55]. The embodied carbon emissions from fuel used by construction equipment in the construction stage A5 and from demolition at the end-of-life stage C1 were ignored [50,55].

Overall, there is a lack of studies on WLCE for a large number of buildings of the same or similar types in the same area based on actual energy consumption and covering all the stages of the building life cycle, resulting in critical knowledge gaps around how variable WLCE can be for these buildings and what might be the key factors contributing to the variations. To fill this gap, this paper aims to, for the first time, explore the variations in WLCE for a large number of buildings of the same or similar types in the same area and investigate the factors that lead to the variations by (1) quantifying the WLCE of 145 residential properties in Cornwall, UK, that covers all stages of the building life cycle, following the methods in the BS EN 15987 standards [24] and The Royal Institution of Chartered Surveyors (RICS) professional statement "Whole-life carbon assessment for the built environment" [28], and (2) statistically analysing the correlations between WLCE results and a wide range of factors related to the buildings and their occupants. Potential carbon reduction strategies were also proposed based on the key factors that can noticeably affect the buildings' WLCE. Our results can help various stakeholders, including designers, building owners, and policymakers, develop decarbonization strategies from a life cycle perspective when designing new buildings or retrofitting existing buildings. This study could also support future modelling research by providing a basis for investigating more factors relevant to carbon emissions that are related to occupant behaviour and building design.

2. Materials and method

To investigate the Whole Life Carbon Emissions (WLCE) of a significant number of buildings of similar types within the same geographic region, we conducted a case study in Cornwall, UK. An overview of our methodology is shown in Fig. 2. We first calculate the WLCE for each individual property and then analyse the correlations between the WLCE results and building attributes and occupant characteristics. To ensure a comprehensive analysis of the WLCE, this study follows a "cradle-to-grave" scope covering the Product stage (A), Use stage (B), and the End-of-Life stage (C) in the building life cycle (see Fig. 1).

As shown in Fig. 2, in this study, the carbon emissions included within the Product stage (A), Use stage (B), and the End-of-Life stage (C) are from the following processes:

- A1-3: Raw material extraction and refining (A1), transporting raw materials to the plant (A2), and processing the raw materials to make building materials (A3).
- A4: The transportation of the materials from the factory gate to the construction site
- A5: Energy use at the construction site
- B4: Replacement of building materials
- B6: Operational energy use for occupants live the life (energy use for heating)
- C1: Energy use of demolition for waste materials at the site
- C2, C4: Transportation of the waste materials to the landfill (C2) and the landfill for final disposal (C4)

A survey was conducted to gather information about the characteristics of the buildings and their occupants. This allowed us to explore how WLCE varies among a large number of buildings in the same area and identify the main factors that contribute to these variations [52]. Detailed descriptions of the case study, the WLCE calculation methods, the assumptions of each process, the scope of each emission factor used, and the method of correlation analysis were presented in the following subsections.

2.1. Case study description and data collection

We quantified the WLCE of 145 existing residential properties, consisting of 79 flats, 17 bungalows, and 49 houses. These properties are typical residential properties in the UK [57] and are described in detail in Table S1 in the supplementary materials. A detailed description of the case properties, including information on their age, construction type, and other information, is also available in the supplementary materials (see Table S5). These properties were selected as high-resolution data on electricity consumption and characteristics of the buildings and their occupants from the questionaries by survey, which are from Smartline, a six-year interdisciplinary research program [58–60]. The electricity consumption was recorded at a maximum frequency of every 3 min by sensors. A detailed description of sensors can be found in our previous publication [102]. The survey was conducted to gather information on various factors related to occupant characteristics and building

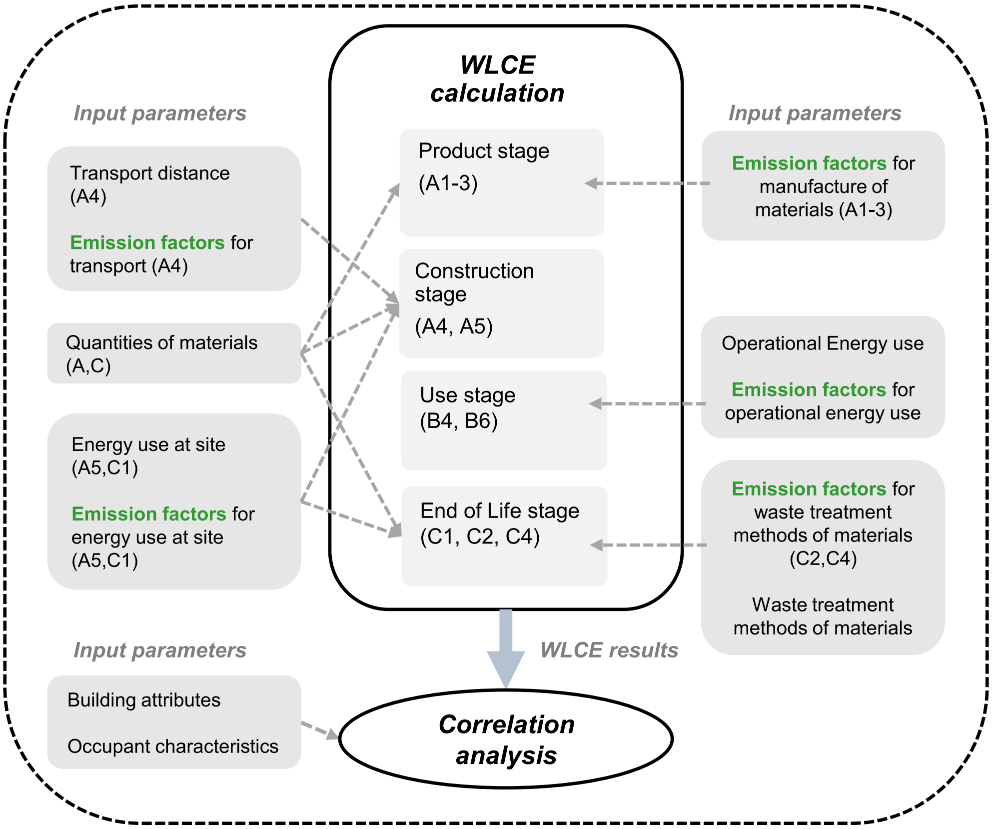


Fig. 2. An overview of the methodology in this paper, with the black frame rectangles showing the life cycle stages included and the dark grey filled rectangles showing the input parameters and data.

Table 1
The scope, parameter used, data sources and assumptions made in this study (according to the standard: BS EN 15978:2011[24], the RICS [28] methodology and the guideline from RIBA [18].).

Life cycle stage	Emission sources	Carbon emission type	Parameters used	Data sources and assumptions made
Product stage (A)	Raw materials supply (A1); Transport of raw materials (A2); Manufacture of building materials (A3)	Embodied	Emission factors for production of materials (A1-3). Quantities of building materials.	Collected from UK government emission factors [62] and ICE database [63].Estimated by a bottom-up method similar to other studies [64,65] and the Centre-line method [66] which were commonly used in industry.
Construction stage (A)	Transport of building materials (A4); Construction-installation process (A5)	Embodied	Quantities of building materials.Average transport distance across different construction site (A4). Emission factors for transport (A4).Energy use during construction installation process at site(A5).Emission factors for energy use at site(A5).	The same as the Product stageAssumed transport scenarios for UK projects from the RICS methodology [28].Collected from UK government emission factors [62]Assumed based on the energy use at site scenario from the EPD [67]. Collected from UK government emission factors [62]
Use stage (B)	Replacement (B4)	Embodied	The life span of the building structure (B4).	Assumed according to the RICS methodology [28,29].
	Operational energy use(B6);	Operational	Operational electricity consumption.Emission factor for electricity consumption.Operational gas consumption.Emission factor for gas consumption.	Measured by sensors.Assumed based on the scenario from the UK National Grid [68]. Estimated using the Energy Performance Certificates available from a UK government website [69].Collected from UK government emission factors [62].
End-of-life stage (C)	Demolition, transportation and disposal of waste (C1,C2,C4)	Embodied	Quantities of building materials.Recycling rate of materials.Emission factor for waste treatment methods of different materials (C2,C4).Energy use duringDemolition at site(C1).Emission factors for demolition at site(C1).	The same as the product stage.Assumed based on the scenario of materials recycling situation. Collected from EPD [70] and UK government emission factors [62].Assumed based on the scenario of the demolition for materials from EPD [71].Collected from the EPD[71].

attributes by Smartline researchers. Detailed responses to the survey questionnaire, including the number of each answer, are available in the supplementary materials (see Tables S2, S3, and S4).

2.2. WLCE calculation method

The carbon emissions in this paper represent the emissions of all relevant greenhouse gases measured in CO_2 equivalents (CO_2eq). A 60-year building lifetime (assumed to be from 2020 to 2080) is adopted in this study, following the BS EN 15978:2011 standard [24]. The calculation methods for carbon emissions from each process of each life cycle stage included in this paper were in accordance with the RICS professional statement "Whole-life carbon assessment for the built environment" [28] and the guideline "Embodied and whole-life carbon assessment for architects" by the Royal Institute of British Architects (RIBA) [18], which have been adjusted to meet our research aim. The RICS professional statement emphasised the practical implementation of European and international standards such as BS EN 15987:2011 and ISO 14044:2006 (Environmental management – life cycle assessment [61]), and outlines additional requirements for calculation and reporting. Table 1 shows the scope ("cradle to grave"), parameters used, data sources, and main assumptions made for each process of the life cycle stages.

