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BIM-based approach for the integrated assessment of life cycle carbon emission intensity and life cycle costs

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Highlight

Integrated assessment betwen the life cycle carbon emissions (LCCE) and life cycle costs (LCC) of buildings is poor.

Most indicators for studying building carbon emissions focus on total carbon emissions rather than unit cost carbon emissions.

This study proposes the concept and framework of building life cycle carbon intensity (CEI).

This study analyzes the key stages of building carbon emissions and converting high-carbon emission materials to low-carbon emission materials.

This study explores achieving the lowest carbon emission under a limited cost throughout the building life cycle.

Abstract:

The construction industry is well known for generating a large amount of carbon emissions and this, together with huge costs of buildings during their life cycle, seriously affects its environmental and economic sustainability. That reducing the former tends to increase the latter is a highly significant problem exacerbating the situation. Finding a solution with the lowest carbon emission at a certain cost is an urgent problem to be solved. Research to date aimed at remedying the situation, however, has been largely focused on either treating the two issues independently or partially conjoined, with little progress in their integrated assessment. In response, this study presents a method for integrating the life cycle carbon emissions (LCCE) and life cycle costs (LCC) of buildings to assess their life cycle carbon emission intensity (CEI) based on BIM technology. Through a public building in China as a case study, the feasibility of the method is verified, the key stages of building carbon emissions are analyzed using CEI, and the conversion of high carbon emission materials to low carbon emission materials is explored. The proposed methodology and framework provide solutions and ideas for achieving optimal costs commensurate with low carbon emissions throughout the building life cycle, facilitating the assessment of carbon emissions at the decision-making and design stages, achieving the optimization of building carbon emissions and costs, and enhancing building life cycle sustainability.

Keywords:

Carbon emission intensity; life cycle carbon emissions; life cycle costs; BIM; life cycle assessment

1. Introduction

While the construction industry improves people’s quality of life and creates tangible benefits to global societies and economies (Goel et al., 2019), it has a significant environmental impact (Hollberg and Ruth, 2016) and is labeled as 'unsustainable' (Yu et al., 2018). As a core industry, it accounts for 30-50% of CO_2 emissions from all sectors worldwide (B. et al., 2015; Lu. et al., 2019), which contribute directly to global warming and the greenhouse effect (Tam et al., 2021; Yang et al., 2018). Reducing CO_2 emissions from buildings has therefore become a main priority for the building industry to reduce energy consumption and achieve energy saving and emission reduction targets (Jiaqi, 2017).

To reduce the life cycle carbon dioxide emissions (LCCE) of buildings, several studies actively investigate ways to mitigate or improve their carbon emissions (Lee et al., 2018) or measures to reduce building carbon emissions and other environmental impacts (Jrade and Jalaei, 2013; Xu et al., 2019; Tam et al.,2022). However, reducing carbon emissions usually leads to increased life cycle costs (LCC) (Islam et al., 2015), which has led to the popularization of research combining LCCE and LCC to balance and optimize carbon emissions and costs (Leckner and Zmeureanu, 2011; Ristimäki et al., 2013; Schmidt et al., 2018; Schwartz et al., 2016).

A further issue is that most indicators used for studying building carbon emissions focus on *total* carbon emissions rather than *unit cost* carbon emissions, resulting in there being no scientific standard for measuring building LCCE in the construction sector.

It is a dilemma for decision-makers to find the lowest carbon emission scheme at a certain cost. In response, based on the synthesis of building LCCE and LCC by BIM technology, this paper proposes the concept and framework of building life cycle carbon intensity and analyses the carbon emissions corresponding to unit costs throughout the life cycle.

The research's purpose is as follows.

1) This research aims to find a method to measure building LCCE per unit cost so that the decision-makers implement the lowest carbon emission scheme solutions at a certain cost throughout the building life cycle.

2) This research proposes the concept and framework of building life cycle carbon intensity (CEI) to fill the gaps that the existing indicators can only calculate the total carbon emissions of the project.

3) This method can analyze the key stages and high carbon emission materials of building carbon emissions and realize the replacement of high carbon emission materials to low carbon emission materials.

This paper consists of six sections. Following this introduction, section 2 reviews the concepts of LCCE, LCC, and the literature relating to LCCE and LCC based on BIM technology. Section 3 proposes the concept of carbon emission intensity (CEI) and constructs a methodological framework for the integrated analysis of LCCE and LCC using CEI and BIM technology. Section 4 combines previous research into the Chinese carbon emission factor database (Islam et al., 2015; Lu et al., 2019), and validates the above methodology using a building in Anhui Province, China, as a case study. Section 5 provides a detailed analysis of the results and discusses the limitations of the study, and section 6 clarifies the conclusions of the work.

2. Literature review

2.1 LCC

While the history of LCC can be traced back to the late 1950s in the U.K, (Klöpffer and Ciroth, 2011), there is no single term for the concept (Goh and Sun, 2015).

The *Construction Best Practice Programme* defines LCC as considering all relevant costs and revenues associated with the acquisition and ownership of constructed assets (Kehily and Underwood, 2017). The scope of the costs involved was subsequently clarified by the International Standards Organisation through ISO 15686-5, which further divides LCC into construction, operation, occupancy, maintenance, and end-of-life costs (International Organization for Standardization, 2017). In summary, the life cycle of a building includes a number of stages, from the production of materials, transportation, construction, operation, and maintenance, to demolition, and the LCC is the sum of the costs incurred by the building at different life cycle stages (Sherif and Kolarik, 1981).

In estimating LCC, some studies use the international standard ISO 15686 (Service Life Planning, Part 5, Whole Life Costing), some use the European Standard BS EN15978, and others use original formulas (Lee et al., 2020; Santos et al., 2020), while still others use BIM-based techniques (Lu et al., 2019; Lu et al., 2020) and machine learning techniques (Ji et al., 2021). Furthermore, The European Commission has developed a series of sector specific LCC calculation tools which aim to facilitate the use of LCC amongst public procurers (Medina-Salgado et al., 2021).

However, as a possible improvement to the traditional LCC approach, Fragonard (Fregonara et al., 2018) and Goulouti (Goulouti et al., 2020) proposed an application of risk analysis in conjunction with Life-Cycle Cost Analysis for selecting the preferable solution between technological options. The focus is on the evaluation of economic–environmental sustainability, considering the presence of risk and uncertainty. These studies had found that by applying sensitivity and probability analysis to LCC, the generated results would indicate in quantitative terms the impact of the various assumptions the better to guide decisions and follow-up work during the building’s life cycle to achieve efficiency.

Consideration of environmental and social factors becomes an urgent issue in LCC. LCC is, to an increasing extent, an effective method for making economic assessments of the built environment through sustainability certification systems of buildings, such as BREEAM and DGNB (Toosi et al., 2020). Importantly, LCC calculations are underpinned by the assumption that assessments of environmental costs are fairly straightforward and apolitical operations. The notion that environmental (and social) costs can be monetized, which underpins LCC, also entails that they are perceived as interchangeable with other costs (Larsen et al., 2022).

The adoption of new technology makes LCC determination more accurate and scientific. BIM technology has developed rapidly in recent years and its data standards

(Fu et al., 2004) and 5D (Kehily and Underwood, 2017) applications have become increasingly mature. It can be used to predict the LCC of buildings during the design stage (Kehily and Underwood, 2017; Lee et al., 2020), and suitable software has been developed for this purpose (J. et al., 2020). This method also allows the impact of different options on the LCC to be evaluated and the optimal option with the lowest LCC to be determined (Jausovec and Sitar, 2019; Rodrigues et al., 2018). BIM-based quantity calculation sheets can directly reflect the consumption of materials and machinery, and can effectively manage multiple data during the construction stage (Lee et al., 2018; Yang et al., 2018), thus enabling rapid costing of the construction stage. Recent research has increasingly focused on the application of BIM-based LCC in sustainable buildings (Ahmad and Thaheem, 2018; Marzouk et al., 2018), where BIM carries information concerning the building's climatic conditions, comfort requirements, and operating schedules, with BIM-based energy consumption software also enabling energy consumption during the operating stage to be simulated (Gan et al., 2018; Peng, 2016; Shadram et al., 2016). Some studies thought an estimation of the building's life span is essential to carrying out LCC methods and also sought an effective way to predict realistic building life spans by applying the latest machine learning prediction methods (Ji et al., 2021). Machine learning techniques have been widely used for predicting facility-related LCC (Gao et al., 2019; Gao et al., 2020), but there is a lack of research on developing machine learning models for the complete life-cycle cost (LCC) analysis of buildings.

2.2 LCCE

Most studies classify LCCE into construction, operation, and demolition stages (Peng, 2016), where the *construction* stage mainly consists of the pre-production of materials and material transportation, and on-site construction (the construction process) (Wan Omar et al., 2014; Yang et al., 2018). Carbon emissions during the *operational* stage mainly consist of energy consumption from heating, ventilation, and air conditioning (HVAC), lighting, water supply (hot and cold), and equipment use (Roh and Tae, 2017). The energy consumption and carbon emissions during the *demolition* stage mainly come from the human and mechanical resources consumed in the demolition of the building (Peng, 2016).

Carbon dioxide equivalent (CO_2-eq) is often used as the unit of measurement for carbon emissions (Turner and Collins, 2013), with its estimation taking into account the collective contribution of such greenhouse gases as CO_2, CH_4, and NO_2 (Gan et al., 2018). However, the accurate computation of carbon emissions is difficult. Firstly, process-based methods for computing LCCE require a large amount of data, leading to high costs and the expenditure of much time (Fenner et al., 2018; Onat et al., 2014). Secondly, the wide variety of materials, equipment, and construction processes involved during the materialization and demolition stages also ma it difficult to accurately estimate their carbon emissions (Li et al., 2010). In addition, carbon emissions vary considerably during the operational stage, depending on climatic conditions, comfort requirements, and operating hours (Ramesh et al., 2010).

In terms of building life-cycle carbon emission calculation, many researchers have established building carbon emission calculation models based on the life-cycle theory, and calculated the life-cycle carbon emissions of residential buildings, public buildings or infrastructure respectively. Filimonau (Filimonau et al., 2021) used the environmental life cycle impact assessment (EIA) approach to assess the life-cycle carbon emission occurring throughout the life cycle of hotels in two South American countries (Brazil and Peru). Petrovic et al. (Petrovic et al., 2021) assessed the carbon emissions of a house in Sweden at all stages from the production, construction and use of building materials to the end of the life cycle of the building. For different research purposes, the boundary range of building carbon emission assessment will also be different. Some studies have focused on the impact of building materials, components, and construction methods on carbon emissions (Sahook et al., 2021; Tabrizikahou et al., 2021), while others focus on the impact of carbon emissions at a specific stage (Cascione et al., 2022).

