sustainability

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Building a Life Cycle Carbon Emission Estimation Model Based on an Early Design: 68 Case Studies from China

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Abstract: The building sector contributes to 50.9 percent of China's carbon emissions. Due to the complexity of the assessment process, it is difficult to predict the entire life cycle carbon emissions of a building at the early stage of design. In this study, a whole-life carbon emission estimation model for the early stage of building design is developed based on comparison of the standard calculations and an analysis of stock cases. Firstly, the standard calculation methods in China, Japan and Europe were compared, and the boundary of the model was defined in three parts: production, construction and demolition and operation. Second, information on 68 examples of Chinese buildings was collected and divided into a training set and a test set at a ratio of 7:3. In the training set, the relationship between carbon emissions and the design parameters was searched, and a carbon emission estimation model applicable to different stages was constructed. Finally, the model was applied to the test set for validation. The results show that the calculation error of the model is within ±15%, and it can quickly estimate carbon emissions based on the design factors, which is helpful for carbon emission assessment work in the early stages of design.

Keywords: building; carbon emission; China; case study; life cycle assessment

Citation: Guo, C.; Zhang, X.; Zhao, L.; Wu, W.; Zhou, H.; Wang, Q. Building a Life Cycle Carbon Emission Estimation Model Based on an Early Design: 68 Case Studies from China. *Sustainability* **2024**, *16*, 744. https://doi.org/10.3390/su16020744

Academic Editor: Aliakbar Kamari

Received: 26 November 2023
Revised: 9 January 2024
Accepted: 12 January 2024
Published: 15 January 2024

1. Introduction

The building sector contributed to 37 percent of global carbon emissions in 2021 [1]. As the world's largest carbon emitter [2], China's building-related carbon emissions amounted to 5.08 billion tons in 2020, accounting for 50.9% of the country's total carbon emissions [3], which is due to its rapid urbanization in recent years [4]. In this context, the assessment of building carbon emissions based on life cycle assessment theory has become a focus of attention for Chinese scholars [5].

Life cycle assessment (LCA) is commonly employed in China to measure the environmental impacts of products [6,7]. Various scholars have already conducted LCA-based studies on carbon emissions in buildings, exploring different construction methods [8], building structures [9], types [10] and green performance [11]. However, assessing the carbon emissions across a building's life cycle has always faced two issues: the absence of a harmonized accounting boundary and the challenges in inventory data collection.

The reasonable delineation of an accounting boundary is a prerequisite for conducting LCA. Although the relevant standards in China [12], Japan [13] and Europe [14] clearly delineate the accounting boundary applicable to local buildings, many scholars have adjusted the accounting boundary in the actual assessment process due to the variability of the inventory data and research objectives [15]. The production of building materials, transport, building construction, operation and demolition are the five most basic stages [12,16,17], which some studies have divided into three stages: implied carbon emissions, operational carbon emissions and demolition carbon emissions [18]. Among these, the operation stage, which is key to a building's carbon emissions, usually only accounts for energy-consumption-related carbon emissions such as cooling, heating, lighting and electrical equipment due to the difficulty of obtaining measurement data [19,20], and ignores maintenance carbon emissions such as envelope renewal and insulation retrofits [11,21,22]. Meanwhile, carbon emissions from demolition are further considered in waste disposal [19] and building material recycling [22], in addition to those from the energy consumption of mechanical equipment and waste transport. In addition, the carbon emissions from occupant commuting have been considered for inclusion in the overall LCA of buildings, as they can reflect the low-carbon nature of a building's location [23]. Therefore, it is important to consider the consistency of the accounting boundary when comparing LCA results across studies [24]; otherwise, it will be difficult to conduct comparative studies [15].

The process of gathering inventory data is essential for carrying out LCA for buildings. This data comprise activity data, which expresses the materials, machinery units and energy used at each stage of a building's lifespan, and carbon emission factors, which calculate the carbon emissions produced by each activity. The standard building carbon assessment methods require detailed activity data and are generally more suitable for assessing existing buildings. However, it is challenging to carry out carbon assessments during the design phase due to the lack of activity data available [25]. Historical data regression [25], statistics [26] and software simulation [10] are the three most commonly used methods to carry out carbon emission assessment at the early design stage.

In terms of predicting total carbon emissions, Mao [25] applied principal component regression, a random forest, a multilayer perceptron and a support vector machine to build a prediction model applicable to the whole-life carbon emissions of Tianjin residences based on the carbon emissions of 207 residences in Tianjin, respectively. At the stage of production and the transport of building materials, obtaining information on the consumption of major building materials based on BIM software and then assessing the carbon emissions of that part is a widely used and reliable method [27]. Based on the analysis of historical data, Wang [18] proposed that carbon emissions from the transport of building materials could be quickly estimated to be 5–10% of the carbon emissions from production. During the construction phase, Fang collected information on 38 residences in the Pearl River Delta region of China as a training set and applied multiple linear regression and random forests to build a prediction model applicable to the carbon emissions from residential construction in the region [5]. In addition, Luo used linear regression to establish an empirical formula for the embodied carbon emissions of steel hybrid office buildings based on the number of building floors by calculating the embodied carbon emissions of 78 steel hybrid office buildings in China [28]. In the operation phase, building energy simulation software is usually used to obtain the operation data of the target building, e.g., EnergyPlus, eQUEST, DesignBuilder, Ecotect, etc. [10,21]. In addition, a few scholars have also obtained the operation energy consumption using the locally released statistical reports on building energy consumption [26]. In the demolition phase, due to the lack of basic data on building demolition, the relevant studies have widely used the empirical value method to estimate the carbon emissions in this phase [13].

In summary, the whole-life carbon assessment of buildings at the design stage relies mainly on specialized software simulations or existing estimation modeling studies. The former requires designers to have the ability to apply the relevant software on the one hand, and on the other hand, it takes a lot of time and effort to carry out simulation at the early stage of design when the design scheme has not yet been determined. The latter is convenient and quick, but due to the significant regional differences in building carbon emissions, it puts higher requirements on the historical cases in the database, which is reflected in the consistency of the year of construction, region, type and structure. The current estimation models widely used in China are limited by the location and type of buildings used, which makes it difficult to meet the estimation needs of most regions. On the other hand, the lack of sample data limits the development of estimation models, and the relevant empirical formulas are still from the period of 2000–2010, which is not up to date. The empirical formulae proposed in 2002 were still used in the "Guidelines on Carbon Emission Accounting for Buildings" issued by Guangdong Province in 2021.

