Sust. Build. **8**, 7 (2025)
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https://doi.org/10.1051/sbuild/2025005

Sustainable Buildings

Available online at:
www.sustainable-buildings-journal.org

Topical issue on: Selected Contributions of the 3rd International Conference on Green Building (ICoGB 2025)

ORIGINAL ARTICLE **OPEN ACCESS**

Life cycle assessment of carbon emissions in steel and concrete factory buildings

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Received: 31 March 2025 / Accepted: 21 August 2025

Abstract. In the context of the escalating global emphasis on carbon neutrality, building carbon emissions are receiving more and more attention. This study utilizes a Life Cycle Assessment (LCA) to evaluate the carbon emissions of steel and concrete factory buildings. The results indicate that the carbon emission intensity for the concrete structure building is 2244.7 kg CO_2/m^2, while for the steel structure building it is 2051.3 kg CO_2/m^2. Analysis across diverse life-cycle stages revealed that, in both types of buildings, the majority of carbon emissions originate from the product and utilization phases. The carbon emission intensity in the product stage for the concrete and steel structure buildings is 518.1 kg CO_2/m^2 and 269.1 kg CO_2/m^2, respectively, while in the use stage, the emissions are 1714.2 kg CO_2/m^2 for the concrete structure and 1776.0 kg CO_2/m^2 for the steel structure. Sensitivity analysis identifies electricity consumption and heating as the most influential carbon emission factors, which also process the greatest potential for emission reductions. Consequently, targeted carbon emission control measures for both building types should focus primarily on improving energy efficiency in the use stage, particularly in electricity consumption and heating. This study provides valuable insights for evaluating and reducing the carbon footprint of factory buildings.

Keywords: Building carbon emissions / life cycle assessment / factory building / sensitivity analysis

1 Introduction

The construction industry is widely recognized as a significant contributor to the global greenhouse effect, accounting for more than 37% of global carbon emissions [1]. It is projected that global building floor space will increase by 17 billion square meters by 2060 [2]. This rapid expansion of building infrastructure is directly associated with an upsurge in the construction sector's total greenhouse gas (GHG) emissions [3]. Consequently, curbing carbon emissions in the construction industry has become a critical focus for nations striving to meet global carbon reduction and sustainable development goals [4–6]. In China, the construction sector has experienced rapid growth, driven by economic and social development, which has consequently led to significant GHG emissions [7]. Reports indicate that CO_2 emissions in the building sector of China are projected to peak at 2519.85–2527.37 million tons in 2026 [7]. Furthermore, according to Zou et al. [1], the CO_2 emissions resulting from the operations of residential buildings are anticipated to reach their peak around 2031 (±3 years), amounting to a total of 0.95 (±0.06) Gt CO_2. In response, China has formulated policies and set goals to achieve a carbon peak by 2030 and carbon neutrality by 2060 [3,8,9]. Therefore, evaluating and reducing carbon emissions in the construction sector is crucial for China's pursuit of low-carbon and sustainable development.

Life Cycle Assessment (LCA) is a prevalent method employed to evaluate the carbon emissions of buildings and quantify their environmental footprints [10–12]. In the context of LCA, the entire construction journey of a building is considered, spanning raw material production, construction, utilization, disposal, and recycling (i.e., from cradle to grave) [13]. Based on the LCA methodology, the life-cycle carbon emission phases within the construction industry mainly include the product stage, operational stage, construction stage, and demolition stage [14–16]. Distinct building types exhibit significant disparities in carbon emissions across different stages. For example, Zhou et al. [2] employed the LCA method to assess the carbon emissions of both traditional and prefabricated buildings. The results indicated that prefabricated buildings emit less carbon than traditional ones. Furthermore,

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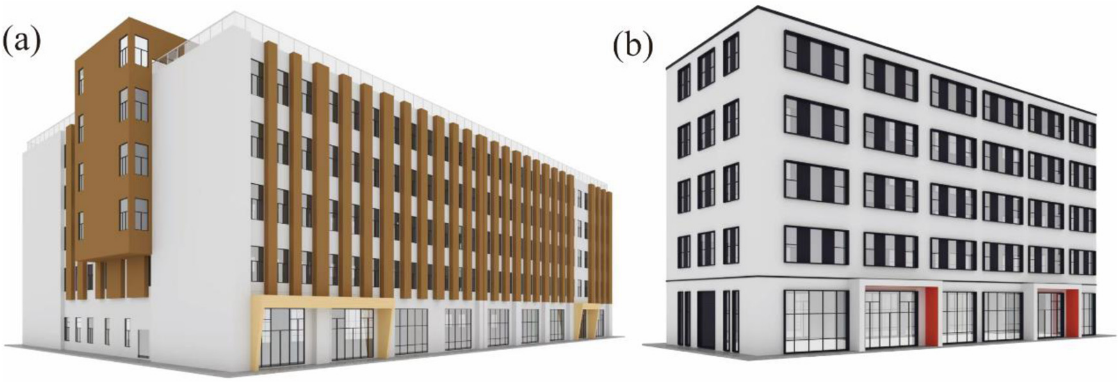

Fig. 1. 3D rendering of the two Buildings (a) 3D rendering of the BHIP building; (b) 3D rendering of the ZSBT building.

Chen et al. [12] discovered that carbon emissions from building materials constituted 94.9% of the total carbon emissions throughout these processes. However, most studies concentrate on the carbon emission accounting of prefabricated buildings, high-rise shear-wall structures, and residential buildings [17,18]. Regarding the carbon emission accounting of factory buildings with diverse structures, research is scarce. It has been demonstrated that residential and factory green buildings influence carbon emissions [8,19]. Factory buildings might emit more carbon from electricity consumption when compared to traditional residential buildings. Similarly, green factory buildings use more environmentally friendly renewable materials to reduce carbon emissions [20]. Moreover, the structural configuration of a building significantly impacts its life-cycle carbon emissions [21,22]. Globally, it is reported that steel- and concrete-structure buildings occupy a considerable proportion of the global building stock, and their impact on overall carbon emissions cannot be ignored. The majority of studies have indicated that concrete and steel contribute to 85% of the total carbon emissions associated with building materials [23,24]. Furthermore, the carbon-reduction control strategies for buildings featuring different structural systems vary significantly. For concrete buildings, alternative materials like aggregates can be utilized to mitigate the carbon emissions resulting from the extensive use of concrete [13,25]. Similarly, for steel structure buildings, studies have shown that under the premise of not affecting safety, steel frame structure buildings are expected to reduce the general use of steel materials to reduce carbon emissions [26]. Accurate carbon emission assessment of steel and concrete factory buildings holds crucial significance for the carbon emission reduction of factory buildings. Nevertheless, numerous factors come into play in building energy consumption and carbon emissions, encompassing building materials, building performance, and service life [27,28]. Therefore, from a life cycle perspective, the accurate and reasonable evaluation of the carbon emissions of buildings throughout their entire life cycle is of great significance for formulating rational and effective carbon reduction methods.