Building information modeling (BIM), which has been used for the assessment of carbon emissions (Lu et al., 2019;), energy (Nizam et al., 2018; Xu et al., 2019), and other environmental impacts (Jalaei and Jrade, 2014; Jrade and Jalaei, 2013), offers a potential way to address and analyze this issue (Bernardette Soust-Verdaguer et al., 2017). BIM technologies can compute carbon emissions (generated during the building life cycle) at the design stage and reduce the time and effort required to manage carbon emissions data (Cavalliere et al., 2019; Kehily and Underwood, 2017; Nwodo and Anumba, 2019; Soust-Verdaguer et al., 2017; Ylmén et al., 2019), eliminating manual data input and significantly speeding up LCA model building (Cavalliere et al., 2019; Röck et al., 2018; Santos et al., 2019). There have been several studies of BIM-based carbon emissions estimation. Peng (2016), for example, has proposed a method for building LCCE based on *Ecotect* and BIM, while Yang et al. (2018) have conducted a case study on BIM-based carbon footprint accounting for residential buildings (Yang et al., 2018). These studies also illustrate the need for a carbon emission factor database to underpin the computation of building LCCE based on BIM.

In terms of what database to use, there are well-established databases that provide carbon emission coefficients for building materials or construction processes. More than 40 LCA databases have been provided by institutes and researchers (Martínez-Rocamora et al., 2016). At present, the databases commonly used include the Inventory of Carbon and Energy (ICE) database (Circular ecology, 2022), Athena database (Athena, 2022), Ecoinvent database (Ecoinvent, 2022), and GaBi database (Sphera, 2022). These four databases not only contain LCA data from their own countries but are also trying to expand their scope by incorporating relevant data from other countries. In addition, there are U.S.Life Cycle Inventory Database in the United States (Nrel, 2022), ELCD in the European Union (ELCD, 2022), Base Carbone in France(ADEME, 2022) and BEDEC in Spanish (ITeC, 2022). Some databases have been deemed nontransparent and several more can be considered incomplete. In order to compare two construction materials, a precise database with high ratings on ‘traceability’, ‘methodology’ and ‘comprehensiveness’ should be used. Accordingly, GaBi Database and Ecoinvent are identified the most complete LCA databases for their integrity, usability and dedicated resources. ELCD is considered the best free database, standing out due to the fact that it merges data from several industry databases, such as Plastics Europe, Eurofer data sets, and EAA (Martínez-Rocamora et al., 2016). In China, there is the *China National Greenhouse Gas Inventory Program* (Peng, 2016) and the *China Life Cycle Database* (Yang et al., 2018), which can be used as references for carbon emission accounting, but these data are oriented towards all sectors and data for construction materials are extremely limited. Faced with the problem of incomplete carbon emission factors for the construction industry, some studies have used the actual measurement and collection of carbon emission processes from the construction process (Mah et al., 2011) or literature reviews to build their own carbon emission factor databases (Cheng B., 2020; Wang et al., 2018), while others use the coefficients provided by products with environmental product declarations (Wang et al., 2020).

In summary, most studies analyze LCC and LCCE in isolation (Leckner and Zmeureanu, 2011; Ristimäki et al., 2013; Schmidt et al., 2018; Schwartz et al., 2016), and a few do so comprehensively, but none achieve the balance and optimization of LCCE and cost. BIM provides a potential method for the comprehensive analysis of building LCCE and LCC. Therefore, the present study uses BIM Technology to comprehensively analyze building LCCE and LCC and the building life cycle CEI, proposes targeted energy-saving and emission reduction measures, and helps to realize the optimal cost under low carbon design in the early design stage.

3. Method

3.1 Framework

In this section, we first delimit the calculation boundary of a building’s LCC and carbon emissions (Fig. 1, Table 1), and then calculate its LCC and LCCE based on BIM

Technology. Finally, the concept of CEI is put forward, and LCCE and LCC are comprehensively analyzed to obtain the carbon emission per unit cost in the life cycle (Fig. 2).

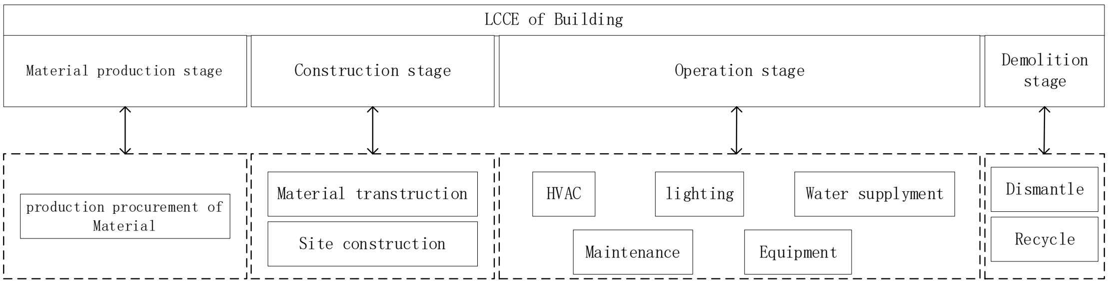

Fig. 1. Calculation boundary of a building's LCCE

Table 1

The scope of activities at each stage

Stage	Activity
Material production stage	The production and procurement of building materials.
Construction stage	The whole process of on-site construction, transportation of building materials to the construction site, transportation of construction waste out of the site, and other construction processes.
Operation stage	The impact of energy and water consumed by the daily operation of the building (refrigeration, heating, ventilation system, lighting, water supply, and equipment use), building maintenance, repair, renovation, and component replacement.
Demolition stage	Building demolition, transportation, and treatment of construction waste.

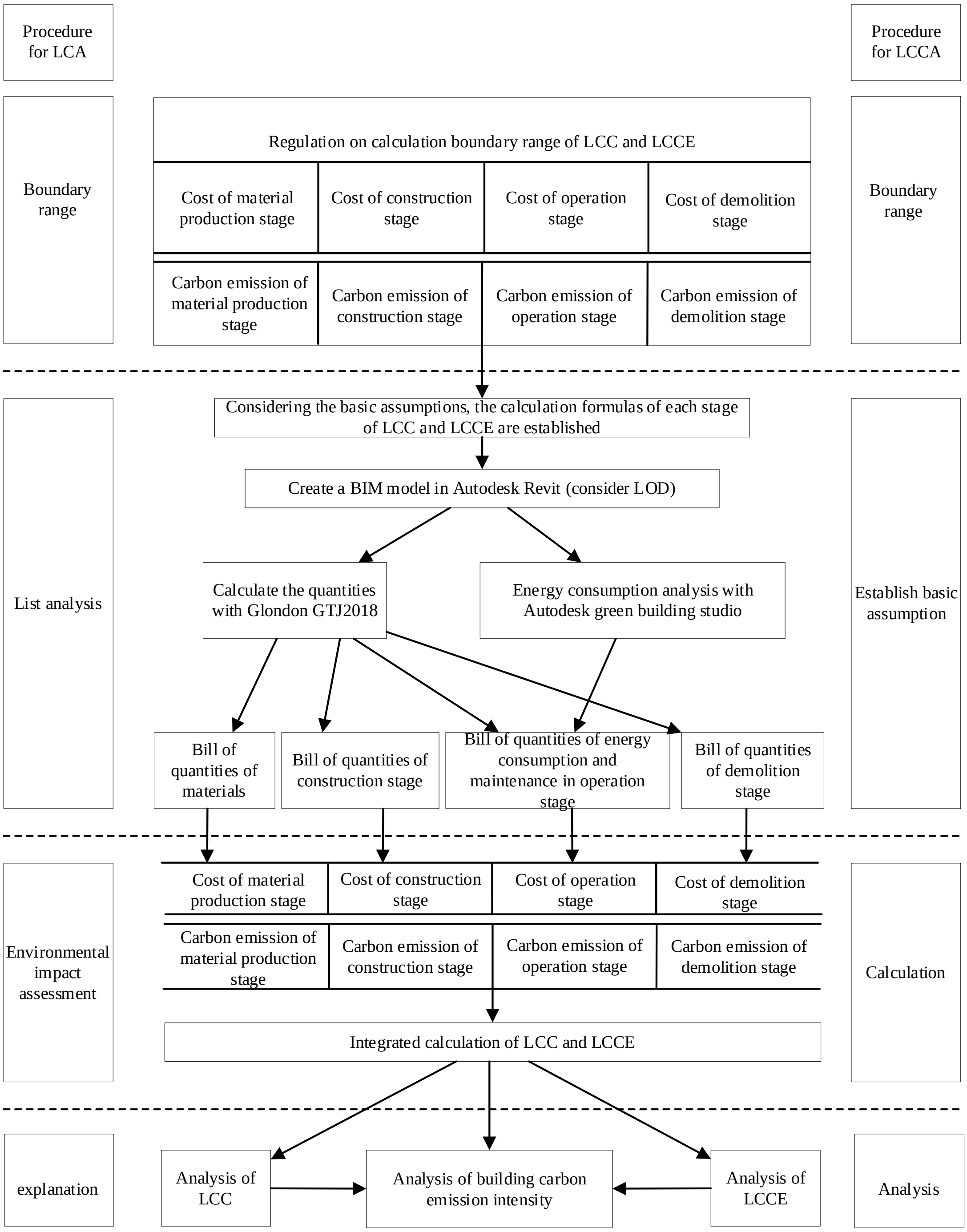

Fig. 2. Framework of building CEI analysis based on BIM

3.2 Use of BIM technology to obtain a life cycle inventory

Autodesk Revit is the core modeling software to build the BIM model and ensure its accuracy; LOD300 is used to create the BIM model (Soust-Verdaguer et al., 2017). Then, the GFC for the Revit plug-in developed by Glondon is used to export the Revit model to Glondon GTJ2018 and supplement more information such as reinforcement. Finally, GTJ2018 is used to compute and export the bill of quantities of maintenance and demolition works in the material production, construction, and operation stages. The operation stage involves the energy consumption consumed by HVAC, lighting, water supply, and equipment, which is computed by simulation based on green building analysis software. Therefore, exporting Autodesk Revit to the green building software Autodesk green building studio obtains the energy consumption list in the operation stage. The life cycle list and data sources required by each stage are shown in Table 2.

Table 2

Life cycle inventory and its data resource

Stage	Detailed List	Direct source of data	Initial modeling of data
Material production stage	Bill of quantities	Glondon GTJ2018	Autodesk Revit
Construction stage	Bill of quantities	Glondon GTJ2018	Autodesk Revit
Operation stage	Maintenance bill of quantities and energy consumption list	Glondon GTJ2018 Autodesk Green Building Studio	Autodesk Revit
Demolition stage	Bill of quantities	Glondon GTJ2018	Autodesk Revit

3.3 Estimating LCCE and LCC

3.3.1 LCCE

According to the above analysis, the whole LCCE of buildings comprises material production, construction, operation, and demolition stages.