This study addresses the above shortcomings and carries out research on carbon emission estimation modeling based on the design factors, making the following contributions:

1. Comparison of building carbon emission calculation standards in different regions. Analyzing the differences in the boundary division of building carbon emission calculation standards in China, Japan and Europe. In addition, the accounting boundary of the estimation model is determined;
2. Collection of carbon emission data for 68 examples of various building types in China. The cases cover four climate zones, two building types and seven building structures in China, and can be used as references for future related studies;
3. Creation of a carbon emission estimation model applicable to Chinese buildings. After the feasibility analysis, it is verified that the model can meet the estimation needs at the early stage of design, and greatly reduce the time, manpower and calculation costs for modeling and data analysis.

The full text is structured as follows. Section 2 describes how to compare the relevant standards, construct a database and estimation model and validate the work. Section 3 presents the results on the standards comparison, database, estimation model and feasibility validation. Section 4 discusses the causes of deviation and describes the limitations of this study. Finally, Section 5 presents the conclusions.

2. Materials and Methods

2.1. Framework and Process

Figure 1 illustrates the process of building this model, which consists of three parts: research scope, inventory analysis, model and verification. Firstly, the boundary division of the model is determined in the research scope. Secondly, the database construction contains two parts: data acquisition and pre-processed data. Finally, the relationship between the carbon emissions at each stage in the database and the design factors is analyzed to establish an estimation model, and the feasibility of the model is verified.

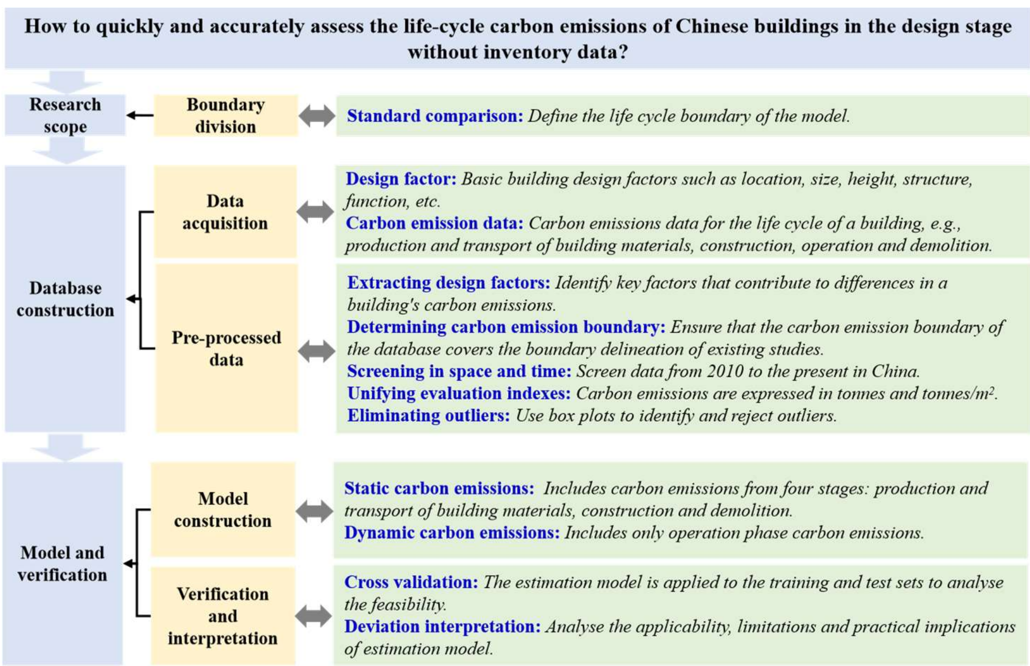


Figure 1. Research framework.

2.2. Boundary Division

LCA determines the environmental load throughout the raw material acquisition, construction, operation and removal, to identify the most important factors affecting the environment and protect it [29]. However, there are differences in the boundary delineation of the building life cycle in different regions [12–14]. In order to determine a reasonable estimation boundary, this study adopts the standard comparison method to analyze the similarities and differences in the accounting boundary and calculation methods of China's Building Carbon Calculation Standard GB/T51366-2019 [12], Japan's LCA Guidelines for Buildings [13] and Europe's EN15978 [14]. Finally, according to the principle of simplified calculation, the model's estimation boundary is formed by ignoring stages that are difficult to calculate and account for a small proportion, and simplifying the operation stage based on the energy demand.

2.3. Data Acquisition

The case data are the basis of the model construction, which contain the basic design factors of the building (geographic location, climatic environment, building scale, structure, etc.) and the carbon emission data (total carbon emission, carbon emission at each stage and percentage). Typically, field studies and literature research are the two ways to obtain case data. However, it is difficult to obtain the large amount of data required for estimation in field studies, so this study uses the literature review method. Peer-reviewed published case data are collected by searching relevant academic websites using the key phrase "building carbon emissions".

2.4. Pre-Processed Data

The case data obtained from the literature review are inconsistent in terms of the design factors, carbon emission boundary, building location, study time and evaluation index. In order to construct the database, it is necessary to pre-process the case data, mainly considering five parts: extracting the design factors, determining the carbon emission boundary, screening in space and time, unifying the evaluation indexes and eliminating outliers, as follows:

- Extracting design factors: There are many factors that affect carbon emissions from buildings, but not all of them have an impact that can be quantified. This study collects information on factors such as the climate environment, building type, structure, height, area and design life of the relevant cases. On the one hand, the influence of these factors is significant, and on the other hand, it can effectively reduce the complexity of the model and save computational resources and time;
- Determining carbon emission boundary: Related studies have delineated a different carbon emission boundary in the accounting process, which is the key factor that makes it difficult to conduct comparative studies [15]. In this study, the carbon emission boundary of the database is determined using standard comparison. In addition, there is a need to ensure that the boundary can cover the boundary delineation of existing studies;
- Screening in space and time: To ensure the timeliness of the estimation model, case study data from 2010 to the present are screened for the China region;
- Unifying evaluation indexes: Carbon emissions in the database are measured in tons (t) and in units of carbon emissions per unit of floor area (t/m^2);
- Eliminating outliers: The interquartile range (IQR) is a common method for detecting outliers [30]. The technique is implemented by dividing the dataset into quartiles in the form of boxplots, defining the lower and upper bounds of the dataset as $Q1 - 1.5 \times IQR$ and $Q3 + 1.5 \times IQR$, respectively, and any data exceeding this defined boundary are considered outliers and discarded [31,32]. The first quartile Q1 means that one quarter of the value is less than it, the third quartile Q3 means that one quarter of the value is greater than it and the interquartile range IQR is the difference between Q3 and Q1.

