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Research paper

A carbon footprint evaluation model for the entire life cycle of building materials – case study

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Abstract: China's carbon emission research started relatively late. In order to further enrich its related research, the study uses a carbon emission factor fusion building information model and a full life cycle method to calculate the building material carbon footprint of to evaluate the carbon emissions of selected projects. In the instance calculation, it was found that the total carbon footprint production during the operation performed the highest, at 56560.23 t CO_2, accounting for 79.37% of the total carbon footprint output throughout the entire life cycle of the construction project. The total carbon footprint generated during the preparation phase of building materials was 11483.56 t CO_2, accounting for 16.11% of the total carbon footprint output throughout the project life cycle. The total production of carbon footprint during the operation phase was the highest, at 56560.23 t CO_2, accounting for 79.37% of the entire project life cycle. The output of carbon footprint during the dismantling and scrapping stage was 2245.8 t CO_2, accounting for 3.15% of the total amount of life cycle assessment carbon footprint in the project. The total amount of carbon footprint generated in the early stage of the construction project was 1.28 t CO_2, and the total amount of carbon footprint generated in constructing was 973.22 t CO_2. The emission of carbon footprint accounted for 1.37% of the entire project life cycle. The obtained result data has a high degree of overlap with existing research results in China and has certain reference value.

Keywords: carbon emission factor method, building materials, full lifecycle, carbon footprint assessment, BIM

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1. Introduction

The evaluation system and standards for green buildings have been established and implemented in many countries and regions. Although there are certain differences in the evaluation standards and systems for each region, the core is the same [1]. Among the various green building standard systems implemented, the Leadership in Energy and Environmental Design (LEED) in the United States and the Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom are the most authoritative and widely used. Carbon footprint, as one of the ways to measure global warming, has more extensive and precise characteristics compared to carbon emission methods. Due to the complex process involved in the completion of construction projects, a single linear formula between construction carbon footprint and building floors is commonly used to calculate carbon emissions, which amplifies the deviation between actual and measured values [2, 3]. At present, green buildings in China are still in the development stage, and the relevant evaluation standards used areBODY basically based on foreign countries, such as the highly commercialized LEED evaluation standards in the United States. This also resulted in the 156 LEED certification cases cited not being well aligned with the actual construction situation in China. Secondly, in terms of carbon footprint calculation, there is also significant room for improvement in relevant research and reference standards in China. Green buildings are still in the development stage and have not yet formed a mature system. In this context, the study attempts to propose a carbon footprint calculation and evaluation model for building materials based on carbon emission factors, in order to enrich research in the field of green buildings in China, and use the constructed model to calculate carbon emissions and implement the concept of green ecological development environment.

Green development has become a focus, and countries are practicing and adhering to the concept and policies of green development in various industries, as well as in the construction industry. To further evaluate the carbon footprint of building systems, Tilba Thomas et al. evaluated their carbon neutrality ability by studying the carbon dioxide emissions of various building materials [4]. Wang et al. attempted to further increase the conversion of low-carbon materials by using a low carbon footprint method that combines thermal extraction and oxygen cracking in dilute alkaline aqueous solutions. They analyzed and evaluated the carbon containing materials using the carbon footprint factor method. The experimental results showed that the proposed method improved the conversion rate by 12% compared to conventional carbon conversion methods [5]. In modern prefabricated building technology, Li et al. studied concrete composite materials and designed prefabricated concrete composite materials using the life cycle method to construct an overall carbon footprint accounting model. Through experiments, they constructed an overall carbon footprint accounting model. The data showed that the constructed model had good accuracy [6]. In the handling of environmental challenges, due to the frequent neglect of the life cycle of physical devices, scholars such as Thibault proposed a framework based on hardware configuration file parameters to measure the carbon footprint of a hardware throughout its entire life cycle, and the effectiveness of the framework was verified through experiments [7] Wiedmann and other scholars used a common city level input-output table method to calculate the carbon footprint at city boundaries. They found that, considering only territorial emissions, the 79 selected C40 cities reported that

4% of their global annual carbon dioxide emissions came from facility related cross-border sources and related services, accounting for 73% and 27%, respectively [8]. Zeng and other scholars proposed a grid based method to evaluate carbon footprint in a certain region using the Intergovernmental Panel on Climate Change's carbon guidelines, and introduced carbon emission indicators to improve and publish net primary production based on process simulation. They calculated the carbon footprint in Fujian Province from 2005 to 2017 [9] Liu et al. used life cycle methods to evaluate the production, transportation, construction, and operation. The experimental results gave the information that wind farms' carbon footprint in the grasslands was 18701.29 tons [10]. Liu and other scholars optimized the cold chain logistics network to achieve the goal of carbon neutrality, using the method of life cycle estimation to calculate the carbon emissions of various links in the fruit and vegetable cold chain. The experimental results showed that the transportation step accounted for 82% of the carbon emissions [11].

Crippa J and other researchers proposed a method for evaluating the building lifecycle using BIM models, aiming to analyze carbon footprint, CO_2 emissions, and energy consumption by integrating BIM. The study collected and critically analyzed relevant research through a systematic literature review, with a focus on the application of integrated BIM and LCA. The research results show that Asia and Europe have conducted more research in this field, and the number of related papers has significantly increased since 2013, indicating the relevance and importance of this topic. The significance of this method is that it helps to promote the automation of LCA processes during project development, improve environmental analysis efficiency, and provide environmental support in decision-making such as material selection [12]. Mohammed A proposed a BIM model approach to achieve sustainability throughout the entire project lifecycle, aimed at managing and optimizing the relationship between BIM and carbon emissions. This study investigates and identifies the potential of modern technologies to address sustainability, simulates sustainability indicators and standards, establishes activatable sustainability strategies, and categorizes sustainability indicators related to project performance to promote connectivity with BIM platforms. The results show that the relationship between BIM and sustainability can be effectively managed, thereby achieving sustainable BIM models throughout the building lifecycle and promoting sustainable development of the construction industry in terms of carbon footprint and environmental impact [13]. Shukra and other scholars proposed a systematic approach to studying the implementation trends of green BIM. This method first uses Scopus database for scientific econometric analysis, then conducts qualitative content review to assert results, and finally conducts exploratory research on second-hand data to compare AEC industry trends. The results show that although 43% of research focuses on energy analysis, other parameters of green buildings such as material selection, site sustainability, waste management, and water efficiency have not been fully considered. This study contributes a new conceptual framework that integrates green building parameters, BIM tools, and evaluation tools to promote sustainable development in the construction industry [14].