The carbon emission in the whole life cycle is calculated by

$$LCCE = CE_{mat} + CE_{con} + CE_{ope} + CE_{dem} \tag{1}$$

where $LCCE, CE_{mat}, CE_{con}, CE_{ope}, CE_{dem}$ denote the carbon emissions from the material production, construction, operation, and demolition stages of the whole life cycle, respectively. $CE_{ope} = CE_{ope1} + CE_{ope2}$. CE_{ope1}, CE_{ope2} are the carbon emissions from energy consumption in the operation stage and carbon emissions from maintenance in the operation stages, respectively.

Material production stage:

The material production stage uses the bill of quantities computation method to compute carbon emissions in terms of component work and measure project work. The carbon emissions during the transportation stage of material production are represented by

$$CE_{mat} = \Sigma CEC_i \times Q_i + \Sigma CEC_j \times Q_j \tag{2}$$

$$CEC_{i/j} = \Sigma q CE_{mat} \tag{3}$$

Here CEC_i and CEC_j denote the comprehensive unit carbon emission coefficient of sub-item works and measure items, respectively; the Q_i and Q_j divisions denote sub-item works and measure item quantity; q is the quantity of materials in unit quantity; and CE_{mat} is the carbon emission coefficient of materials (Lu et al., 2019).

The dispersion of materials and manufacturers' creates difficulties certainty unseen in monitoring the carbon footprint of materials during the production process. Several studies have refined a database of coefficients for the Chinese construction industry that can be used to estimate carbon emissions during the production stage. One of these formed a database of carbon emission factors for energy consumption, labor, materials, and machinery shifts through extensive data collection and integration (Lu et al., 2019). A list of carbon emission factors for construction materials is also provided in the Chinese standard released in 2019 for estimating the carbon emissions from buildings (GB/T51366-2019). They present the carbon emissions from the material production process up to forming in final coefficients and, when combined with the list of materials used, the material-related carbon emission values can be estimated, which significantly reduces computation difficulty.

Construction stage:

In the construction stage, the bill of quantities method is also used to estimate carbon emissions of each sub-work and measurement work. The carbon emissions are firstly computed according to the quota numbers of labor and machinery units; next, the carbon emissions of individual projects are computed; then, these are aggregated to obtain the total carbon emissions of the whole construction stage. The construction stage carbon emissions are represented by

$$CE_{con} = \Sigma CEC_i \times Q_i + \Sigma CEC_j \times Q_j \tag{4}$$

$$CEC_{i/j} = \Sigma pCE_{lab} + \Sigma rCE_{mech} \tag{5}$$

Where CEC_i and CEC_j denote the comprehensive unit carbon emission coefficients of component work and measure items, respectively; he Q_i and $, Q_j$ divisions denote component work and measure item quantities; *p* and *r* is the quantity of man-days and machinery shifts in unit quantities; CE_{lab} and CE_{mech} are the carbon emission coefficients of man-days and machinery shifts (Lu et al., 2019).

Operation Stage:

The operational carbon emissions mainly consist of carbon emissions resulting from the energy consumption of building equipment, which should be deducted if the building uses renewable energy, calculated by

$$CE_{ope1} = CE_{SY} \times Y \tag{6}$$

$$CE_{SY} = CEC_e \times (Q_i - Q_{re}) + CEC_f \times (Q_f - Q_{re}) \tag{7}$$

Where CE_{SY} is the annual carbon emissions generated of energy consumption during the operation stage of the building; CEC_e and CEC_f are the unit carbon emission factors of electricity and fuel, respectively (Lu et al., 2019); Q_e and Q_f are the consumption of electricity and fuel; Q_{re} is the reduction of electricity and fuel from renewable energy systems; and Y is the life of the building.

Demolition stage:

The maintenance process and the demolition stage of the operation stage are calculated in the same way as the construction stage, with

$$CE_{ope2} = CE_{dem} = \Sigma CEC_i \times Q_i + \Sigma CEC_j \times Q_j \tag{8}$$

$$CEC_{i/j} = \Sigma pCE_{lab} + \Sigma rCE_{mech} \tag{9}$$

Where the meaning of the symbols is the same as before.

3.3.2 LCC

Building LCC is represented by

$$LCC = C_{mat} + C_{con} + C_{ope} + C_{dem} \tag{10}$$

where $LCC, C_{mat}, C_{con}, C_{ope}$, and C_{dem} denote the costs of the material production, construction, operation, and demolition stages of the whole life cycle, respectively.

Material production stage:

The use of a bill of quantities pricing in the materials production stage is represented by

$$C_{mat} = \Sigma CC_i \times Q_i + \Sigma CC_j \times Q_j \tag{11}$$

$$CC_{i/j} = \Sigma q C_{mat} \tag{12}$$

where CC_i and CC_j indicate the comprehensive unit price of sub-item work and measure items, respectively; Q_i and Q_j indicate the sub-item work and measures, respectively; q is the quantity of materials in the unit quantity of works; and C_{mat} is the market price of materials.

Construction stage:

The construction stage is also costed using the bill of quantities method for component work and measure item work. The cost of the construction stage is represented by

$$C_{con} = \Sigma CC_i \times Q_i + \Sigma CC_j \times Q_j + C_{rule} + C_{tax} \tag{13}$$

$$CC_{i/j} = \Sigma p C_{lab} + \Sigma r C_{mech} + C_{manage} + C_{profit} \tag{14}$$

where CC_i and CC_j indicate the comprehensive unit price of the component project and measure project, respectively; Q_i, and Q_j denote the quantity of component work and measure items, respectively; p and r are the quantity of man-days and machinery shifts in the unit quantity; C_{lab} and C_{mech} are the market price of man-days and machinery shifts; C_{manage} and C_{profit} are the management fee and profit of the unit quantity; and C_{rule}, and C_{tax} are the fee and tax.

Operation stage:

The operating stage costs are mainly from HVAC, lighting, water supply, fuel, electricity, and water consumed by the use of equipment. The calculation is represented by

$$C_{ope1} = (C_f + C_e + C_w) \times Y \tag{15}$$

$$C_{f/e/w} = CC_1 \times Q_1 + CC_2 \times Q_2 + \cdots + CC_n \times Q_n \tag{16}$$

Where $C_f, C_e,$ and C_w are the annual fuel, electricity, and water costs during the operation stage of the building, respectively; Y is the service life of the building; $CC_1, CC_2, \dots, CC_n$ are the fuel, electricity, and water prices for the first, second, ... , nth level, respectively; $Q_1, Q_2, \dots, Q_n$are the bases of fuel, electricity, and water for the first, second, ... , nth level, respectively.

Demolition stage:

The calculation of the maintenance process and the demolition stage of the operation stage is the same as for the construction stage. It is represented by

$$C_{ope2} = CE_{dem} = \Sigma CC_i \times Q_i + \Sigma CC_j \times Q_j + C_{rule} + C_{tax} \tag{17}$$

$$CC_{i/j} = \Sigma pC_{lab} + \Sigma rC_{mech} + C_{manage} + C_{profit} \tag{18}$$

where the meaning of the symbols is the same as before.

3.4 Building CEI

The concept of a building's CEI is introduced here for the first time, defining it as the carbon emissions per unit cost over the entire life cycle (Eq. 19), with

$$\Delta = LCCE/LCC \tag{19}$$

where Δ represents the carbon emissions generated per unit cost (CNY) (kgCO$_2$-eq).

3.5 Determination of the optimal cost under a low carbon emission regime

Based on the CEI, a comprehensive analysis and optimization of LCC and LCCE can be carried out, mainly consisting of the following elements.

1) A comparative analysis of the CEI of each stage of the building life cycle process, and the identification of the key stages that play a decisive role in the LCCE.
2) Refine the analysis of the key stages, analyze which factors have the greatest CEI at that stage, and optimize them to determine the measures for low carbon emission reduction.
3) Computing the optimal cost under a low carbon emission regime for the whole life cycle of the building.

4. Case study

4.1 Overview of the case

To validate the methodology, this study selects a case study of a public building in Anhui Province, China. This building has been used in the author's prior research (Lu et al., 2021) and the information and drawings are adequate and transparent.

The building is located in Chuzhou City, which has a typical mid-latitude monsoon climate with hot summers and cold winters (GB50176-2016), the building has a reinforced concrete frame structure system (Fig. 3), with a total construction area of 6367 m^2 and a base area of 1703 m^2. It has 4 floors, a building height of 15.9 m, and a design life of 50 years. After the construction of the building is completed, it enters a 50-year operational period, with a maintenance refurbishment expected after 25 years and demolition at the end of 50 years.

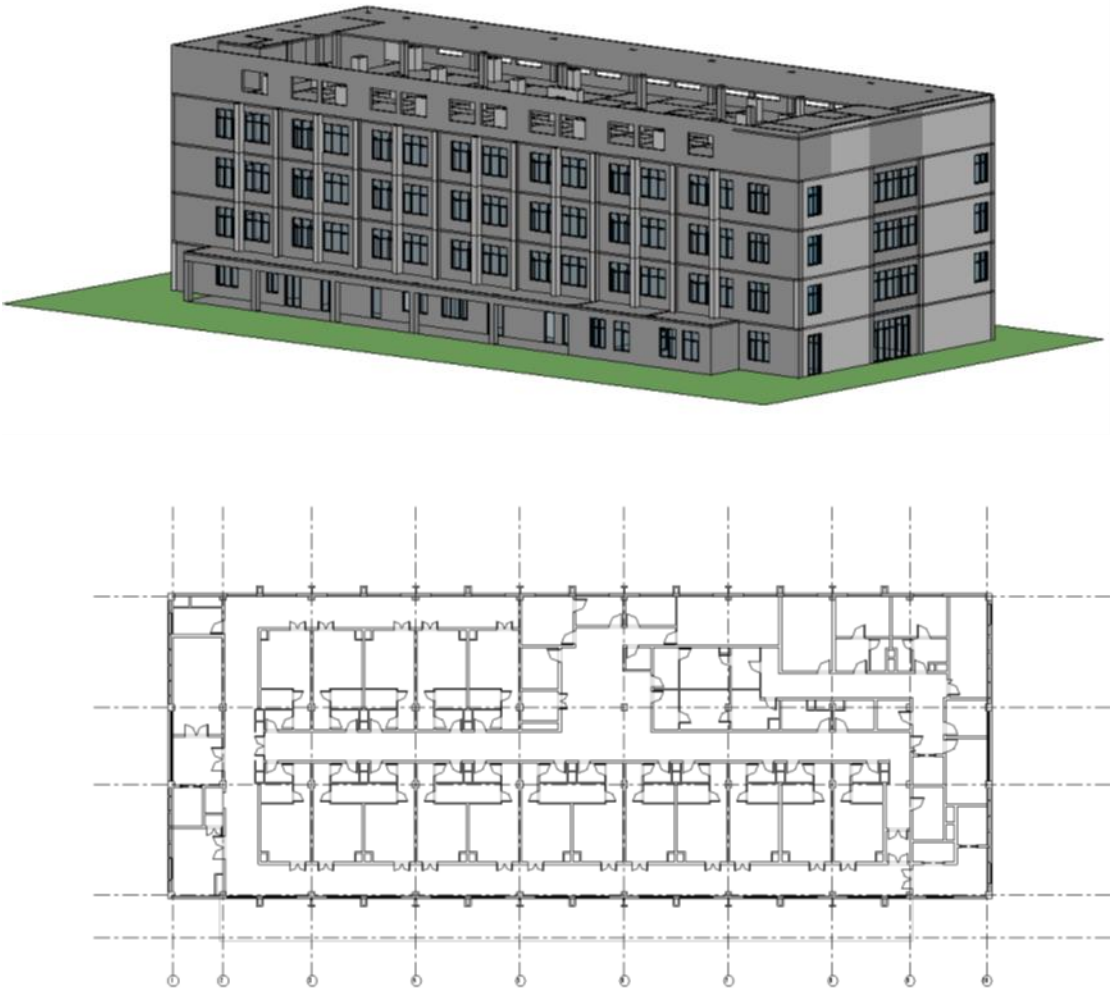

Fig. 3. Case building

The carbon emissions and costs were computed for the production stage (2 years), construction stage (2 years), operation stage (50 years), and demolition stage (0.5 years) as described in section 3, and the results were collated.