After constructing the database using the above steps, the training set and test set are randomly divided at a ratio of 7:3. The training set is used to train the estimation model, with fitting to obtain empirical formulas, etc., while the test set is used to evaluate the feasibility of the model.

2.5. Model Construction

The five basic stages of a building's life cycle (production of building materials, transport, construction, operation and demolition) are divided into static and dynamic carbon emissions, and the estimation model is constructed in an appropriate way according to the emission characteristics of each stage.

- Static carbon emissions: Includes carbon emissions from four stages: production of building materials, transport, construction and demolition.

Carbon emissions from the production of building materials and transport are estimated with reference to the Japanese standard CASBEE [33], using empirical values on the carbon emissions per unit area. The estimation formulas of the empirical value method were established as shown in Equations (1)–(3).

$$C_{PT} = C_P + C_T = (1 + P)\cdot(C_d \cdot S) \tag{1}$$

$$P = \frac{\sum_{i=1}^{n} P_i}{n} = \frac{\sum_{i=1}^{n} (C_{ti}/C_{pi})}{n} \tag{2}$$

$$C_d = \frac{\sum_{i=1}^{n} C_{di}}{n} = \frac{\sum_{i=1}^{n} (C_{pi}/S_i)}{n} \tag{3}$$

where C_{PT} is the carbon emissions from the production of building materials and transport ($kgCO_2e$), C_P is the carbon emissions from the production of building materials ($kgCO_2e$), C_T is the carbon emissions from the transport ($kgCO_2e$), P is the average percentage of transport in production (%), C_d is the average carbon emission per unit area ($kgCO_2e/m^2$), S is the area of the target building (m^2), n is the number of cases, P_i is the percentage of transport in production for case i (%), C_{ti} is the carbon emissions from the transport in case i ($kgCO_2e$), C_{pi} is the carbon emissions from the production of building materials in case i ($kgCO_2e$), C_{di} is the average carbon emission per unit area in case i ($kgCO_2e/m^2$) and S_i is the area of the target building in case i (m^2).

Relevant studies have shown that the carbon emissions from the construction and demolition of buildings are positively correlated with scale, and the number of floors and building area are typical indicators that reflect the building volume [25]. Therefore, regression analysis can be used to establish empirical formulas for the construction and demolition phases, as shown in Equation (4). In order to evaluate the accuracy of each regression model, several evaluation indices were considered, as shown in Equations (5) and (6).

$$C_{C/D} = S(aX + b) \tag{4}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y})^2}{\sum_{i=1}^{n} (y_i - \overline{y})^2} \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y} - y_i)^2}{n}} \tag{6}$$

where $C_{C/D}$ is the carbon emissions from the construction or demolition ($kgCO_2e$), a and b are constant, X represents the building levels aboveground, R^2 is the coefficient of determination, $\hat{y}$ and y_i are the predictive and actual value, $\overline{y}$ is the average value, and $RMSE$ is the root mean square error.

- Dynamic carbon emissions: Includes only operational phase carbon emissions. As the carbon emissions at this stage are affected by influencing factors such as residents' lifestyles [34] and the local energy structure [35], and the emission cycle is long, it is difficult to find a specific determinant to construct an empirical formula. Therefore, this study adopts the indicator estimation method to quickly assess the carbon emissions at this stage according to the energy consumption and energy carbon emission coefficients, as shown in Equation (7). The indicators of building energy consumption required for estimation can be obtained from the following three sources. Detailed data are available in Tables S3–S9.

(a) National standards: These contain limit and guideline values for building energy consumption in major cities in China. The heating of buildings mainly involves coal and natural gas consumption, while non-heating mainly includes the electricity consumption caused by HVAC, lighting, lifts, etc., during operation;
(b) Local standards: Chinese provinces have formulated appropriate standards for heating and power consumption based on the local conditions, such as Beijing, Tianjin and Shaanxi Province;
(c) Statistical reports on local building energy consumption: Only Shanghai and Shenzhen in China currently publish annual reports on building energy consumption, including the average energy consumption of all types of public buildings.

$$C = E \cdot EF \tag{7}$$

where C is carbon emissions ($kgCO_2e$), E is the energy consumption during building operation (unit), including coal for heating, electricity, natural gas and domestic water and EF is the carbon emission factor of each energy source ($kgCO_2e$/unit).

2.6. Verification and Interpretation

The estimation model is applied to each case in the training and test sets to estimate the carbon emissions over the whole life cycle, and the deviation rate (d) at each stage is examined by comparing the estimation results with the original data, as shown in Equation (8). The deviation rate (D) of the estimation model consists of the deviation rate of each stage, as shown in Equation (9). In addition, the reasons for the deviation at each stage are analyzed, including the differences in calculation methods and data, to further illustrate the universality, limitations of use and practical significance of the estimation model.

$$d = \frac{C_e - C_s}{C_s} \cdot 100\% \tag{8}$$

$$D = \frac{\sum_{i=1}^{n} d_i}{n} \tag{9}$$

where C_e is the estimated result, C_s is the case study value, d_i is the deviation rate for the i case and n is the number of cases involved in the validation.