The equation for calculating WLCE in this study is based on a combination of embodied and operational carbon emissions, as shown in Equation (1) [72]. This formula has been developed by Ekundayo et al. (2019) [72] and is consistent with the commonly used methods in the UK, including those from RIBA [18] and RICS [28]. This equation is aimed at establishing a standardised method for modelling life cycle carbon emissions, as suggested by previous researchers such as Moncaster and Symons [73] and Roger Flanagan and Carol Jewell [74], given the varied and occasionally confusing literature on the topic.

$$\begin{aligned}Whole\ life\ carbon\ emissions\ (WLCE) = Embodied\ (ECO_2)\\ + Operational(OCO_2)\end{aligned} \tag{1}$$

In the following subsections of each life cycle stage A to C, we also provide a detailed description of the calculation methods used for each process of the life cycle stages of buildings included in this paper, compassing the calculation methods, the assumptions made, the data sources, and the scope of each emission factor. These methods are based on the guidelines from RIBA, the methodology from RICS, and the BS EN 15978 standards. For modules A1 to A3, C1, and C4, project-specific scenarios were developed at the building level to calculate emissions, while for modules A4, A5, B4, and C2, the project's location was also taken into account. To ensure accuracy, this study utilised environmental performance declarations (EPDs and equivalents) for UK-manufactured construction products [70,75,76].

We created an inventory dataset that is available in the supplementary materials and contains input parameters for calculating the emissions for each process of life cycle stages, such as the material quantities, the emission factors for materials of different processes to generate results of embodied emissions, and input data on energy use and emission factors (carbon intensity) of the national grid and natural gas to produce operational carbon emissions.

For embodied carbon emissions, we also referred to the RICS guideline "Methodology to Calculate Embodied Carbon of Materials [29]" from RICS. To calculate operational carbon emissions, we took a different approach than the one outlined in the guideline. Instead of estimating the energy use of a building's entire lifespan using software or models like BREEAM energy models [64], we used the actual electricity consumption of 145 residential properties over a year to obtain a more accurate reflection of real-world energy usage.

2.2.1. Product stage

The emissions from the product stage were generated from raw material extraction and refining (i.e., primary manufacture) (A1), transporting raw materials to the plant (A2), and processing the raw materials to make building materials (i.e., secondary manufacture) (A3).

The carbon emissions from the product stage of the building life cycle were computed by multiplying the quantities m_i (kg) of different building materials used by their corresponding emission factors $q_{man,i}$ (kg CO_2eq/kg) shown in Eq.2.

$$Emissions_{manufacture} = \sum\nolimits_{i=1}^{n} (q_{man,i} \times m_i) \tag{2}$$

Ten main materials, including steel, cement, mortar, concrete, brick, plaster, timber, insulation, glass, and unplasticized polyvinyl chloride (uPVC), were considered in this paper due to a lack of actual quantities of all building materials, following the guidelines of whole life carbon assessment for the built environment and the methodology of embodied carbon emissions of materials from RICS [29,77]. Based on the methodology from RICS, building components, including the substructure (foundations), the superstructure (roof, external walls, windows and external doors, and internal walls and partitions), were considered in embodied carbon calculations in this study.

The actual bill of quantities (BoQ) for building materials was not directly available for the properties in this study. Therefore, we followed a widely used bottom-up method to estimate the Materials Intensities (MIs) and quantities for the ten main construction materials for each property, with the following steps [64,65,74–76]: (1) Identifying the case study's scope and boundaries; (2) Collecting information and data, such as the floor area, age, and type of case residential buildings, divided the case buildings into different categories by their characteristics and selected the represented building in the different category; (3) Developing a general model for calculating the building materials of all building components for each material for a single building; (4) Adapting the model from step 3 and the information from step 2 to determine the material quantities for the represented buildings in each category; (5) Calculating the MIs for each represented building and establishing the MIs database; and (6) Lastly, using the MI database and the spatial information (floor area) to estimate the quantiles of building materials for every building in different a category.

Some assumptions had to be made during the above steps based on the type, age, and geometry of the case residential properties, in accordance with the methodology of embodied carbon emissions of materials from RICS [29]. The report "The housing stock of the United Kingdom" from the Building Research Establishment (BRE) [57] was used in step (2) to help collect information on the typical residential properties in the UK. The model used in step (3) for quantifying the MIs was the Centre-line method that was commonly used in industry for estimating the quantities of building materials [66]. It was also aligned with the assumptions of the building components in this paper, including the substructure (foundations) and the superstructure (roof, external walls, windows and external doors, and internal walls and partitions). More detailed information regarding the estimation of the BoQ for building materials is provided in the supplementary materials, including a discussion of the bottom-up approach used to develop the MIs database, the scope and assumptions made during the calculation process, a brief description of centre-line method, the completed table of centre-line method, the MIs database calculation results for ten materials (see Table S7), the average results of MIs of the ten materials (see Fig.S2), the summary of the MIs results and the comparison of the results with other studies (see Table S6), the results of the quantities of main building materials (see Fig. S3(a)), and the limitations of the method.

The emission factors of the ten main materials processes A1-3 in stage A (see Table 2) were collected from the GHG emission conversion factors published by the UK government [62] and The Inventory of Carbon and Energy (ICE) [63], a database developed by the University of Bath. The emission factors from the ICE database were the average "cradle-to-gate" emission factors, covering the emissions from the processes of raw material extraction, manufacturing, and transportation

Table 2
Emission factors (A1-3) for the 10 main building materials from the UK government [62] and ICE database [63].

Building materials	Emission factors (kg CO_2eq/kg)	Source
Steel	2.89	[63]
Cement	0.74	[63]
Mortar	0.182	[63]
Concrete	0.131	[62]
Brick	0.24	[62]
Plasterboard	0.12	[62]
Timber	0.41	[62]
Insulation	1.86	[62]
Glass	0.86	[62]
uPVC	3.16	[63]

until they leave the "gate" of the factory (see A1-3 in Fig. 1). The emission factors sourced from the UK government report are "scope 3" emission factors that include the emissions from extraction, primary processing, manufacturing, and transportation of primary materials up to the point of sale [62].

2.2.2. Construction stage

Emissions from the construction stage include energy and fuel consumption during the transportation of material from the factory gate to the construction site (A4), as well as all works during the construction-installation process such as remediation, clearance, demolition of existing structures, and ground improvement (A5) [29]. The calculations for the emissions from the transport of the building materials (A4) during the construction stage were computed by multiplying the transport distances d_i (km) of the building materials from the production plant to the construction site, the quantities of building materials m_i (tonnes) and the emission factor $q_{tran,i}$ (kg CO_2eq/t-km) for transport shown in Eq.3.

$$Emissions_{transport} = \sum\nolimits_{i=1}^{n} q_{tran,i} \times (d_i \times m_i) \tag{3}$$

The chosen mode of transportation is assumed to be road-based, utilising heavy goods vehicles (HGVs) such as lorries [28,73,78], which are commonly used in the logistics and transportation industry for transporting goods, including construction materials over long distances. The emission factor used for HGVs is 0.11133 kg CO_2eq/t-km, obtained from the UK government emission factors [62]. This is a "scope 3″ emission factor that includes the upstream and downstream freight emissions associated with transporting goods. The average transport distance to and from the factory is assumed differently by the material's original place based on the default transport scenarios for UK projects from the RICS [28]. We assumed that all the concrete materials were sourced and transported within the UK at a 50 km transport distance. The other building materials, such as plasterboard, brick, and insulation, were manufactured domestically with a 300 km transport distance. The energy used for the concrete pump during the construction-installation process (A5) was assumed to be 1 L/m3 of diesel based on the scenarios from the EPD [67] of C60 Ready-mix Concrete generated from BRE global based on the EN 15804 EPD Verification Scheme. The emission factor used for diesel is 2.59411 kg CO_2eq/litres, obtained from the UK government emission factors [58]. This is a "scope 1″ emission factor that covers the direct emissions resulting from the combustion of the diesel fuel [62].

2.2.3. Use stage

Emissions from the use stage mainly result from operational energy use (B6) for household heating, lighting, ventilation, air conditioning, etc. Following the scope in the RICS guideline, the emissions related to the replacement (B4) and operational energy use (B6) during the building use stage were considered in this paper. There will also be additional carbon emissions arising from the other processes that were excluded in this paper, such as maintenance, repair, and refurbishment of building elements (B2, B3, B5), the use or application of the installed product e.g. refrigerants, paints, carpets (B1) and the water use (B7) [29].

The emissions arising from the replacement (B4) of the building component in the use stage were in line with building materials in stage A. It is assumed that the replacement of the building components is 'like for like' for consistency and is fully replaced. The lifespans of the different building components are assumed based on the RICS professional statement [28,29], which is 30 years for the roof, external doors, and windows.

The operational carbon emissions from the use stage were computed by multiplying the yearly energy consumption $E_{yearly,j}$ (kWh) with the corresponding emission factors $q_{energy,j}$ (kg CO_2eq/kWh) shown in Eq.4. In this paper, the lifespan was assumed to be 60 years from 2020 to 2080.

$$Emissions_{operation} = \sum\nolimits_{j=2020}^{2080} q_{energy,j} \times \left(E_{yearly,j}\right) \tag{4}$$

In this paper, to ensure a more robust analysis of energy use, we checked the survey information, which showed that 14 properties used electricity for heating (12 using grid electricity and 2 using solar photovoltaic (PV) systems), while 131 properties used natural gas for heating. Therefore, the annual electricity consumption is assumed to be the actual consumption measured by the sensors for each property over an entire year during 2018 and 2019 and to stay the same for other years. For properties using natural gas for heating, the annual gas consumption used for heating is the estimated gas consumption for heating in the Energy Performance Certificates (EPCs) collected from a UK government website [69]. The discussion, analysis, and comparison of energy use between electricity and gas, as well as the energy use by different types of properties (see Table S9 and S10), are available in the supplementary materials.