4.2 Case results

4.2.1 Estimating LCC and LCCE

The estimated LCC of the building is CNY 798,425,72.10. The cost of each stage, the proportion of LCC by stage, and the average annual cost per unit area by stage are shown in Table 3.

Table 3

LCC estimates

Stage	Cost (CNY)	Proportion (%)	Average annual cost per unit area (CNY/(m^2*y))
Material production	6,102,740.44	7.64	479.25
Construction	3,281,802.34	4.11	257.72
Operation	69,398,155.09	86.92	217.99
Demolition	1,059,874.23	1.33	332.93
Total	*79,842,572.10*	*100*	*230.09*

The LCCE of the building is computed to be 40,102.98 tCO$_2$-eq. The annual average carbon emissions of each stage, the proportion of each stage to the total LCCE, and the annual average carbon emissions of each stage for different time spans are shown in Table 4.

Table 4

LCCE estimates

Stage	Carbon emission (tCO$_2$-eq)	Proportion (%)	Average annual carbon emission (tCO$_2$-eq/y)
Material production	3,144.16	7.84	1,572.08
Construction	112.83	0.28	56.42
Operation	36,601.37	91.27	732.03
Demolition	244.62	0.61	489.24
Total	*40,102.98*	*100*	*735.83*

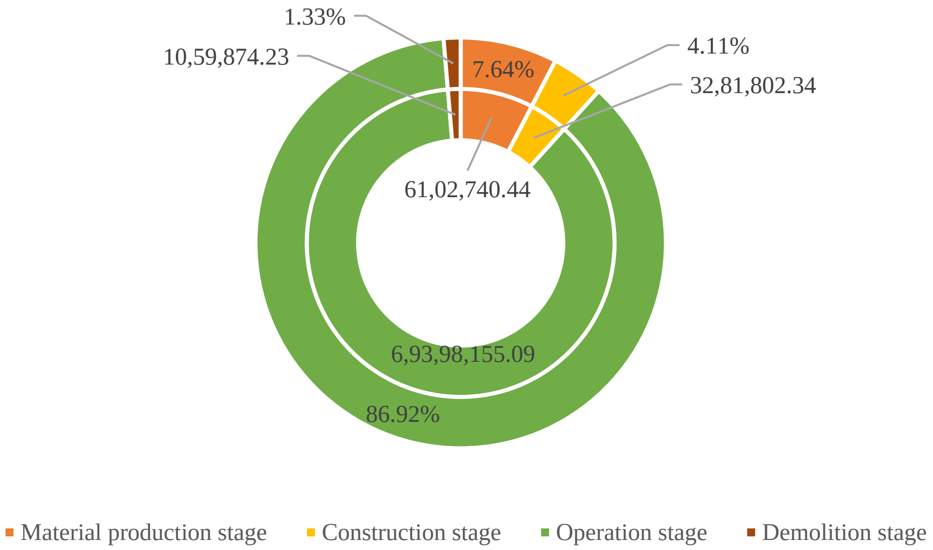

Fig. 4. Composition of LCCE of the case building

Combining the computed LCCE (Table 4) with the analysis of its composition (Fig. 4) and the analysis of the annual average LCCE (Fig. 5), it can be seen that the carbon emissions of the operation stage account for 91.27% of the total carbon emissions in the whole life cycle.

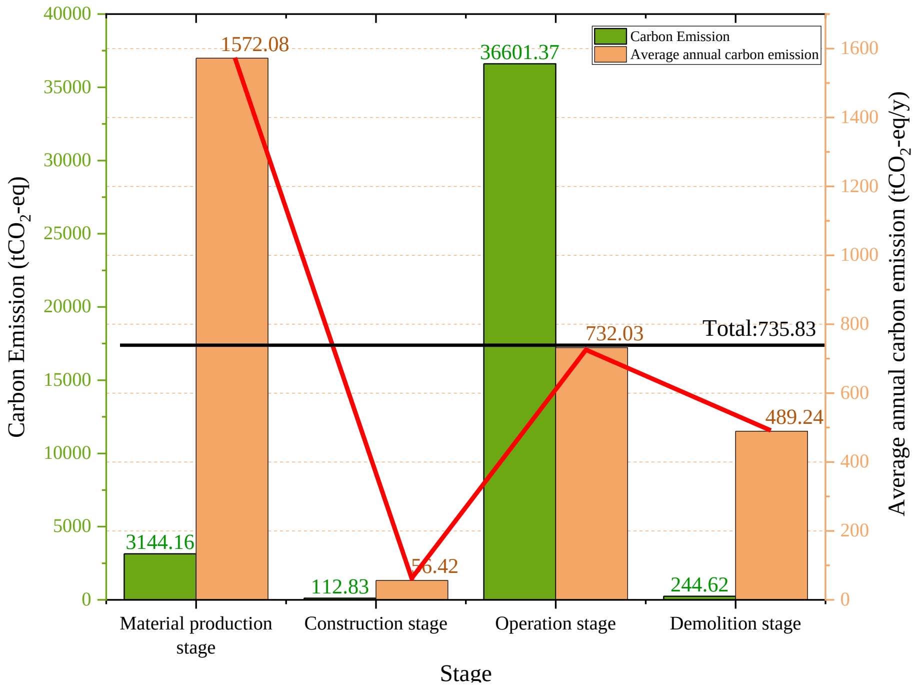

Fig. 5. Analysis of life cycle average annual carbon emission of case building

Due to the different time spans of each stage, it is usual to compare the total carbon emissions of each stage in the life cycle. The carbon emissions per unit time of each stage are computed separately for different time spans to fully compare the carbon emissions of each stage and make a more accurate judgment.

As can be seen from Fig. 5, the average annual carbon emissions of the operational stage are smaller than the overall average annual carbon emissions. However, the difference from the previous comparison is more obvious, in that the annual average carbon emissions of the material production stage are much larger than the overall annual average carbon emission, because the demand for material is matched in the construction process. The demand is more in a short period, so the carbon emission generated per unit of time becomes the largest in the four stages. We then delved further into the carbon emissions of the materials production stage (Fig. 6).

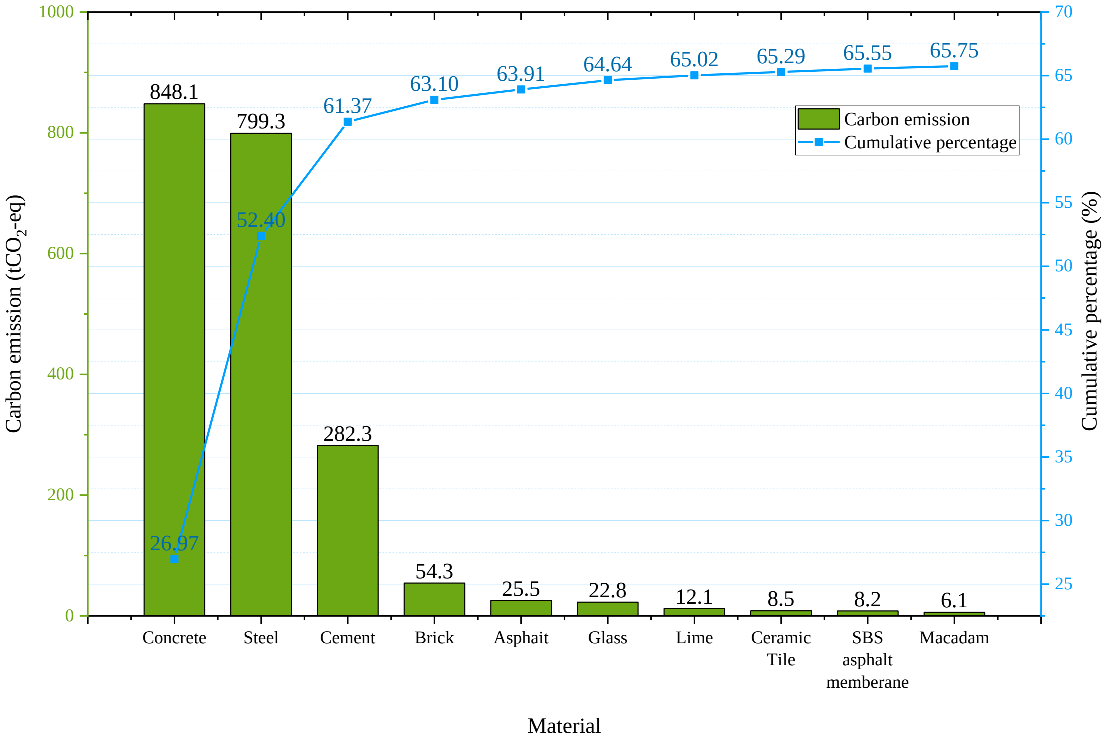

Fig. 6. Composition analysis of the main materials carbon emissions at the material production stage

Fig. 6 shows the ten construction materials with the highest carbon emissions during the material production stage. Their cumulative emissions amount to 2067.2 tCO_2-eq, accounting for 65.75% of the carbon emissions during the material production stage.

Concrete, steel, and cement contribute the most. This is mainly due to the reinforced concrete structures, which consume large amounts of concrete (2590.7 m^3), steel (399.7 tonnes), and cement (524.8 tonnes), which in turn have very high carbon emission factors (Lu et al., 2019), and therefore produce very large total carbon emissions. In recent years, a large number of studies have investigated the use of ultra-high performance concrete (UHPC) (Sheheryar et al., 2021), blast furnace steel (Tsupari et al., 2015), and fly ash (Tushar et al., 2022) to replace the materials currently used in buildings – effectively reducing carbon emissions and the cost of construction materials.

4.2.2 Estimating CEI

Table 5 shows the results of combining the LCCE and LCC to obtain the CEI for each stage ($\Delta = LCCE/LCEC$).