3. Results

3.1. Research Scope

As shown in Table 1, China divides the boundary into the production and transport of building materials, construction and demolition and the operation stage. Only Japan considers the environmental load related to design supervision, whereas Europe has a more detailed division of the production stage than China and Japan. China lacks calculations for the design, maintenance and renewal, waste disposal and recycling aspects. Although the design phase has a significant subsequent impact on carbon emissions, considering that the phase itself accounts for a very small share of carbon emissions, it is not considered for inclusion in the accounting boundary in this study.

Table 1. The standard comparison results of building life cycle boundary division.

China GB/T 51366-2019	Japan LCA Guidelines for Buildings	Europe EN15978	Estimation Boundary
·**Production and transport** (a) Production (b) Transport ·**Construction and demolition** (a) Construction (b) Demolition (c) Waste transport ·**Operation** (a) Energy consumption in operation stage, including HVAC, domestic hot water, lighting and elevators, etc. (b) Renewable energy (c) Water consumption (d) Building carbon sink system	·**Design stage** ·**Newly build/reconstruction/repair /renovate/dispose** ·**Operation** (a) Energy consumption, including air conditioning, mechanical ventilation, equipment, elevator, hot water, sanitary facilities, energy-saving equipment, etc. (b) Water consumption (c) Sewage and waste ·**Maintenance** (a) Maintenance costs	·**Product** A1 Raw materials supply A2 Transport A3 Manufacturing ·**Construction** A4 Transport A5 Construction ·**Use** B1 Use B2 Maintenance B3 Repair B4 Replacement B5 Refurbishment B6 Operational energy use B7 Operational water use ·**End of life** C1 Demolition C2 Transport C3 Waste processing C4 Disposal	·**Production and transport** (a) Production (b) Transport ·**Construction and demolition** (a) Construction (b) Demolition ·**Operation** (a) Heating energy consumption (b) Power consumption (c) Natural gas (d) Domestic water (e) Maintenance

In summary, this study ignores the carbon emissions from design and waste transport, which have relatively low carbon emissions, and adds the carbon emissions from maintenance in the operation phase based on Chinese standards. The proposed estimation boundary includes the production and transport phase, the construction and demolition phase and the operation phase. Among them, the production part contains the carbon emissions from the supply and manufacture of raw materials, the transport part involves the carbon emissions caused by the energy consumption of vehicles when delivering building materials to the construction site, the construction and demolition phase contains the carbon emissions caused by the electricity and fuel consumption of machinery and equipment and the carbon emissions from the use of the building in the operation phase arise mainly from the four parts of energy consumption for heating, non-heating, natural gas and domestic water and the carbon emissions from maintenance.

3.2. Database Construction

Life cycle carbon emissions data for 117 buildings were collected through literature research. The time boundary was 1996–2022, and the spatial boundary included 84 cases in China and 33 cases in other countries. The data pre-processing methodology described in Section 2.4 was used to exclude non-compliant data from the above cases, resulting in 68 cases of Chinese buildings with detailed carbon emissions data from 2010 to 2022. The climate division included 16 cases in zone I (severe cold), 19 in zone II (cold), 23 in zone III (hot summer and cold winter), 9 in zone IV (hot summer and warm winter) and 1 in zone V (mild). In terms of the building function (Figure 2), there are 39 cases of residential (F–R) and 29 cases of public buildings (F–P). In terms of the building structure (Figure 1), there are 6 cases of concrete structures (S–C), 12 cases of frame structure s(S–F), 16 cases of frame–shear structure (S–FS), 16 cases of steel–concrete structures (S–SC), 3 cases of masonry structures (S–M), 4 cases of steel structures (S–S) and 11 cases of wood structures (S–W).

(**a**) (**b**)

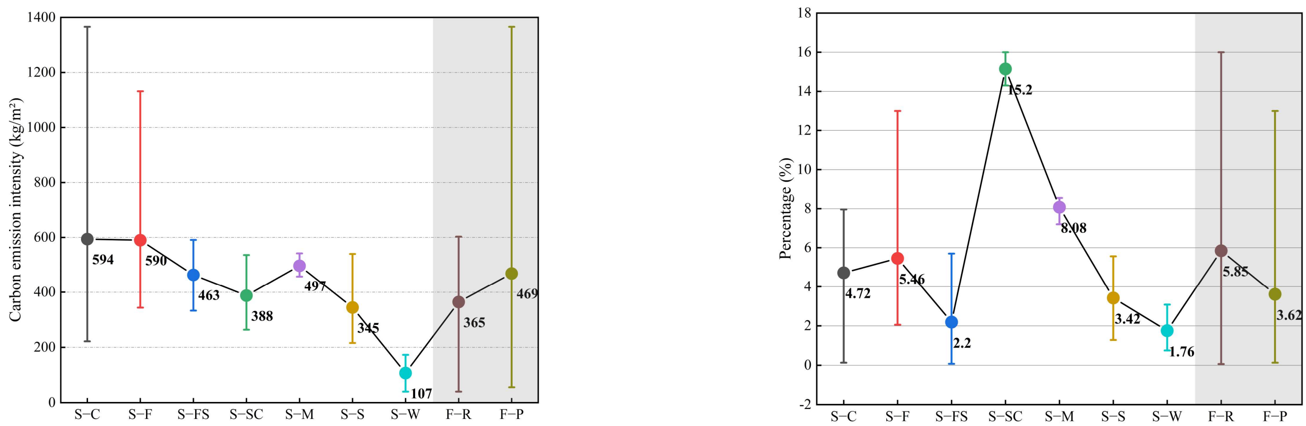
Figure 2. Distribution of cases in the database. (**a**) Distribution of building functions; (**b**) distribution of building structures.

The database boundary is divided into three stages: production and transport, construction and demolition, operation (stages 1, 2 and 3, respectively). We analyzed the proportion of carbon emissions for each stage in the database. Stage 1 accounts for around 10~30 percent of the total emissions, stage 2 for less than 5 percent and stage 3 for up to 70~90 percent. Key information on the database is given in Table S1.