The carbon intensity (the level of carbon emitted for each unit of energy generated) of grid electricity is a key factor in determining the impacts of operational energy use. Renewable energy such as wind power and solar energy have much lower carbon intensity than fossil fuels [79]. In the UK, there has been significant progress in decarbonizing electricity supply, with the country being one of the global leaders among major economies. Between 2013 and 2020, the carbon intensity of grid electricity in the UK reduced by 66% [68]. To take into account future grid decarbonisation in estimating the emissions due to electricity consumption over the life of the buildings, we estimated the carbon intensity for electricity used every year from 2020 to 2080 based on the UK Future Energy Scenarios (FES) published by the National Grid in 2021 [68]. This carbon intensity can be considered as "scope 2″ emissions that cover the provision of electricity to the grid. Following the guidance in the RICS professional statement, we used a conservative scenario from the FES report called "Steady Progression", where the emissions by 2050 will be reduced by around 73% compared with 1990 levels. It is the slowest decarbonisation scenario, with minimal behaviour change and decarbonization in power but not heat. The carbon intensity of grid electricity under the "Steady Progression" scenario is available for the year 2020, 2030, and 2050 in the FES report and listed in Table 3, based on which the carbon intensity of grid electricity in every year from 2020 to 2080 was estimated. The details of the assumptions and estimations for future carbon intensity in each year are available in the supplementary materials.

Table 3
Annual average carbon intensity (B6) of UK grid electricity in the "Steady Progression" scenario from the National Grid [68].

Year	Carbon intensity of UK grid electricity (kg CO_2eq/kWh)
2020	0.155
2030	0.042
2050	0.014

The carbon emission factor for natural gas used is 0.184 kg CO_2eq/kWh, taken from the UK government emission factors [62]. This is a “scope 1” emission factor, covering the direct emissions from the natural gas combusted. Based on the “Steady Progression” scenario, the annual natural gas use for each property is assumed to be constant over the building’s lifespan.

2.2.4. End-of-life stage

End-of-life emissions are those associated with energy use during building demolition (C1), transportation (C2), waste disposal process (C3), and landfill of waste (C4) [29]. Demolition (C1) includes all emissions associated with dismantling a building. Demolition is assumed to consume 0.01 kWh of grid electricity per kg of building materials [71]. The 'scope 2′ emission factor of grid electricity from the UK government emission factors [62] is used. It is assumed that all of the waste is collected and transported to the waste treatment centre and that all building materials, except those that can be recycled, are then taken to landfill for final disposal (C4). The only material assumed to be recycled is steel, with a 95% recycling rate [80].

Transportation (C2) distance to the landfill is assumed to be 50 km, and the transportation mode is assumed to be road by HGVs. C3 is directly linked to Module D, which is beyond the cradle-to-grave scope and was excluded in this paper. C3 represents the carbon cost to bring the materials to an ‘out-of-waste’ state, whereas D represents the potential benefit.

Embodied carbon emissions during the end-of-life stage were computed by multiplying the quantities of materials m_i (kg) and emission factors $q_{EoL,i}$ (g CO_2eq/kg), as shown in Eq.5 [73].

$$Emissions_{end-of-life} = \sum_{i=1}^{n} (q_{EoL,i} \times m_i) \quad (5)$$

Table 4 shows a summary of the emission factors for the materials in stage C, including processes C2 and C4. We could not collect the emission factors of each process for all materials from one data source, as they are not directly available. The emission factor for steel was directly collected from an environment product declaration (EPD) [70 71] created by researchers using the software One Click EPD Generator in accordance with European and international standards, ISO14040/14044 and professional LCA databases such as Ecoinvent. For other main materials that needed to be landfilled, the UK government emission factors [62] were used. These emission factors include “scope 3” emissions, which cover collection, transportation, and landfill emissions. The emission factors for cement and mortar were not available from the ICE database, the UK government, or EPDs and were therefore assumed to be 1.26 g CO_2eq/kg, the same as that of concrete.

2.3. Correlation analysis between the factors and the WLCE

To investigate the factors that might affect WLCE, we conducted data pre-processing, which included extracting and organising raw data and screening for potential key factors from a survey questionnaire. The raw data was obtained from the questionnaire of the survey, which collected information from occupants of case residential properties and sensor data supplied by Smartline project researchers. The original dataset used in this study, which contained 100 variables, was collected and organised from the raw data.

After obtaining and organising the original dataset, we conducted a multi-step screening process to select the most useful variables for our analysis. Firstly, we removed over 30 variables that were least relevant to building carbon emissions or posed potential data ethics risks, such as gender, national identity, ethnicity, employment situation, IMD decile value [81], and property address. Next, we removed more than 40 variables based on their direct relevance to whole-life carbon emissions, such as the presence of a kitchen or information about pets. Additionally, we eliminated over 10 variables that only applied to a very small portion of the sample, such as whether an electricity smart metre is installed.

After conducting a multi-step screening process, we selected 15 preliminary factors for our study. These factors include floor area, number of bedrooms, property type, glazing type, loft insulation thickness, roof insulation type, window frame materials, wall construction type, age of the main occupant, indoor hours per week, number of occupants, type of heating system, boiler control habits, whether to avoid heating to save money, and window opening habits. Detailed information about these factors, including the range and frequency of each answer, is provided in the supplementary materials of this paper (see Table S2, S3, S4).

To analyse the dataset, we categorised the 15 factors into two groups based on their nature, building-related and occupant-related. The factors and their data types were summarised in Table 5. Prior to analysis, we conducted a check for missing data and then removed the outliers, such as properties with an annual electricity consumption of<100 kWh or more than 10,000 kWh. To normalize the dataset, we employed the centring and scaling transformations [78] to improve the normality of the data for the input variables.

We visualised the Pearson correlation coefficient (Pearson’s r) and pairwise correlation between all variables and WLCE using a correlation heatmap. The Pearson correlation coefficient can range from −1 to 1, indicating the degree of correlation between variables. A significance level was set as 0.05 ($P < 0.05$) to determine the significance of the correlation. The relationship between continuous, discrete variables and WLCE was visualised on scatterplots with an overlaid linear regression line. The relationship between categorical variables and WLCE was presented by boxplots. These analyses and visualizations were conducted using the Pandas packages [82], Scikit-learn packages [83], and Seaborn library [84] in the Python programme (Python version 3.9 [85]).

3. Results and discussion

3.1. Building WLCE

The WLCE and WLCE intensity (WLCE normalised by per square metre) for 145 case properties and the average value of different property types are presented in this section (see Fig. 3). Fig. 3 (a) shows

Table 5
Groups of factors and their data types.

Type of Data	Building-related data	Occupant-related data
Continuous variable	Floor area (m^2);	Age of main occupant; Indoor hours per week;
Discrete variables	Number of bedrooms;	Number of occupants;
Categorical variable	Property type; Type of heating system; Glazing type; Loft insulation thickness; Roof insulation type; Window frame materials; Wall construction type	Boiler control habit; Whether avoid heating to save money; Window opening habit;

Table 4
Emission factors (C2, C4) for end-of-life stage of main building materials.

Building materials	Steel	Insulation	Concrete	Brick	Plasterboard	Timber	Glass	uPVC
Emission factors (g CO_2eq/kg)	4.81	1.26	1.26	1.26	71.95	828.12	8.99	8.99