Table 5
CEI estimates of the case building

Stage	Cost (CNY)	Carbon emissions (tCO_2-eq)	Δ ($kgCO_2$-eq/CNY)
Material production	6,102,740.44	3,144.16	0.515
Construction	3,281,802.34	112.83	0.034
Operation	69,398,155.09	36,601.37	0.527
Demolition	1,059,874.23	244.62	0.231
Total	*79,842,572.10*	*40,102.98*	*0.502*

The CEI is computed at different stages (Eq. 19, Table 5, Fig. 7), which gives the amount of carbon emissions that the case building will generate per unit cost.

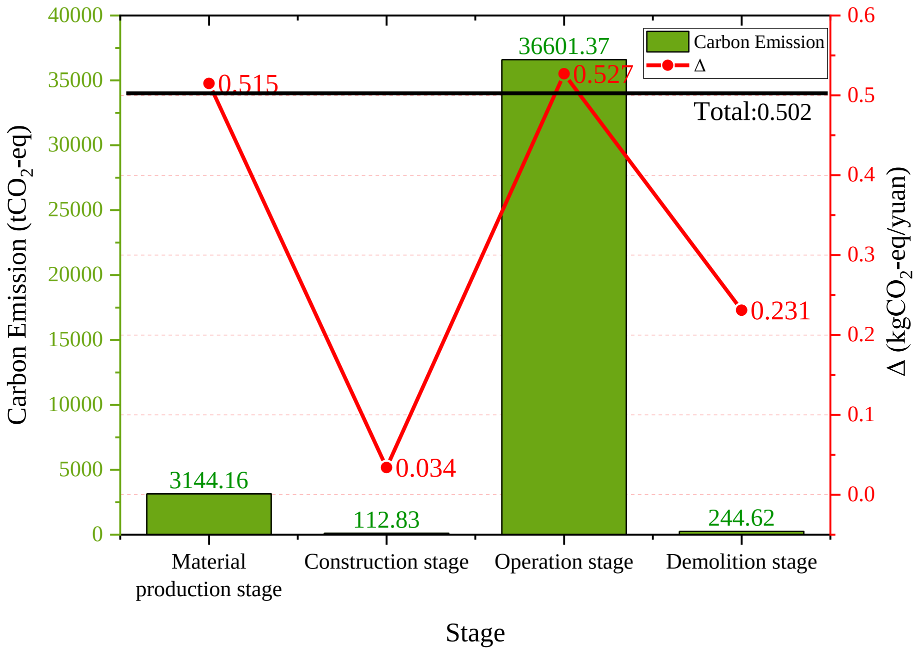

Fig. 7. CEI Analysis of the case building

The life cycle CEI of the case building is 0.502 kgCO$_2$-eq/CNY, and the CEI of the material production, construction, operation, and demolition stages are 0.515 kgCO$_2$-eq/CNY, 0.034 kgCO$_2$-eq/CNY, 0.527 kgCO$_2$-eq/CNY, and 0.231 kgCO$_2$-eq/CNY, respectively. As it has the highest CEI, the operational stage is studied in depth in the next section.

4.2.3 Comparative analysis of CEI in the operation stage

The carbon emissions from the operational stage include those from (1) energy consumption (fuel, electricity) during operation (36,600.00 tCO$_2$-eq) and (2) the maintenance of buildings (labor, machinery) during operation (1.37 tCO$_2$-eq). As Fig. 8 shows, they are mainly from energy consumption in the four areas of HVAC, lighting, water supplement, and equipment.

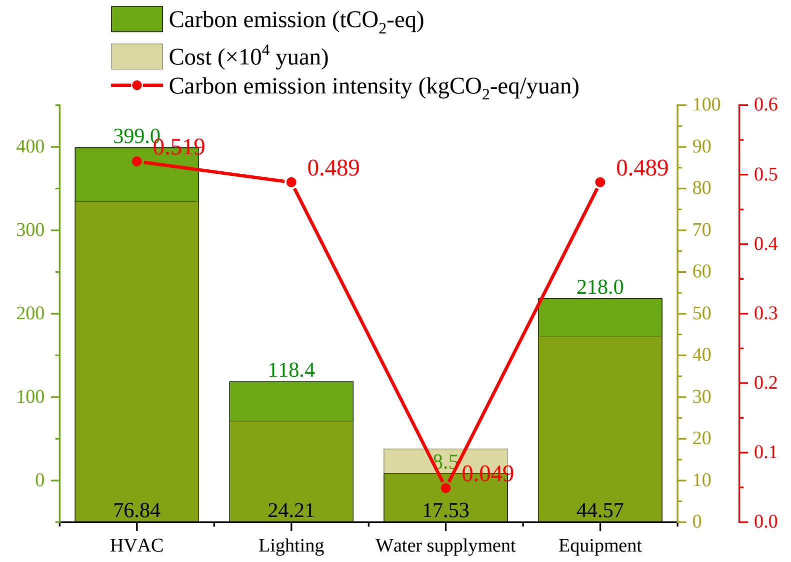

Fig. 8. Analysis of energy consumption CEI at the operation stage

HVAC contributes the most to the carbon emissions generated during this stage and has the highest CEI. The categories of building services and HVAC systems make up the major sources of energy use in buildings. The case building is located in Anhui Province, China, and specific features are set from three categories: cooling, ventilation and heating (see Table 6).

Table 6

HVAC system of the case building

Types	Equipment	Features
Cooling	Central VAV, HW heating, chiller 5.96	Setpoint 26°C, cooling air temperature 14°C, dehumidification setpoint 60%
Ventilation		Single fresh air volume 11.10L/s, 6 air changes per hour
Heating		Setpoint 26°C, heating temperature 32°C, dehumidification setpoint 60%

When structural and electromechanical BIM models of the building is constructed, the BIM model was imported into Autodesk Green Building Studio to create spatial volumes (see Fig. 9). Then, the energy consumption of the building's HVAC system was acquired to calculate the corresponding carbon emissions (see Table 7).

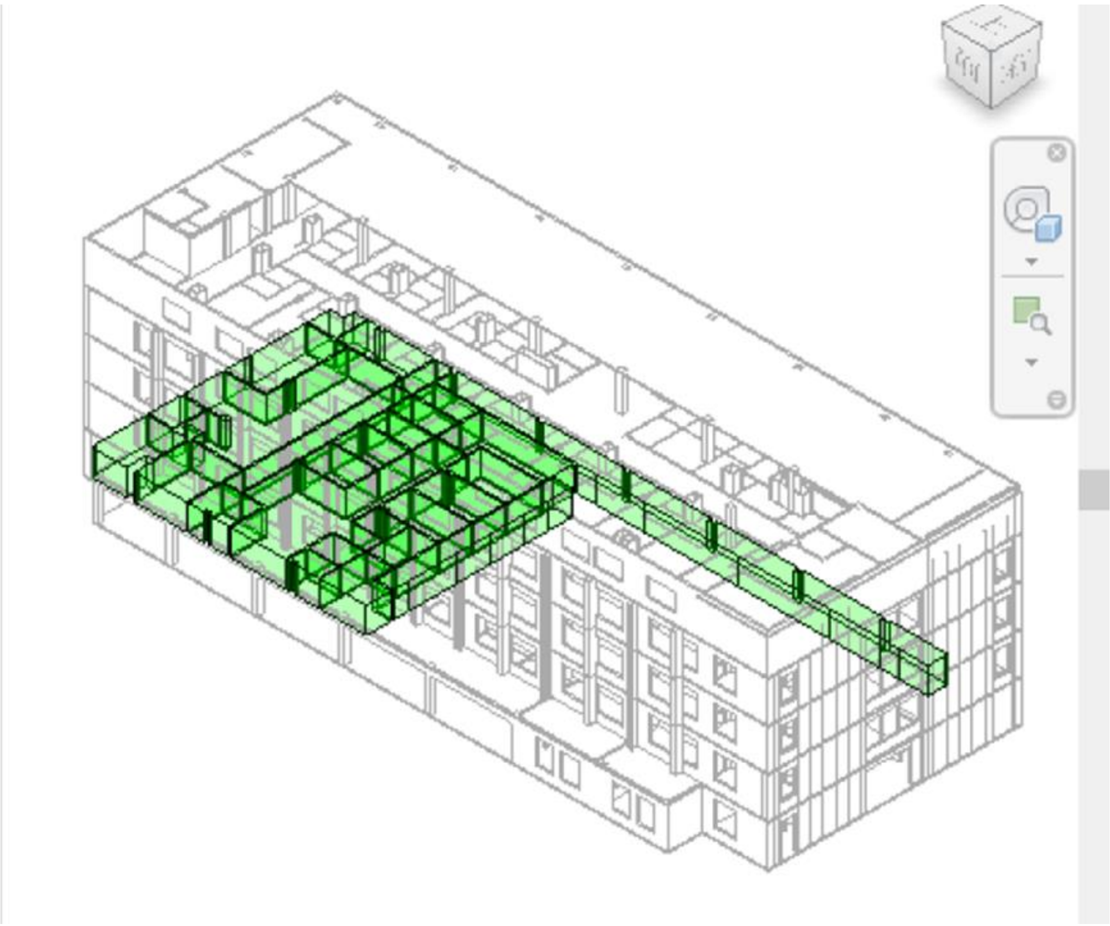

Fig. 9. Heat and cold loads of the case building

Table 7
HVAC system energy consumption and carbon emissions of the case building

Types	Energy consumption	Carbon emissions (tCO_2-eq)
Fuel	2,999,421MJ	149.5
Electricity	570,736kWh	249.5
Total	/	*399.0*

The analysis result of this case is consistent with the existing research, which also points to the need to seek optimization of heating and air conditioning equipment (Guan et al., 2013) and to adapt the building's electrical structure (Ramon and Allacker, 2021) to reduce carbon emissions during the operational stage.

The average monthly CEI at the operational stage in winter (December, January, February) and summer (June, July, August) is 0.545 kgCO2-eq/CNY and 0.546 kgCO2-eq/CNY, which are significantly higher than the 0.528 kgCO2-eq/CNY and 0.526 kgCO2-eq/CNY in spring (March, April, May) and fall (September, October, November) (see figure 10.).