3.3. Estimation Model

3.3.1. Production and Transport

Based on the different building structures and functions, empirical values for the carbon intensity of production and the proportion of transport were analyzed, as shown in Figure 3. Among them, the carbon emission intensity of the building material production for the S–W and S–S buildings is 107 $kgCO_2e/m^2$ and 345 $kgCO_2e/m^2$, respectively, which is significantly lower than that of S–C, which is 594 $kgCO_2e/m^2$, and the carbon emission intensity of building material production for F–P is 469 $kgCO_2e/m^2$, which is slightly higher than that of F–R, which is 365 $kgCO_2e/m^2$. In addition, the proportion of carbon emissions from the transport stage of production is basically stable at around 5%, while that of S–SC is as high as 15.2% and that of S–M is 8.08%. Detailed data on the components are shown in Table 2. In addition, it was summarized that the concrete consumption per unit area is 0.3~0.5 m^3/m^2 and the steel consumption is 0.04~0.07 t/m^2.



(**a**) (**b**)

Figure 3. Analysis of carbon emissions from cases based on structure and function. (**a**) Carbon intensity of production; (**b**) proportion of transport.

Table 2. Empirical values of carbon emissions for different building structures and functions.

Classification	Emission Range ($kgCO_2e/m^2$)	C_d ($kgCO_2e/m^2$)	Percentage Range (%)	P (%)	Production and Transport
S–C	222~1366	594	0.13~7.96	4.72	$C_P = 622.04 \cdot S$
S–F	344~1132	590	1.4~13	5.46	$C_P = 622.21 \cdot S$
S–FS	333~591	463	0.07~7.8	2.20	$C_P = 473.19 \cdot S$
S–SC	264~536	388	14.3~16	15.15	$C_P = 446.78 \cdot S$
S–M	457~542	497	7.2~8.55	8.08	$C_P = 537.16 \cdot S$
S–S	216~540	345	1.28~5.56	3.42	$C_P = 356.80 \cdot S$
S–W	40~173	107	0.75~3.08	1.76	$C_P = 108.88 \cdot S$
F–R	40~603	365	0.06~16	5.85	$C_P = 386.35 \cdot S$
F–P	56~1366	469	0.13~13	3.62	$C_P = 485.98 \cdot S$

3.3.2. Construction and Demolition

The carbon emissions during this stage come from the fuel and power consumed by mechanical equipment. Previous studies have shown that the type, structure and scale of buildings are significantly related to the carbon emissions in this stage [22]. Therefore, this study establishes an empirical formula by analyzing the relationship between the above three design elements and the carbon emissions at this stage. In order to simplify the analysis, the number of floors and area are used to quantify the building scale in terms of the design elements, and the selection of the emission index per unit area in terms of carbon emission can effectively reduce the complexity of the fitting.

In summary, the empirical formulae that can be used to estimate the carbon emissions during the construction and demolition phases are obtained, Table 3. The empirical formulae have a good fit in terms of R^2. In terms of the RMSE, the formulas can basically meet the estimation needs, except for the concrete and masonry structures, which have larger errors.

Table 3. Carbon intensity of production and share of transport in different structures and functions.

Classification	Construction	R^2	RMSE	Demolition	R^2	RMSE
S–C	$C_C = S(2X - 3.78)$	0.79	11.8829	$C_D = S(1.74X - 1.68)$	0.58	0.4739
S–F	$C_C = S(0.16X + 35)$	0.63	0.7012	$C_D = S(2.9X - 0.33)$	0.87	3.1329
S–FS	$C_C = S(2X + 15.34)$	0.86	4.6505	$C_D = S(1.7X + 3.9)$	0.84	2.5484
S–SC	$C_C = S(0.74X + 4.08)$	0.96	0.6717	$C_D = S(0.65X + 0.13)$	0.95	2.1728
S–M	$C_C = S(1.31X + 17.54)$	0.79	10.3775	$C_D = S(0.04X + 10.93)$	0.55	3.1871
S–S	$C_C = S(0.33X + 10.33)$	0.99	0.0177	$C_D = S(4.77X + 1.66)$	0.99	5.7601
S–W	$C_C = S(0.17X + 29.5)$	0.75	0.1048	$C_D = S(0.12X + 29.66)$	0.62	0.1585
F–R	$C_C = S(0.66X + 23.11)$	0.67	3.3669	$C_D = S(0.49X + 16.56)$	0.61	1.9003
F–P	$C_C = S(1.1X + 25.31)$	0.65	4.2470	$C_D = S(2.88X + 19.37)$	0.93	4.2254

Note: C_C and C_D are the carbon emissions during construction and demolition ($kgCO_2e$), respectively; S is the construction area of the target building (m^2) and X is the number of floors above ground.

3.3.3. Operation

The estimation methods for the five key aspects of heating energy, power, natural gas, domestic water and maintenance during the operation of the building are shown in Table 4:

1. Heating energy consumption: The three main energy sources for heating buildings in China are coal, natural gas and electricity. For buildings where coal is the primary heating energy source, the heating energy consumption can be converted from raw coal. For buildings using natural gas as the heating energy source, the natural gas formula in Table 4 can be used, although natural gas is currently only used for heating in Beijing and Tianjin, China [36]. If the target building is electrically heated, the electricity consumption can be combined with the power consumption for the calculation;

2. Power consumption: Power consumption is the sum of electricity used for lighting, lifts and other building equipment. This part of the estimate relies on two indicators: the power consumption of the building and the carbon emission factor for electricity;
3. Natural gas: Natural gas is mainly used for daily cooking and domestic hot water, and in some Chinese cities, it is also used for heating. The measured data of the target building or the local area should be prioritized. Otherwise, the consumption data of natural gas can be estimated based on the per capita natural gas consumption (33.6 m^3) and per capita living area (39.8 m^2) published in the 2020 China Statistical Yearbook;
4. Domestic water: Measured data should be used when available. Otherwise, data can be obtained from the 2020 China Statistical Yearbook and China Water Resources Bulletin, including the per capita living area (39.8 m^2) and per capita domestic water consumption (207 L/d; converted into 0.207 t/d considering the water density and 365 d/y);
5. Maintenance: Maintenance carbon emissions are estimated by multiplying the sum of carbon emissions from production, transport and construction by a maintenance factor M. The maintenance factor M = (1% × n1 + 20% × n2 + 25% × n3), where n1, n2 and n3 are the number of minor, intermediate and major repairs, respectively, throughout the life cycle of the building. In this study, a maintenance factor of 0.65 was chosen for prediction based on one major repair and two medium repairs (excluding minor repairs) based on the service life of components and equipment specified in the Chinese standard.