In this study, two factory buildings, one with a steel structure and the other with a concrete structure, were chosen for the assessment of carbon emissions. By utilizing the data from the project cost list, the carbon emissions of these two buildings across the product, construction, utilization, and end-of-life stages were evaluated via LCA. The carbon-emission sources of the two distinct structures were compared and analyzed. Additionally, sensitivity analysis was employed to pinpoint the key carbon emission sources for both buildings. This study holds significant importance for the selection of factory building structures and carbon reduction management.

2 Materials and methods

2.1 Case study description

In this study, two factory cases were compared. One is the Binhai New City Information Industry Park (BHIP), located in Fuzhou, Fujian Province. The other, located in Nanping, Fujian Province, is named Zhongsheng Biotechnology Co., Ltd. (ZSBT). The 3D renderings of the two buildings are shown in Figure 1. The buildings were constructed between 2019 and 2022. The two projects adopt different structural systems. The BHIP project features a reinforced-concrete structure, while the ZSBT project has a steel structure. The BHIP building (concrete building) consists of three floors with a total gross floor area of 75,403 m^2. It includes 1 basement with an area of 3662.69 m^2 and three engineering buildings with areas of 12613.76 m^2 (#1), 17191.14 m^2 (#2), and 41935.47 m^2 (#3) respectively. The project is mainly used for various business services, such as equipment manufacturing and property management. The ZSBT building (steel building) consists of three buildings with a total gross floor area of 11,956 m^2. It includes 1 office building with an area of 419 m^2 and 2 factory buildings with areas of 2,344 m^2 and 9,193 m^2, respectively. The steel building is mainly engaged in poultry and livestock slaughtering and processing. Both facilities are situated in Fujian Province and serve as factory buildings, making them comparable. To analyze the differences in their carbon emissions, it is beneficial to calculate the emissions per square meter using the LCA method, considering the variation in their sizes.

2.2 Carbon emission accounting boundary

The carbon emissions of concrete and steel factory buildings throughout all stages primarily stem from four phases: the product stage, usage stage, construction stage,

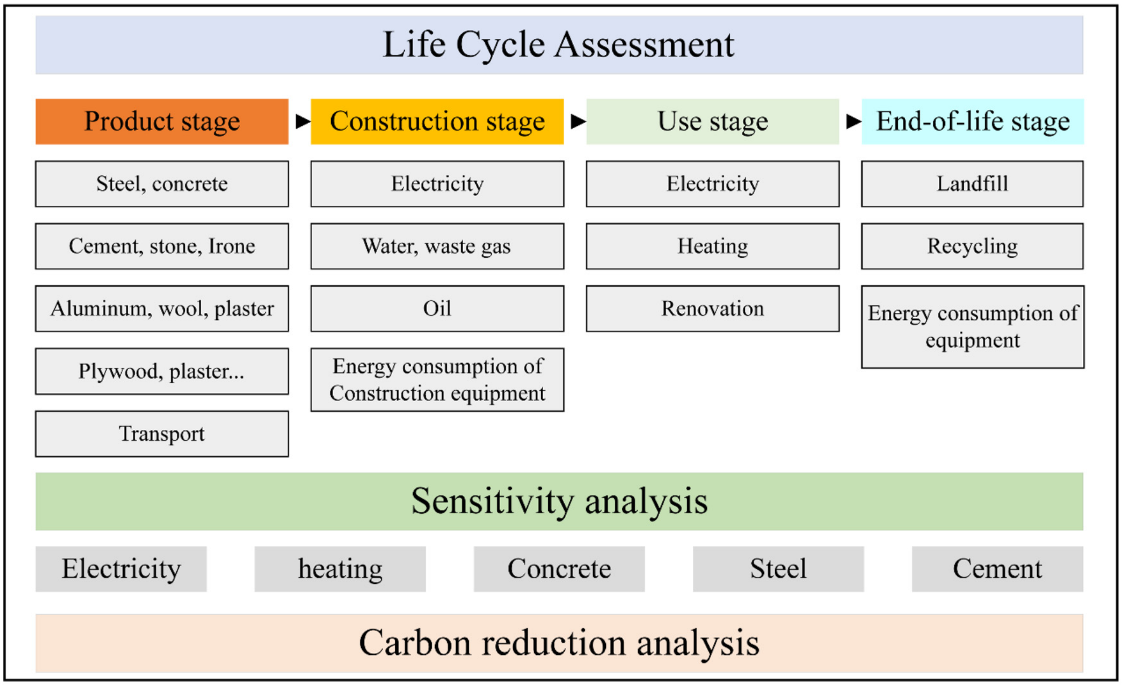

Fig. 2. System boundaries used in the LCA for the steel and the concrete building.

and end-of-life stage (Fig. 2). Firstly, energy consumption occurs during the production and transportation of building materials. In this study, notable disparities exist in the utilization of building materials between the two buildings. Secondly, energy consumption and replacement of building materials take place during the building's construction. Thirdly, in the usage stage, energy consumption and renovation of construction materials occur for the two buildings. The energy consumption of factory buildings mainly originates from heating, domestic hot water, lighting, elevators, product production, ventilation, and air conditioning (HVAC), etc. Moreover, as the two buildings have different structures and are factory buildings, they consume significantly more energy than other buildings. Due to the limitations of the collected dataset, the building's carbon sequestration process was not included in the full-life-cycle carbon sink calculation. The carbon emissions in the end-of-life phase encompass energy consumption, material landfilling, and recycling.