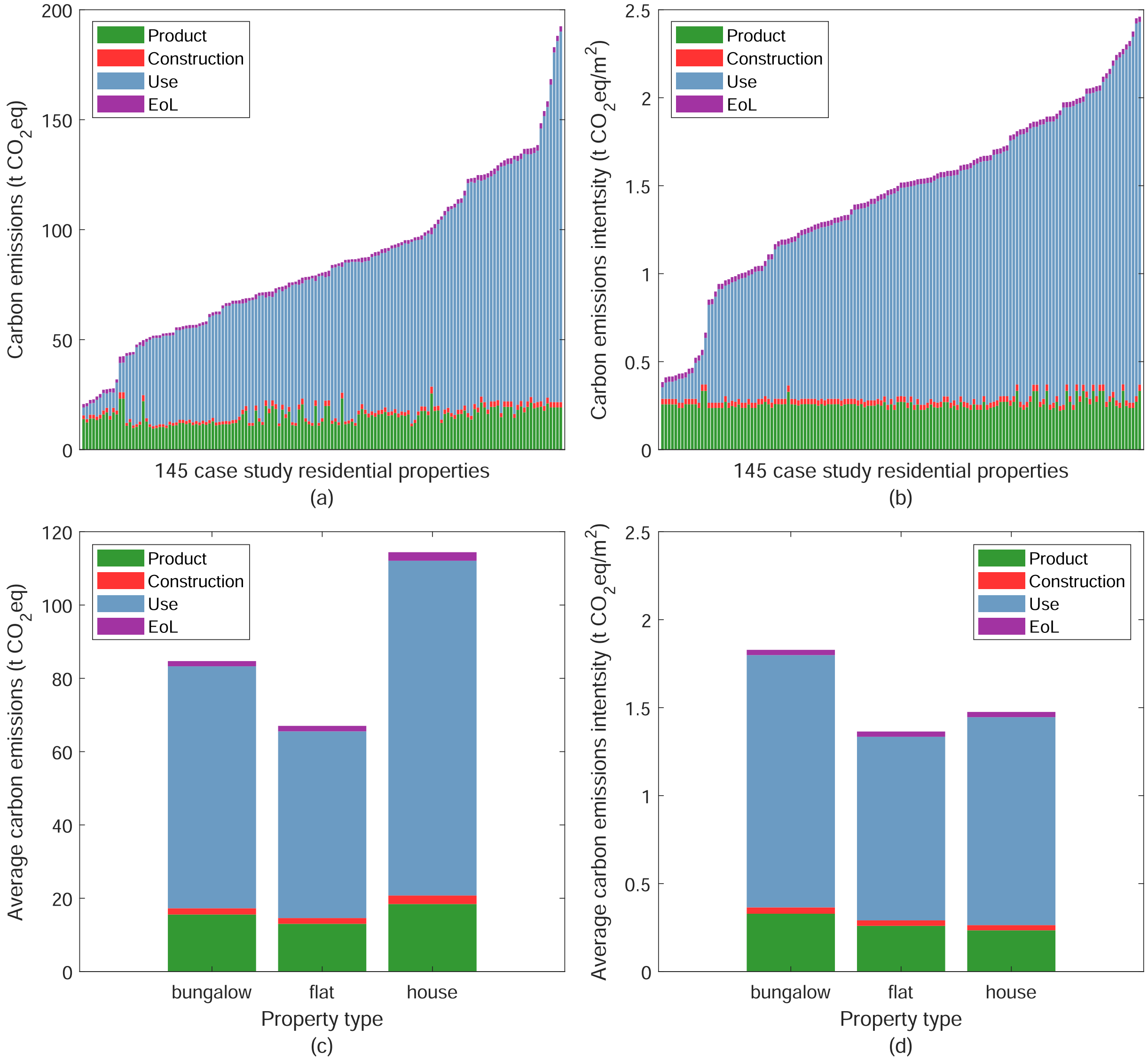


Fig. 3. (a) WLCE results for each case study property and different life cycle stage, with the value of WLCE ascending from left to right; (b) WLCE intensity results for each case study property and different life cycle stage, with the value of WLCE intensity ascending from left to right. (c) WLCE results for the three property types on average for different life cycle stage; (d) WLCE intensity results for the three property types on average for different life cycle stage.

WLCE results for each case study property and different life cycle stage, with the value of WLCE ascending from left to right. Fig. 3 (b) shows WLCE intensity results for each case study property and different life cycle stage, with the value of WLCE intensity ascending from left to right. Fig. 3 (c) presents WLCE results for the three property types on average for different life cycle stages. Fig. 3 (d) presents WLCE intensity results for the three property types on average for different life cycle stages.

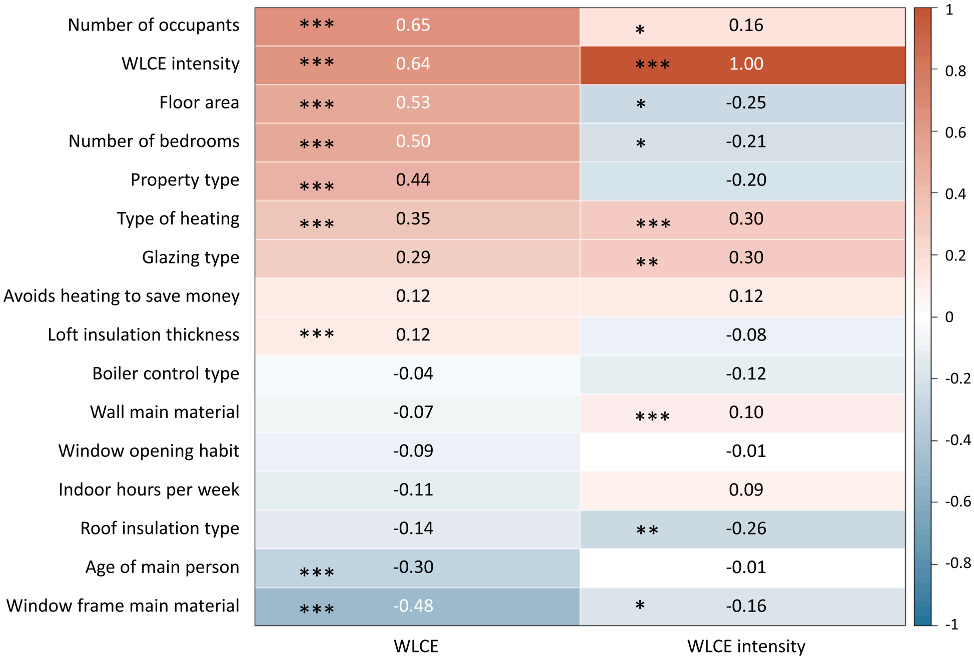
The WLCE of case study residential properties ranges from 21 to 193 t CO_2eq (see Fig. 3 (a)). The WLCE intensity of case study residential properties ranges from 0.5 to 2.6 t CO_2eq/m^2 (see Fig. 3 (b)). The average WLCE of the three property types are 67, 114, and 85 t CO_2eq for flat, house, and bungalow, respectively (see Fig. 3 (c)). The average WLCE intensity for the three property types are 1.4, 1.5, and 1.9 t CO_2eq/m^2 for bungalow, flat, and house, respectively (see Fig. 3 (d)). On average, houses have a higher WLCE than flats and bungalows while bungalows, have a higher WLCE intensity than flats and houses.

The analysis reveals significant variations among buildings in the same area, particularly for operational carbon emissions from the use stage. The share of operational carbon emissions in the WLCE of the case study buildings ranges from 19% to 86%, with the average share being 71%. The details of the calculation results, including the values of the min, max, standard deviation, mean, 25%, and 75% for WLCE and WLCE intensity and emissions from each life cycle stage, are available in the supplementary materials. The embodied and operational emission results are also available in the document of supplementary materials (see Fig. 3, Table S8, Fig. S5, Table S11).

These results suggest that even for similar types of buildings in the same area, i.e., residential properties in this paper, there are significant variations in their WLCE and WLCE intensity. This suggests that the WLCE of a limited number of individual buildings could not be generalized to represent the WLCE of their building types, as this may result in significant inaccuracies.

3.2. Correlation analysis

The correlation analysis was conducted to explore the potential reasons that might explain the variations in the WLCE results of these buildings. The correlation heat map (see Fig. 4) shows the Pearson correlation coefficient (Pearson's r) value and the pair correlation between the chosen factors and WLCE. The heatmap uses a colour scale to represent the correlation coefficients, where red indicates a positive



	WLCE	WLCE intensity
Number of occupants	*** 0.65	* 0.16
WLCE intensity	*** 0.64	*** 1.00
Floor area	*** 0.53	* -0.25
Number of bedrooms	*** 0.50	* -0.21
Property type	*** 0.44	-0.20
Type of heating	*** 0.35	*** 0.30
Glazing type	0.29	** 0.30
Avoids heating to save money	0.12	0.12
Loft insulation thickness	*** 0.12	-0.08
Boiler control type	-0.04	-0.12
Wall main material	-0.07	*** 0.10
Window opening habit	-0.09	-0.01
Indoor hours per week	-0.11	0.09
Roof insulation type	-0.14	** -0.26
Age of main person	*** -0.30	-0.01
Window frame main material	*** -0.48	* -0.16

Fig. 4. Correlation heatmap between all factors considered and WLCE. Red colour represents a positive correlation and blue colour represents a negative correlation. The correlation was considered strong when the absolute value of the Pearson correlation coefficient (Pearson's r) was greater than 0.6 and statistically significant ($P < 0.05$). The asterisks indicate significant correlation, with *, ** and *** representing $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

correlation and blue indicates a negative correlation. Asterisks indicate statistically significant correlations, with “significant at $p < 0.05$″, ″significant at $p < 0.01$″, and “significant at $p < 0.001$″ denoting the levels of significance. Absolute values for the Pearson correlation coefficient lower than 0.35 indicate a weak correlation, values higher than 0.36 are considered moderate correlation [86].

The results show that the number of occupants and floor area are significantly correlated with WLCE. Other factors, including the number of bedrooms, type of property, window frame material, age of the main occupant, type of heating system, and type of glazing, are also correlated with WLCE with a descending strength of correlation. Factors with a P-value greater than 0.05 were considered statistically insignificant and will not be discussed further.

Scatterplots with an overlaid regression line also show these correlations in detail (see Fig. 5). It displays the relationship between various continuous and discrete variables and their impact on WLCE. The scatterplots show that the number of occupants, floor area, and number of bedrooms have a positive correlation with WLCE, while the age of the main person has a negative correlation with WLCE. The larger the floor area and the greater the number of bedrooms, the higher the WLCE of the residential properties (see Fig. 5(a),(b)). The more occupants and the younger the main occupant is, the higher the WLCE of the residential properties (Fig. 5 (c),(d)). The reason for this is that the larger the residential property, the more building materials and energy are required, leading to a higher WLCE. More occupants and younger occupants are expected to lead to more indoor activities, which could consume more energy and increase operational carbon emissions.

Boxplots show the correlation results of the categorical variables in detail (see Fig. 6). The boxplots provide a visual representation of the upper and lower quartiles, median, highest and lowest values, and outliers of the dataset for each category. Specifically, the boxplots show how the type of property, heating type, glazing type, window frame materials, and loft insulation thickness relate to WLCE. The polar lines represent the highest and lowest values, while the points represent the outliers that are determined using a method based on the interquartile range. This figure provides insights into how different categorical variables influence the WLCE of residential properties.

The results show that the WLCE of properties that use natural gas for heating is significantly higher than that of properties that use electricity for heating (see Fig. 6(a)). The first reason is that while evaluating the WLCE, the decarbonization of grid electricity was considered under the National Grid “steady progression” scenario. In this scenario, the carbon intensity of grid electricity will decrease in the future with more renewable technology, but the carbon intensity of gas does not change. Therefore, properties that only use electricity for heating will have lower operational emissions than properties that use gas for heating. Further, about 80% of the properties that use electricity for heating are through air-source heat pumps (see input energy use in the inventory dataset in supplementary materials). Heat pumps are energy recovery systems that use electricity to transfer higher temperature heat from the external environment, such as the air to the heating and hot water circuits of a building [87]. Air source heat pumps have high energy efficiency [88] and therefore require lower energy, which leads to lower operational carbon emissions than using gas for heating. There are two properties that also use PV system among the properties that use electricity for heating (see input energy use in the inventory dataset in the supplementary materials). The shares of the operational emissions in the WLCE for the properties with PV installed are lower than 50%, while those for all other properties are higher than 50% (the average value of all properties is 71%). This finding implies that properties that use renewable energy sources, such as solar PV, have a low operational emissions share but a high embodied emissions share of total WLCE. This highlights the need to pay more attention to embodied emissions in buildings with renewable energy sources, as they have a more significant impact on the total WLCE. The key finding here is that electrification of heating and the use of energy-efficient systems such as air-source heat pumps and renewable energy such as solar PV could be effective solutions for WLCE reduction.

