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Establishing industry-based benchmarks for embodied carbon in buildings: A statistical analysis of 85 case studies in China

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ABSTRACT

This research presents a comprehensive statistical analysis of embodied carbon intensities across 85 diverse building projects in China, encompassing residential, prefabricated, factory, office, school, medical, and villa buildings. The analysis evaluates the contributions of concrete, steel reinforcement, and concrete blocks, which collectively dominate the structural carbon footprint, with a focus on the material production phase within a cradle-to-gate boundary. The results reveal significant variations in embodied carbon intensities, ranging from 199.9 to 339.5 kg CO_2e/m^2 across building types, with high-rise office buildings exhibiting the highest intensities. Concrete and steel reinforcement collectively account for up to 90 % of emissions, highlighting critical material hotspots. Additionally, the study quantifies the substantial carbon impact of basements and formworks—often overlooked in carbon assessments—finding that basement emissions can constitute up to 70 % of total embodied carbon. By establishing statistical benchmarks and identifying key drivers, this study proposes the application pathway for these benchmarks in low-carbon building practices, providing a robust foundation for developing targeted carbon reduction strategies in building design and construction. The findings offer essential insights for policymakers, designers, and industry stakeholders aiming to implement low-carbon building practices and support China's climate targets.

1. Introduction

The control of climate change has become a central focus worldwide in the pursuit of sustainable development [1]. The global agreement on climate change aims to significantly reduce global greenhouse gas emissions and limit the global temperature rise to within 1.5 °C–2 °C this century. Carbon dioxide (CO_2) is the most significant greenhouse gas in the atmosphere, accounting for approximately 97 % of the total global warming potential [2]. The primary sources of CO_2 emissions are cement production and the combustion of fossil fuels [3]. Consequently, 37 % of global CO_2 emissions are due to building use [4]. The CO_2 emissions caused by

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building use can be categorized into two aspects: embodied carbon and operational carbon [5]. Embodied carbon includes emissions generated during the production, transportation, on-site construction and disposal related to building materials [6]. Operational carbon refers to emissions produced by the equipment required to maintain the internal environment or functionality of a building during its operational phase [7]. Historically, operational carbon accounted for the majority of carbon emissions in the construction industry [8]. However, with growing awareness of energy conservation and the widespread adoption of low-carbon architecture design, operational carbon emissions have been effectively reduced [9–12]. In contrast, the proportion of embodied carbon emissions in buildings has gradually increased [13,14]. According to the research of Röck et al. [15], embodied carbon emissions account for ~20 %–25 % of life cycle carbon emissions. This value escalates to 45 %–50 % for highly energy-efficient buildings and surpasses 90 % in extreme cases.

The establishment of a calculation system and statistical benchmark for embodied carbon emissions in buildings based on life cycle assessment (LCA) has become an important research direction. Geographical regions such as Europe, Asia, North America, and Australia have accumulated rich knowledge in the field of embodied carbon studies [16–20]. Chastas et al. [21] collected 95 case studies of residential buildings from various countries. Their assessment of embodied carbon intensity, based on different system boundaries, ranged from 179.3 to 1050 kg CO_2e/m^2. Robati and Oldfield [22] evaluated the embodied carbon of mass timber and concrete buildings in Australia. They found that the embodied carbon intensities of mass timber and concrete buildings ranged from 196 to 590 kg CO_2e/m^2 and from 307 to 618 kg CO_2e/m^2, respectively. Parece et al. [23] evaluated two reinforced concrete structures for residential buildings in Portugal using BIM-based models. They found that the embodied carbon intensity was calculated to be 375 kg CO_2e/m^2 for the single residential building and 426 kg CO_2e/m^2 for the multi-residential building. Belizario-Silva et al. [24] evaluated the cradle-to-gate embodied carbon intensities of 53 reinforced concrete structures in Brazil. They found that the embodied carbon intensities related to material production ranged from 35 to 140 kg CO_2e/m^2. Although these studies provide references for establishing statistical benchmarks, the relatively limited number of cases and complex data backgrounds remain important factors contributing to significant dispersion and uncertainty in research results.

As the largest developing country, China's share of embodied carbon has reached nearly 43 % of the total carbon emissions in the construction industry [25]. The high embodied carbon emissions are primarily attributed to the shorter lifespan of buildings and the larger volume of materials used [26]. Zhang et al. [27] evaluated the embodied carbon intensity of 403 high-rise residential buildings in China using a cradle-to-gate system boundary. They found that the median values of embodied carbon related to structural materials production ranged from 258.8 to 282.3 kg CO_2e/m^2, with concrete and steel reinforcement accounting for 59.2 % and 20.1 % of the embodied carbon, respectively [28]. Guan et al. [29] evaluated 114 residential and public buildings in China, distinguishing the low-time variability component of embodied carbon emissions in buildings. They found that the embodied carbon during the material production stage ranged from 196.9 to 282.3 kg CO_2e/m^2. Luo et al. [30] assessed the cradle-to-site embodied carbon emissions of 78 office buildings in China and found that the embodied carbon intensities during the materialization stage ranged from 250 to 490 kg CO_2e/m^2, with over 80 % of the contribution coming from concrete, steel reinforcement, and wall materials. It is worth noting that although these studies are representative and provide strategies for carbon reduction in China's construction industry, they are mostly limited to specific building types or outdated datasets and ignore the contribution of basements and formworks to embodied carbon emissions, which may affect the accuracy and universality of the research results. The industry-based benchmarks related to building embodied carbon and their application pathways in low-carbon building practices remain unclear.

The above studies indicate that although embodied carbon intensity varies across different regions, selecting low-carbon materials and optimizing structural design can significantly reduce embodied carbon emissions [31–34]. It is crucial to establish embodied carbon benchmarks for buildings tailored to the development status of different countries [35,36]. Generally, the embodied carbon emissions generated during material production account for the majority of the embodied carbon emissions in buildings [37–39]. Therefore, it is of great significance to research the assessment of embodied carbon related to material production, especially for concrete and steel reinforcement. This study employs a process-based approach to calculate the embodied carbon intensities associated with material production across various building types. It should be emphasized that the research data is novel and reliable, provided by the domestic construction companies. Overall, the research content of the paper is presented as follows: First, the research scope, boundary decision, and calculation methods are introduced in Section 2. Second, the data collection is presented in Section 3. Third, the results of calculated embodied carbon intensities are analyzed in Section 4, and relevant discussions on embodied carbon benchmarks are suggested in Section 5. Finally, the conclusions and prospects of the research are clarified in Section 6. The novelty and contributions of this study are as follows: Firstly, the existing knowledge base was further enriched with collected data, and the impact of different building types and variables on embodied carbon was analyzed through formal statistical tests, which has certain reference value for further understanding the carbon emissions status of China's construction industry. Furthermore, this study quantified the embodied carbon contributions of basements and formworks, which are often overlooked in similar statistical studies, providing strategies for low-carbon application pathways of basements and formworks. Ultimately, this study established statistical benchmarks based on 85 different types of buildings and provided pathways for applying these benchmarks in low-carbon building practices to support China's carbon neutrality goals.

2. Methodology

2.1. Research scope

Embodied carbon in buildings generally encompasses the phases of material production, off-site transportation, on-site construction, building maintenance, and end-of-life [40]. It has been demonstrated that the cradle-to-gate phases, which include raw material supply, transportation, and manufacturing, are the primary contributors to embodied carbon in buildings [41,42]. Preliminary studies indicate that the production of building materials is the most significant factor, accounting for over 80 % of the embodied carbon emissions during the cradle-to-gate phases [43–47]. As shown in Fig. 1, this study focuses on the embodied carbon calculation of structural materials, mainly including concrete, steel reinforcement, and concrete blocks. Notably, the defined system boundary aligns with Stages A1 to A3 of the EN 15978: 2011 standard and falls within the cradle-to-gate phases [48]. Additionally, the embodied carbon emissions of basements and formwork were also considered.

2.2. Research method

The embodied carbon related to the production of building materials can be calculated using a process-based method [43]. The embodied carbon intensity of buildings within the system boundary of the cradle-to-gate phases in this study refers to the amount of carbon emitted per unit building area during the production process of building materials. For the assessment of embodied carbon emissions, the entire building and 1 m^2 building area are typically used to reflect the functional differences among various types of buildings. Since layouts and volumes may vary across buildings, this study adopts 1 m^2 of building area as the functional unit to ensure the comparability of embodied carbon emissions across different types of buildings. It is worth noting that the building area referred to here refers is the gross building area enclosed by the exterior walls of the building, including the total area of all floors. Therefore, the process-based embodied carbon intensity is described as:

$$ECI = \frac{ECQ}{A} = \frac{\Sigma(Q_i \times EF_i)}{A} \tag{1}$$

where ECI is the embodied carbon intensity (kg CO_2e/m^2), ECQ is the embodied carbon quantity (kg CO_2e), A is the total building area (m^2), Q_i is the quantity of material “i” (in the corresponding unit, for example, concrete in m^3 and steel in kg), EF_i is the carbon emission factor of material “i” (kg CO_2e/unit).