2.3 Data set sources and data limitations

The carbon emission data of the cases in this study are based on cost-list analysis and database analysis (Supplementary Material 1). The data in the material production phase and the construction phase mainly rely on the cost-list analysis of the two buildings. The advantage is that a complete and detailed list of materials and energy consumption can be obtained, including the types of construction materials, engineering equipment, and electricity and water consumption. In the use stage, carbon emissions are accounted for according to a 50-year life cycle, including the electricity consumption system and the heat consumption system. The data for this stage were calculated based on the electricity consumption of the two buildings and the heat consumption per square meter of the building. The coefficient of heat consumption (i.e., e_i) is determined according to [17]. It is worth mentioning that the calculation of heat consumption does not include unheated basements, such as the basement of the BHIP building. In the end-of-life phase, the disposal processes of all waste materials should be considered, including recycling or landfilling. The equipment energy consumption in the end – of – life phase was calculated according to that in the construction phase. In the LCA of the two buildings, the actual engineering situation is complex, and the data sources and analysis methods have limitations. For example, labor costs, energy consumption data, and data collection are all restricted. The inaccuracies in data quality in this study mainly encompass the following aspects: (1) This study obtained detailed construction-material consumption and transportation-equipment consumption based on the construction cost lists of the two buildings. However, in the actual calculation, some materials were treated as cut-offs following the IPCC guidelines because there was no clear consumption quantity and carbon-emission factor for reference. Specifically, data sets with materials accounting for less than 0.1% of the total and without a queryable emission factor were not considered. In total, the materials excluded from consideration should not exceed 5% of the total material consumption. (2) Due to collection limitations, this study did not obtain data related to the carbon sinks of the two buildings, such as green space, green-energy supply, and solar-power efficiency. (3) The majority of the data in this research was sourced from field survey data. The error was primarily attributed to the discrepancy between the system boundary and the time boundary of the study. Moreover, due to database update restrictions, the carbon emission data for some materials or unit processes may not be accurate.

2.4 Carbon emissions calculation method

The carbon emissions of two factory buildings during various phases were calculated according to the standard method [25] and the methods of Andersen et al. [17].

2.4.1 Product stage

The carbon emissions in the product stage are computed following GBT 51366-2019, and the calculation methods are as follows:

$$C_{JC} = \frac{C_{SC} + C_{ys}}{A} \tag{1}$$

where the C_{JC} denotes the carbon emissions in the production and transportation phase of building materials, with the unit of (kg CO_2 e/m^2); C_{SC} represents the carbon emissions in the production phase, with the unit of (kg CO_2 e), calculated according to equation (2); C_{ys} represents the carbon emissions during the transportation stage, with the unit of (kg CO_2 e), calculated according to equation (3); A is the floor area (m^2).

$$C_{SC} = \sum_{i=1}^{n} M_i F_i \tag{2}$$

where the C_{SC} denotes the carbon emissions in the production stage, with the unit (kg CO_2 e); F_i is the carbon emission factor of the ith type of building materials, expressed as (kg CO_2 e /unit building material);M_i is the consumption of the ith type of building materials (t).

$$C_{ys} = \sum_{i=1}^{n} M_i D_i T_{i.} \tag{3}$$

Here, the C_{ys} denotes the carbon emissions during the building materials transportation stage, with the unit (kg CO_2 e); M_i denotes the consumption of the ith type of building materials (t); D_i stands for the transportation distance of the ith type of building materials, in kilometers, (km); T_i is the carbon emission factor of the transport distance per unit weight under the transport mode of the ith type of building materials, expressed as (kg CO_2 e/(t · km)).

It should be noted that the building materials predominantly utilized in the two cases account for over 95% of the total building materials consumption. Additionally, some building materials (weight $< 0.1\%$) are not taken into account.

2.4.2 Construction stage

The carbon emissions are computed following equation (4):

$$C_{JZ} = \frac{\sum_{i=1}^{n} E_{jz,i} EF_i}{A}. \tag{4}$$

Here, represents the carbon emission per unit of floor area during the construction stage, with the unit (kg CO_2 e/m^2); $E_{jz,i}$ denotes the total energy consumption of the ith type of energy, with the unit (kWh or kg);EF_i is the carbon-emission factor of the ith energy source during the building construction stage. A stands for the floor area, with the unit (m^2).

2.4.3 Use stage

The calculation of carbon emission includes domestic hot water, lighting elevators, and HVAC etc. The carbon emissions were computed according to the service life of 50 years. In the use stage, basements are considered to be free of thermal energy carbon emissions when calculating the BHIP building carbon emissions. Following equations (5)–(7), the carbon emissions in the use stage are computed as follows:

$$C_M = \frac{C_r + Q_{rp}}{A} \tag{5}$$

$$C_r = c_i \sum_{i=1}^{n} E_i \tag{6}$$

$$Q_c = c_i e_i \sum_{i=1}^{n} Q_i. \tag{7}$$

Here, theC_M represents the carbon emission per unit building area in the building's operation, with the unit (kg CO_2 /m^2);C_r denotes the energy consumption of the building during the use stage, (kg CO_2). Q_c is the thermal energy consumption of the building during the use stage, (kg CO_2); A stands for the floor area (m^2); c_i is the carbon-emission factor of electric energy, which is 0.5217 (kg CO_2/kWh) in this study. E_i represents the power consumption of the equipment during the use stage, with the unit (kWh); e_i is the carbon emission factor of heating energy, 63.9 (kWh/m^2) according to Andersen et al. [17]; Q_i denotes the total area of the building that consumes heat (m^2).

2.4.4 End-of-life stage

The carbon emissions in this stage are calculated according to equation (8):

$$C_{CC} = \frac{E_{cc,i} + M_i}{A}. \tag{8}$$

Here, C_{CC} represents the carbon emission per unit building area at the end-of-life stage (kg CO_2 e /m^2); denotes the total consumption of the ith class of energy at the end-of-life stage (kWh or kg);M_i is the carbon emission from material landfill; the material landfill and recycling ratio can be found in Table S1 of the Supplementary Material 1; A is the floor area (m^2).

$$E_{cc} = (\sum_{i=1}^{n} f_{cc,i} * EF_i). \tag{9}$$

Table 1. The carbon emission factor of each component in this study.

Components	Carbon emission factor	Unite	Components	Carbon emission factor	Unite
Electricity	0.5217	Kg CO_2/kWh	Steel	2050	Kg CO_2/t
Gasoline	67.91	t CO_2/TJ	Cement	735	Kg CO_2/m^3
Diesel oil	72.59	t CO_2/TJ	Iron	2280	Kg CO_2/t
Water	0.168	Kg CO_2/m^3	Stone	2.18	Kg CO_2/m^3
Concrete	295	Kg CO_2/m^3			

Here, E_{cc} represents the total consumption of the ith class of energy in the end-of-life stage, with the unit (kWh or kg); $f_{CC,i}$ denotes the energy-consumption factor of the ith demolition project, (kWh /engineering unit). It was defined as 10% of the energy consumption during the construction stage. EF_i is the carbon emission factor.