Another key area that determines WLCE is the building envelope, including windows. Windows consist of two basic elements, the glazing unit and frame, which have a major impact on the thermal performance of the window [89]. The relation between the window glazing type and window frame materials is shown in Fig. 6(b) and (c). In this study, properties that use double-glazed windows with low emissivity (low + E) coatings have significantly lower WLCE than those that use single-glazed windows (see Fig. 6(b)). Double-glazed windows could effectively reduce energy loss [90], while the Low + E coating is an invisible microscopic coating that could be applied to the glass in order to

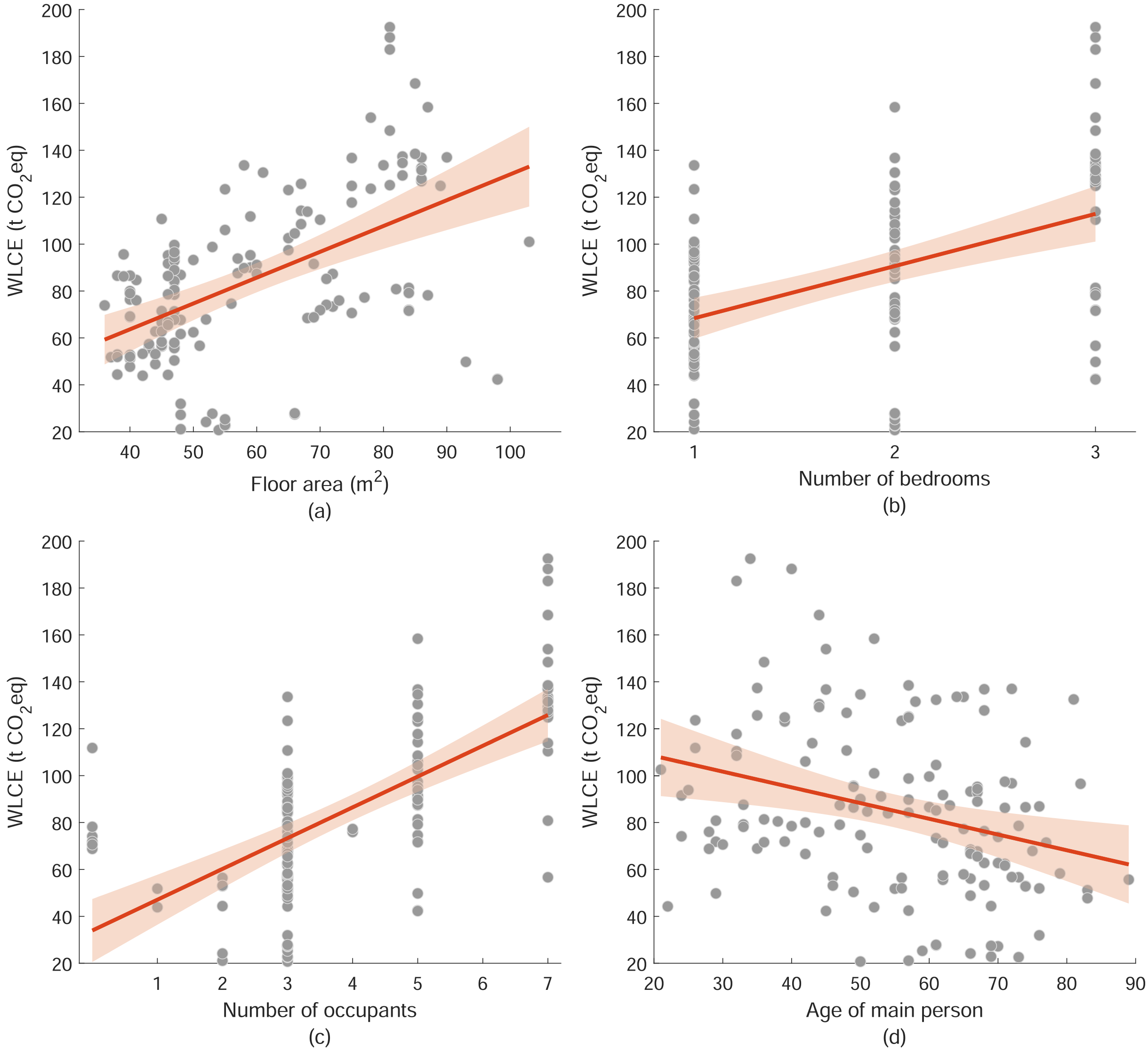


Fig. 5. Relation between continuous, discrete variables and WLCE. Scatter plots and the overlaid regression line. The colourful shade shows the confidence interval of the regression estimation is 95%.

improve its thermal efficiency and insulation effect [91–93]. It provides a higher level of visible daylight transmission, retains the aesthetics and outside view, and will simultaneously reduce the solar radiation and heat load [94]. Therefore, properties with double-glazed windows have lower operational carbon emissions, resulting in lower WLCE.

In terms of window frames, properties with wooden frames have a lower WLCE than those with the Unplasticized Polyvinyl Chloride (uPVC) frames (see Fig. 6(c)). Wood has long been used as a window frame material, but uPVC is currently the most popular material for frames in the UK thanks to its lower price [95,96]. The wood window frame has the lowest thermal conductivity of any other frame material and has high energy performance [97], which can reduce heat loss and therefore energy consumption [89,95], resulting in lower operational carbon emissions. The energy performance of uPVC windows strongly relies on airtightness [96]. In this study, the discussion on the impacts on WLCE of the windows is only moderate for the operational carbon emissions, not only because the main significant variation in WLCE results between the properties is the operational carbon emissions. The quantities of window frame materials were also not considered when calculating the embodied carbon emission, consequently, the results could not imply the impact on embodied carbon emissions.

Fig. 6(d) presents the relationship between loft insulation thickness and WLCE. Good thermal insulation of the building envelope is an effective way to reduce residential properties' WLCE. The thickness of loft insulation recommended by the UK Government is currently 270 mm, but some new properties are increasing their level of loft insulation to greater than 270 mm [98,99]. In the case study, properties with loft insulation greater than 270 mm have a lower WLCE than those with<270 mm (see Fig. 6(d)). Although we lack data on detailed loft insulation material types, and the insulation materials used can have an effect because of many factors, such as the thermal resistance of different types of materials [100], our results still show that thicker insulation is likely to provide better insulation performance, leading to reduced energy consumption for heating [101] and lower operational emissions.

In conclusion, building attributes (such as floor area, the number of bedrooms, glazing type, and window frame) and the characteristics of the occupants (such as the number of occupants and the age of the main occupant) both contributed to the significant variations in the WLCE of different residential properties in the same area in our case study. Energy-efficient building design and a low-carbon lifestyle for occupants are therefore two potential approaches to reducing building WLCE. Technically, promising building-related strategies include electrification of heating, using renewable energy systems, installing double-glazed windows with low emissivity (low + E) coatings, using wood as