Moreover, considering that the building cases were collected in China, the carbon emission factors corresponding to local material production technology were consistent with the source of material consumption. Therefore, the emission factors provided in relevant standards were initially adopted, and data from relevant studies were considered for building materials not covered by those standards [49,50].

This study conducted statistical analysis, contribution analysis, significance analysis, and scenario analysis on the embodied carbon emissions. The statistical analysis of embodied carbon in buildings is based on the embodied carbon intensity of different building types. It includes statistical indicators such as the sample mean, median, standard deviation, and concentration interval. These indicators offer a comprehensive understanding of the statistical characteristics and help determine the industry-based benchmark for embodied carbon emissions in buildings. The contribution analysis identified the embodied carbon contributions of each building and material type across all collected buildings. The characteristics of embodied carbon driving factors were analyzed using the statistical indicators mentioned above. The scenario analysis explored the potential impact of basements and formworks on embodied carbon emissions. Finally, the study proposed carbon reduction strategies at different levels and through technical approaches, offering valuable insights for reducing embodied carbon emissions in building projects.

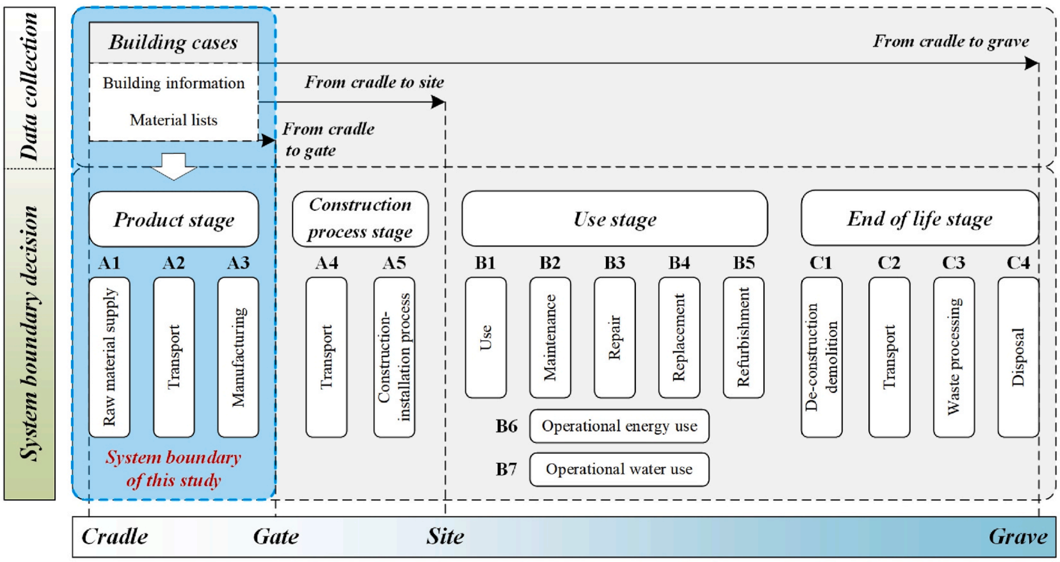

Fig. 1. System boundary of embodied carbon calculation.

3. Data collection

3.1. Overview of the collected building cases

As shown in Fig. 2a, this study compiled a dataset containing 85 different types of buildings in China, including 36 residential buildings, 13 prefabricated buildings, 9 factory buildings, 9 office buildings, 6 school buildings, 5 medical buildings, and 7 stacked villa buildings. The embodied carbon intensity of each building was calculated within a defined system boundary and statistical range.

The construction years of the collected buildings are illustrated in Fig. 2b. Buildings constructed within the past five years (2019–2023) account for 98 %, reflecting current architectural design concepts, material utilization, and construction techniques, which significantly impact building carbon emissions. Furthermore, with the growing awareness of sustainable development and environmental protection, new buildings are placing greater emphasis on energy conservation and carbon reduction in their structural design, material production, and subsequent construction processes. Evaluating the carbon emissions of these new buildings can help understand the latest progress and effectiveness of the construction industry in reducing carbon emissions. This provides a solid basis for estimating the embodied carbon emissions of local buildings. It is worth noting that the introduction of such young samples may potentially deviate from existing buildings with a wider stock in design concepts, material production, and construction techniques, thereby differentiating the characteristics of embodied carbon emissions. Moreover, although two office buildings were constructed in 2017, causing a skewed distribution of construction times, this does not significantly affect the accuracy of the research results. This is because buildings, especially high-rise buildings, often have longer construction periods and thus less significance in terms of time. Based on historical data statistics, the average lifespan of buildings in China is about 30–35 years, with high-rise buildings potentially having a longer service life [51,52].

The regional distribution of the collected building cases is shown in Fig. 2c. A total of 79 % of the projects originate from Hubei Province, with more than half concentrated in Wuhan City, while 16 % are from Jiangxi and 5 % from Guangdong. This concentration reflects the dominant role of Wuhan as a construction hub in central China but also introduces a potential regional bias. For

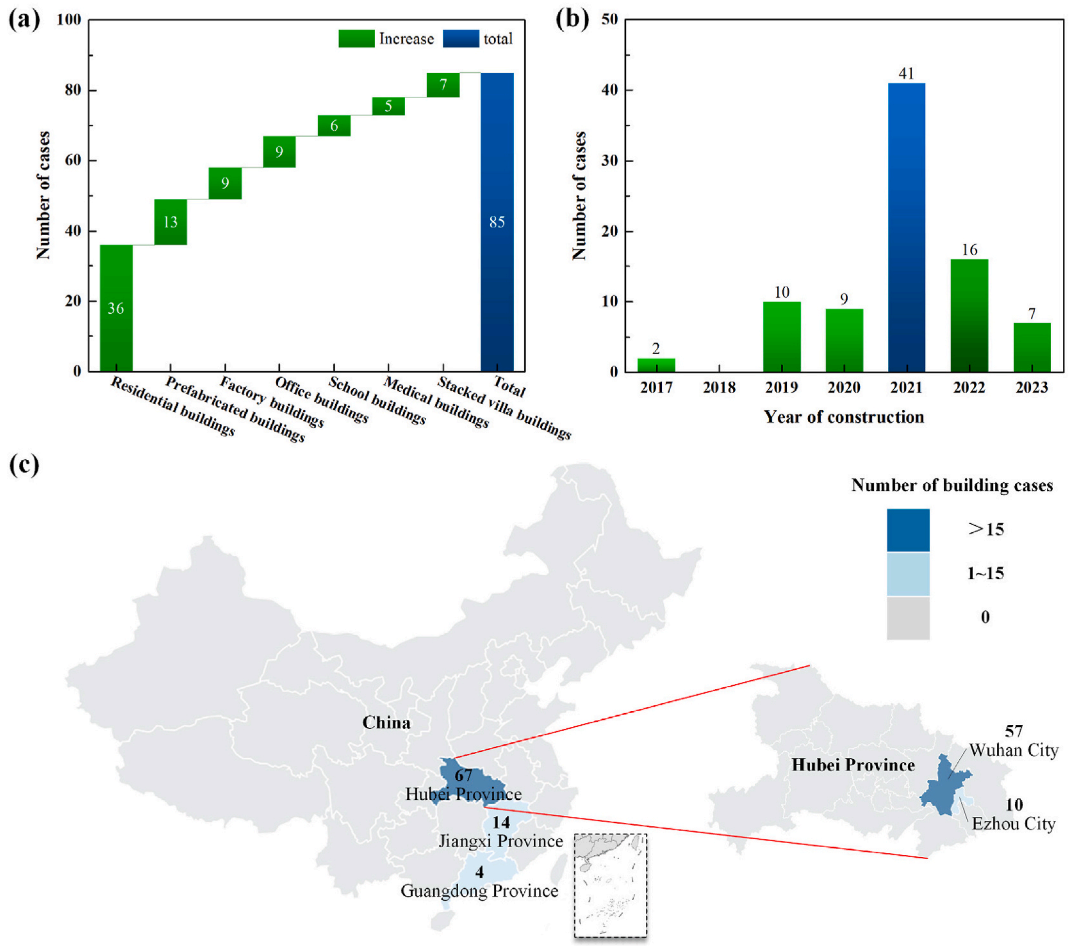

Fig. 2. Data collection of the 85 building cases in China: (a) building type, (b) year of construction, (c) regional distribution.

comparison, Wuhan alone accounts for nearly 9 % of the annual new floor area constructed in central China, which partly justifies its weight in the dataset. Nevertheless, building practices, climate conditions, and regulatory requirements differ substantially across China's provinces, which may limit the direct transferability of the results to northern or western regions. To contextualize applicability, it is important to note that the seismic fortification intensity of these cases (6–7°, GB/T 50011-2010 [53]) is representative of much of central and southern China, but not of coastal high-seismic or northern cold-climate regions [54]. Future benchmark development should therefore aim to expand the dataset geographically and validate whether the identified thresholds remain robust across other Chinese climatic and regulatory contexts.