2.5 Data statistics and sensitivity analysis

The life-cycle carbon footprint of the two factory buildings encompasses numerous aspects of materials and energy consumption. The carbon emission factor of each component in this study is shown in Table 1. Additionally, it has been confirmed that carbon emission factors fluctuate throughout the life cycle. Therefore, conducting a sensitivity analysis of the carbon emission sources is of great significance. The sensitivity analysis was carried out using the method proposed by Yao et al. [26]. The data of the sensitivity analysis are shown in Table S2 (Supplementary material 2). The software IBM SPSS Statistics (version 27.0) was employed to perform statistical analyses on the data. A p-value of less than 0.05 and 0.01 was regarded as significant and highly significant, respectively. Software Origin 9.0 was used for drawing.

3 Results

3.1 Building carbon emissions intensity

The results of the carbon emission analysis for the two building cases are presented in Figure 3. For building BHIP (the concrete building), the total carbon emission amounts to 2244.7 kg CO_2/m^2. Specifically, the production stage contributes 518.1 kg CO_2/m^2, the construction stage 11.4 kg CO_2/m^2, the use stage 1714.2 kg CO_2/m^2, and the end-of-life stage 1.3 kg CO_2/m^2. This reveals that the carbon emissions of building BHIP are predominantly concentrated in the material production and use stages, accounting for 23.1% and 76.4% respectively (Fig. 3c). As depicted in Figure 3a, for building ZSBT (the steel building), the total carbon emission is 2051.3 kg CO_2/m^2. The production stage emits 269.1 kg CO_2/m^2, the construction stage 5.6 kg CO_2/m^2, the use stage 1776.0 kg CO_2/m^2, and the end stage 0.56 kg CO_2/m^2. As shown in Figure 3d, the life-cycle carbon emissions of building ZSBT are mainly centered on the material production and use stages, with proportions of 13.1% and 86.6%, respectively. The results indicated that both buildings were markedly higher during the use phase compared to other stages. This may be because two factory buildings consume a lot of electricity to maintain production or factory activities in the use stage. For instance, the main function of the ZSBT building is for the slaughter of poultry and livestock, which causes electricity consumption during the use stage. The results further demonstrated that despite the difference in the main structures of the two factory buildings, their total life-cycle carbon emissions were comparable. Moreover, carbon emissions from the material production stage and the usage stage account for the highest proportion. The findings aligned with the study conducted by Wu et al. [6]. According to Wu et al. [6], the carbon emissions of office buildings primarily stem from the operation stage (i.e., the use stage) and the material production stage. Seyedabadi et al. [13] evaluated and compared the carbon footprints of two buildings, one designed with steel frames and the other with concrete frames, according to the structural design codes of the European Union (EC), USA (ACI, AISC), Canada (CSA), and Australia (AS). The results indicated that the carbon emissions of the steel-structured building were 119–142 kgCO_2-eq/m^2 floor area, while those of the concrete-structured building were 134–221 kgCO_2-eq/m^2 floor area. In this study, the carbon emissions of the two factory buildings are significantly higher than those in the research according to Seyedabadi et al. [13]. The possible reason is that in developed countries, the use of green power grids during the building operation stage leads to a reduction in carbon emissions. This result further indicated that increasing the proportion of green power use can significantly reduce the carbon − emission intensity of buildings in China during the use stage. Additionally, residential buildings have also been identified as a significant source of carbon emissions during the use stage [22]. For example, Yao et al. [26] reported that the carbon emissions of residential buildings in the use stage reached 145,620 t, accounting for approximately 93.6% of the total carbon emissions. The contribution of different energy sources to the life-cycle carbon emissions of the two buildings is illustrated in Figure 3b. The results indicate that the carbon emissions of both buildings mainly originated from electricity consumption and heating. The carbon emissions from electricity accounted for 48.2% and 54.3% of the total carbon emissions (Figs. 3e and 3f), respectively. The carbon emissions from heating accounted for 28.6% and 32.5% (Figs. 3e and 3f),