In summary, the calculation of carbon footprint and carbon emissions have become the focus of people's attention today, and the full life cycle and computer technology are also widely used in the design and calculation of carbon footprint models in various industries. However, in the construction industry, especially the carbon footprint calculation research and data of building materials used in construction are still in the development stage, and related research is not as mature as in the West. Based on this, a carbon emission factor based building material carbon footprint evaluation model is proposed, which integrates the entire life cycle and building information modeling (BIM), to enrich thebuilding material carbon footprint projects in China.

The aim of this study is to construct a carbon footprint calculation and evaluation model for building materials based on carbon emission factors, in order to fill the research gap in the field of green buildings in China. Through this model, it is expected to improve the accuracy of carbon emission calculations, promote the localization process of green building standards, promote the implementation of China's green ecological development concept, and support sustainable development goals.

The contribution of this study is that by refining the use of carbon emission factors, the proposed model can improve the accuracy of carbon emission calculation and reduce measurement bias. At the same time, the model has been localized and optimized based on the characteristics of Chinese architecture, which is expected to improve its effectiveness in practical applications in China. The constructed model comprehensively considers the full lifecycle carbon footprint of building materials, providing a comprehensive carbon footprint assessment from material production, transportation, use, and demolition.

2. Constructing a building material carbon footprint model supported by the carbon emission factor method

This section is based on the carbon emission factor method, integrating BIM and Life Cycle Assessment (LCA) for accomplishing the purpose of creating a carbon footprint calculating solution for building materials. According to relevant references, carbon footprint factors for different building materials are selected for calculation, and the corresponding carbon emissions are output.

2.1. Construction of carbon footprint calculation models for BIM and LCA

With the booming development of the construction industry, the development of green building industry is receiving more and more attention from people. Against the backdrop of global warming, various industries have begun to strictly control greenhouse gases such as carbon dioxide. Carbon footprint is admitted as the indicator for measuring greenhouse gas output. Carbon footprint generally includes carbon emissions, and can be used as the total carbon emissions generated by a product or service throughout the entire process, making it more representative. The inspection process for carbon footprint in the construction industry is shown in Fig. 1.

The building materials used in the construction industry generally include three categories: inorganic, organic, and composite materials, and the carbon footprint calculation methods for them generally use three foreign methods: actual measurement, input-output, and emission coefficient. The general measurement method is to estimate and evaluate the results using the

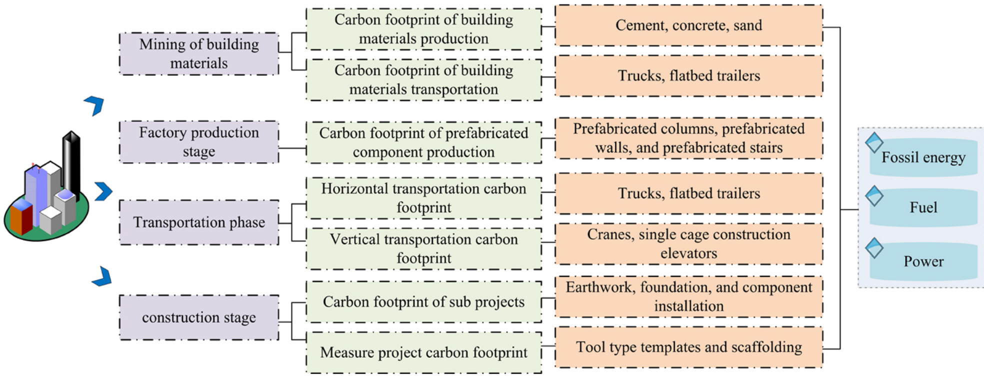

Fig. 1. Carbon footprint inspection process for the construction industry

surveyed data, which has the advantages of convenience and directness. The disadvantage is that the data obtained by the instrument cannot exclude interference during gas exchange, and the accuracy and representativeness of the measured data are not strong enough. The input-output method follows the basic law of material conservation, also known as the material balance algorithm, and its calculation formula is shown in Eq. (2.1).

$$CF_1 = \sum (I_i - O_i) \tag{2.1}$$

In Eq. (2.1), CF_1 represents the carbon footprint calculated using the input-output method; I_i represents the amount of materials and energy input in Stage i; O_i represents the material and energy output in the stage. This method requires obtaining detailed data in advance for each stage of construction, and as a construction project with a large time span, there may be significant deviations between the results obtained from calculating the input and output data of each stage and the actual values. The emission coefficient method, as a method of calculating average carbon emissions based on carbon footprint factors, can balance and consider multiple factors, such as equipment energy consumption during construction, construction site conditions, and construction level, The calculation formula is shown in Eq. (2.2).

$$CF_2 = \sum (A_i \times EF_i) \tag{2.2}$$

In Eq. (2.2), CF_2 represents the carbon footprint calculated using the carbon emission coefficient method; A_i represents the level of activity in stage i, such as the amount of fuel consumed, the amount of materials used, etc; EF_i represents the emission coefficient in stage i, representing the carbon emissions per unit of activity level. After selecting the carbon footprint factor, the corresponding carbon emissions can be calculated based on it, and it will not change with the changes of other factors, with a certain degree of stability [15].