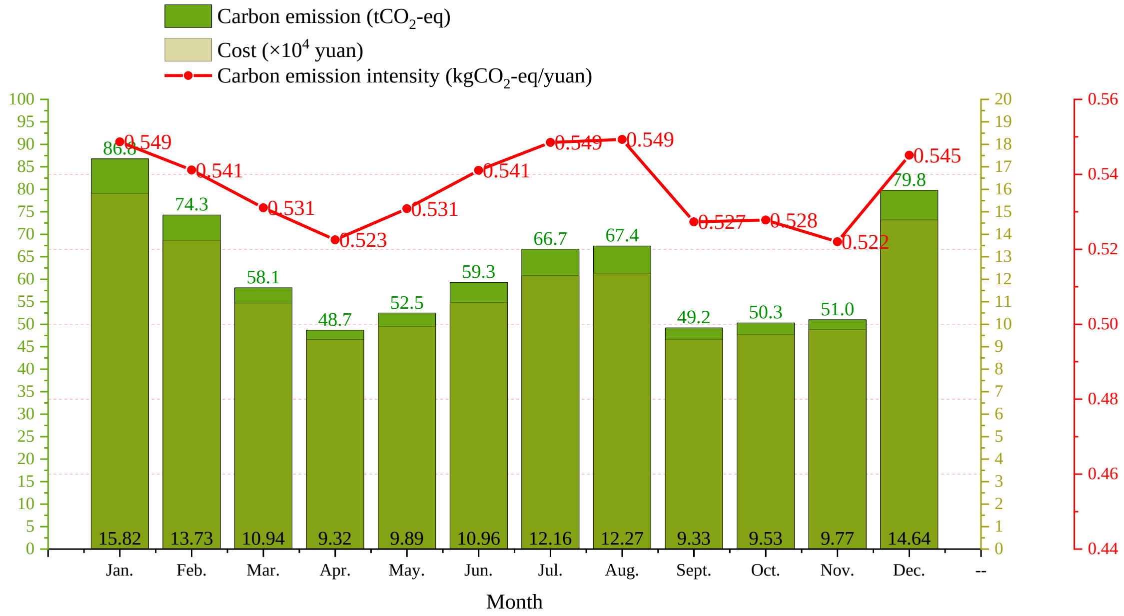

Fig. 10. Analysis of monthly CEI at operation stage

One possible reason for this phenomenon is the case in Anhui Province, China, where winters are cold and summers are hot, leading to increased energy consumption and higher carbon emissions compared to other regions. Another reason is that public buildings require better ventilation, cooling, and heating conditions, resulting in higher parameter settings for HVAC than residential building types.

4.2.4 Optimization analysis of the lowest carbon emission under a limited cost

Due to tedious calculations, this study only focuses on the optimization analysis of the material production stage with the largest carbon emissions.

The case building'concrete are repalced with ultra-high-performance concrete (UHPC) (Sheheryar et al., 2021), fly ash-based geopolymer concrete (FGC) (Zhang et al., 2020), waste glass cullet concrete (WGC) (Xiao et al., 2020), and mixed material geopolymer concrete (MGC) (Singh and Middendorf, 2020). Then, the carbon emissions and cost of the concrete are calculated. The results of the cabon emission and cost are listed in Table 8.

The results show that, compared with traditional concrete, alternative concrete can achieve significant energy saving and emission reduction in the case building. However, the cost increases with the corresponding decrease in CEI. Decision-makers are stuck in the dilemma of how to find a trade-off between carbon emission and cost. Finding a solution with the lowest carbon emission at a certain cost is an urgent problem to be solved. This study utilizes two-dimensional coordinates to draw the area between carbon emissions and costs. Then the scheme with the smallest product area is considered the best solution, achieving a balance between low cost and low carbon emissions (see Fig.10).

Table 8

Comprehensive analysis of carbon emission and cost of different concrete

Types of concrete	Carbon emissions (tCO_2-eq)	Cost ($\times 10^4$ CNY)	Δ ($kgCO_2$-eq/CNY)	(Carbon emission)× (Cost) ($\times 10^7$(tCO_2-eq*CNY))
Case study concrete	848.1	140.35	0.604	119.03
UHPC	703.9	147.37	0.478	103.73
FGC	661.5	148.77	0.445	98.41
WGC	678.4	154.39	0.439	104.74
MGC	585.2	161.40	0.363	94.45

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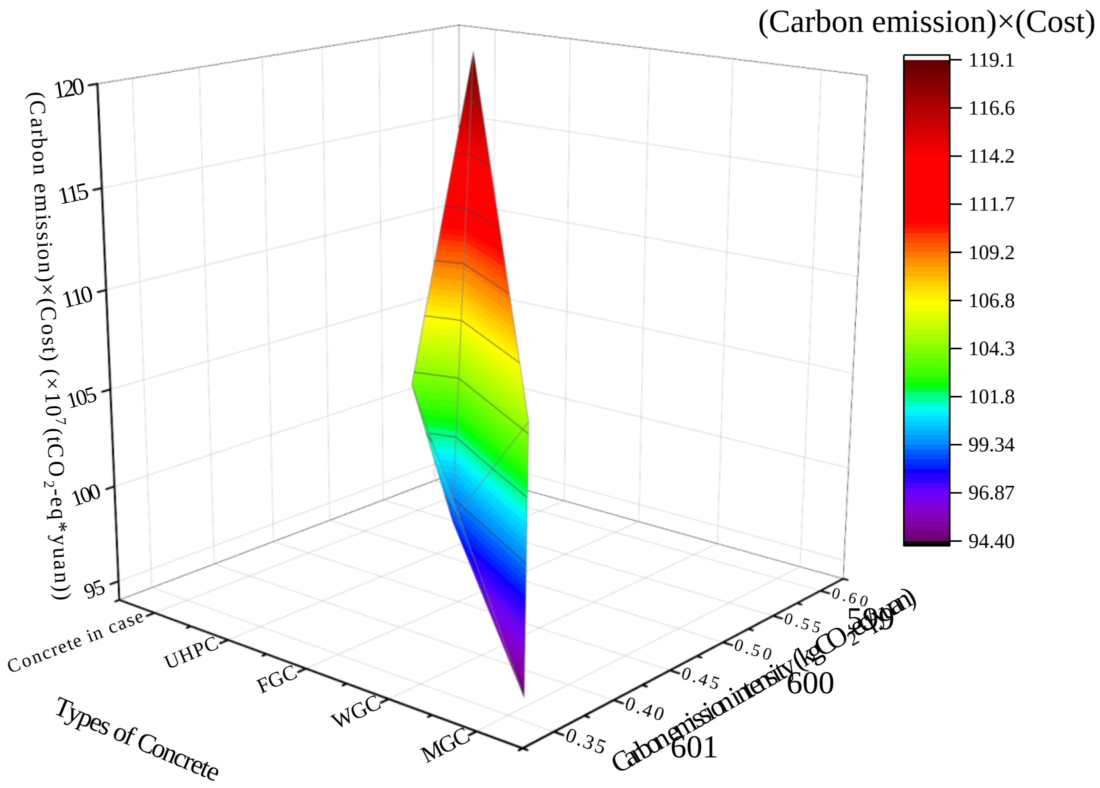

Fig. 11. Comprehensive analysis of carbon emission and cost of different concrete

5. Discussion

5.1 Further integration of BIM and advanced technologies

This study develops and demonstrates a comprehensive assessment and analysis method for integrating building LCCE and LCC based on BIM as a way to quickly and efficiently analyze the building life cycle CEI in the pre-design stage and to make a preliminary determination of the most cost-effective designs within a low carbon emission regime for the building life cycle. With the continued research and use of BIM and LCCE and LCC, this framework has a broad scope in the future.

However, the accuracy of BIM-based estimation varies according to the BIM model details. In setting up the LOD, which represents the level of detail and steps of the BIM model, and conducting modeling during the construction project, creating a model that contains only the necessary information is necessary. If the LOD is set too high or too low, problems like overwork and rework and lack of information will arise. The missing objects in the 3D model will cause problems in the accuracy and reliability of BIM-based estimation. In addition, the BIM-based method is challenging to apply to preliminary estimation because the detailed BIM model is constructed at the detailed design stage. A combination of BIM and case-based reasoning method or machine learning approaches may be a way to address preliminary estimation at the initial phase of the project life cycle. Further integration of BIM and advanced technologies are the future trend.

5.2 CEI and the area between carbon emissions and costs

A life cycle assessment (LCA) is the assessment of the environmental impact of a given product over its life (ISO, 2006a; ISO, 2006b). For the LCA environmental impact indicators, some studies focus on a single environmental indicator, such as carbon emissions or energy consumption, while others cover multiple environmental impact indicators, such as acidification potential (AP), eutrophication potential (EP), the abiotic depletion potential of materials (ADPM), human health respiratory effects potential (HHREP). Of these environmental impact indicators, energy and greenhouse gases emissions are the most common indicators (Lu et al., 2021). Because greenhouse gas emissions (CO2, CH4, N2O, etc.) can be more readily quantified than other impacts, especially carbon emissions (also called carbon footprint)are the easiest to calculate. Hence, most research only focuses on carbon emissions. The aim of this study is to analyze the integrated assessment of LCC and LCCE. That is, this study only takes into account the effect of CO2.

This study describes the development of an integrated method to assist decision-makers in optimizing the life cycle carbon emissions and cost of a building. It firstly makes a joint analysis of LCCE and LCC through the bridge of building CEI. The method departs from previous similar studies, where most building's LCCE and LCC have been analyzed independently (Leckner and Zmeureanu, 2011; Ristimäki et al., 2013; Schmidt et al., 2018) or partially integrated analysis of LCC and LCCE (Lu et al., 2020).

The concept of carbon intensity is commonly used in the macroeconomic analysis (Cheng and Yao, 2021; Yang et al.,2020), and this paper applies it to buildings for the first time. Building CEI can not only analyze the relationship between carbon emissions and construction costs but also the stages of high carbon emissions and materials with high carbon emissions to control the balance between construction costs and carbon emissions.

Most indicators for studying building carbon emissions focus on total carbon emissions rather than unit cost carbon emissions. When evaluating the low carbon reduction potential between different projects or materials, it is not scientific to directly compare total emissions. CEI, as an indicator of carbon emissions per unit cost, plays a critical role in this situation. It is a scientific and reasonable choice to use CEI to compare the carbon emissions of different materials, stages and projects.

At the same time, decision-makers hope to find a solution that optimizes both carbon emissions and costs. However, low carbon emissions and low costs conflict with each other, with the former low and the latter high. This study utilizes two-dimensional coordinates to draw the area between carbon emissions and costs. Then the scheme with the smallest product area is considered the best solution, achieving a balance between low cost and low carbon emissions.

CEI can also be used throughout the life cycle of prefabricated buildings to achieve carbon emission and cost optimization. Prefabricated components significantly reduce carbon emissions in the construction stage (Li et al., 2021),but increase the life cycle cost (Jang et al., 2022). Hence, it is valuable research direction that using the CEI method to analyze construction processes and materials with high carbon emissions, and to achieve material replacement without increasing costs.

This study provides a method for optimizing high carbon and high cost building materials or schemes, which can be used for material substitution or scheme substitution in the early design stage so as to obtain the most optimum dual optimization of carbon emissions and costs.

The work is limited in that the existing library of carbon emission factors that we have combined is currently incomplete and needs to be expanded with further accumulation. In addition, software development limitations have resulted in the study being based on only primary materials. Further research is required to develop procedures to analyze cost inventories and carbon emission inventories in one-to-one correspondence in o to better explore all stages more comprehensively.