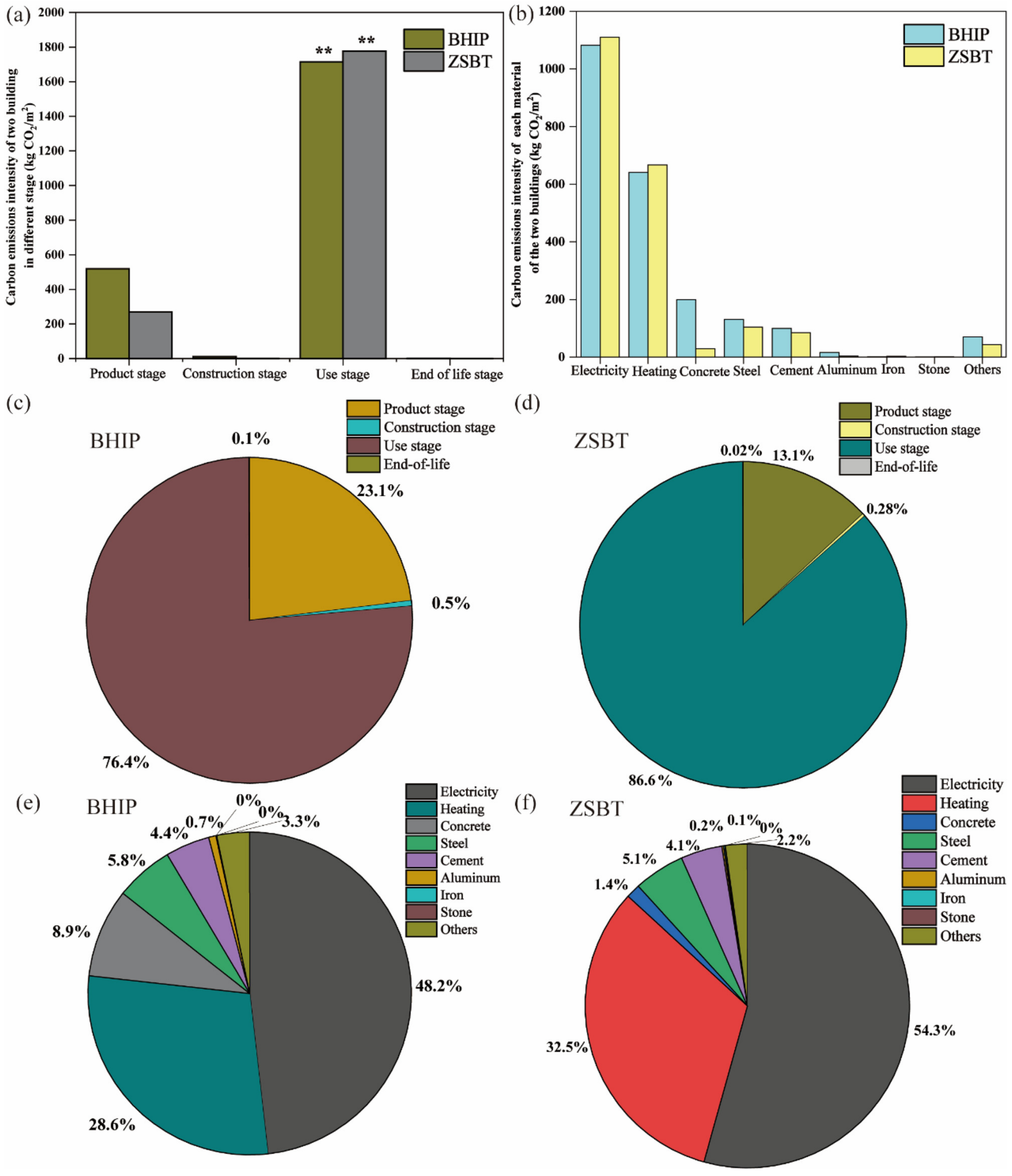

Fig. 3. The carbon emission intensity of BHIP and ZSBT buildings at different stages of the life cycle and different materials. (a) The carbon emission intensity of BHIP and ZSBT buildings at different stages of the life cycle, (kg CO_2/m^2); (b) The carbon emission intensity of different materials of BHIP and ZSBT buildings, (kg CO_2/m^2); (c) The ratio of carbon emission intensity of BHIP building in different stages; (d) The ratio of carbon emission intensity of ZSBT building in different stages; (e) The ratio of carbon emission intensity of BHIP building materials; (f) The ratio of carbon emission intensity of ZSBT building materials. Note: * means a significant level, and ** means an extremely significant level.

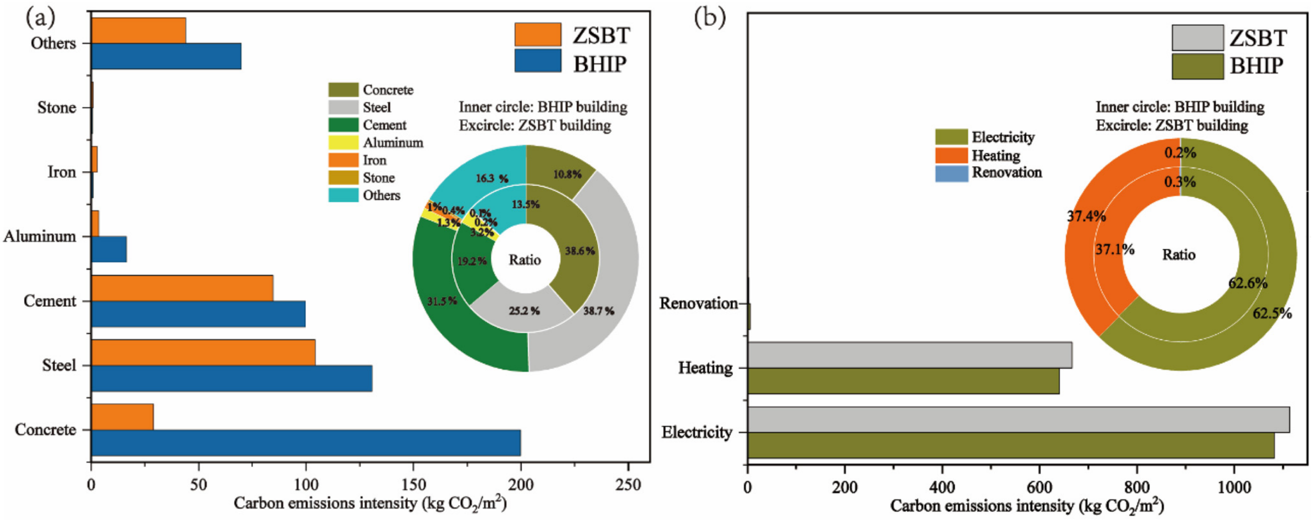

Fig. 4. The carbon emission intensity of BHIP and ZSBT buildings in product stage (a) and use stage (b).

respectively. Additionally, the carbon emissions from concrete accounted for 8.9% of the BHIP buildings. The carbon emissions from steel accounted for 5.1% of the total carbon emissions of the ZSBT building. It is noteworthy that the BHIP building is a concrete-based structure, and the carbon emissions from steel were approximately 130.7 kg/m^2, accounting for about 5.8% (Fig. 3e). This revealed that the carbon emissions from steel in concrete buildings should not be overlooked. Meanwhile, the ZSBT building is a steel-framed structure, and the carbon emissions from steel were approximately 104.2 kg/m^2, accounting for about 5.1%. Intriguingly, the carbon emissions from steel in concrete buildings were higher than those in steel-structured buildings. According to the carbon emission accounting checklist, it was discovered that although the BHIP building is concrete-based, a large number of bolts, steel pipes, and steel-structure railings might be utilized during the construction process. The high carbon emissions associated with steel in the concrete factory building BHIP are notable. This may be attributed to the use of steel structural components. Furthermore, carbon emissions from other materials are also shown in Figure 3. The use of cement and aluminum is also a significant source of carbon emissions in both buildings.