Based on this, the study considers combining the carbon footprint factor with BIM for visual analysis of carbon emissions, ensuring that the designed carbon emission model can ensure certain effectiveness in the early stages. Due to the fact that the carbon emissions involved are a process of carbon emission calculation, considering the carbon emissions of the entire project is a part that cannot be neglected. Therefore, the study introduces LCA based on BIM. LCA, as a method for analyzing, quantitatively calculating, and evaluating the entire life cycle of products, covers various environmental impact indicators of carbon emissions in the construction industry, such as resource consumption, energy consumption, biological toxicity, and land use, and has a comprehensive evaluation scope Strong system logic, emphasis on environmental impact, and relevance to different research objects. The LCA technology framework is shown in Fig. 2.

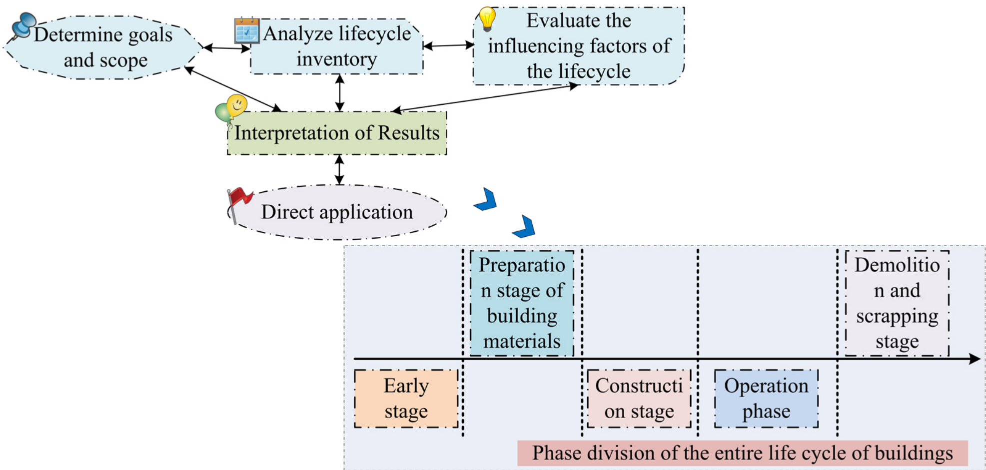

Fig. 2. LCA technology framework and division of stages throughout the entire life cycle of buildings

In Fig. 2, the International Organization for Standardization divides the entire lifecycle assessment into four parts: determining purpose and scope, inventory analysis, impact assessment, and structural analysis. On the basis of dividing the entire life cycle stages of green buildings at home and abroad, this article divides the entire life cycle of green buildings into five stages: planning and design stage (also known as the preliminary stage), building material preparation, construction stage, use and maintenance stage (also known as the operation stage), and dismantling and scrapping stage. Among them, the building material preparation and construction stage can be collectively referred to as the materialization stage. The delineation and interpretation of spatial boundaries is studied for the main building and auxiliary buildings, and construct corresponding carbon footprint calculation models. The carbon emission calculation formula of the model is shown in Formula (2.3).

$$D = (p + t + c + m + d) \cdot A \tag{2.3}$$

In Formula (2.3), D represents the sufficient amount of carbon emissions during the total construction process, i.e. carbon footprint. p is the total amount of carbon footprint in the early stage of construction, t is the total amount of carbon footprint during the preparation of building materials, c is the total amount of carbon footprint during the construction stage, m is the total amount of carbon footprint during the operation stage, and d is the total amount of carbon footprint generated during the demolition of buildings during construction. All of the above carbon footprint quantities are measured in tons. A is the selected carbon footprint factor. Due to the significant differences between different building areas, heights, and uses, it is necessary to set a universal building carbon footprint indicator as a horizontal comparison for carbon footprint calculations between different buildings. Considering that existing research often uses functional units of buildings as horizontal indicators for comparison, the study combines current reference materials for analysis, and also uses building area as the horizontal comparison indicator for this study, Compare and calculate the building area as the carbon footprint concentration, as shown in Formula (2.4).

$$f = (p + t + c + m + d)/s \tag{2.4}$$

In Formula (2.4), f is the carbon footprint concentration index, and s is the building area.

According to the characteristics of LCA, one of the key factors in the green building industry is low-carbon emissions, which results in lower design efficiency, greater design difficulty, and longer design time compared to ordinary conventional construction industries. Therefore, this study analyzes the early stage of building materials, material preparation stage, construction stage, operation stage, and scrapping and demolition stage, aiming to build a carbon footprint calculation model that can have significant comparison and higher accuracy with conventional carbon emission models [16]. The list of LCA carbon footprint calculation and evaluation models for green buildings is shown in Fig. 3.

From Fig. 3, it can be seen that the model constructed by the research institute starts from the early stage of green building, material preparation stage, construction stage, construction stage, and waste treatment stage when calculating the carbon footprint of the project. The carbon footprint calculated by the model covers a wide range and has corresponding representativeness.