Table 4. Carbon emission estimation methods for each part of the operation stage.

Content	Calculation Method
Heating energy consumption	$C_1 = \frac{B_m}{Q} \times S \times A \times EF_m$ where C_1 is the carbon emissions from burning coal for heating ($kgCO_2e$), B_m is the building heating energy consumption index [$kgce/(m^2 \cdot a)$], Q is the converted raw coal coefficient (kgce/kg), S is the area of the building (m^2), A is the design life of the building, EF_m is the carbon emission factor of raw coal ($kgCO_2e/kg$).
Power consumption	$C_2 = B_e \times S \times A \times EF_e$ where C_2 is the carbon emissions from power consumption ($kgCO_2e$), B_e is the building power consumption index [$kWh/(m^2 \cdot a)$], EF_e is the carbon emission factor of electricity ($kgCO_2e/kWh$).
Natural gas	$C_3 = D \times S \times A \times EF_r$ where C_3 is the carbon emissions caused by natural gas consumption ($kgCO_2e$), D is the annual natural gas consumption per unit area [$m^3/(m^2 \cdot a)$], EF_r is the carbon emission factor of natural gas ($kgCO_2e/m^3$).
Domestic water	$C_4 = D \times 365 \times A \times EF_w$ where C_4 is the carbon emissions caused by domestic water ($kgCO_2e$), D is the daily consumption (t/d), EF_w is the carbon emission factor of water ($kgCO_2e/t$).
Maintenance	$C_5 = M \times (C_P + C_C)$ where C_5 is the carbon emissions caused by maintenance updates ($kgCO_2e$).

3.3.4. Direct Estimation Model

The operation carbon emissions of buildings account for more than 70% of the total carbon emissions, which has a significant impact. The relationship between the operation and total carbon emissions is fitted and analyzed in the datasets of residential and public buildings, respectively, and the analysis process is shown in Figure 4. The results are shown in Equations (10) and (11), and the R^2 of the estimation formula for residential buildings is 0.9575, and that for public buildings is 0.9380, which shows a better fitting effect and estimation ability.

$$\text{Residential buildings: } C_{Total} = 1.095C_o + 5.7041, \text{R} = 0.96, \text{RMSE} = 5.7356 \tag{10}$$

$$\text{Public buildings: } C_{Total} = 1.112C_o + 4.3859,\ \text{R} = 0.94,\ \text{RMSE} = 8.2695 \tag{11}$$

where C_{Total} and C_o are the carbon emission intensity throughout the building life cycle and during the operation stage [$kgCO_2e/(m^2{\cdot}a)$], respectively.

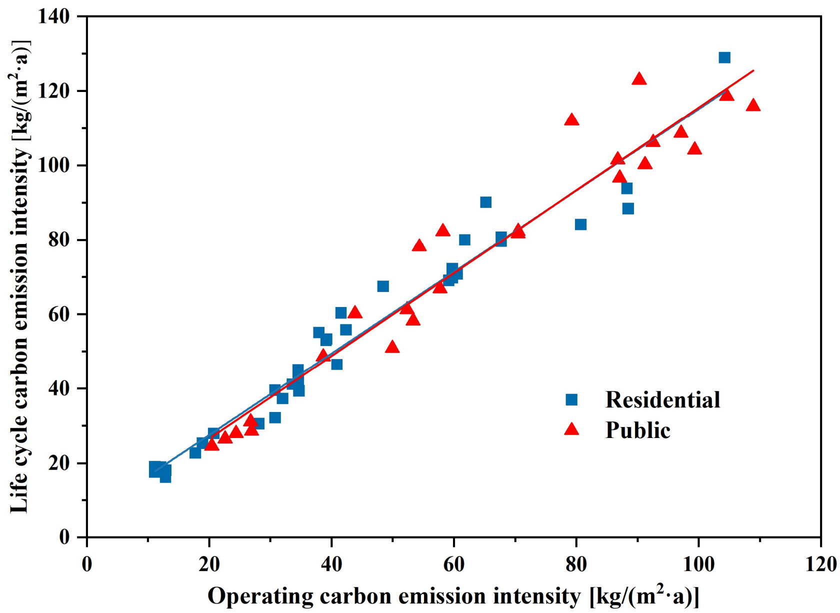


Figure 4. Results of carbon emission fitting analyses for residential and public buildings.

In conclusion, by analyzing the carbon emission data of different building structures and building types in the database, the structure-based estimation model A, the type-based estimation model B and the most direct estimation model C were established. The flow of the estimation work is shown in Figure 5, where the input side consists of parameter inputs and the basic database, and the model calculation process can choose three different calculation methods, and the final output of carbon emissions at each stage and the total carbon emissions are output.

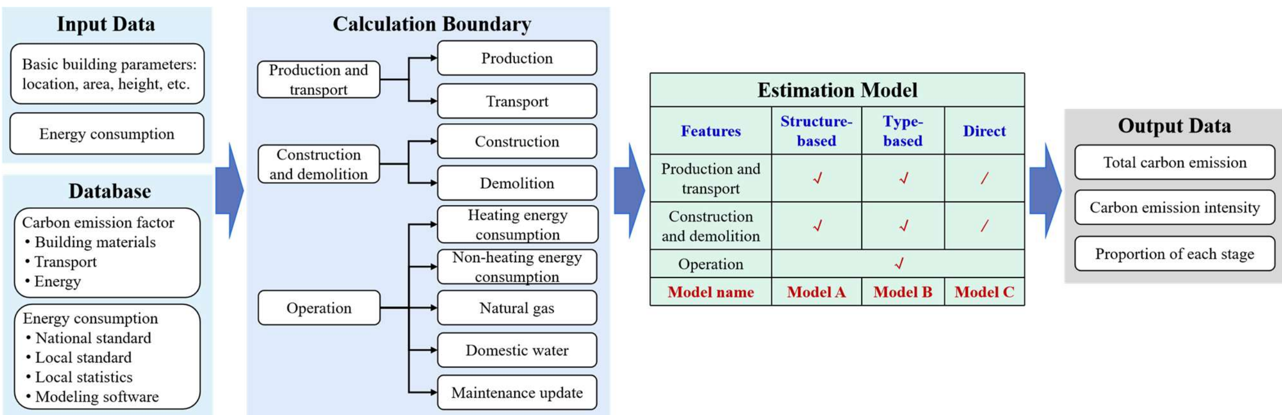


Figure 5. The flow of the estimation work.