3.2. Basic information on building features

Fig. 3a–c illustrate the building height, number of floors, and building area, respectively. It should be emphasized that different types of structures were adopted in the collected buildings. Structural type refers to the structural system adopted by a building when subjected to loads and transmitting forces, which determines the building's mechanical behavior, stability, seismic performance, and material usage. The collected residential buildings are high-rise structures, reaching heights of up to 100 m. These buildings typically utilize frame-shear wall structures (F-SWS) constructed with reinforced concrete. This structure is based on the frame structure (FS) and adds shear walls to improve the lateral stiffness and seismic performance of the structure. The height of prefabricated buildings generally ranges from 75 to 100 m. These buildings commonly consist of prefabricated frame-shear wall structures (PF-SWS). The structural forms of the factory buildings are mainly classified as FS and F-SWS. Office buildings, which have the highest average height among the collected buildings, reaching up to 150 m, typically adopt frame-core tube structures (F-CTS). This is a common form of high-rise building structure consisting of peripheral frames and a central core tube. This structural system effectively enhances the lateral stiffness of buildings in response to wind loads. School buildings and stacked villa buildings generally range in height from 15 to 20 m and commonly adopt FS. This structural system offers good flexibility and adaptability, making it suitable for a wide range of building forms. Medical buildings, depending on their height, consist of FS or F-SWS. Due to the special protection requirements in the radiation zones, medical buildings usually incorporate prestressed technology to prevent concrete cracking and reduce radiation penetration. It is worth noting that there is a strong positive correlation between building height, number of floors, and building area. The proportions of different structural types are shown in Fig. 3d, including 48 % F-SWS, 15 % PF-SWS, 26 % FS, and 11 % F-CTS.

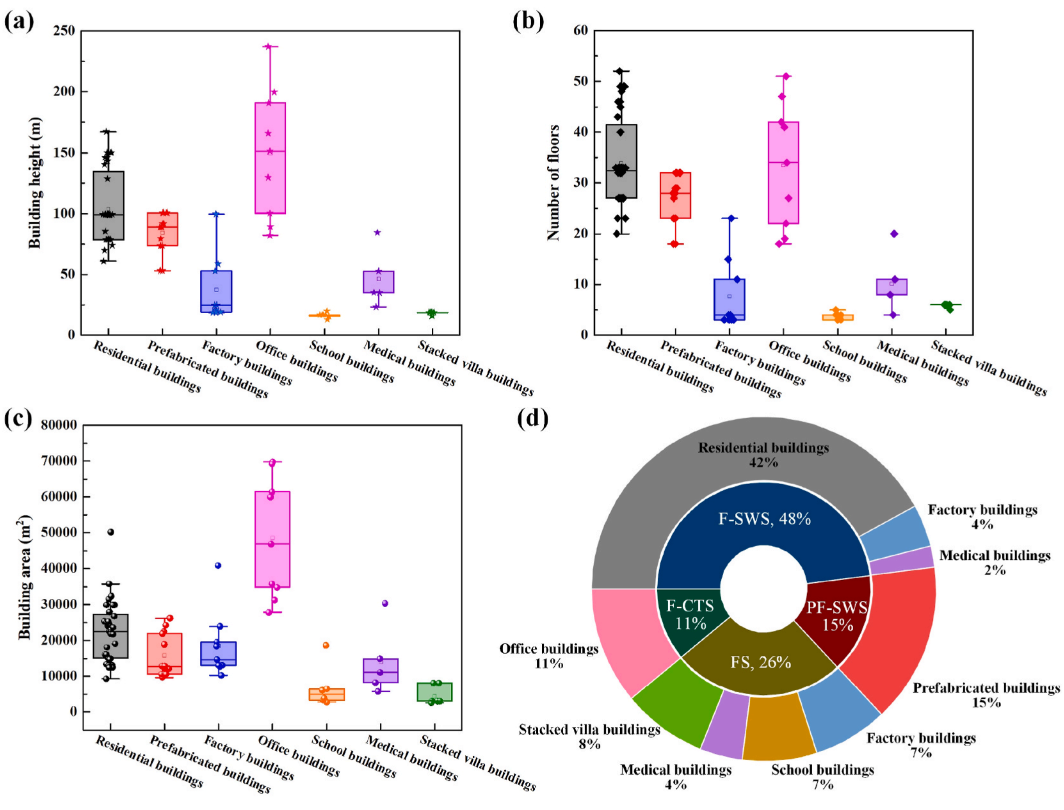

Fig. 3. Basic information of the collected buildings: (a) building height, (b) number of floors, (c) building area, (d) structure type.

3.3. Calculation of embodied carbon emissions

Data on the usage of structural materials for the 85 different types of buildings were collected. Given that concrete and steel reinforcement account for over 80 % of the embodied carbon associated with material production, this study focuses on commonly utilized structural materials: concrete, steel reinforcement, and concrete blocks. The embodied carbon emissions from the production of these materials are likely to represent almost entirely the embodied carbon emissions of the main structure during the cradle-to-gate phase. It should be emphasized that the basic information and material consumption for the collected building cases were derived from the design documents and bills of quantities supplied by domestic construction companies. The data is both novel and reliable, and the research findings can serve as a reference for establishing statistical benchmarks for embodied carbon emissions in buildings. In this study, the quantity of embodied carbon emissions corresponding carbon emission factor associated with material production. The embodied carbon intensity of buildings is calculated as the ratio of carbon emissions to building area, as defined in Eq. (1).

This study employs the carbon emission factor method, a widely recognized and commonly used approach for estimating carbon emissions. The reference ranges and values for carbon emission factors are based on the Chinese standard GB/T 51366-2019 [49]. Additionally, this study includes the carbon emission calculation for formwork. However, the carbon emission factor for formwork has not been incorporated into the carbon emission factor database in the Chinese standards. Consequently, the methods proposed by Zhang et al. [50] were employed to calculate the carbon emission factor. The collected carbon emission factors for building materials are presented in Table 1. Detailed information on the 85 collected building cases, including building height, building area, number of floors, and material usage, is provided in Table S1 (Supplementary material).

4. Results and analysis

4.1. Statistical analysis of embodied carbon emissions

Embodied carbon intensities are crucial indicators for evaluating the embodied carbon emissions in buildings. The embodied carbon intensities of different types of buildings related to structural material production are shown in Fig. 4a. These intensities can be calculated using Eq. (1), which represents the embodied carbon emissions per unit of building area. The average embodied carbon intensities of different types of buildings range from 199.9 to 339.5 kg CO_2e/m^2. The highest embodied carbon intensities were observed in office buildings, particularly those with greater heights and more floors. Compared to the building area, the performance-based design concept, represented by safety, has led to an increase in the amount of building materials used [20]. It is important to note that the higher carbon content in high-rise buildings is driven not only by safety performance but also by the construction and energy consumption associated with their structural complexity, which are significant factors contributing to high carbon emissions [55].

Additionally, the structural design requirements for seismic and radiation resistance in medical and school buildings lead to higher material usage and increased embodied carbon intensities. In contrast, residential buildings, prefabricated buildings, and stacked villa buildings exhibit lower embodied carbon intensities. Residential buildings often require fewer materials to construct larger building areas, driven by economic considerations. Prefabricated buildings, in particular, consume fewer materials due to the high precision in the production of prefabricated components, resulting in the lowest embodied carbon intensities. The embodied carbon emissions related to material production are illustrated in Fig. 4b. The highest embodied carbon emissions were observed in office buildings, consistent with the earlier analysis of embodied carbon intensities. Interestingly, while school and medical buildings have higher embodied carbon intensities, their embodied carbon emissions were lower. This can be attributed to the typically higher floor heights (around 4 m) of school and medical buildings compared to the typical floor heights (around 3 m) in residential buildings. At the same building height, a higher floor height results in fewer floors and a smaller building area, which increases embodied carbon intensities.

Statistical analysis of the embodied carbon intensities of buildings provides valuable references for establishing industry-based benchmarks. The mean, median, standard deviation, and concentration interval of embodied carbon intensity are presented in Table 2. It can be observed that the differences between the mean and median values for different types of building are relatively small. There is a positive correlation between the standard deviation and the degree of data dispersion. Moreover, the normal probability density distribution of the embodied carbon intensity of the collected buildings is shown in Fig. 5a and b. The interval between the lower and upper percentiles represents the 95 % confidence interval, reflecting the reliability of the statistical analysis of the collected data.

The differences in the mean embodied carbon intensity of various building types can be tested through analysis of variance. As shown in Fig. 5c, the difference between the embodied carbon mean values of different types of buildings is reflected. A larger standard deviation indicates greater data dispersion, reflecting variability in data collection and uncertainty in the assessment of embodied carbon. ffice buildings and medical buildings exhibit significant data dispersion, while prefabricated buildings and stacked villa

Table 1
Carbon emission factors of building materials.