2.2. Factor selection and database construction

In the early stage of construction materials, the main consideration is project decision-making and project design, with a focus on analyzing and investigating all the sources of carbon footprint generation in the early stage [17]. The calculation Formula for carbon footprint involved is shown in Formula (2.5).

$$D_1 = Q \cdot M \cdot N \cdot F_e \tag{2.5}$$

In Formula (2.5), D_1 represents the total emissions of carbon footprint in the early stage. Q is the average annual electricity consumption per unit area during the design of office buildings, measured in kWh (m^2/year). M is the per capita office area in the early stage of construction, in square meters. N is the duration of the design, measured3 in years. F_e is the carbon footprint factor for electricity, expressed in $kgCO_2$/kWh. The preparation stage of building materials mainly involves the storage of building materials and corresponding construction. The Formula for calculating carbon footprint in the material storage stage is shown in Formula (2.6).

$$D_2 = \sum_{i=0}^{j} Q_i (1 + u_i) \cdot f_i \tag{2.6}$$

Fig. 3. List of LCA carbon footprint calculation and evaluation models for green buildings

In Formula (2.6), D_2 represents the total amount of carbon footprint during the material storage stage, in units of pieces. j is the total quantity of materials, Q_i is the total quantity consumed and used for the i type of material, in kilograms. u_i is the production loss rate when the i-th material is consumed and used, in %. f_i is the carbon footprint factor of the i-th material, in kgCO_2/unit. The carbon footprint analysis during the construction primarily considers the carbon footprint from the machinery, equipment, personnel, and vehicles transporting building materials during construction. The calculation Formula is shown in Formula (2.7).

$$D_3 = \sum_{i=1}^{j} z_i \cdot g_i + \sum_{i=1}^{j} q \cdot f + C_3 \tag{2.7}$$

In Formula (2.7), D_3 is used to represent the symbol of the total carbon footprint amount in construction, z_i is the total number of i-type machines, g_i is the carbon footprint factor for each i-type machine, q is the number of manual working days during the construction period, and f is the manual carbon footprint factor for each construction day. C_3 represents the total footprint transportation amount during the construction and transportation. Similarly, considering the calculation method during the operation phase, which involves the energy consumption of various electrical and mechanical equipment in construction, the updating of building materials, and the greening rate of green plants, the corresponding Formula for calculating the total amount of carbon footprint is shown in Formula (2.8).

$$D_4 = \sum_{i=1}^{j} K_i \cdot T_i \cdot Fe \cdot y \cdot n + \sum_{i=1}^{j} Q_i (1 + u_i) o_i \cdot f + \frac{\sum_{i=1}^{j} j_i \cdot A_i - 600 \cdot R \cdot S}{40} \tag{2.8}$$

In Formula (2.8), D_4 represents the total amount of carbon footprint during the operation phase, and K_i represents the power of the i-th device, in watts. T_i is the annual operating time of the i-th device, measured in hours. y is the service life of the equipment, in years. n is the total number of equipment in the building, and o_i is the number of maintenance updates for the i-th material, measured in times. The plant species' per unit area carbon reduction is a total of 40 years, measured in kg/m^2. A_i is the green area of the i-th plant, in square meters. R is the green space ratio, S is the land area, in square meters. Finally, calculate the total amount of carbon footprint in the scrapping stage, with an overall focus on carbon footprint calculation for building demolition and waste transportation [18, 19]. The relevant Formula is shown in Formula (2.9).

$$D_5 = 0.1 \cdot D_3 + \sum_{i=0}^{j} M_i \cdot B_i \cdot d_i \tag{2.9}$$

In Formula (2.9), D_5 represents the total amount of carbon footprint in the scrap stage, and M_i represents the amount of waste for the i-th material, in kilograms. B_i is the carbon footprint factor corresponding to each kilometer of the i-th material waste transportation vehicle, and d_i is used to represent the symbol of the waste transportation distance, in kilometers.

At present, experimental methods are generally used to select and determine the carbon footprint factor. Due to some differences in the determination of similar carbon factors at home and abroad, and different experimental designs and conditions, as well as the performance of experimental equipment used, have a significant impact on the carbon footprint factor [20]. Based on experimental methods, this study adheres to the principles of data similarity, priority of data authority, mean value, and priority of new data. According to the different key points in each construction process, the selection and determination of carbon footprint factors are divided into five parts: energy, building materials, construction machinery, transportation, and labor. The commonly used energy sources in China are generally coal, oil, and electricity. Based on relevant domestic and foreign references [21], the corresponding coal carbon footprint factor is determined. The comparison of complete energy consumption in the construction industry of different provinces in China is shown in Fig. 4.

In Fig. 4, the depth of the color represents the energy consumption and carbon footprint of each province. The darker the color, the greater the energy consumption and carbon footprint of the province. The carbon footprint of the construction industry in each province is closely