3.4. Feasibility Verification

This section describes the feasibility of the model and the specific estimation methodology. In this study, the estimation model was first substituted into the 53-case training set and then into the 15-case test set for cross-validation. The HDD (Heating Degree Day) and CDD (Cooling Degree Day) in different regions will have an important impact on buildings' operating energy consumption. Therefore, this study considered the HDD and CDD in selecting energy consumption indicators. The energy consumption indicators selected for estimation were derived from the standard and statistical values officially released by China. For instance, two buildings in Shenzhen and Shanghai differed in their HDD and CDD, leading to different energy consumption indicators, despite both being office buildings. During estimation, the heating energy consumption index was uniformly selected from the regional central heating constraint value of the provincial capital city where the building was located. Natural gas and water consumption were calculated according to the latest relevant statistics released by the Chinese government in 2020. For the power consumption indicators, according to specific building functions and whether the buildings are considered green, the constraints and guidance values were obtained from the national standards. For residential buildings, only the constraint value of each household was in the national standard. Therefore, cases for which the number of households was not provided were converted according to 100 m^2/household.

Based on the characteristics of the different cases in the training and test sets, the life cycle carbon emissions were calculated according to the above model usage method. The average deviation rate of each stage was obtained using Equations (8) and (9), as listed in Table 5. Previous studies on relevant forecasting models have had deviation rates between 10 and 30 percent [5,37]. Therefore, achieving a prediction result with a 15% deviation rate in the absence of detailed inventory data at the early design stage is acceptable. The results of the validation of the three models show that models A and B are superior to model C.

Table 5. Deviation rate of each stage of the model.

		Model A	**Model B**	**Model C**
Training set	Stage 1	1.6%	−12%	—
	Stage 2	0.6%	2%	—
	Stage 3	16.5%	16.5%	—
	LCA	11.6%	12.1%	12.3%
Test set	Stage 1	−20.5%	−15.6%	—
	Stage 2	−16%	−10.1%	—
	Stage 3	1.77%	1.77%	—
	LCA	7.18%	−2.49%	−12.8%

4. Discussion

4.1. Deviation Analysis

Figure 6 provides a detailed comparison of the estimation results of each model step with the original data. This section summarizes and discusses the factors associated with the large deviations at each stage and highlights the key points to consider when calculating carbon emissions.

Figure 6a illustrates the results of the stage 1 comparison. Calculation boundaries and carbon emission factors are key to the deviations. For example, XL-3 and 4 have reduced carbon emissions by incorporating recycling into their calculation boundaries, and XL-33 requires carbon emission factors for building materials that are less current.

Figure 6b shows the results of the stage 2 comparison. The discrepancy in the data is related to the calculation method and the construction method. For example, for XL-36, the carbon emissions from demolition are estimated to be 27 times higher than the carbon emissions from construction using the Japanese standard provision method, reflecting the limitations of the estimation models in different regions, while CS-4 used a modular timber frame wall system with a construction time of only 20 h, and therefore the actual carbon emissions were lower than the model estimates. This estimation model is limited by database constraints and is only applicable to conventionally constructed buildings.

The comparison results shown in Figure 6c indicate the feasibility of the index estimation method used in this model. The data anomalies in stage 3 had the greatest impact on the LCA due to the differences in calculation boundaries, methods, energy consumption indicators and carbon emission factors. For example, the carbon emissions from heating and maintenance were not included for XL-1. The power consumption index of XL-8 was 104.17 kWh/(m^2·a), but the standard 65 kWh/(m^2·a) was used for estimation. XL-42 adopted the North China grid factor of 0.884 from 2012, while the estimation process adopted the latest version from 2019. The power factor of CS-2 was 1.246, which is 1.3 times the value chosen in this study.