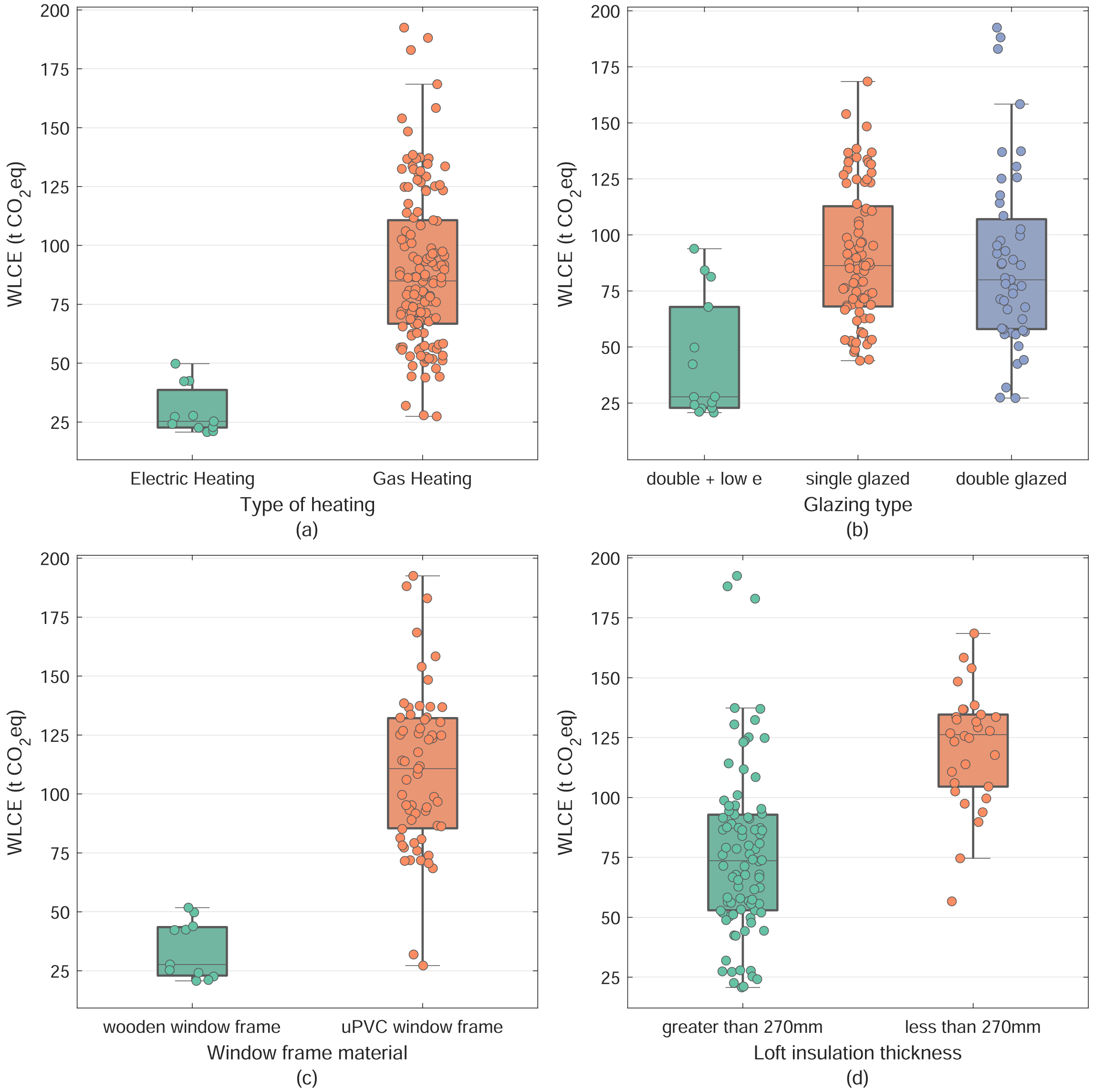


Fig. 6. Relation between categorical variables and WLCE. The boxplot shows the upper and lower quartiles and the medians of the dataset; the polar lines show the highest and lowest values, and all data points are visualised with "outliers" determined using a method that is a function of the interquartile range.

window frame material, and enhancing building insulation. In terms of occupants, choosing properties with smaller floor areas and/or the number of bedrooms, when possible, can also reduce the WLCE. These results enable different stakeholders to better understand the characteristics of WLCE of residential properties and implement carbon emission reduction strategies in a long-term and holistic way.

3.3. *Limitations and future work*

The limitations of this study are mainly related to data availability and the associated assumptions made. The gas use was obtained from EPC rather than from actual measurements, which may have affected the accuracy of the results. We included ten types of materials used in components of the building substructure (foundations) and superstructure (roof, external walls, windows and external doors, and internal walls and partitions). We used a simplified bottom-up method and Centre-line method and made some assumptions to estimate the quantities of ten main building materials for a large number of residential properties based on the type, age, and geometry of residential properties from the survey data as the actual BoQ of each property was unavailable. Furthermore, only the embodied emissions from building materials were considered, not those from the energy systems. In the end-of-life stage, we assumed that 95% of steel is recycled, but all other materials are not. The life spans of buildings and building components were assumed following the RICS guideline, though they might differ from the actual life spans in practise. These simplified methods and assumptions could introduce uncertainties into the embodied carbon emissions of building materials calculated.

For future work, actual gas use, either measured by sensors or recorded by occupants, and actual BoQ of building materials and energy systems can be used to improve the accuracy and completeness of the operational and embodied carbon emissions. Additional end-of-life scenarios aligned with circular economy principles also need to be considered. Future research could also collect more detailed data on a more comprehensive set of factors relating to building attributes and occupant characteristics and behaviours to explore other factors that can potentially affect the WLCE.

4. Conclusion

This paper quantified the WLCE of 145 residential properties in Cornwall that cover the three typical property types in the UK (flat, house, and bungalow). The results indicate that the WLCE varies significantly among these properties, ranging from 21 to 193 t CO_2eq, with WLCE intensity ranging from 0.5 to 2.6 t CO_2eq/m^2. Operational carbon emissions are the most significant emission source for most properties, with their share in the WLCE being 71% on average. The analysis also revealed that the average WLCE for flat, house, and bungalow types were 67, 114, and 85 t CO_2eq, respectively, with an average WLCE intensity of 1.4, 1.5, and 1.9 t CO_2eq/m^2.

Our findings highlight the urgent need to recognise the significant variations in building WLCE, even for similar buildings in proximity. Therefore, the WLCE of a limited number of buildings might not accurately represent the average WLCE of their building type.

Furthermore, this paper also statistically analysed the factors that led to the significant variations in the WLCE of the residential properties considered. The key factors that might affect the WLCE of these properties were investigated based on an analysis of the correlation between the WLCE calculation results and a range of building-related and occupant-related factors using data collected through a survey.

The results suggest that the number of occupants and the floor area have a strong positive correlation with WLCE. Other factors such as the number of bedrooms, type of property, window frame material, age of the main occupant, type of heating system, and type of glazing are also correlated with WLCE with a descending strength of correlation.

These results suggest that building attributes and the characteristics of the occupants both contributed to the significant variations in WLCE of different properties in our case study. Energy-efficient building design and a low-carbon lifestyle for occupants are therefore two potential approaches to reducing building WLCE. Specifically, this study recommends using electric heating instead of gas heating, choosing natural window frame materials such as wood, installing low + e glazing for windows, and improving property insulation. The information can support decision-making in sustainable building design from a life cycle perspective during the early stages of design or the retrofiting of existed buildings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was financially supported by the China Scholarship Council, the University of Exeter, and the Smartline project (05R16P00305) has received £3,740,920 and the Smartline Extension project (05R18P02819) has received up to £3,307,703 of funding from the England European Regional Development Fund as part of the European Structural and Investment Funds Growth Programme 2014-2020. The Ministry of Housing, Communities and Local Government (and in London the intermediate body Greater London Authority) is the Managing Authority for European Regional Development Fund. Established by the European Union, the European Regional Development Fund helps local areas stimulate their economic development by investing in projects which will support innovation, businesses, create jobs and local community regenerations. For more information visit https://www.gov.uk/european-growth-funding. With additional funding of £25k from the Southwest Academic Health Science Network and £200k from Cornwall Council. We appreciate the support of Coastline Housing Limited, particularly Mr. Mark England in providing access to data on the case study buildings.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2023.113387.

References

[1] J. Tollefson, IPCC says limiting global warming to 1.5 °C will require drastic action, Nature 562 (7726) (Oct. 2018) 172–173, https://doi.org/10.1038/d41586-018-06876-2.
[2] 'Energy Technology Perspectives, – Analysis', IEA https://www.iea.org/reports/energy-technology-perspectives-2020 2020 accessed Mar. 19, 2021.
[3] H. de Coninck *et al.*, 'Strengthening and Implementing the Global Response', *Glob. Warm. 15°C Summ. Policy Mak.*, pp. 313–443, 2018.
[4] S. Hellweg, L.M.i Canals, Emerging approaches, challenges and opportunities in life cycle assessment, Science 344 (6188) (Jun. 2014) 1109–1113, https://doi.org/10.1126/science.1248361.
[5] D. Vuarnoz, S. Cozza, T. Jusselme, G. Magnin, T. Schafer, P. Couty, E.-L. Niederhauser, Integrating hourly life-cycle energy and carbon emissions of energy supply in buildings, Sustain. Cities Soc. 43 (2018) 305–316.
[6] 'LCA Compendium – The Complete World of Life Cycle Assessment', *Springer*. https://www.springer.com/series/11776 (accessed May 11, 2022).
[7] Life cycle assessment, 'ISO 14040:2006: Environmental management — Life cycle assessment — Principles and framework', *ISO*. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html (accessed Jan. 15, 2021).
[8] M. L. Brusseau, 'Chapter 32 - Sustainable Development and Other Solutions to Pollution and Global Change', in *Environmental and Pollution Science (Third Edition)*, M. L. Brusseau, I. L. Pepper, and C. P. Gerba, Eds., Academic Press, 2019, pp. 585–603. doi: 10.1016/B978-0-12-814719-1.00032-X.
[9] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: A review, Renew. Sustain. Energy Rev. 26 (Oct. 2013) 379–388, https://doi.org/10.1016/j.rser.2013.05.001.
[10] I. Vázquez-Rowe, A. Marvuglia, S. Rege, E. Benetto, Applying consequential LCA to support energy policy: Land use change effects of bioenergy production, Sci. Total Environ. 472 (Feb. 2014) 78–89, https://doi.org/10.1016/j.scitotenv.2013.10.097.
[11] S.M. El Haggar, CHAPTER 13 - Rural and Developing Country Solutions, in: F. J. Agardy, N.L. Nemerow (Eds.), Environmental Solutions, Academic Press, Burlington, 2005, pp. 313–400, https://doi.org/10.1016/B978-012088441-4/50015-0.
[12] R.H. Crawford, Validation of a hybrid life-cycle inventory analysis method, J. Environ. Manage. 88 (3) (Aug. 2008) 496–506, https://doi.org/10.1016/j.jenvman.2007.03.024.
[13] J. Pryshlakivsky, C. Searcy, Fifteen years of ISO 14040: a review, J. Clean. Prod. 57 (Oct. 2013) 115–123, https://doi.org/10.1016/j.jclepro.2013.05.038.
[14] C.K. Chau, T.M. Leung, W.Y. Ng, A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings, Appl. Energy 143 (Apr. 2015) 395–413, https://doi.org/10.1016/j.apenergy.2015.01.023.
[15] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review, Renew. Sustain. Energy Rev. 29 (Jan. 2014) 394–416, https://doi.org/10.1016/j.rser.2013.08.037.
[16] A. Atmaca, N. Atmaca, Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey, Energy Build. 102 (Sep. 2015) 417–431, https://doi.org/10.1016/j.enbuild.2015.06.008.
[17] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, N. Aste, 'Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review', Sustain. Cities Soc. 60 (Sep. 2020), 102248 https://doi.org/10.1016/j.scs.2020.102248.
[18] 'Embodied and whole life carbon assessment for architects sustainable design'. https://www.architecture.com/knowledge-and-resources/resources-landing-page/whole-life-carbon-assessment-for-architects (accessed Sep. 20, 2022).
[19] A. Stephan, L. Stephan, Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate, Appl. Energy 280 (Dec. 2020), 115932, https://doi.org/10.1016/j.apenergy.2020.115932.
[20] 'Net zero energy buildings: International projects of carbon neutrality in buildings', *RIBA Books*. https://www.ribabooks.com/Net-zero-energy-buildings-International-projects-of-carbon-neutrality-in-buildings_9783920034805 (accessed Apr. 03, 2023).
[21] 'The Net Zero Carbon Buildings Commitment', *World Green Building Council*. https://www.worldgbc.org/thecommitment (accessed Mar. 19, 2021).
[22] W. Pan, K. Li, Y. Teng, Rethinking system boundaries of the life cycle carbon emissions of buildings, Renew. Sustain. Energy Rev. 90 (Jul. 2018) 379–390, https://doi.org/10.1016/j.rser.2018.03.057.
[23] X.J. Luo, Retrofitting existing office buildings towards life-cycle net-zero energy and carbon, Sustain. Cities Soc. 83 (Aug. 2022), 103956, https://doi.org/10.1016/j.scs.2022.103956.
[24] 'BS EN 15978:2011 - Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method'. https://shop.bsigroup.com/ProductDetail?pid=000000000030256638 (accessed Mar. 08, 2021).