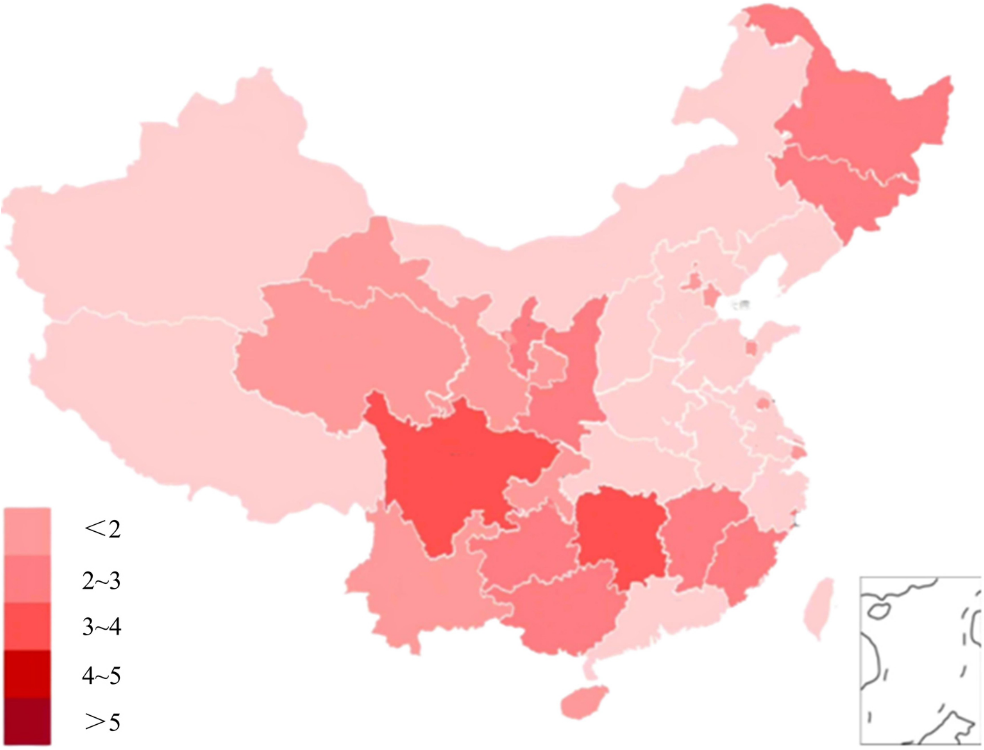

Fig. 4. Comparison chart of carbon footprint of construction industry in different provinces

related to its energy consumption. As a result, the construction industry has a high degree of consistency in energy use and carbon emissions, and the more energy consumption, the higher the carbon footprint. Based on the petroleum carbon footprint factor data summarized by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations, the corresponding petroleum carbon footprint factor is determined through conversion. At the same time, considering the complexity of power carbon footprint, the study used the data provided in the China Life Cycle Basic Database as a reference, combined with seven major power grids in North China, East China, South China, Northeast, Northwest, and Southwest to confirm the power carbon footprint factor. Finally, the power carbon footprint factor was set at 1.04 $kgCO_2$/kWh. Due to the diversity and complexity of building materials used in the construction process, this study is based on the building material data released by the IPCC and supplemented with the corresponding factor in conjunction with the 2019 China Building Carbon Emission Calculation Standard, in order to determine the factor. And according to the relevant data reference, confirm the corresponding transportation carbon footprint factor and artificial carbon footprint factor. After confirming the required carbon footprint factors for each stage, in order to further clarify the footprint calculating under materialization stage, the study continued to integrate BIM for calculation. The framework constructed is shown in Fig. 5.

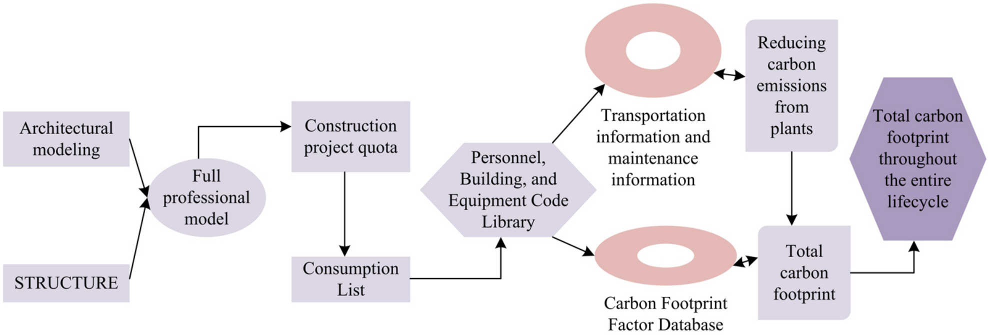

Fig. 5. Carbon footprint calculation framework

In Fig. 5, the carbon footprint calculation framework built by integrating BIM displays more detailed carbon footprint projects in the materialization stage, including material preparation, construction project quotas, consumption lists, etc., which is consistent with the carbon footprint calculation of most construction projects.

3. Theoretical calculation and example application of carbon footprint calculation model

In order to verify the effectiveness of the proposed model, the experiment mainly analyzes the building carbon footprint from the conversion of energy factors, the consumption and production of building materials, and the carbon footprint generated by raw material transportation. Although there are, experiments were conducted to calculate the carbon footprint of a certain construction project during its operational phase. Finally, calculate the carbon footprint of the demolition and scrapping stages, including the carbon footprint of construction demolition, transportation, and waste treatment. Summarize the carbon footprint data of each stage of the entire lifecycle for comparative analysis, and summarize the carbon footprint output ratio of each stage.

3.1. Theoretical calculation and example application of carbon footprint calculation model

In order to verify the effectiveness of the carbon footprint calculation model proposed by the research institute, this study takes a certain building as an example to quantitatively evaluate the carbon footprint of each stage of the entire life cycle of the building project, and calculate the contribution of different stages to overall carbon emissions. The experimental environment includes selecting a typical commercial office building project with a building area of 42157.63 square meters, a service life of 40 years, and a structural design service life of 50 years. The project consists of a podium and a tower, with 3 and 18 floors respectively. The top is equipped with green facilities, and carbon reducing vegetation is planted outdoors, covering an area of over 10%. The experimental data is sourced from IPCC research data and relevant domestic and foreign literature, covering energy consumption, carbon footprint of building materials, carbon footprint of transportation, carbon footprint of operation stage, and carbon footprint of demolition and scrapping stage. The experiment uses BIM technology for data simulation and calculation. According to the research data of IPCC, the selected energy factors were converted and the settlement results are shown in Fig. 6.