Material	Specification	Unit	Reference range (kg CO_2e/unit)	Reference value (kg CO_2e/unit)	Source
Concrete	Not exceeding 50 MPa	m^3	100~667	295	GB/T 51366-2019 [49]
Steel reinforcement	Hot-rolled steel bar	t	1827~4808	2340	GB/T 51366-2019 [49]
Concrete block	Aerated concrete block	m^3	0~625	270	Zhang et al. [50]
Formwork	Plywood	m^3	271~696	487	Zhang et al. [50]

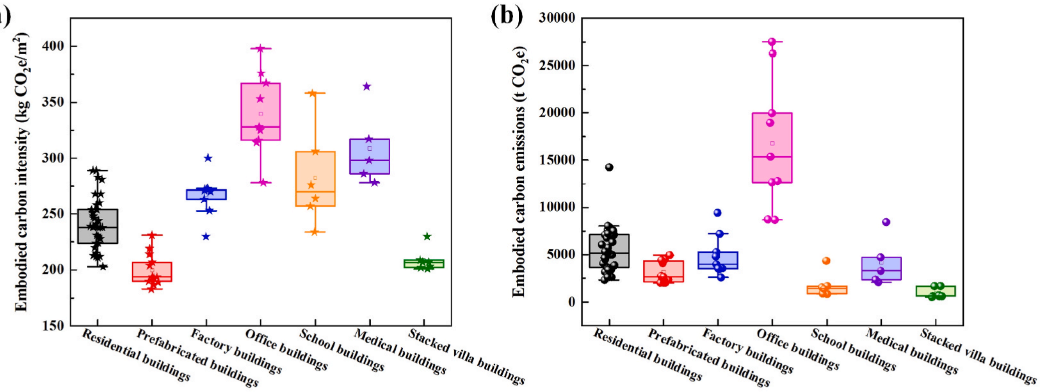

Fig. 4. Embodied carbon intensities and emissions of the 85 building cases: (a) embodied carbon intensity, (b) embodied carbon emissions.

Table 2
Statistics of embodied carbon intensities of the 85 buildings.

Indicator	Statistics	Residential buildings	Prefabricated buildings	Factory buildings	Office buildings	School buildings	Medical buildings	Stacked villa buildings
Embodied carbon intensity (kg CO_2e/m^2)	Mean	240.6	199.9	267.1	339.5	282.6	308.7	208.4
	Median	238.0	193.9	270.7	327.6	270.2	298.0	206.9
	Standard deviation	23.1	14.2	18.7	37.2	43.8	34.4	10.2
	Concentration interval	225~250	185~208	260~270	315~365	260~305	285~315	200~210
Embodied carbon emissions (t CO_2e)	Mean	5430.4	3138.6	4873.4	16765.8	1793.9	4179.7	914.3
	Median	5142.4	2659.8	3992.1	15354.4	1471.7	3296.1	612.1
	Standard deviation	2311.3	1144.6	2169.8	6938.1	1302.7	2596.9	519.7
	Concentration interval	3500~7000	2000~4000	3500~5050	12500~20000	1000~2000	2400~4800	500~1500

buildings show less variability. It is worth noting that school buildings have the highest standard deviation of embodied carbon intensities; however, their standard deviation for embodied carbon emissions is relatively small. This may be due to the large amount of material used and fluctuations in the building area. Notably, residential buildings exhibited stable changes in embodied carbon intensities and emissions, largely due to the relatively large number of statistical cases. It is recommended to increase data collection for building cases to ensure the reliability of carbon emission benchmarks in future studies. Additionally, polynomial regression analysis was used to analyze the specific impact of independent variables (including building area, building height, and number of floors) on the dependent variable (embodied carbon emissions). The t-value reflects the degree of influence of the independent variable on the dependent variable. Based on the results of the polynomial regression analysis, we found that the order of t-values is: building area > building height > number of floors, indicating that building area has the greatest impact on embodied carbon emissions, followed by building height and then the number of floors. Moreover, compared with the building height and number of floors, the building area has a minimum standard error of 0.016, indicating that the regression model provides the most accurate description of the relationship between the independent and dependent variables, as shown in Fig. 5d.

The concentration interval represents the range within which the embodied carbon intensities of different types of buildings were concentrated. More than half of the embodied carbon intensity values for each building type fall within the concentration interval, indicating that the embodied carbon intensities of buildings are controllable. According to the Buildings Performance Institute Europe, benchmark systems define reference values for measuring and managing performance related to building carbon emissions. Bottom-up benchmarks are based on actual building carbon emission levels obtained from statistical datasets and can be established by setting reference values that are lower than the current building average level or do not exceed the best building emission level of the same category [56]. Hollberg et al. [57] also recommend using percentile methods to obtain different types of values, including best practice, reference and target values, as benchmarks for reference. Therefore, the upper limit of the concentration interval (approximately 65 % from the bottom to the top) can be recommended as the limit for embodied carbon emissions. For example, for the residential buildings in this study, an embodied carbon intensity of 250 kg CO_2e/m^2 can be considered the boundary between high-carbon and low-carbon buildings. Furthermore, for different regional characteristics and building types, the boundaries of embodied carbon intensity may face further refinement, which largely depends on the number of statistical samples. With the continuous advancement of low-carbon materials and carbon reduction technologies, China's carbon neutrality goals will be supported by continuously reducing the boundary between the embodied carbon intensity of high-carbon and low-carbon buildings.

It is worth noting that the selection of this benchmark is based on statistical analysis and expert judgment, combined with practical

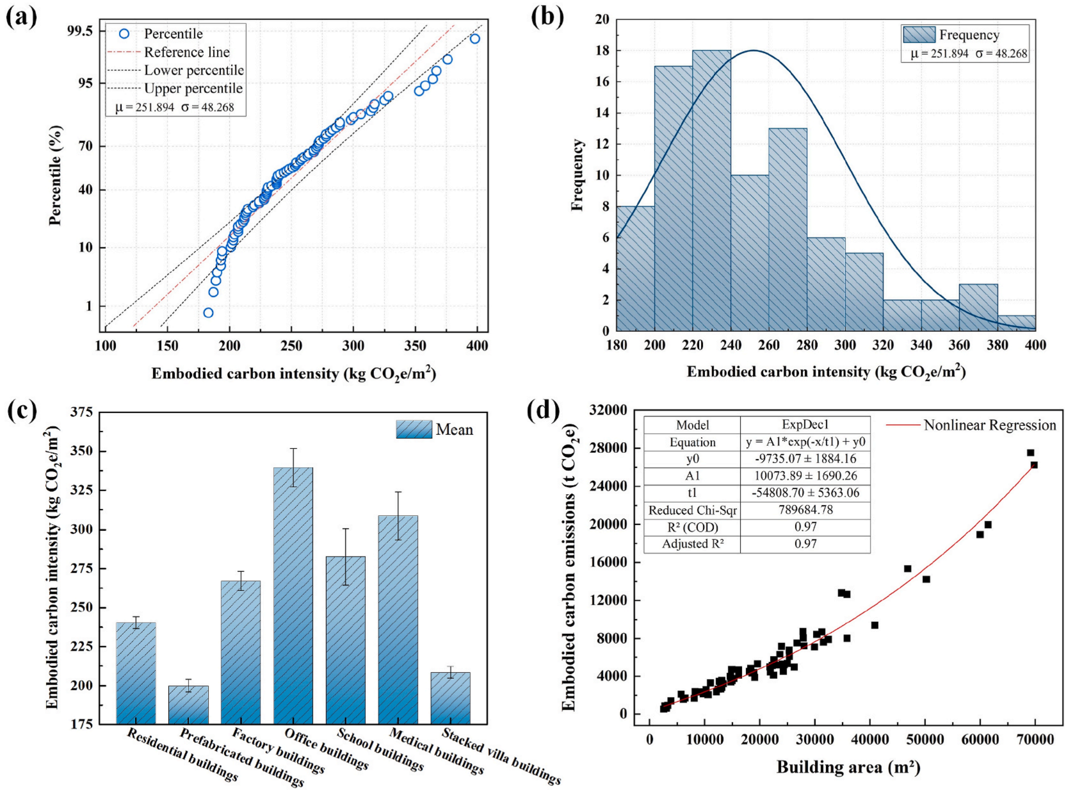

Fig. 5. Formal statistical tests of embodied carbon of the 85 building cases: (a) and (b) Normal probability of the embodied carbon intensities, (c) analysis of variance of embodied carbon intensities for different types of buildings, (d) regression analysis of building area to embodied carbon emissions.