3.2 Building carbon emission analysis for each sub-stage

3.2.1 The product stage and use stage

The production stage and the use stage are the primary sources of carbon emissions for the two factory buildings. Consequently, analyzing the composition of carbon-emission sources in these two stages is of great significance. The results of the two buildings during the production stage are presented in Figure 4a. During the production stage, concrete, steel, and cement were the major carbon-emission sources for both buildings. For the BHIP building, concrete was the main contributor to carbon emissions. The carbon emissions from the concrete of the BHIP buildings amounted to 199.9 kg CO_2/m^2, accounting for 38.6%. The carbon emissions from steel, cement, and aluminum in the production stage of BHIP buildings were 130.7, 99.7, and 16.3 kg CO_2/m^2, respectively, accounting for 25.2%, 19.2%, and 3.2% of the total carbon emissions. Additionally, as depicted in Figure 4, steel was the main source in the production stage of ZSBT buildings. The carbon emissions from the steel of ZSBT buildings were 104.2 kg CO_2/m^2, constituting 38.7% of the total carbon emissions. The carbon emissions from cement, concrete, and aluminum in the production stage of ZSBT buildings were 84.7 kg CO_2/m^2, 29.0 kg CO_2/m^2, and 3.5 kg CO_2/m^2, accounting for 31.4%, 10.8%, and 1.3% of the total carbon emissions. This indicates that due to their different structures, the two buildings have distinct major sources of carbon emissions. The carbon emissions of the two buildings during the use stage are depicted in Figure 4b. In this stage, the sources of carbon emissions include electricity, heating, and material renovation. As illustrated in Figure 4b, heating and electricity consumption are the dominant sources of carbon emissions. The carbon-emission intensities from electricity and heating in BHIP buildings are 1073.2 and 640.9 kg CO_2/m^2, accounting for 62.6% and 37.1% of the total. Similarly, the carbon-emission intensities from electricity and heating in ZSBT buildings are 1109.3 and 666.7 kg CO_2/m^2, also accounting for 62.6% and 37.1% of the total.

3.2.2 The construction stage and end-of-life stage

The carbon emission intensities of the construction stage and end-of-life stage of the buildings are presented in Table 2. During the construction stage, the primary sources of carbon emissions include oil consumption, electricity, water, and waste gas. As depicted in Table 2, the carbon emission intensities of BHIP buildings resulting from electricity and oil consumption were 7.88 and 3.45 kg CO_2/m^2, accounting for 69.4% and 30.4% of the total in this stage. The carbon emissions from waste gas and water consumption were merely 0.01 and 0.014 kg CO_2/m^2. Furthermore, the carbon emission intensity of ZSBT buildings generated by electricity and oil consumption

Table 2. Carbon emission intensity in the construction stage and the end-of-life stage.

Stage	Component	Building	Carbon intensity (kg CO_2/m^2)
Construction stage	Electricity	BHIP	7.88
		ZSBT	3.9
	Waste gas	BHIP	0.009
		ZSBT	0.35
	Gasoline and diesel oil	BHIP	3.45
		ZSBT	1.36
	Water	BHIP	0.014
		ZSBT	0.09
End-of-life stage	Landfill, recycling	BHIP	1.14
		ZSBT	0.56

Note: The ratio of landfill and recycling was detailed in supplementary material 1.

was 3.9 and 1.36 kg CO_2/m^2, accounting for 69.3% and 24.2%, respectively. In the construction stage, much equipment derived from oil or electricity was used, and this served as the primary source of carbon emissions. The machinery data of the BHIP building and ZSBT building were summarized in Tables 3 and 4. In the construction stage, the main mechanical equipment energy type of the BHIP building is diesel oil, while the mechanical equipment type of the ZSBT building is mainly electricity. During the end-of-life stage, carbon emissions are predominantly calculated according to the proportion of waste and reuse of various materials [17]. As presented in Table 2, the carbon emission intensities of BHIP buildings and ZSBT buildings was 1.36 kg CO_2/m^2 and 0.56 kg CO_2/m^2, respectively. There were significant differences in carbon emission intensity between the two types of factory buildings during both their construction phase and end-of-life stage. It may be that concrete buildings in the construction stage need to use a lot of car transport and concrete mixing equipment. These devices are generally high in fuel and electricity consumption. Therefore, the carbon emission intensity of concrete buildings is markedly higher than that of steel-structured buildings. In the end-of-life stage, steel-structured buildings have a higher rate of material recycling compared to concrete buildings.

3.3 Building life cycle sensitivity analysis and environmental impact assessment

Building life cycle sensitivity analysis holds paramount significance in identifying key carbon emission factors and appraising carbon emission reduction strategies. As depicted in Figure 3, the main sources of carbon emissions from the two buildings are electricity, heating, concrete, steel, and cement. Therefore, according to the method of Yao et al. [26], the impact factors of the main carbon emission sources were increased by 20% and 10% and decreased by 10% and 20%. The carbon emission intensity accounting results of the two buildings after the adjustment of carbon emission factors are presented in Table 3. The baseline carbon emission values of the two buildings are 2244.7 kg CO_2/m^2 for concrete buildings and 2051.3 kg CO_2/m^2 for steel buildings. As illustrated in Figure 5, the results demonstrate that the electricity carbon emissions factor is the most sensitive. Thus, electricity consumption has the most significant emission reduction potential and is a key factor in residential buildings. Moreover, the heating carbon emission factor also significantly influences the total carbon emissions of the building. Hence, during the entire life cycle of the two buildings, measures aimed at reducing carbon emissions from heating should also be taken into consideration.

4 Discussion

4.1 Building carbon emissions and carbon reduction strategy analysis

This study evaluated the carbon emission fluxes of two factory buildings with different structures, including concrete buildings (BHIP) and steel buildings (ZSBT). The evaluation results showed that the life cycle carbon emissions of concrete structures and steel structures are 2244.7 and 2051.3 kg CO_2/m^2, respectively. This indicated that the life cycle carbon emission flux of factory buildings with two different structures was similar. In this study, it was found that the carbon emissions of the two factory buildings predominantly stem from the production stage and the use stage. During the product stage, the carbon emission intensity of BHIP buildings and ZSBT buildings was approximately 518.1 and 269.1 kg CO_2/m^2, accounting for 23.1% and 13.1%, respectively. The results demonstrated that the carbon emissions of BHIP buildings were significantly higher than those of ZSBT buildings in the production stage. Further analysis of the carbon emission composition of the production stage showed that the main carbon emission materials in the production stage include concrete, steel, cement, aluminum, and stone (Fig. 3). Moreover, the carbon emission intensity of concrete in the BHIP building was 199.9 kg CO_2/m^2, accounting for about 38.6%. As the most extensively utilized material in

Table 3. The machinery data in the construction stage of the BHIP building.