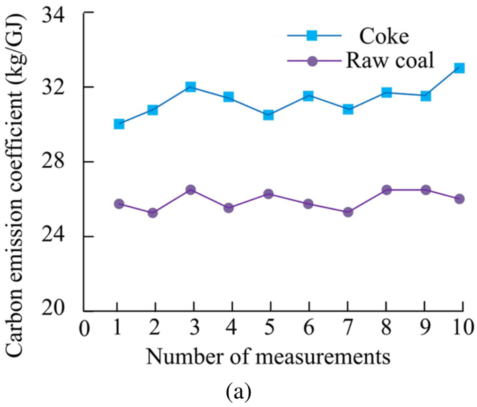

Fig. 6. Carbon footprint factors of raw coal and coking coal; (a) Carbon emission coefficient of raw coal and coke, (b) Carbon dioxide emission

From Fig. 6a, it can be seen that the average carbon emission coefficients of raw coal and coking coal for ten measurements are 26.8 kg/GJ and 29.2 kg/GJ, respectively. From Fig. 6b, the carbon dioxide emissions from ten measurements of raw coal and coking coal are 1.91 and 2.83, respectively. The commonly used petroleum in China is diesel and gasoline. After converting the two's factor reference data, the result is a gasoline carbon footprint factor of 2.36 $kgCO_2/L$ and diesel is 2.50 CO_2/L. In the operation phase, for green buildings that are already in use, monitoring energy can effectively understand the situation of water and electricity consumption, and then determine the total electricity and water consumption of each department in the project year. As a result, raw coal and coking coal directly affect the energy consumption and carbon emissions of buildings. Accurately measuring and monitoring the use of these energy sources can effectively assess the carbon emissions level of buildings throughout their lifecycle. The study determined the energy carbon footprint factor and constructed a carbon footprint model to statistically analyze the annual electricity and water consumption of the project. The information that the experiment outcomes is manifested in Fig. 7.

From Fig. 7a, it can be seen that among the total annual electricity consumption of the project, the annual consumption of socket energy consumption is the highest, at 788600 kilowatts per project year. Next is lighting energy consumption, which is 519000 kilowatts per project year. The total annual electricity consumption of the entire project is 1.37436 million kilowatts, with a calculated proportion of 1%. The total annual water consumption of the project in Fig. 7b is 47677.08 tons. The annual consumption of office water is the

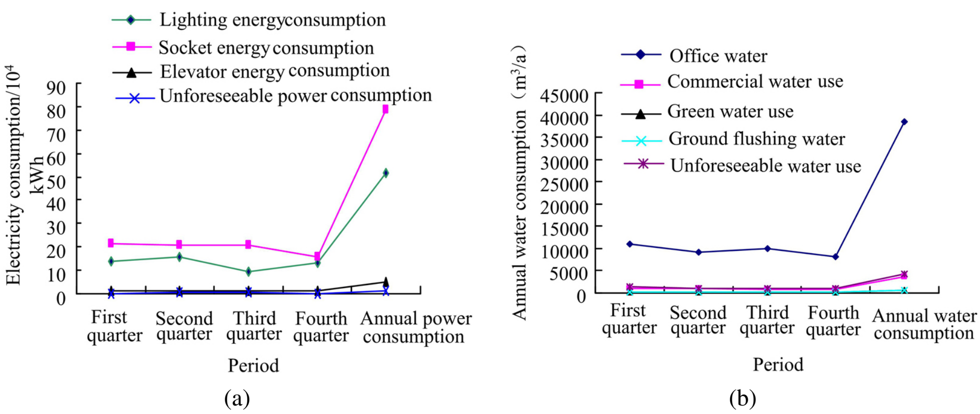

Fig. 7. Integration of electricity and water consumption for the project year; (a) Annual total electricity consumption of the project, (b) Annual water consumption of the project

highest at 38452.90 m^3/project year, followed by unforeseeable water at 4334.28 m^3/project year. The annual consumption of commercial water is 3650 m^3/project year, while the annual consumption of other green water and ground flushing water is not significantly different, but there is a significant difference compared to office, commercial, and unforeseeable water.

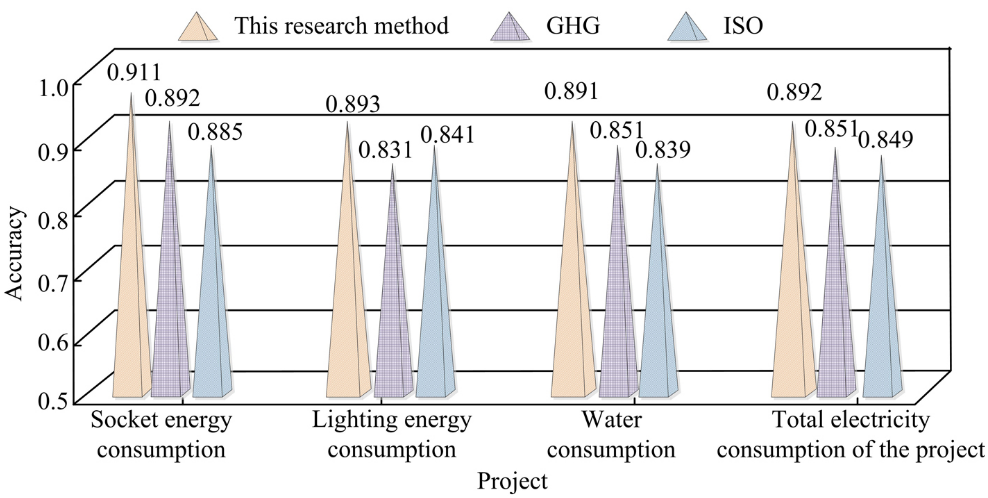

Fig. 8. Comparison results of accuracy calculation using three methods

In order to better validate the superiority of the proposed method, the study chose to compare and verify it with the GHG protocol and ISO standards, and the results are shown in Fig. 8. The results in the figure show that the average calculation accuracy of the proposed method can reach 0.901, while GHG and ISO are 0.852 and 0.836, respectively. Therefore, compared to GHG and ISO, the method proposed by the research institute takes into account more influencing factors, making it more accurate and applicable for calculating energy carbon emissions.