engineering considerations and existing policy targets. First, it corresponds to a noticeable inflection point in the cumulative distribution of the data. This suggests that it is a boundary within the dataset, rather than an unfounded statistical division. Moreover, the benchmark reflects consistency with existing policy targets. China's carbon emissions reached an astonishing 11.61 billion tons in 2023, which is a significant difference from those of developed countries such as the United States (5.03 billion tons) and the European Union (2.39 billion tons) [58]. Among these, the construction industry accounted for approximately 48.3 % of China's carbon emissions [25]. Unlike developed countries, China has not yet peaked in carbon emissions (expected in 2030), and the time between peaking and achieving carbon neutrality (expected in 2060) is relatively short. China's construction industry is at a critical turning point, approaching the final stage of rapid development towards the carbon peak and immediately transitioning to low-carbon development with carbon neutrality after achieving the carbon peak. Some representative studies have provided unique insights

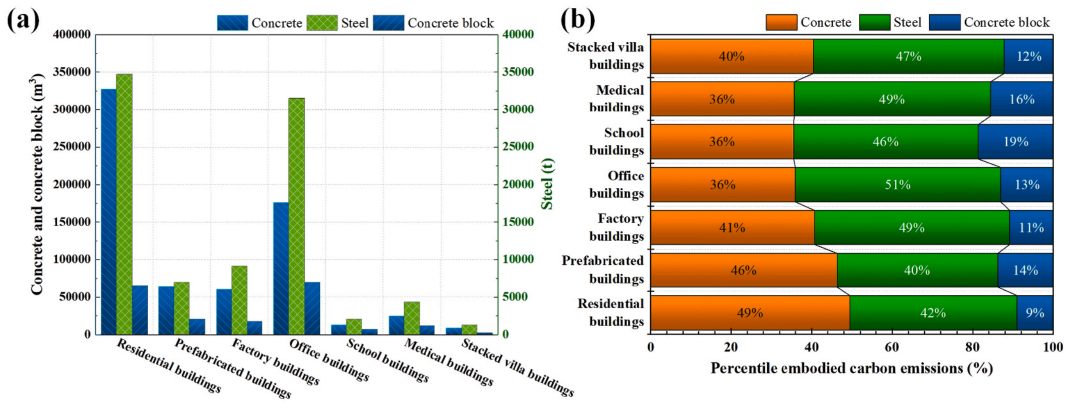

Fig. 6. Proportion of embodied carbon emissions from different structural materials in each type of building: (a) material usage; (b) percentile carbon emissions of different materials.

and potential policy directions for the low-carbon development of China's construction industry [59,60]. Therefore, this benchmark is considered more appropriate than other possible values. It is not so stringent as to make the benchmark impractical for low-carbon building practices, nor so lenient as to affect progress toward China's carbon neutrality. Although the selection of this benchmark is based on observed data inflection points and practical relevance, it involves a certain degree of expert judgment. Future research using larger datasets could explore more data-driven methods to objectively determine optimal thresholds.

4.2. Contribution analysis of different structural materials

It has been proven that structural materials are the most important factor affecting embodied carbon intensity. The material usage for each building type is shown in Fig. 6a. It is worth noting that, based on the carbon emission factor of materials, the carbon emissions per ton of steel reinforcement are approximately 10 times higher than those per cubic meter of concrete (about 2.4 tons) with a compressive strength of 30 MPa. Although concrete and steel reinforcement have different functional units and serve distinct functions, the proportion of steel reinforcement used significantly impacts the embodied carbon intensity of buildings. In concrete structures of the same volume, the higher the steel reinforcement ratio, the higher the embodied carbon emissions. The proportion of embodied carbon emissions from different structural materials in each type of building is presented in Fig. 6b. The embodied carbon emissions from concrete and steel reinforcement account for 36 %–49 % and 40 %–51 %, respectively. It is observed that schools are particularly high. This is a key factor contributing to the high embodied carbon intensities of these buildings. In contrast, residential buildings and prefabricated buildings, which use a lower proportion of steel reinforcement, exhibited relatively lower embodied carbon intensities.

The embodied carbon intensities of structural materials determine the quantities of embodied carbon emissions in buildings. As shown in Fig. 7a–c, the embodied carbon intensities of concrete, steel reinforcement, and concrete blocks range from 80 to 140 kg CO_2e/m^2, 80–200 kg CO_2e/m^2, and 20–55 kg CO_2e/m^2, respectively. Office buildings, school buildings, and medical buildings have higher embodied carbon intensities from steel reinforcement and concrete blocks. The notably, primary reason for this is that these buildings have a high steel reinforcement content, which significantly contributes to embodied carbon emissions, as shown in Fig. 7d. Notably, the proportion of steel reinforcement in the concrete meets the minimum reinforcement ratio requirement. It is essential to acknowledge that while non-structural elements, such as insulation, cladding, and finishes, significantly contribute to embodied carbon, variations among different buildings pose challenges to the availability and quantifiability of these data. Consequently, this study primarily focuses on structural materials, with the intention of considering non-structural elements in further research.

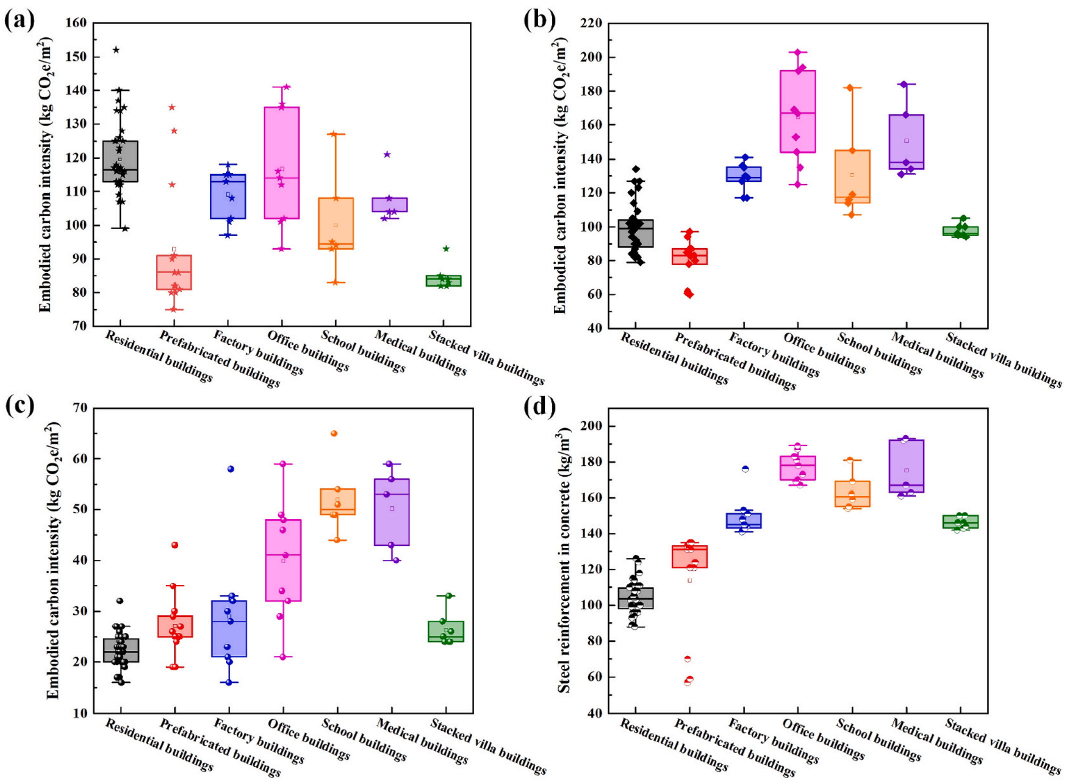

Fig. 7. Contribution of embodied carbon emissions of structural materials: (a) (b) and (c) Embodied carbon intensity of concrete, steel reinforcement and concrete blocks; (d) proportion of steel reinforcement in concrete.

4.3. Significant analysis of building features

According to the calculation method of embodied carbon intensity, building area is also an important factor affecting the embodied carbon intensity. However, the building area is significantly influenced by the building height and the number of floors. Moreover, the functionality of a building depends on its structural type. Different structural types will impose certain restrictions on building area and floor height. Therefore, it is important to conduct a significance analysis to evaluate the impact of building features on embodied carbon intensity.

The impact of factors such as building area, building height, and number of floors on embodied carbon intensity is illustrated in Fig. 8a–c. It can be observed that the embodied carbon intensity is roughly positively correlated with building area, building height, and number of floors. As building height increases, more structural materials are required for the lower floors to improve their load-bearing capacity, which also contributes to higher carbon emissions. It is also worth noting that when the building area ranges from 1000 to 3000 m^2, the embodied carbon intensities exhibit relatively small variability, mainly ranging from 200 to 300 kg CO_2e/m^2. The determinacy of data within this range can provide a reference for embodied carbon benchmarks related to structural materials.