Machinery	Energy	Machine-team (no.)	Energy consumption (kg or kWh /team)
Crawler type single bucket excavator ($1.25\,\mathrm{m}^3$)	Diesel oil	122.782	63
Crawler hydraulic excavator (BY-VH350)	Diesel oil	100.265	63
Diesel rail pile driver (3.5 t)	Diesel oil	150.528	56.9
Percussion drill (Type 22)	Electricity	790.417	40
Mortar mixer (200L)	Electricity	832.521	8.61
Truck (6t)	Diesel oil	551.888	33.24
Truck (8t)	Diesel oil	71.77	35.49
Truck (10t)	Diesel oil	4.0	46.27
Truck (15t)	Diesel oil	56.259	56.74
Dump truck (15 t)	Diesel oil	401.748	52.93
Dump truck (4 t)	Gasoline	1.129	38.38
Crawler crane (25 t)	Diesel oil	150.528	36.98
Bar bending machine (d: 40mm)	Electricity	953.531	12.8
Dc arc welding machine ($32\mathrm{kV}\cdot\mathrm{A}$)	Electricity	1134.921	96.53

Note: Energy carbon dioxide emission factors refer to Table 1.

Table 4. The machinery data in the construction stage of the ZSBT building.

Machinery	Energy	Machine-team (no.)	Energy consumption (kg or kWh /team)
Electric tamper (20–62 N m)	Electricity	273.552	16.6
Electric air compressor ($10\,\mathrm{m}^3$/min)	Electricity	145.727	403.2
Sand blasting machine ($3\,\mathrm{m}^3$/min)	Electricity	139.192	28.41
Mortar mixer (200L)	Electricity	31.011	8.61
Ac arc welding machine (21 kVA)	Electricity	24.968	147
Dump truck (15t)	Diesel oil	24.006	52.93
Ac arc welding machine (32kVA)	Electricity	20.374	96.53
Truck (6 t)	Diesel oil	17.049	33.24
Track flat car (10 t)	Diesel oil	20.338	6.03
Truck crane (25 t)	Diesel oil	15.021	38.41
Truck crane (8 t)	Diesel oil	10.357	28.34
Electric air compressor ($1\,\mathrm{m}^3$/min)	Electricity	8.198	40.3
Truck (4 t)	Gasoline	0.05	31.34
Fork crane (5 t)	Gasoline	0.2	26.46

Note: Energy carbon dioxide emission factors refer to Table 1.

construction, concrete has the advantages of low cost, good durability, and easy shaping [13,27]. Therefore, for BHIP buildings, the carbon reduction of concrete is particularly important. The utilization of cement and aggregate can mitigate the environmental impact caused by the heavy use of concrete [26,28]. Furthermore, the adoption of new manufacturing processes and green alternative technologies in the production process of concrete is also very necessary for its carbon reduction [29]. The results further indicated that steel was heavily used in building the BHIP and ZSBT buildings (Fig. 3). The carbon emission intensity of steel in the BHIP and ZSBT buildings was 130.8 and 104.2 kg CO_2/m^2, accounting for 25.2% and 38.7%, respectively. The results indicated that the carbon emissions stemming from the use of steel should not be ignored for concrete factory buildings. It is reported that steel is widely used in construction, and the steel demand will double in the next 37 years. Furthermore, carbon emissions resulting from steel consumption constitute 9% of the world's total carbon dioxide emissions [30]. Currently, the strategy for carbon reduction of steel in buildings is mainly focused on the reduction or replacement

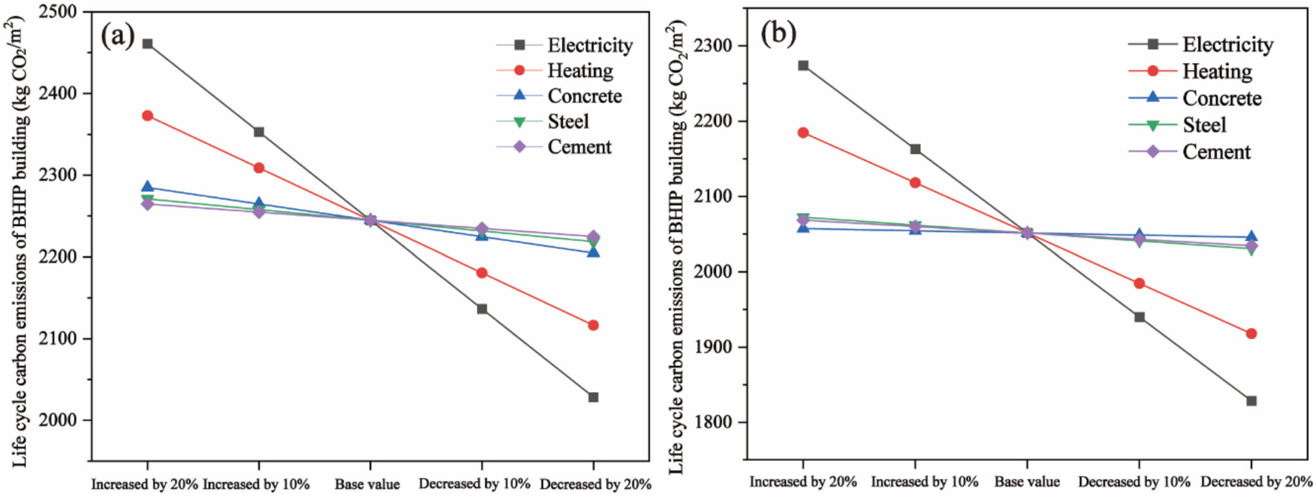

Fig. 5. Sensitivity analysis chart of different carbon emission factors, including electricity, heating, concrete, steel, and cement. (a) BHIP building; (b) ZSBT building.

of steel [13]. For instance, material savings of 30–40% in steel construction have proved to be feasible [31]. Similarly, the potential to reduce steel by nearly half in steel-framed buildings has also been reported without compromising safety [22]. Besides, for buildings with steel structures and precast concrete structures, changes in structural components alone can lead to a 200-350 change [13]. In the use stage, the carbon emission intensities of the BHIP building and ZSBT building were 1714.2 and 1776.0 kg CO_2/m^2, accounting for 62.6% and 62.5% of the carbon emissions, respectively. The results demonstrated that electricity and heating were the primary sources of carbon emissions for both the BHIP and ZSBT buildings. Additionally, the sensitivity analysis revealed that the carbon-emission factors of electricity and heating were the most sensitive (Fig. 5). In China, thermal power generation constitutes the primary source of electricity [32]. The large consumption of electricity will not only bring serious carbon emissions but also lead to immeasurable environmental harm [33,34]. Currently, green energy is being rapidly developed and applied in China, including hydropower, wind power, and nuclear energy [35]. Moreover, the significant increase of green energy in the energy supply structure also contributes to the reduction of heating carbon emissions. Therefore, carbon emissions associated with electricity consumption in buildings will be significantly reduced in the future. Additionally, it has been reported that the utilization of energy-efficient appliances and green energy storage systems contributes to the carbon reduction of residential buildings [16,36]. Hence, this may also be a reasonable strategy for curbing carbon emissions in factory buildings.