[25] E. Standards, 'EN 15804+A2', *https://www.en-standard.eu*. https://www.en-standard.eu/csn-en-15804-a2-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/ (accessed May 24, 2023).

[26] 'ISO 21930:2017 Sustainability in buildings and civil engineering works', *ISO*, Aug. 11, 2017. https://www.iso.org/standard/61694.html (accessed May 24, 2023).

[27] Guide-to-Building-Life-Cycle-Assessment-by-One-Click-LCA'. Accessed: May 24, 2023. [Online]. Available: https://www.oneclicklca.com/wp-content/uploads/2018/03/7-steps-guide-to-Building-Life-Cycle-Assessment-white-paper-by-One-Click-LCA.pdf.

[28] 'Whole Life Carbon Assessment for the Built Environment, 1st edition', *RICS*. https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/ (accessed Sep. 21, 2022).

[29] Royal Institution of Chartered Surveyors, Methodology to calculate embodied carbon of materials: RICS information paper, Royal Institution of Chartered Surveyors, Coventry, 2012.

[30] W. Zhu, W. Feng, X. Li, Z. Zhang, Analysis of the embodied carbon dioxide in the building sector: A case of China, J. Clean. Prod. 269 (Oct. 2020), 122438, https://doi.org/10.1016/j.jclepro.2020.122438.

[31] C. Allen, P. Oldfield, S.H. Teh, T. Wiedmann, S. Langdon, M. Yu, J. Yang, Modelling ambitious climate mitigation pathways for Australia's built environment, Sustain. Cities Soc. 77 (2022), https://doi.org/10.1016/j.scs.2021.103554.

[32] R. O'Hegarty, O. Kinnane, Whole life carbon quantification of the built environment: Case study Ireland, Build. Environ. 226 (Dec. 2022), 109730, https://doi.org/10.1016/j.buildenv.2022.109730.

[33] R.O. Hegarty, O. Kinnane, A whole life carbon analysis of the Irish residential sector - past, present and future, Energy Clim. Change 4 (Dec. 2023), 100101, https://doi.org/10.1016/j.egycc.2023.100101.

[34] X.J. Luo, An integrated passive and active retrofitting approach toward minimum whole-life carbon footprint, Energy Build. 295 (Sep. 2023), 113337, https://doi.org/10.1016/j.enbuild.2023.113337.

[35] B. Izaola, O. Akizu-Gardoki, X. Oregi, Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building, Sustain. Prod. Consum. 40 (2023) 252–264.

[36] M. Norouzi, A.N. Haddad, L. Jiménez, S. Hoseinzadeh, D. Boer, Carbon footprint of low-energy buildings in the United Kingdom: Effects of mitigating technological pathways and decarbonization strategies, Sci. Total Environ. 882 (Jul. 2023), 163490, https://doi.org/10.1016/j.scitotenv.2023.163490.

[37] J.-J. Ma, G. Du, Z.-K. Zhang, P.-X. Wang, B.-C. Xie, Life cycle analysis of energy consumption and CO2 emissions from a typical large office building in Tianjin, China, Build. Environ. 117 (May 2017) 36–48, https://doi.org/10.1016/j.buildenv.2017.03.005.

[38] M.K. Ansah, X. Chen, H. Yang, L. Lu, P.T.I. Lam, An integrated life cycle assessment of different façade systems for a typical residential building in Ghana, Sustain. Cities Soc. 53 (Feb. 2020), 101974, https://doi.org/10.1016/j.scs.2019.101974.

[39] L. Gustavsson, A. Joelsson, R. Sathre, Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building, Energy Build. 42 (2) (Feb. 2010) 230–242, https://doi.org/10.1016/j.enbuild.2009.08.018.

[40] B. Petrovic, J.A. Myhren, X. Zhang, M. Wallhagen, O. Eriksson, Life cycle assessment of a wooden single-family house in Sweden, Appl. Energy 251 (2019), 113253, https://doi.org/10.1016/j.apenergy.2019.05.056.

[41] B. Rosselló-Batle, A. Moià, A. Cladera, V. Martínez, Energy use, CO2 emissions and waste throughout the life cycle of a sample of hotels in the Balearic Islands, Energy Build. 42 (4) (Apr. 2010) 547–558, https://doi.org/10.1016/j.enbuild.2009.10.024.

[42] J. Sim, J. Sim, The atmospheric environmental impact of a Korean traditional building's life cycle, along with carbon footprint analysis, Sustain. Cities Soc. 28 (Jan. 2017) 172–186, https://doi.org/10.1016/j.scs.2016.09.008.

[43] Y. Liu, J. Zhang, J. Xu, Y. Wang, B. Li, S. Zhang, Carbon emission-based life cycle assessment of rural residential buildings constructed with engineering bamboo: A case study in China, J. Build. Eng. 76 (Oct. 2023), 107182, https://doi.org/10.1016/j.jobe.2023.107182.

[44] X. Zhang, J. Xu, X. Zhang, Y. Li, Life cycle carbon emission reduction potential of a new steel-bamboo composite frame structure for residential houses, J. Build. Eng. 39 (Jul. 2021), 102295, https://doi.org/10.1016/j.jobe.2021.102295.

[45] X. Wu, B. Peng, B. Lin, A dynamic life cycle carbon emission assessment on green and non-green buildings in China, Energy Build. 149 (Aug. 2017) 272–281, https://doi.org/10.1016/j.enbuild.2017.05.041.

[46] L. Xiang-Li, R. Zhi-Yong, D. Lin, An investigation on life-cycle energy consumption and carbon emissions of building space heating and cooling systems, Renew. Energy 84 (Dec. 2015) 124–129, https://doi.org/10.1016/j.renene.2015.06.024.

[47] D. Shi, Y. Gao, R. Guo, R. Levinson, Z. Sun, B. Li, Life cycle assessment of white roof and sedum-tray garden roof for office buildings in China, Sustain. Cities Soc. 46 (Apr. 2019), 101390, https://doi.org/10.1016/j.scs.2018.12.018.

[48] S. Roh, S. Tae, S.J. Suk, G. Ford, S. Shin, Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea's green building index certification system, Renew. Sustain. Energy Rev. 53 (Jan. 2016) 954–965, https://doi.org/10.1016/j.rser.2015.09.048.

[49] D. Li, P. Cui, Y. Lu, Development of an automated estimator of life-cycle carbon emissions for residential buildings: A case study in Nanjing, China, Habitat Int. 57 (Oct. 2016) 154–163, https://doi.org/10.1016/j.habitatint.2016.07.003.

[50] M. Xikai, W. Lixiong, L. Jiwei, Q. Xiaoli, W. Tongyao, Comparison of regression models for estimation of carbon emissions during building's lifecycle using designing factors: a case study of residential buildings in Tianjin, China, Energy Build. 204 (Dec. 2019), 109519, https://doi.org/10.1016/j.enbuild.2019.109519.

[51] S. Roh, S. Tae, Building Simplified Life Cycle CO2 Emissions Assessment Tool (B-SCAT) to Support Low-Carbon Building Design in South Korea, Sustainability 8 (6) (Jun. 2016) 567, https://doi.org/10.3390/su8060567.

[52] Z. Luo, L. Yang, J. Liu, Embodied carbon emissions of office building: A case study of China's 78 office buildings, Build. Environ. 95 (Jan. 2016) 365–371, https://doi.org/10.1016/j.buildenv.2015.09.018.

[53] C. Peng, Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling, J. Clean. Prod. 112 (Jan. 2016) 453–465, https://doi.org/10.1016/j.jclepro.2015.08.078.

[54] F. Pomponi, A. Moncaster, Embodied carbon mitigation and reduction in the built environment – What does the evidence say? J. Environ. Manage. 181 (Oct. 2016) 687–700, https://doi.org/10.1016/j.jenvman.2016.08.036.

[55] X. Yang, M. Hu, J. Wu, B. Zhao, Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China, J. Clean. Prod. 183 (May 2018) 729–743, https://doi.org/10.1016/j.jclepro.2018.02.070.

[56] R. Kumanayake, H. Luo, A tool for assessing life cycle CO2 emissions of buildings in Sri Lanka, Build. Environ. 128 (Jan. 2018) 272–286, https://doi.org/10.1016/j.buildenv.2017.11.042.

[57] The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust'. Accessed: Apr. 03, 2023. [Online]. Available: https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf.