In addition, structural type has a significant influence on embodied carbon intensity. As shown in Fig. 8d, the embodied carbon intensities of F-CTS can reach up to 400 kg CO_2e/m^2, almost twice that of PF-SWS. The embodied carbon intensities of F-SWS and FS are relatively moderate, generally falling between 200 and 300 kg CO_2e/m^2. It is worth noting that the embodied carbon intensities of F-SWS and PF-SWS, used for residential and prefabricated buildings, are relatively concentrated. As shown in Fig. 8e, based on analysis of variance, it was found that the standard errors of embodied carbon intensities for F-SWS and PF-SWS are smaller compared to FS and F-CTS, indicating less variability and lower dispersion within these datasets. A possible reason for this is that the quantity of these building cases is greater than that of other structures, which helps establish benchmarks for embodied carbon emissions. Therefore, it is recommended that further data collection and analysis are necessary to reduce the variability and uncertainty of embodied carbon intensities.

4.4. Scenario analysis of basements and formworks

In previous studies on calculating embodied carbon emissions, basements and formworks are often excluded due to their complexity and uncertainty. However, the embodied carbon emissions associated with the material production of basements and formworks do indeed exist. Therefore, it is necessary to calculate the carbon emissions related to basements and formworks and clarify their contribution to the embodied carbon emissions of buildings.

As shown in Fig. 9a, the embodied carbon intensities of basements in various building types were evaluated based on the ratio of carbon emissions to building area. The embodied carbon intensities of basements are approximately 1.5–4 times higher than those of above-ground structures, with an average value generally ranging from 635 to 882.5 kg CO_2e/m^2. This can be explained by the fact

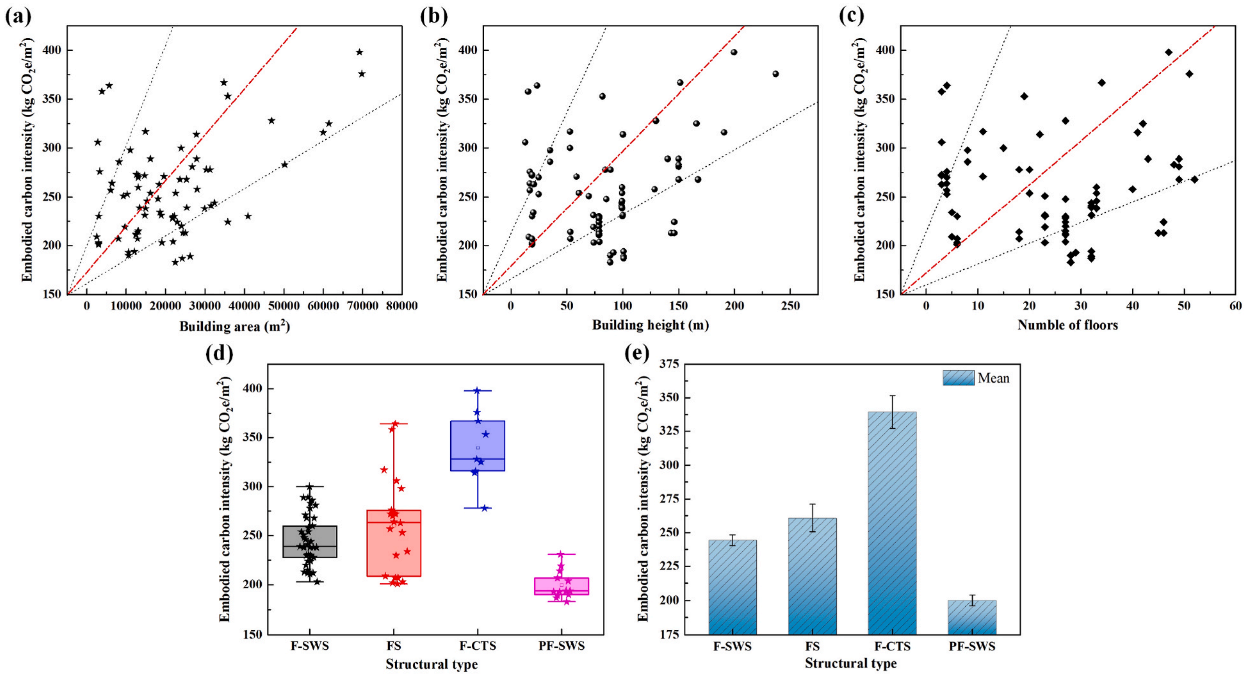

Fig. 8. The impact of building parameters on embodied carbon intensity: (a) building area, (b) building height, (c) number of floors, (d) and (e) structural type.

that the materials used in basements typically include a foundation structure made of mass concrete, which supports the upper structure. Compared to above-ground structures, the embodied carbon emissions of basements account for between 43 % and 70 % of the total embodied carbon emissions of buildings, as shown in Fig. 9b. It is worth noting that in buildings with fewer floors and lower heights, such as school buildings, medical buildings, and stacked villa buildings, the embodied carbon emissions of basements are approximately twice those of above-ground structures. This indicates that the smaller the building height and number of floors, the higher the contribution of embodied carbon emissions from basements.

Additionally, ground conditions, seismic effects, and basement functionality may all have significant impacts on embodied carbon emissions [61]. For public buildings with high population density and safety performance, such as schools and medical buildings, factors like ground layout, seismic design, and the construction of concrete parking structures lay the foundation for an underground "embodied carbon iceberg". In the case of stacked villa buildings, the complexity of structural design and the civil defense construction of basements may be important factors contributing to high carbon emissions.

It should be noted that the research results align with a publicly published research report by Alter, which also suggests that the embodied carbon emissions from basements (including foundations) can constitute up to 50 %–60 % [61,62]. Therefore, whether the embodied carbon emissions of the basement are considered within the calculation boundary will significantly impact the results of embodied carbon assessments. This is one of the reasons for the significant discrepancies observed in current embodied carbon assessments.

Moreover, the embodied carbon intensities of formworks in above-ground structures were evaluated, as shown in Fig. 10a. Since only the carbon emissions caused by the production of required plywood formwork materials are considered here, it is assumed that the system boundary still corresponds to stages A1 to A3. It is assumed that all formworks are made of plywood, and the carbon emission factor for plywood is taken from the reported studies [50]. Based on common situations in the actual construction process, plywood formwork can be reused 3 to 5 times [63,64]. The final embodied carbon intensity of the formwork is one-third of the ratio between the carbon emissions of the formwork and the building area. The results indicate that the embodied carbon intensities of formworks typically range from 6 to 13 kg CO_2e/m^2, accounting for only 2 %–5 % of the embodied carbon intensity of above-ground structures, as shown in Fig. 10b.

It is worth noting that not all buildings use plywood formwork. In some high-rise buildings, aluminum alloy and plastic formwork are highly reusable and repeatable, and are commonly used for typical floors. Compared to plywood formwork, aluminum alloy formwork has a turnover rate of approximately 150 times, while plastic and steel formwork have a turnover rate of about 50 times [64, 65]. It is essential to recognize the impact of region-specific material production and processing techniques on the turnover rate of formwork, which is contingent upon local policies and the construction market. Moreover, the choice of formwork is not only closely related to local material production processes and construction techniques but also highly dependent on building height and structural form. Although plywood formwork has a lower initial carbon footprint, aluminum alloy and plastic formwork offer longer service lives and higher turnover rates. Therefore, for high-rise buildings with a significant number of typical floors (at least 25 floors), using aluminum alloy or plastic formwork with higher turnover rates may result in lower embedded carbon emissions, but this requires further research to confirm.

In addition to material usage, the impact of low-carbon materials and construction methods on embodied carbon emissions should not be overlooked. However, low-carbon materials have not yet been incorporated into existing carbon emission calculation methods. This has hindered suppliers' enthusiasm for producing low-carbon materials, as these often come at a higher cost and result in lower environmental pollution. Moreover, replacing concrete with high-performance materials is a meaningful step towards reducing carbon emissions. Therefore, it is crucial to include building materials of various grades, especially high-carbon-intensity materials such as concrete and steel reinforcement, in the carbon emission factor database.

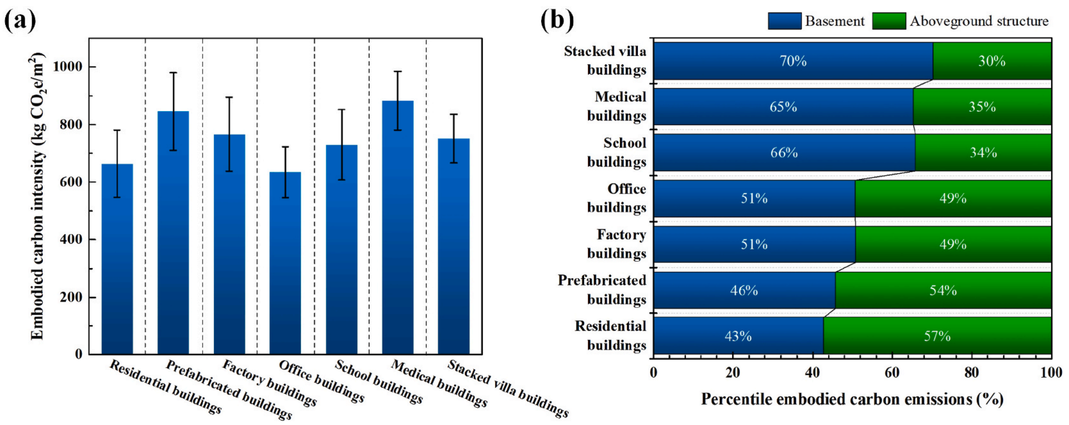

Fig. 9. Embodied carbon contribution of basement: (a) embodied carbon intensity; (b) proportion of embodied carbon emissions.