4.2 Research constraints and prospects for future studies

This study not only assessed the life-cycle carbon emissions of two factory buildings with distinct structural designs but also proposed carbon emission reduction strategies based on the results of the sensitivity analysis. However, the complexity of building carbon emission accounting leads to the limitations of this study. Firstly, the data list during the production phase and the construction phase was mainly based on the cost list of the two buildings. The advantage of this is that the materials and equipment could be more detailed. However, in the actual accounting process, the material is too fine, the carbon emission factor cannot be completely matched with the equipment or material. Therefore, in the accounting process, we ignored the materials with less use and less impact according to the cut-off rule. It should be noted that the completeness of carbon-emission accounting data significantly influences the accuracy of carbon-emission accounting results. Therefore, to enhance the accuracy of building carbon-emission accounting, more detailed data collection regarding building carbon emissions should be carried out. Additionally, carbon-emission factors vary significantly among different countries and cities. When conducting building carbon – emission accounting, the differences between countries and regions should also be taken into consideration. Furthermore, during the calculation process, the carbon emissions of certain materials are replaced by the raw materials used in manufacturing. For instance, the carbon emission factor of steel was used to substitute the carbon emission factor of galvanized steel pipe in this study. To a certain extent, this will ensure the truth of the data and the integrity of the accounting list materials. However, it will inevitably lead to carbon emissions that do not match the actual results. Besides, the study allocated 60% of the carbon emissions from heating sources to electricity in the use stage. There may be some error in the actual heating energy consumption. The two factory buildings selected in this study are located in Fujian Province, southern China. Southern China needs heating for a short time in winter, and electric heating (air conditioning, etc.) is the most important source of heating. Based on this, 60% of the electric heating distribution may be much lower than the actual electricity consumption. Therefore, an increase in electricity consumption in factory buildings will raise carbon emissions. Hence, more strategies ought to be implemented to regulate the carbon emissions from building electricity consumption. Besides, there are significant climatic differences between the northern and southern regions of China. For instance, the temperature in southern regions remains relatively high throughout the year, while in the north, it is extremely cold in winter. This leads to differences in the energy utilization structures of factories in northern and southern China. In the south, factory electricity consumption is mainly for summer cooling and industrial production. In the north, however, coal-burning is often used for winter heating instead of relying on a large amount of thermal energy supply. As a result, electricity consumption in northern regions is likely to be more focused on industrial product manufacturing. Therefore, the conclusions of this study can be somewhat helpful for evaluating the carbon emissions of factories in southern China, but further research may be required when applying these findings to the northern regions. Moreover, due to the lack of facility information regarding the greening of the two buildings or their carbon sinks, this study did not take into account the impact of the carbon sink when calculating the life-cycle carbon emissions of the two buildings. Finally, the impact of electrical appliances on the environment is ignored in the carbon emission impact analysis. With the Chinese government's attention to climate change, especially the proposal of the two-carbon strategy, the proportion of green energy supply in China will be greatly increased in the future [7]. Existing thermal power generation will gradually be supplanted by hydropower and solar power [37]. Consequently, carbon emissions from building electricity consumption will be significantly diminished [1]. In addition, as a coastal province in China, the use of marine energy will also be a key strategy for building carbon reduction [38]. For instance, ocean heat conversion technology and ocean electricity conversion technology will be the main sources of building heat and electricity in coastal provinces in the future [39]. Ocean energy conversion technology can provide large amounts of electricity to coastal communities, significantly reducing operational carbon emissions [40]. The utilization of marine energy systems will significantly contribute to the green and low-carbon development of China's coastal buildings, and may even enable these buildings to achieve the "zero-carbon" goal [41,42]. The advancement of new energy distribution and management technologies is also crucial to the future carbon reduction of buildings. In conclusion, as an important source of carbon emissions, the emissions and potential impacts of buildings cannot be ignored. The main development direction in the future is to adopt various technologies and strategies to achieve carbon emission reduction in buildings.

5 Conclusion

In this study, the Life Cycle Assessment was conducted to evaluate the carbon emissions of steel and concrete-based factory buildings. The results indicated that the carbon emission intensity of concrete structure building and steel structure building were 2244.7 and 2051.3 kg CO_2/m^2, respectively. Analysis of carbon emissions across different stages revealed that the carbon emissions of the two buildings predominantly stem from the production stage and the use stage. The carbon emission intensity of concrete structure building and steel structure building in the use stage was 1714.2 and 1776.0 kg CO_2/m^2. The sensitivity analysis results showed that electricity and heating are the most sensitive carbon emission factors and have the most significant emission reduction potential.

Funding

This research was supported by the Natural Science Foundation of Jiangsu Province (No. BK20220682).

Conflicts of interest

The authors have nothing to disclose.

Data availability statement

The authors declare that the primary data supporting the conclusions of this paper are available in the text.

Author contribution statement

Conceptualization X.Y. and J.R.; Methodology, Y.C.; Software X.Y.; Investigation, Q.Z.; Formal Analysis, Y.C.; Resources X.Y.; Data Curation X.Y.; Writing – Original Draft Preparation, X.Y.; and J.R. Funding Acquisition J.R.

Supplementary materials

The Supplementary Material including supplementary material 1 and supplementary material 2.

Table S1. The material landfill and recycling ratio of two commercial buildings at the end-of-life.

Table S2. Sensitivity analysis of main carbon emission factors (kg CO_2/m^2).

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Cite this article as: X. Yu, Y. Cai, Q. Zhu and J. Ren: Life cycle assessment of carbon emissions in steel and concrete factory buildings*. Sust. Build. **8**, 7 (2025). https://doi.org/10.1051/sbuild/2025005