[58] T. Menneer, Z. Qi, T. Taylor, C. Paterson, G. Tu, L.R. Elliott, K. Morrissey, M. Mueller, Changes in Domestic Energy and Water Usage during the UK COVID-19 Lockdown Using High-Resolution Temporal Data, Int. J. Environ. Res. Public. Health 18 (13) (Jun. 2021) 6818.

[59] 'Smartline Project', *Smartline*. https://www.smartline.org.uk (accessed Sep. 05, 2021).

[60] A.J. Williams, K. Maguire, K. Morrissey, T. Taylor, K. Wyatt, Social cohesion, mental wellbeing and health-related quality of life among a cohort of social housing residents in Cornwall: a cross sectional study, BMC Public Health 20 (1) (Dec. 2020) 985, https://doi.org/10.1186/s12889-020-09078-6.

[61] Life cycle assessment, 'ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines', *ISO*, Aug. 12, 2014. https://www.iso.org/standard/38498.html (accessed Apr. 03, 2023).

[62] 'Greenhouse gas reporting: conversion factors 2019', *GOV.UK*. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019 (accessed May 20, 2022).

[63] 'Bath Inventory of Carbon and Energy (ICE) | Greenhouse Gas Protocol'. https://ghgprotocol.org/Third-Party-Databases/Bath-ICE (accessed Sep. 03, 2021).

[64] A. Romero Perez de Tudela, C.M. Rose, J.A. Stegemann, Quantification of material stocks in existing buildings using secondary data—A case study for timber in a London Borough, Resour., Conservat. Recycl.: X 5 (2020) 100027.

[65] P. Gontia, C. Nägeli, L. Rosado, Y. Kalmykova, M. Österbring, Material-intensity database of residential buildings: A case-study of Sweden in the international context, Resour. Conserv. Recycl. 130 (Mar. 2018) 228–239, https://doi.org/10.1016/j.resconrec.2017.11.022.

[66] happhoadmin7, 'Center Line Method for Calculating the Quantities of Building Materials', *Happho*, Nov. 14, 2020. https://happho.com/center-line-method-for-calculating-the-quantities-of-building-materials/ (accessed Sep. 09, 2022).

[67] 'Environmental Product Declaration provided by: Saudi Readymix Concrete Co Ltd'. Accessed: Nov. 14, 2022. [Online]. Available: https://www.greenbooklive.com/pdfdocs/en15804epd/BREGENEPD000278.pdf.

[68] 'FES Documents archive | National Grid ESO'. https://www.nationalgrideso.com/future-energy/future-energy-scenarios/archive (accessed Sep. 07, 2022).

[69] 'Find an energy performance certificate (EPC) by postcode - Find an energy certificate - GOV.UK'. https://find-energy-certificate.digital.communities.gov.uk/find-a-certificate/search-by-postcode (accessed Mar. 12, 2021).

[70] 'The PCR | EPD International'. https://www.environdec.com/product-category-rules-pcr/the-pcr (accessed Sep. 20, 2022).

[71] A. H. Elma Avdyli, *EPD_Steel_Purlins_and_Steel_Framing_Voestalpine_Metsec*, Feb. 10, 2023. https://manage.epdhub.com/?epd=HUB-0024.

[72] D. Ekundayo, S.O. Babatunde, A. Ekundayo, S. Perera, C. Udeaja, Life cycle carbon emissions and comparative evaluation of selected open source UK embodied carbon counting tools, Constr. Econ. Build. 19 (2) (2019) Nov, https://doi.org/10.5130/AJCEB.v19i2.6692.

[73] A.M. Moncaster, K.E. Symons, A method and tool for "cradle to grave" embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards, Energy Build. 66 (Nov. 2013) 514–523, https://doi.org/10.1016/j.enbuild.2013.07.046.

[74] 'A Practical Approach to Whole Life Appraisal for Construction', in *Whole Life Appraisal for Construction*, John Wiley & Sons, Ltd, 2004, pp. 129–148. doi: 10.1002/9780470773635.ch8.

[75] 'Home | EPD Hub'. https://www.epdhub.com/ (accessed Apr. 03, 2023).

[76] 'Environmental Product Declarations (EPD) for UK manufactured construction products', *ConstructionLCA*, Jan. 29, 2022. https://constructionlca.co.uk/uk_epd/ (accessed Nov. 14, 2022).

[77] 'whole-life-carbon-assessment-for-the–built-environment-november-2017'. Accessed: Aug. 23, 2022. [Online]. Available: https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the–built-environment-november-2017.pdf.

[78] '2011 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors', p. 102, 2011.

[79] 'What is carbon intensity? | National Grid ESO'. https://www.nationalgrideso.com/future-energy/net-zero-explained/what-carbon-intensity (accessed Aug. 23, 2022).

[80] '2020 Steel Statistical Yearbook published', *worldsteel.org*. https://worldsteel.org/media-centre/press-releases/2020/2020-steel-statistical-yearbook-published/ (accessed Apr. 03, 2023).

[81] 'Index of Multiple Deprivation (IMD) - Understanding Herefordshire'. https://understanding.herefordshire.gov.uk/inequalities/index-of-multiple-deprivation-imd/ (accessed May 25, 2022).

[82] 'Package overview — pandas 1.5.1 documentation'. https://pandas.pydata.org/docs/getting_started/overview.html (accessed Nov. 02, 2022).

[83] 'scikit-learn: machine learning in Python — scikit-learn 1.1.3 documentation'. https://scikit-learn.org/stable/ (accessed Nov. 02, 2022).

[84] M. Waskom, seaborn: statistical data visualization, J. Open Source Softw. 6 (60) (Apr. 2021) 3021, https://doi.org/10.21105/joss.03021.

[85] 'Python Release Python 3.9.0', *Python.org*. https://www.python.org/downloads/release/python-390/ (accessed Jun. 09, 2022).

[86] S.S. Garud, I.A. Karimi, M. Kraft, Design of computer experiments: A review, Comput. Chem. Eng. 106 (Nov. 2017) 71–95, https://doi.org/10.1016/j.compchemeng.2017.05.010.

[87] P. Carroll, M. Chesser, P. Lyons, Air Source Heat Pumps field studies: A systematic literature review, Renew. Sustain. Energy Rev. 134 (Dec. 2020), 110275, https://doi.org/10.1016/j.rser.2020.110275.

[88] S. Shao, H. Zhang, S. You, W. Zheng, L. Jiang, Thermal performance analysis of a new refrigerant-heated radiator coupled with air-source heat pump heating system, Appl. Energy 247 (Aug. 2019) 78–88, https://doi.org/10.1016/j.apenergy.2019.04.032.

[89] M. Asif, T. Muneer, J. Kubie, Sustainability analysis of window frames, Build. Serv. Eng. Res. Technol. 26 (1) (Feb. 2005) 71–87, https://doi.org/10.1191/0143624405bt118tn.

[90] C. Buratti, E. Moretti, Experimental performance evaluation of aerogel glazing systems, Appl. Energy 97 (Sep. 2012) 430–437, https://doi.org/10.1016/j.apenergy.2011.12.055.

[91] C. Schaefer, G. Bräuer, J. Szczyrbowski, Low emissivity coatings on architectural glass, Surf. Coat. Technol. 93 (1) (Aug. 1997) 37–45, https://doi.org/10.1016/S0257-8972(97)00034-0.

[92] G. KiranKumar, S. Saboor, T.P. Ashok Babu, Investigation of Various Low Emissivity Glass Materials for Green Energy Building Construction in Indian Climatic Zones, Mater. Today: Proceed. 4 (8) (2017) 8052–8058.

[93] A.M. Nilsson, A. Roos, Evaluation of optical and thermal properties of coatings for energy efficient windows, Thin Solid Films 517 (10) (Mar. 2009) 3173–3177, https://doi.org/10.1016/j.tsf.2008.11.083.

[94] S. Somasundaram, A. Chong, Z. Wei, S.R. Thangavelu, Energy saving potential of low-e coating based retrofit double glazing for tropical climate, Energy Build. 206 (Jan. 2020), 109570, https://doi.org/10.1016/j.enbuild.2019.109570.

[95] 'uPVC vs Wooden Windows | Windows Guide'. https://www.windowsguide.co.uk/articles/wooden-casement-windows-vs-upvc (accessed Jun. 12, 2022).

[96] 'Popular Windows, a Comparison', *Enlightened Windows*, Jan. 28, 2019. https://enlightenedwindows.co.uk/windows/comparing-most-popular-windows/ (accessed Jun. 14, 2022).

[97] 'Are wood window frames insulated enough? | Bill Butters Windows & Doors'. https://billbutterswindows.co.uk/latest-news/are-wood-window-frames-insulated-enough/ (accessed Jun. 14, 2022).

[98] 'Conservation of fuel and power: Approved Document L', *GOV.UK*. https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l (accessed Jun. 12, 2022).

[99] J. Bartlett, 'Loft Insulation, The Complete Guide to Types & Costs', *Evergreen Energy*, Oct. 05, 2017. http://www.evergreenenergy.co.uk/insulation/loft-insulation-guide/ (accessed Jun. 12, 2022).

[100] A. Byrne, G. Byrne, A. Davies, A.J. Robinson, Transient and quasi-steady thermal behaviour of a building envelope due to retrofitted cavity wall and ceiling insulation, Energy Build. 61 (Jun. 2013) 356–365, https://doi.org/10.1016/j.enbuild.2013.02.044.

[101] 'Insulation Overview', *GreenBuildingAdvisor*. https://www.greenbuildingadvisor.com/green-basics/insulation-overview-2 (accessed Jun. 12, 2022).

[102] T. Menneer, M. Mueller, S. Townley, A cluster analysis approach to sampling domestic properties for sensor deployment, Build. Environ. 231 (2023) 110032, https://doi.org/10.1016/j.buildenv.2023.110032.