3.2. Practical application analysis of carbon footprint calculation model

After completing the energy calculation, study and select a certain building project for instance calculation. In the selected research object, the total planned area of the building is 101231 m^2, and the total construction area is 42157.63 m^2. The research project consists of a podium and a tower, with 3 and 18 floors respectively. The building of the project is mainly used for commercial offices, and the project has a service life of 40 years. The structural design specifies a service life of 50 years. A certain area of green facilities should be installed on the top of the podium and tower, and a large area of carbon reducing vegetation should be planted outdoors, with a coverage area of over 10%. Based on relevant literature review and domestic and foreign data reference, the material consumption and material production carbon footprint of the building project were measured using the proposed footprint calculating solution constructed by the research institute, as shown in Table 1.

Table 1. The footprint of material production and materials consumption

Name	**Consumption (t or m^2)**	**Material carbon footprint (t CO_2)**
Medium sand	324.19	3.90
Cement	161.52	125.89
Rebar	2294.93	5576.65
Welding rod	22.10	452.60
Iron wire	4.50	72.10
Steel formwork	275.79	/
Scaffolding fixtures	164.22	/
Scaffolding steel pipe	262.63	/
Concrete	16815.48	4388.86
Water	19453.19	5.08
Plastic film	24728.64	1.05
Concrete aerated block	1196.82	71.62
Cement mortar	55.03	110.24
Embedded iron parts	38.77	89.15
Styrene-Butadiene-Styrene	9335.81	120.92
Polyurethane waterproof coating	20.33	420.56
Organic glass	27500.02	217.55
Asphalt waterproof coating	21.04	367.26
Ceramic tile	17831.02	290.19
Lime	123.23	147.87

From Table 1, the most carbon footprint generated by building materials is steel bars, consuming 2294.93 tons of steel bars and generating 5576.65 tons of carbon dioxide. On average, each ton of steel bar consumed will produce 2.43 tons of carbon footprint. The second largest producer of carbon footprint is concrete, with 16815.48 m^3 of concrete producing 4388.86 tons of carbon footprint. The amount of carbon footprint produced by welding rods is 452.6 tons, while the production of carbon footprint from other building materials is below 400 tons. Some materials like steel formwork, scaffolding fixtures, and scaffolding steel pipes do not produce carbon footprint.

After completing the carbon production footprint calculation, it is necessary to calculate the carbon footprint generated by the transportation of raw materials. The study sets the transportation distance for all building materials to be 100 km, transported by the same heavy-duty truck to the construction site, and stipulates that the truck's load capacity is 40 tons. The fuel consumption of the truck is 40 liters per 100 kilometers, and the energy used is diesel. Finally, it is set that the raw materials required for construction have the same quality as the finished raw materials transported to the construction site. The transportation related information and carbon footprint results during the material preparation stage are shown in Table 2.

From Table 2, it can be seen that there is no significant positive correlation between the transportation volume of materials and the footprint. The highest output during the construction phase is concrete, which is 41.60 tons of carbon dioxide, followed by organic glass, which is 6.90 tons of carbon dioxide. The carbon footprint output of steel bars is 5.81 tons of carbon dioxide. The carbon output values of other building materials during the construction phase are relatively small, mostly below 1 ton.

Due to the selected building being an office type, the main consideration during the office phase is the carbon footprint caused by changes in electricity and water resources. At the same time, attention should also be paid to the carbon footprint changes during material maintenance and replacement during the operation phase. According to the model constructed by the research institute, the carbon footprint calculation results during the operation is manifested in Table 3.

From Table 3, during the operation phase, the total amount of carbon footprint generated by the power system is the highest, with a value of 62887.99 tons of carbon dioxide. The total water, tiles, and coatings' footprint during the operation phase is 545.44 t CO_2, 290.85 t CO_2, 418.02 t CO_2, respectively. The vegetation set can achieve a carbon reduction of 1927.22 tons of CO_2, and the total carbon footprint during the operation phase is 62215.92 tons of CO_2. During the entire construction project, due to the presence of demolition and scrapping in each stage, the carbon footprint model was used to calculate the amount of work involved in demolition construction, transportation, and waste disposal, resulting in the corresponding total amount of carbon footprint. The experimental results are shown in Fig. 9.

From Fig. 9, it can be seen that the quantity of work during the demolition construction, transportation, and waste disposal stages is consistent, at 56902.34 tons. However, there are significant differences in the total amount of carbon footprints in each stage. The total amount of carbon footprints in the construction demolition stage is 1666.53 t CO_2, ranking first in the total carbon footprint output through entire construction. Next is the waste treatment stage, where the total output of carbon footprint is 437.58 t CO_2. Finally, during the dismantling and transportation stage, the carbon footprint output was the smallest among the three stages, at

Table 2. Transport related information and carbon footprint results during the material preparation stage

Name	Transportation volume (t orm^{2}orm^3)	Carbon footprint (t)	Transportation frequency
Medium sand	324.19	0.90	9
Cement	161.52	0.46	2 5
Rebar	2294.62	5.81	55
Welding rod	22.10	0.03	2
Iron wire	4.50	0.03	2
Steel formwork	275.79	0.78	8
Scaffolding fixtures	164.22	0.46	5
Scaffolding steel pipe	262.63	0.67	7
Concrete	16815.48	41.60	384
Water	19452.42	0.02	/
Plastic film	] 24728.64	0.03	2
Concrete aerated block	19800.02	4.92	46
Cement mortar	55.03	0.24	3
Embedded iron parts	38.77	0.03	2
Styrene-Butadiene-Styrene	9335.72	0.03	2
Polyurethane waterproof coating	20.33	6.90	2
Organic glass	27500.02	0.03	64
Asphalt waterproof coating	21.04	0.03	2
Ceramic tile	17831.02	0.90	6
Lime	123.23	0.35	4