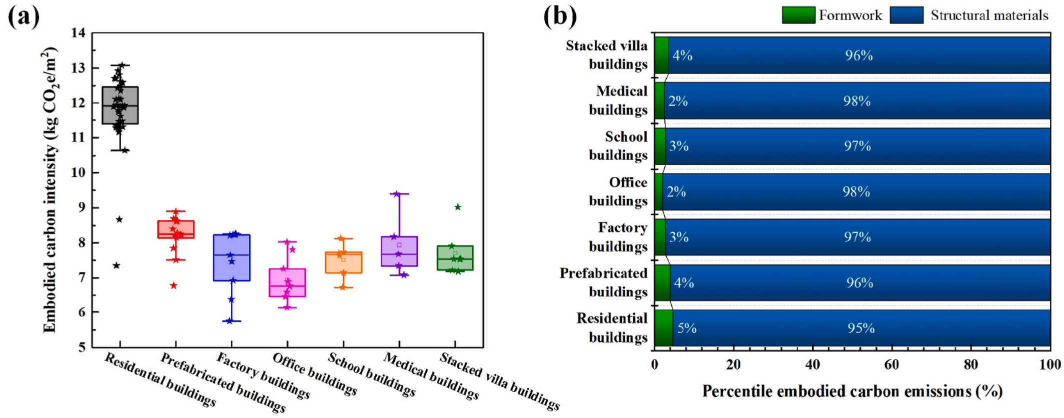

Fig. 10. Embodied carbon contribution of formwork: (a) embodied carbon intensity; (b) proportion of embodied carbon emissions.

5. Discussion

5.1. Comparison with other studies

This paper presents an assessment of the embodied carbon of structural materials for 85 building cases in China, with mean values ranging from 199.9 to 339.5 kg CO_2e/m^2. This provides further data to supplement the establishment of statistical benchmarks. To verify the reliability and reproducibility of the research results, a comparison with previous studies on the embodied carbon emissions of different building types is presented in Table 3. For Chinese residential and public buildings, several influential studies have reached similar conclusions. Zhang et al. [27] evaluated 403 high-rise residential buildings and found that the median embodied carbon intensity of structural materials ranged from 258.8 to 282.3 kg CO_2e/m^2. Guan et al. [29] analyzed the embodied carbon of residential and public buildings during the material production stage, with values ranging from 196.9 to 260.7 kg CO_2e/m^2. These findings are within the scope of this study. Luo et al. [30] assessed the embodied carbon of 78 office buildings, with a range of 250–490 kg CO_2e/m^2. This range is broader than the results found in this study, which assessed 9 office buildings with embodied carbon intensities ranging from 278.1 to 397.9 kg CO_2e/m^2. The primary reason for the difference is that the study encompasses more office building cases and extends to a wider system boundary (from cradle to site, A1-A5). For prefabricated buildings, Teng and Pan [66] conducted a representative assessment of the full life cycle embodied carbon of high-rise prefabricated buildings in Hong Kong, China. Although the embodied carbon intensity reached a high level of 561 kg CO_2e/m^2, nearly half of the embodied carbon contribution came from on-site

Table 3
Comparison with the statistical results of embodied carbon emissions from previous studies.

Embodied carbon intensity	Calculating boundary	Country and region	Type of building or structure	Number of cases	Author/year
Median values of 258.8–282.3 kg CO_2e/m^2 for structural materials	Material production and transportation phases (A1-A4)	China	High-rise residential buildings	403	Zhang et al. [27]
196.9–260.7 kg CO_2e/m^2 for material production stage	Full life cycle embodied carbon	China	Residential buildings and public buildings	114	Guan et al. [29]
250–490 kg CO_2e/m^2 (average value of 326.8 kg CO_2e/m^2)	Cradle-to-site phase (A1-A5)	China	Office buildings	78	Luo et al. [30]
561 kg CO_2e/m^2 (41 % comes from concrete and steel production)	Full life cycle embodied carbon	Hong Kong, China	Prefabricated buildings	1	Teng and Pan [66]
50–320 kg CO_2e/m^2 (mean value of 170 kg CO_2e/m^2)	Full life cycle embodied carbon	Belgium, Denmark, Finland, France, Netherlands	Load-bearing structure (e.g. structural frame, walls, floors)	769	Röck et al. [67]
Median values of 119, 185 and 228 kg CO_2e/m^2 for timber, reinforced concrete, and steel frames, respectively	Full life cycle embodied carbon	UK	Three structural systems (timber, reinforced concrete, and steel frames)	127	Hart et al. [16]
158–277 kg CO_2e/m^2	Cradle-to-site phase (A1-A5)	South Korea, Italy and China	Reinforced concrete structures	80	Helal et al. [20]
35–140 kg CO_2e/m^2	Material production stage (A1-A3)	Brazil	Reinforced concrete structures	53	Belizario-Silva et al. [24]
375 kg CO_2e/m^2 for the single residential and 426 kg CO_2e/m^2 for the multi-residential building	A1-A3 module and B4 module	Portugal	Reinforced concrete structures	2	Parece et al. [23]

and off-site construction, as well as component transportation. Therefore, only about 41 % (approximately 230 kg CO_2e/m^2) came from the production of structural materials, such as concrete and steel reinforcement. This is consistent with the embodied carbon calculation results for the material production stage of 13 prefabricated buildings in this study, which ranged from 182.5 to 231.0 kg CO_2e/m^2. These representative case studies in China show a high degree of consistency with the results of this study, highlighting the accuracy and reliability of the findings.

Additionally, several other highly acclaimed studies have examined benchmarks for embodied carbon. Notably, Röck et al. [67] evaluated the embodied carbon intensity of 769 structural frameworks (covering European countries such as Belgium, Denmark, Finland, France, and the Netherlands) throughout their entire life cycle, with values ranging from 50 to 320 kg CO_2e/m^2. These values are generally lower than the calculation results of this study. Other similar studies have also shown that developed countries in Europe generally have lower embodied carbon intensities in buildings [16,20]. This indicates a high level of attention to embodied carbon emissions in the construction sector within Europe. For instance, the Centre for European Policy Studies mentioned in their report "Policies to Reduce Lifecycle Carbon Emissions from the Construction Sector" that lifecycle carbon emissions from buildings account for 40 % of EU CO_2 emissions, with the management of embodied carbon emissions lagging behind [68]. The EU has implemented corresponding policy measures, such as integrating the concept of eco-cities into urban renewal, effectively reducing embodied carbon emissions by preserving old buildings. In particular, a statistical benchmark study on the material production stage of 53 reinforced concrete structures in Brazil revealed the lowest embodied carbon intensity, ranging from 35 to 140 kg CO_2e/m^2, which may be attributed to its specific building practices and material production methods [24]. As one of the largest global markets for sustainable building certification, Brazil has fostered the advancement of related efforts in the field of low-carbon buildings [69]. However, a study on two reinforced concrete structures in Portugal found that the cradle-to-gate embodied carbon intensity can reach up to 375–426 kg CO_2e/m^2, likely influenced by limitations in building renovation efficiency, material production, and construction techniques [23]. This suggests that buildings in different geographical regions are subject to varying regulations, building characteristics, climatic conditions, and local codes. Consequently, more influencing factors must be considered when making meaningful comparisons. It is crucial to establish a globally shared carbon footprint database and a mutually recognized carbon emission accounting system to facilitate the promotion of these study results in other regions of China and even in other countries.

5.2. Pathway for establishing industry-based benchmark

The establishment of industry-based benchmarks for embodied carbon emissions is crucial not only for the development of sustainable materials and low-carbon technologies within the local construction market but also for achieving global climate control goals. The creation of benchmarks can be approached from the following aspects:

(1) **Statistical analysis of carbon emissions**: This serves as a critical foundation for establishing benchmarks based on specific scenarios, including regional characteristics and structural types [28]. Regionalism encompasses local material production methods, design styles, and the level of construction technology, all of which significantly impact embodied carbon emissions [70]. The structural type reflects the influence of the proportion of different materials and components on embodied carbon intensity [71,72]. The former provides a comprehensive evaluation of the local construction market and technological level at a macro level. Meanwhile, the latter offers a more detailed analysis of material usage and building features for different structural types. Therefore, these benchmarks for embodied carbon emissions are provided in this study, based on statistical analysis, expert judgment, practical engineering considerations, and existing policy targets, marking the boundary between low-carbon and high-carbon buildings. It is essential to note that the threshold for embodied carbon emissions varies across different types of buildings and those with distinct regional characteristics. Furthermore, with the continuous advancement of low-carbon materials and carbon reduction technologies, the boundary between low-carbon and high-carbon buildings can be progressively lowered, thereby supporting the low-carbon development of the construction industry. It is worth noting that case studies within specific contexts are valuable for establishing industry-based benchmarks for embodied carbon emissions that account for regional characteristics. The applicability and accuracy of the benchmark improve as the quantity of statistical data increases.