6. Conclusion

In the past, assessments of life cycle carbon emissions (LCCE) and life cycle costs (LCC) based on building information modeling (BIM) have often been carried out independently, and most studies have not considered carbon emissions per unit of time. Nor have they analyzed the relationship between the two in an integrated manner, leading to biased optimization results.

This paper proposes a framework for analyzing the LCCE and LCC of buildings using BIM technology, providing a design stage where the LCCE and LCC of a building can be computed quickly and effectively, and the intensity of the building's carbon emissions can be analyzed.

The results of the case study show that the replacement of high carbon emitting materials such as concrete, steel, and cement, can be effective in reducing carbon emissions and costs in both the materials production stage and the operational stage, redirecting cost savings to the construction stage to increase the industrial production of buildings, and thereby reducing carbon emissions in both the construction and demolition stages. The research idea of optimizing the cost of buildings while achieving low carbon emissions is realized, allowing buildings to be quickly assessed for carbon emissions at the design stage, and thus contributing to balancing the environmental and economic impact of buildings and improving the sustainability of the construction industry.

CRediT authorship contribution statement:

Xiaoyan Jiang: Conceptualization, Methodology, Writing-Original draft preparation, Funding acquisition; Yubing Zhang: Data curation, Software, validation; Caiyun Cui: Supervision; Martin Skitmore: Writing- Reviewing and Editing,

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References

ADEME. Base Carbone website. ⟨http://www.basecarbone.fr/⟩; 2022[accessed 10.09.2022].

Ahmad, T., and Thaheem, M. J. (2018). Economic sustainability assessment of residential buildings: A dedicated assessment framework and implications for BIM. *Sustainable Cities and Society, 38*, 476-491. doi:10.1016/j.scs.2018.01.035

Athena SMI. Athena database content. <http://www.calculatelca.com/wp-content/uploads/2012/10/LCI_Databases_Products.pdf> (Aug.31,2015).

Cascione, V., Roberts, M., Allen, S., Dams, B., Maskell, D., Shea, A., ... & Emmitt, S. (2022). Integration of life cycle assessments (LCA) in circular bio-based wall panel design. *Journal of Cleaner Production*, 344, 130938. doi:10.1016/j.jclepro.2022.130938

Cavalliere, C., Habert, G., Dell'Osso, G. R., and Hollberg, A. (2019). Continuous BIM-based assessment of embodied environmental impacts throughout the design process. *Journal of Cleaner Production, 211*, 941-952. doi:10.1016/j.jclepro.2018.11.247

Cheng B., L. J., Tam V.W.Y., Yang M. (2020). A BIM-LCA approach for estimating the greenhouse gas emissions of large-scale public buildings: A case study. *Sustainability*. *12*(2), 685.

Cheng, Y., & Yao, X. (2021). Carbon intensity reduction assessment of renewable energy technology innovation in China: A panel data model with cross-section dependence and slope heterogeneity. *Renewable and Sustainable Energy Reviews*, 135, 110157. doi:10.1016/j.rser.2020.110157

Circular ecology. Embodied Carbon - The ICE Database. ⟨https://circularecology.com/embodied-carbon-footprint-database.html⟩; 2022 [accessed 10.09.2022].

Ecoinvent Centre. Ecoinvent website. ⟨ https://ecoinvent.org/the-ecoinvent-database/ ⟩; 2022 [accessed 10.09.2022.

ELCD. European reference life-cycle database website. ⟨https://eplca.jrc.ec.europa.eu/ELCD3/ ⟩; 2022 [accessed 10.09.2022].

Fenner, A. E., Kibert, C. J., Woo, J., Morque, S., Razkenari, M., Hakim, H., and Lu, X. (2018). The carbon footprint of buildings: A review of methodologies and applications. *Renewable and Sustainable Energy Reviews, 94*, 1142-1152. doi:10.1016/j.rser.2018.07.012

Filimonau V, Rosa M S, Franca L S, et al. Environmental and carbon footprint of tourist accommodation: A comparative study of popular hotel categories in Brazil and Peru [J]. *Journal of Cleaner Production*, 2021, 328: 129561. doi:10.1016/j.jclepro.2021.129561

Fregonara, E., Ferrando, D. G., & Pattono, S. (2018). Economic–environmental sustainability in building projects: Introducing risk and uncertainty in LCCE and LCCA. *Sustainability*, 10(6), 1901. doi:10.3390/su10061901

Fu, C., Kaya, S., and Aouad, M. J. C. I. (2007). The development of an IFC-based lifecycle costing prototype tool for building construction and maintenance-integrating lifecycle costing to nD modeling. *Construction Innovation* *7*(1), 85-98. hdoi:10.1108/14714170710721313

Gan, V. J. L., Deng, M., Tse, K. T., Chan, C. M., Lo, I. M. C., and Cheng, J. C. P. (2018). Holistic BIM framework for sustainable low carbon design of high-rise buildings. *Journal of Cleaner Production, 195*, 1091-1104. doi:10.1016/j.jclepro.2018.05.272

Gao, X., Pishdad-Bozorgi, P., Shelden, D. R., & Hu, Y. (2019). Machine learning applications in facility life-cycle cost analysis: A review. Computing in Civil Engineering 2019: *Smart Cities, Sustainability, and Resilience*, 267-274. doi:10.1061/9780784482445.034

Gao, X., & Pishdad-Bozorgi, P. (2020). A framework of developing machine learning models for facility life-cycle cost analysis. *Building Research & Information*, 48(5), 501-525. doi:10.1080/09613218.2019.1691488

Goel, A., Ganesh, L. S., and Kaur, A. (2019). Sustainability integration in the management of construction projects: A morphological analysis of over two decades' research literature. *Journal of Cleaner Production. 236*, 117676. doi:10.1016/j.jclepro.2019.117676

Goh, B. H., and Sun, Y. (2015). The development of life-cycle costing for buildings. *Building Research & Information, 44*(3), 319-333. doi:10.1080/09613218.2014.993566

Goulouti, K., Padey, P., Galimshina, A., Habert, G., & Lasvaux, S. (2020). Uncertainty of building elements' service lives in building LCA & LCC: What matters?. *Building and Environment*, 183, 106904. doi:10.1016/j.buildenv.2020.106904

Guan, Y., Shao, C. F., Tian, X. G., and Ju, M. T. (2013). Carbon footprint attributed to aluminum substitution for copper in the Chinese indoor air conditioner industry. *Journal of Cleaner Production, 51*, 126-132. doi:10.1016/j.jclepro.2013.01.027

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., and Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment, 1*(11), 559-573. doi:10.1038/s43017-020-0093-3

Hammond, G., & Jones, C. (2008). Inventory of carbon & energy: ICE (Vol. 5). Bath: Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath.

Hollberg, A., and Ruth, J. (2016). LCA in architectural design—a parametric approach. *The International Journal of Life Cycle Assessment, 21*(7), 943-960. doi:10.1007/s11367-016-1065-1

International Standard Organisation (ISO) (2006a) Environmental management—Life cycle assessment: Principles and framework.ISO14040, Geneva

International Standard Organisation (ISO) (2006b) Environmental management—Life cycle assessment: Requirements and Guidelines. ISO14044, Geneva

International Organization for Standardization (2017). ISO 15686-5: 2017. Buildings and constructed assets-service-life planning — part 5: Life-cycle costing.

Islam, H., Jollands, M., and Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renewable and Sustainable Energy Reviews, 42*, 129-140. doi:10.1016/j.rser.2014.10.006

ITeC. BEDEC database website. 〈 https://en.itec.cat/database/〉; 2022[accessed 10.09.2022].

Jalaei, F., and Jrade, A. (2014). An automated BIM model to conceptually design, analyze, simulate, and assess sustainable building projects. *Journal of Construction Engineering, 2014*, 1-21. doi:10.1155/2014/672896

Jang, H., Ahn, Y., and Roh, S. (2022). Comparison of the embodied carbon emissions and direct construction costs for modular and conventional residential buildings in South Korea. *Buildings, 12*(1). doi:10.3390/buildings12010051

Jausovec, M., and Sitar, M. (2019). Comparative evaluation model framework for cost-optimal evaluation of prefabricated lightweight system envelopes in the early design stage. *Sustainability, 11*(18). doi:10.3390/su11185106

Ji, S., Lee, B., & Yi, M. Y. (2021). Building life-span prediction for life cycle assessment and life cycle cost using machine learning: A big data approach. *Building and Environment*, 205, 108267. doi:10.1016/j.buildenv.2021.108267

Jiaqi, L. S. L. (2017). Research on green building design optimization based on life cycle cost and carbon emissions. *Construction Economy, 38*(10), 59-65. doi:10.14181/j.cnki.1002-851x.201710059

Jrade, A., and Jalaei, F. (2013). Integrating building information modelling with sustainability to design building projects at the conceptual stage. *Building Simulation, 6*(4), 429-444. doi:10.1007/s12273-013-0120-0

Kehily, D., & Underwood, J. (2017). Embedding life cycle costing in 5D BIM. *Journal of Information Technology in Construction*, *22*, 145-167. http://www.itcon.org/paper/2017/8

Klöpffer, W., and Ciroth, A. (2011). Is LCC relevant in a sustainability assessment? *The International Journal of Life Cycle Assessment, 16*(2), 99-101. doi:10.1007/s11367-011-0249-y

Larsen, V. G., Tollin, N., Sattrup, P. A., Birkved, M., & Holmboe, T. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering*, 50, 104203. doi:10.1016/j.jobe.2022.104203

Leckner, M., and Zmeureanu, R. (2011). Life cycle cost and energy analysis of a Net Zero Energy House with solar combi system. *Applied Energy, 88*(1), 232-241. doi:10.1016/j.apenergy.2010.07.031

Lee, J., Tae, S., and Kim, R. (2018). A study on the analysis of CO_2 emissions of apartment housing in the construction process. *Sustainability*, *10*(2), 365. doi:10.3390/su10020365

Lee, J., Yang, H., Lim, J., Hong, T., Kim, J., and Jeong, K. (2020). BIM-based preliminary estimation method considering the life cycle cost for decision-making in the early design stage. *Journal of Asian Architecture and Building Engineering, 19*(4), 384-399. doi:10.1080/13467581.2020.1748635

Li, X., Zhu, Y., and Zhang, Z. (2010). An LCA-based environmental impact assessment model for construction processes. *Building and Environment, 45*(3), 766-775. doi:10.1016/j.buildenv.2009.08.010

Li, X. J., Lai, J. Y., Ma, C. Y., and Wang, C. (2021). Using BIM to research carbon footprint during the materialization stage of prefabricated concrete buildings: A China study. *Journal of Cleaner Production, 279*. doi:10.1016/j.jclepro.2020.123454

Lin, B., & Liu, H. (2015). CO2 emissions of China's commercial and residential buildings: Evidence and reduction policy. *Building and Environment*, 92, 418-431. doi:10.1016/j.buildenv.2015.05.020

Lu, K., Jiang, X., Tam, V. W. Y., Li, M., Wang, H., Xia, B., and Chen, Q. (2019). Development of a carbon emissions analysis framework using building information modeling and life cycle assessment for the construction of hospital projects. *Sustainability*. *11*(22), 6274. doi: 0.3390/su11226274

Lu, K., Jiang, X., Yu, J., Tam, V. W., and Skitmore, M. 2021. Integration of life cycle assessment and life cycle cost using Building Information Modeling: A critical review. *Journal of Cleaner Production*, 285, 125438. doi: 10.1016/j.jclepro.2020.125438

Mah, D., Manrique, J. D., Yu, H., Al-Hussein, M., and Nasseri, R. (2011). House construction CO_2 footprint quantification: a BIM approach. *Construction Innovation, 11*(2), 161-178. doi:10.1108/14714171111124149

Marzouk, M., Azab, S., and Metawie, M. (2018). BIM-based approach for optimizing life cycle costs of sustainable buildings. *Journal of Cleaner Production, 188*, 217-226. doi:10.1016/j.jclepro.2018.03.280

Medina-Salgado, M. S., García-Muiña, F. E., Cucchi, M., & Settembre-Blundo, D. (2021). Adaptive life cycle costing (LCC) modeling and applying to Italy ceramic tile manufacturing sector: Its implication of open innovation. *Journal of Open Innovation: Technology, Market, and Complexity*, 7(1), 101. doi:10.3390/joitmc7010101

Martínez-Rocamora, A., Solís-Guzmán, J., & Marrero, M. (2016). LCA databases focused on construction materials: A review. *Renewable and Sustainable Energy Reviews*, 58, 565-573.