Table 3. Carbon footprint calculation results during operation

Name	Number	Life	Total carbon footprint (t CO_2)
Electricity	151.19	40	62887.99
Water	52444.81	40	545.44
Ceramic tile	17831.02	Updated every 30 years	290.85
Coating	40.29	Updated every 10 years	418.02
Plant carbon reduction	4400.02	40	-1927.22

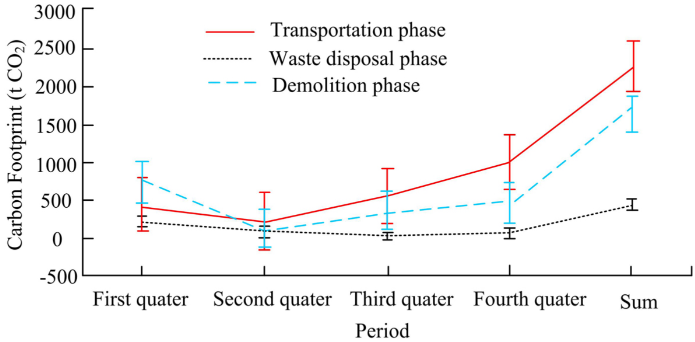

Fig. 9. Dismantling the carbon footprint during the scrapping stage

141.17 t CO_2. The total amount of carbon footprint during the dismantling and scrapping stage is 2245.28 tons of CO_2. Using BIM technology and carbon footprint model, calculate and summarize the carbon footprint amount at each stage of the entire life cycle of the selected research object. The relevant data results are shown in Fig. 10.

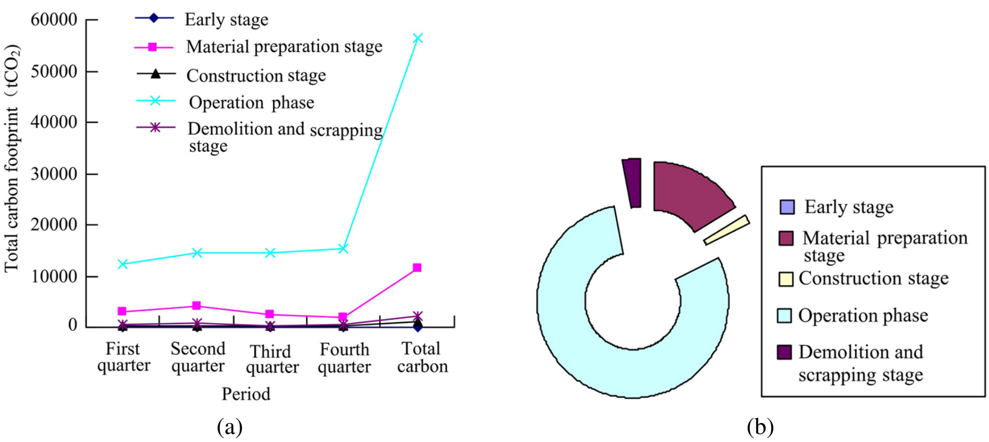

Fig. 10. The carbon footprint of each stage of the research project's entire life cycle; (a) Summary of carbon footprints at different stages, (b) The proportion of carbon footprint at each stage

From Fig. 10a, it gives the information the total carbon footprint production during the operation phase is the highest, at 56560.23 t CO_2, accounting for 79.37% of the total carbon footprint production in the LCA of the entire construction project. According to the analysis of carbon footprint output in operation of existing construction projects, the proportion of carbon footprint in operation of construction projects is generally 70% to 80% of the total carbon footprint in the LCA of the] project. The carbon footprint model constructed by the research institute for calculating the footprint in the operation phase, which is consistent with the existing research results. The second highest carbon footprint output is in the construction material preparation stage, with a total carbon footprint of 11483.56 t CO_2, accounting for 16.11% of the LCA carbon footprint output in the entire construction material preparation stage. Similar to existing research results. The total output of carbon footprint in constructing is 973.22 t CO_2, accounting for 1.37% of the total carbon footprint in the project LCA. The carbon output during the dismantling and scrapping stage is 2245.8 t CO_2, accounting for 3.15% of the total carbon footprint of the project LCA. However, in the early stages of the project, the main focus is on planning and designing the construction project, so the total carbon footprint will be relatively small, with a value of 1.28 t CO_2, accounting for 0% of the entire life cycle.

4. Conclusions

To further enrich the calculation of carbon footprint in China's building materials industry, a carbon footprint calculation and evaluation model based on carbon emission factors, integrating BIM and LCA, is proposed. The experimental results showed that the carbon footprint calculation model constructed by the research institute had a total electricity consumption of 1.3743 million kilowatts in the annual energy calculation of the project, with an annual water consumption of 47677.08 tons, of which office water accounted for the largest proportion, Each project consumed 38452.90 m^3/year. Based on the energy data obtained from the model, an example building project was selected for corresponding calculations. The total amount of carbon footprint generated in the early stage of the building project was 1.28 t CO_2, and the total amount of footprint generated in construction was 973.22 t CO_2, with LCA accounting for 1.37%. The carbon output during the dismantling and scrapping stage was 2245.8 t CO_2, accounting for 3.15% of the total LCA. The total footprint generated during the preparation of building materials was 11483.56 t CO_2, accounting for 16.11% of the project's LCA footprint output. The total production during the operation phase was the highest, at 56560.23 t CO_2, accounting for 79.37% of the total project LCA carbon footprint output. Compared with existing research data, the carbon footprint calculation model constructed by the research institute has certain reference value. However, due to the use of foreign research results in terms of data and not being well adapted to the actual situation in China, there is still room for improvement.

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