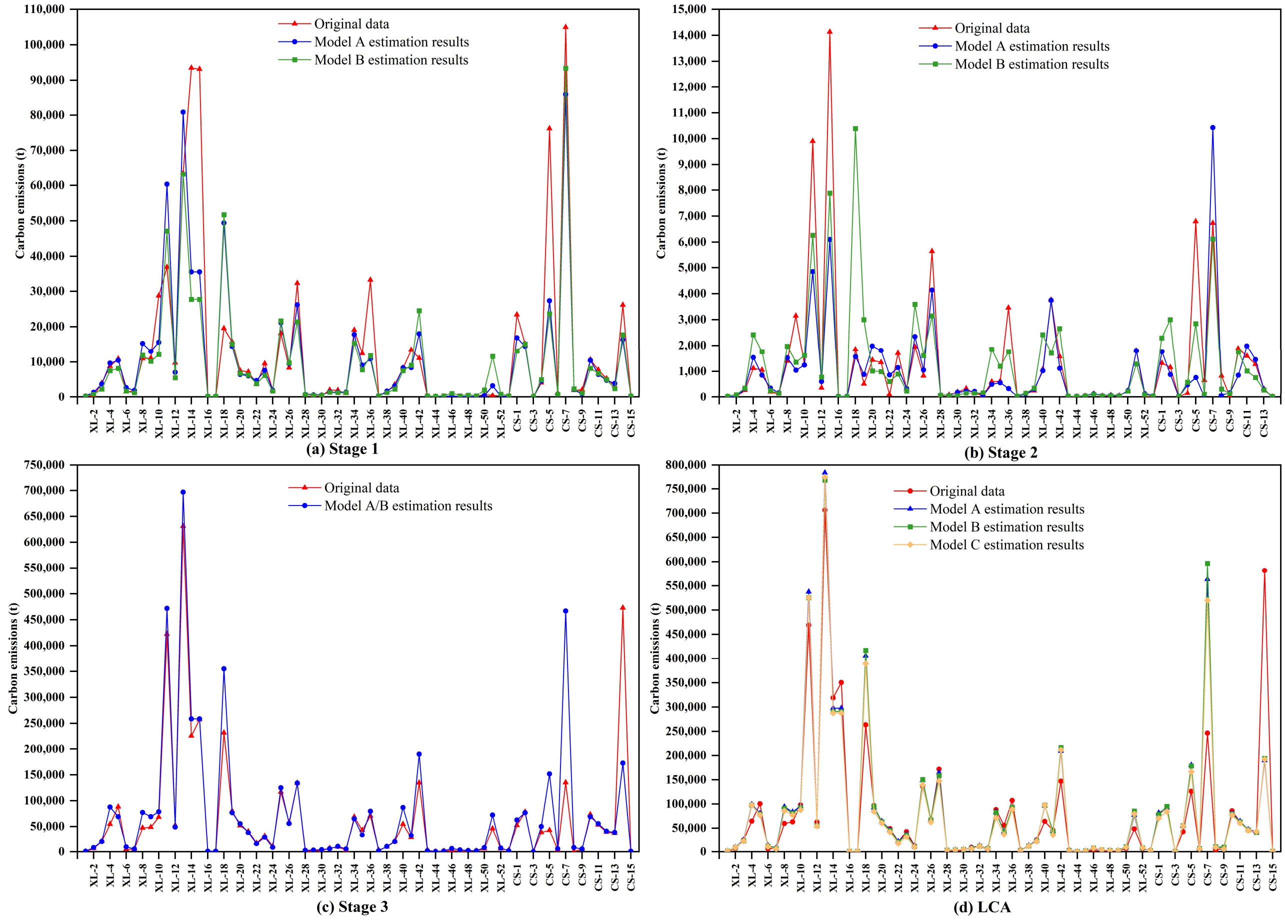


Figure 6. Comparison of original data and estimated results.

Finally, this study shows the deviation of the life cycle calculation results for all cases in Figure 6d, which demonstrates the feasibility of using the model to estimate the life cycle carbon emissions of buildings in China.

4.2. Limitation

The model is mainly limited by the database, including the quantity, quality and degree of refinement. Compared to Europe and the United States, China's research on building carbon emissions started late, and the relevant data collected in this study are still limited.

The model is designed to estimate the life cycle carbon emissions of different buildings and takes into account the energy consumption indicators of different building types. Therefore, this study does not extend the analysis to the energy consumption of components in the operational stage. Further detailed analysis would help to identify potential energy-efficient and low-emission components in buildings. However, two limitations are worth mentioning: (1) the insufficient basic data for each sub-component, and (2) the limitations on the total energy consumption in the energy performance standards for civil buildings are not limited to the energy consumption of each sub-component. In the future, with the maturity of subcomponent metering in China's buildings, we may see a refinement of management and improvement of the basic data, with the operation stage deserving further, in-depth study.

5. Conclusions

The aim of this study was to develop a universal life cycle carbon emission estimation model to meet the needs of non-specialists in the early design phase. Three main conclusions were reached:

A comparison of the Chinese, European and Japanese standards for calculating carbon emissions from buildings showed that only Japan assesses the environmental loads at the design stage and only China does not consider the carbon emissions from maintenance. Europe considers recycling building materials but places it outside the life cycle of the building. The carbon emissions boundary for the estimation model was identified as production and transport (stage 1), construction and demolition (stage 2) and operation (stage 3).

The life cycle carbon emissions data of 68 Chinese buildings were collected in a database using literature research. They contain information on the basic parameters of the buildings (location, climate zone, function, height, area, etc.), carbon emissions at each stage, carbon intensity and percentage. By analyzing the emission data, it was found that the carbon emissions of stage 1 were 10–30%, stage 2 represented less than 5%, and stage 3 represented 70–90%.

A carbon emission estimation model for Chinese buildings has been developed. The model is easy to use, and the user only needs to have some basic professional knowledge to use the model to complete the estimation. In this study, the model was applied to both the training and test sets for feasibility analysis, and was found to have a good performance, with a total deviation rate of less than ±15% over the whole life cycle. Applying the model to estimating carbon emissions at the early stage of building design will help to quickly quantify the carbon reduction in different structures, with wood and steel structures having significantly lower carbon emissions than traditional concrete and frame-shear wall structures. More importantly, the estimation results of this model provide a baseline value of carbon emissions without considering any carbon reduction measures, and designers can select the appropriate carbon reduction scheme based on the difference between this baseline value and the target value, which can guide further design refinement. In addition, due to the lack of a common rapid estimation method for building carbon emissions in China, this study will provide a reference for the calculation of carbon emissions in the absence of inventory data.

In addition, using deviation analysis, this study summarizes the inconsistencies in the boundary and data selection when assessing carbon emission calculation in each stage of China's current building life cycle. The cases collected in this paper are limited due to data privacy and availability. The lack of similar databases in China hinders the development of the relevant empirical values and prediction models. In the future, more case data will be collected to further optimize the model and improve its applicability. The estimation model can be further developed by combining it with a carbon emission reduction technology database.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su16020744/s1, Detailed database information, the fitting analysis process, energy consumption indicators across China and the detailed process and results of model validation are provided in the Supplementary Materials. In addition, references [38–71] are cited in the Supplementary Materials.

Author Contributions: C.G.: conceptualization, investigation, visualization, formal analysis and writing—original draft. X.Z.: methodology, writing—review and editing. L.Z.: funding acquisition, project administration. W.W.: resources, data curation. H.Z.: funding acquisition, supervision, validation, writing—review and editing. Q.W.: project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research and Demonstration of Low Carbon Emission Reduction Design Methods and Key Technologies for Hospitals and Biological Laboratory Buildings (Grant No. 202201063307300007) and the National Natural Science Foundation of China (Grant No. 72374121).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Refer to Supplementary Materials.

Acknowledgments: The authors would like to thank the editor and the anonymous referees for their comments and suggestions, which were most useful in revising the paper. The authors also would like to acknowledge Qian Wang and Junbo Zhao for their kind help with the paper.

Conflicts of Interest: The authors declare that they have no financial and personal relationships with any other people or organizations that could have inappropriately influenced this work.

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