Nrel. The U.S. Life Cycle Inventory (USLCI) Database. 〈 https://www.nrel.gov/lci/〉; 2022 [accessed10.09.2022].

Nizam, R. S., Zhang, C., and Tian, L. (2018). A BIM based tool for assessing embodied energy for buildings. *Energy and Buildings, 170*, 1-14. doi:10.1016/j.enbuild.2018.03.067

Nwodo, M. N., and Anumba, C. J. (2019). A review of life cycle assessment of buildings using a systematic approach. *Building and Environment, 162*. doi:10.1016/j.buildenv.2019.106290

Onat, N. C., Kucukvar, M., and Tatari, O. (2014). Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach. *Building and Environment, 72*, 53-62. doi:10.1016/j.buildenv.2013.10.009

Patacas, J., Dawood, N., & Kassem, M. (2020). BIM for facilities management: A framework and a common data environment using open standards. *Automation in Construction*, 120, 103366. doi:10.1016/j.autcon.2020.103366

Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *Journal of Cleaner Production, 112*, 453-465. doi:10.1016/j.jclepro.2015.08.078

Petrovic B, Myhren J A, Zhang X, et al. Life cycle assessment of a wooden single-family house in Sweden [J]. *Applied Energy*, 2019, 251: 113253. doi:10.1016/j.apenergy.2019.05.056

Ramesh, T., Prakash, R., and Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592-1600. doi:10.1016/j.enbuild.2010.05.007

Ramon, D., and Allacker, K. (2021). Integrating long term temporal changes in the Belgian electricity mix in environmental attributional life cycle assessment of buildings. *Journal of Cleaner Production, 297*. doi:10.1016/j.jclepro.2021.126624

Ristimäki, M., Säynäjoki, A., Heinonen, J., and Junnila, S. (2013). Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy, 63*, 168-179. doi:10.1016/j.energy.2013.10.030

Röck, M., Hollberg, A., Habert, G., and Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Building and Environment, 140*, 153-161. doi:10.1016/j.buildenv.2018.05.006

Rodrigues, F., Matos, R., Alves, A., Ribeirinho, P., and Rodrigues, H. (2018). Building life cycle applied to refurbishment of a traditional building from Oporto, Portugal. *Journal of Building Engineering, 17*, 84-95. doi:10.1016/j.jobe.2018.01.010

Roh, S., and Tae, S. (2017). An integrated assessment system for managing life cycle CO2 emissions of a building. *Renewable and Sustainable Energy Reviews, 73*, 265-275. doi:10.1016/j.rser.2017.01.139

Sahoo K, Bergman R, Runge T. Life-cycle assessment of redwood lumber products in the US [J]. *International Journal of Life Cycle Assessment*, 2021, 26(8): 1702-20. doi:10.1007/s11367-021-01937-7

Santos, R., Aguiar Costa, A., Silvestre, J. D., and Pyl, L. (2020). Development of a BIM-based environmental and economic life cycle assessment tool. *Journal of Cleaner Production, 265*. doi:10.1016/j.jclepro.2020.121705

Santos, R., Costa, A. A., Silvestre, J. D., and Pyl, L. (2019). Integration of LCA and LCC analysis within a BIM-based environment. *Automation in Construction*, *103*, 127-149. doi:10.1016/j.autcon.2019.02.011

Schmidt, M., Crawford, R. H. (2018). A framework for the integrated optimisation of the life cycle greenhouse gas emissions and cost of buildings. *Energy and Buildings*, *171*, 155-167. doi:10.1016/j.enbuild.2018.04.018

Schwartz, Y., Raslan, R., and Mumovic, D. (2016). Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building refurbishment case study. *Energy, 97*, 58-68. doi:10.1016/j.energy.2015.11.056

Shadram, F., Johansson, T. D., Lu, W., Schade, J., and Olofsson, T. (2016). An integrated BIM-based framework for minimizing embodied energy during building design. *Energy & Buildings*. *128*. doi:10.1016/j.enbuild.2016.07.007

Sheheryar, M., Rehan, R., and Nehdi, M. L. (2021). Estimating CO_2 emission savings from ultrahigh performance concrete: A system dynamics approach. *Materials, 14*(4). doi:10.3390/ma14040995

Sherif, Y. S., and Kolarik, W. J. (1981). Life cycle costing: Concept and practice. *Omega (Oxford), 9*(3), 287-296. doi:10.1016/0305-0483(81)90035-9

Singh, N. B., and Middendorf, B. (2020). Geopolymers as an alternative to portland cement: An overview. *Construction and Building Materials, 237*. doi:10.1016/j.conbuildmat.2019.117455

Soust-Verdaguer, B., Llatas, C., and García-Martínez, A. (2017). Critical review of BIM-based LCA method to buildings. *Energy and Buildings, 136*, 110-120. doi:10.1016/j.enbuild.2016.12.009

Sphera. GaBi Database website. ⟨https://gabi.sphera.com/support/latestupdate/⟩; 2022 [accessed 10.09.2022].

Tabrizikahou, A., & Nowotarski, P. (2021). Mitigating the energy consumption and the carbon emission in the building structures by optimization of the construction processes. *Energies*, 14(11), 3287. doi:10.3390/en14113287

Tam, V. W., Le, K. N., Tran, C. N., and Illankoon, I. C. S. (2021). A review on international ecological legislation on energy consumption: Greenhouse gas emission management. *International Journal of Construction Management*, *21*(6), 631-647. doi:10.1080/15623599.2019.1576259

Tam, V. W., Zhou, Y., Illankoon, C., & Le, K. N. (2022). A critical review on BIM and LCA integration using the ISO 14040 framework. *Building and Environment*, 213, 108865. doi:10.1016/j.buildenv.2022.108865

Toosi, H. A., Lavagna, M., Leonforte, F., Del Pero, C., & Aste, N. (2020). Life cycle sustainability assessment in building energy retrofitting: a review. *Sustainable Cities and Society*, 60, 102248. doi:10.1016/j.scs.2020.102248

Tsupari, E., Kärki, J., Arasto, A., Lilja, J., Kinnunen, K., and Sihvonen, M. (2015). Oxygen blast furnace with CO_2 capture and storage at an integrated steel mill – Part II: Economic feasibility in comparison with conventional blast furnace highlighting sensitivities. *International Journal of Greenhouse Gas Control, 32*, 189-196. doi:10.1016/j.ijggc.2014.11.007

Turner, L. K., and Collins, F. G. (2013). Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials, 43*, 125-130. doi:10.1016/j.conbuildmat.2013.01.023

Tushar, Q., Bhuiyan, M. A., Zhang, G., Maqsood, T., and Tasmin, T. (2022). Application of a harmonized life cycle assessment method for supplementary cementitious materials in structural concrete. *Construction and Building Materials, 316*. doi:10.1016/j.conbuildmat.2021.125850'

U.S.Lifecycleinventorydatabase.NationalRenewableEnergyLaboratory. ⟨https://www.lcacommons.gov/nrel/search⟩; 2015[accessed31.08.15].

Wan Omar, W.-M.-S., Doh, J.-H., and Panuwatwanich, K. (2014). Variations in embodied energy and carbon emission intensities of construction materials. *Environmental Impact Assessment Review, 49*, 31-48. doi:10.1016/j.eiar.2014.06.003

Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., and CNY, H. (2018). Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study. *Journal of Cleaner Production, 172*, 3154-3166. doi:10.1016/j.jclepro.2017.11.087

Wang, N., Satola, D., Houlihan Wiberg, A., Liu, C., and Gustavsen, A. (2020). Reduction strategies for greenhouse gas emissions from high-speed railway station buildings in a cold climate zone of China. *Sustainability, 12*(5). doi:10.3390/su12051704

Xiao, R., Ma, Y., Jiang, X., Zhang, M., Zhang, Y., Wang, Y., . . . He, Q. (2020). Strength, microstructure, efflorescence behavior and environmental impacts of waste glass geopolymers cured at ambient temperature. *Journal of Cleaner Production, 252*. doi:10.1016/j.jclepro.2019.119610

Xu, Z., Wang, S., and Wang, E. (2019). Integration of BIM and energy consumption modelling for manufacturing prefabricated components: A case study in China. *Advances in Civil Engineering, 2019*, 1-18. doi:10.1155/2019/1609523

Yang, G., Zha, D., Wang, X., & Chen, Q. (2020). Exploring the nonlinear association between environmental regulation and carbon intensity in China: the mediating effect of green technology. *Ecological Indicators*, 114, 106309. doi:10.1016/j.ecolind.2020.106309

Yang, X., Hu, M., Wu, J., and Zhao, B. (2018). Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. *Journal of Cleaner Production*, *183*. doi:10.1016/j.jclepro.2018.02.070

Ylmén, P., Peñaloza, D., and Mjörnell, K. (2019). Life cycle assessment of an office building based on site-specific data. *Energies, 12*(13). doi:10.3390/en12132588

Yu, W. D., Cheng, S. T., Ho, W. C., and Chang, Y. H. (2018). Measuring the sustainability of construction projects throughout their lifecycle: A Taiwan lesson. *Sustainability*, *10*(5), 1523. doi:10.3390/su10051523

Zhang, P., Gao, Z., Wang, J., Guo, J., Hu, S., and Ling, Y. (2020). Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. *Journal of Cleaner Production, 270*. doi:10.1016/j.jclepro.2020.122389

Declaration of interests

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