These statistical benchmarks can be directly operationalized in practice. For instance, design institutes could adopt benchmark thresholds as early-stage design targets, ensuring that material choices and structural concepts remain within low-carbon ranges. Municipal permitting authorities could also integrate such thresholds as reference values when evaluating new construction projects, similar to how operational energy intensity targets are used in building codes. Furthermore, industry certification schemes such as BREEAM, DGNB, or the EU Level(s) framework already incorporate embodied carbon indicators; aligning the proposed benchmarks with these systems would accelerate their adoption in China. In the absence of formal national regulations, voluntary adoption through green building standards and procurement guidelines represents a feasible first step toward mainstreaming embodied carbon benchmarks in design and permitting practice.

(2) **Bottom-up statistical benchmark**: Establishing a bottom-up statistical benchmark for embodied carbon emissions more effectively addresses the environment challenges in the industry. The ideal method for creating a benchmark would involve considering a country's climate control goals and then allocating carbon reduction targets to the construction industry [73,74]. However, this top-down model often fails to account for significant regional differences in economic development fully. In contrast, a bottom-up benchmark model is more likely to reflect the carbon emission disparities across different regions [75,76].

By analyzing the carbon emission levels and the potential for carbon reduction in various regions, it becomes easier to establish a widely accepted industry-based benchmark. By conducting research on the embodied carbon emissions of buildings and establishing a shared carbon footprint database and a unified carbon emission assessment system, a clear boundary between low-carbon and high-carbon buildings can be proposed based on data analysis. This can promote the control of carbon emissions during the material production phase, as well as the research, development, and application of low-carbon materials. Undoubtedly, achieving a balance between climate control goals and regional economic development is a complex task. The establishment of a bottom-up statistical benchmark for embodied carbon emissions is likely to contribute more effectively to the sustainable development of the construction industry.

(3) **Integration of low-carbon design concepts**: Embodied carbon in buildings not only has spatial and temporal properties but also exhibits significant stage explosiveness, especially during the early stages of material production [77]. Based on the existing embodied carbon assessment system, low-carbon materials with shorter lifetimes may have lower carbon emissions in the early stages of their lifecycle compared to high-strength materials with longer lifetimes. However, from a broader perspective, the involvement of other construction activities, such as demolition and reconstruction, can lead to significant changes. Therefore, it is essential to integrate low-carbon design concepts into the carbon emission assessment system across the entire life cycle of buildings in the early design stage. From a spatial perspective, embodied carbon emissions can be broken down into emissions from various building materials. Establishing carbon emission benchmarks for materials could be a prerequisite for creating similar benchmarks for buildings and industries. This could involve introducing time attributes into the carbon emission factors of materials at the current stage, thereby "annualizing" the carbon emissions of materials per unit strength, such as $CO_2e/(MPa \cdot year)$. Furthermore, from a whole-life cycle perspective, attention is not only given to the production of materials but also to the stages of transportation, construction, and end-of-life, in terms of their contribution to the embodied carbon in buildings, providing carbon emission evaluation metrics such as $CO_2e/(m^2 \cdot year)$. The purpose of proposing these strategies is to offset long-standing concerns about the performance and service life of low-carbon materials by introducing a temporal dimension. Establishing these benchmarks may help emphasize the strength and longevity of building materials while reducing embodied carbon emissions and supporting China's carbon neutrality goals.

5.3. Limitations

While this study provides valuable insights into the establishment of industry-based benchmarks for embodied carbon emissions, some limitations should be acknowledged to contextualize the findings.

First, although the research data in this study is novel and represents the current construction technology and design concepts in the Chinese construction market, it cannot be denied that the number of building cases collected is still limited, especially for building types other than residential buildings. The statistics on the embodied carbon intensity of buildings provided the data foundation for establishing industry-based benchmarks. However, the number of statistical samples can affect the assessment of embodied carbon intensity. The statistics on embodied carbon intensities exhibited a certain degree of dispersion, making it crucial to collect as much carbon footprint information as possible from building cases to improve the accuracy of the industry-based benchmarks. Furthermore, given that 98 % of the buildings in this study are less than five years old, these benchmarks and conclusions may better reflect new construction trends rather than the wider stock of existing buildings. Future research should include a more diverse range of building ages to validate and extend these findings. Moreover, although the authenticity of the data is unquestionable and comes from the business departments of local construction companies, the accuracy of the analysis results is somewhat limited by the quality of the data provided by the suppliers. As a result, the analysis results based on the collected dataset may deviate from the actual carbon emissions in the region. Finally, the statistical analysis of embodied carbon emissions focuses solely on the production of structural materials in the cradle-to-gate phase, excluding other factors such as transportation, construction, and disposal related to building materials. Moreover, this study did not include non-structural elements such as insulation, cladding, internal partitions, finishes, and building services, which can substantially contribute to the overall embodied carbon. Several studies have shown that non-structural elements can account for 20 %–40 % of total embodied carbon depending on building type and boundary conditions. For instance, Röck et al. [15,78] highlighted that in highly energy-efficient buildings, building services and finishes can exceed the embodied carbon of the main structure. Similarly, Cabeza et al. [79] found that insulation materials alone may contribute 10 %–20 % of cradle-to-gate embodied emissions in residential buildings. While these contributions are significant, the availability of consistent and high-quality data across projects remains a challenge, leading to wide variability in reported values. Future research should therefore expand benchmarks to include non-structural components, ensuring a more comprehensive assessment of embodied carbon in buildings.

6. Conclusion

Based on a dataset containing 85 different types of buildings in China, this study evaluated the embodied carbon intensities associated with the production of structural materials within the cradle-to-gate phases. The driving factors affecting embodied carbon emissions in buildings were assessed based on statistical characteristics. Industry-based benchmarks for embodied carbon emissions were analyzed, and potential strategies for reducing carbon emissions were discussed. The main findings of this study are summarized as follows:

(1) The average embodied carbon intensities of different types of buildings range from 199.9 to 339.5 kg CO_2e/m^2. Material usage and building area are the primary factors influencing embodied carbon intensity. The embodied carbon intensities of different

types of buildings generally follow a normal distribution. The average, median, and upper limits of the concentration intervals for embodied carbon intensities can serve as references for establishing industry-based benchmarks.

(2) The embodied carbon intensities of concrete, steel reinforcement, and concrete blocks range from 80 to 140 kg CO_2e/m^2, 80–200 kg CO_2e/m^2, and 20–55 kg CO_2e/m^2, respectively. The embodied carbon emissions of concrete and steel reinforcement account for 36 %–49 % and 40 %–51 %, respectively, of the total embodied carbon emissions associated with the production of the main structural materials. The proportions of concrete and steel reinforcement are key determinants of embodied carbon emissions in buildings.

(3) Building height, number of floors, and structural type are also important factors influencing embodied carbon intensity. These factors correlate strongly with material usage and building area. The embodied carbon intensity of F-CTS can reach up to 400 kg CO_2e/m^2, nearly twice that of PF-SWS. The embodied carbon intensity of F-SWS and FS ranges from 200 to 300 kg CO_2e/m^2.

(4) The embodied carbon emissions of the basement and formwork are significant. The embodied carbon intensity of basements is approximately 1.5–4 times that of above-ground structures, with an average range of 635–882.5 kg CO_2e/m^2. Basements can account for up to 70 % of a building's total embodied carbon emissions. The embodied carbon intensity of formworks generally ranges from 6 to 13 kg CO_2e/m^2, constituting only 2 %–5 % of the embodied carbon emissions of above-ground structures.

This study offers a comprehensive understanding of the embodied carbon intensities associated with various building types. The statistical characteristics and driving factors identified can be used to establish industry-based benchmarks for embodied carbon emissions. The findings also suggest strategies for reducing carbon emissions. It is worth noting that the evaluation was based on a dataset containing 85 different types of buildings in China and has certain regional characteristics. Further extensive building samples could enhance the accuracy and reliability of the statistics.

Additionally, by conducting comparative analyses across regions, the study aims to reveal the differences in embodied carbon emissions of buildings and the reasons behind them among various regions. Moreover, considering the limitations of the collected data, this study focused solely on embodied carbon emissions related to the production of structural materials. Future research could address other life cycle phases, including transportation, construction and end-of-life.

CRediT authorship contribution statement

Zengfeng Zhao: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Chao Pan:** Writing – original draft, Methodology, Investigation, Formal analysis. **Gang Yang:** Validation, Resources, Investigation. **Chenyuan Ji:** Validation, Resources, Investigation. **Carlos José Massucato:** Writing – review & editing, Validation, Resources. **Shady Attia:** Writing – review & editing, Validation, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.114372.

Data availability

Data will be made available on request.

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