Hindawi
Advances in Civil Engineering
Volume 2020, Article ID 8853536, 9 pages
https://doi.org/10.1155/2020/8853536

Research Article

Estimation Method of Carbon Emissions in the Embodied Phase of Low Carbon Building

Hongwei Liu, Jun Li, Yafei Sun, Yanshu Wang, and Haichun Zhao

College of Civil Engineering, Yancheng Institute of Technology, Yancheng, China

Correspondence should be addressed to Jun Li; lijun@ycit.edu.cn

Received 24 May 2020; Revised 7 November 2020; Accepted 12 November 2020; Published 10 December 2020

Academic Editor: Dan Ma

The carbon emission at the embodied phase is a complex combination, extending the life cycle of the building, defining the process of the embodied phase scientifically and finding out the direct and indirect carbon emission sources in the embodied phase. Building materials have the characteristics of "low carbon surface, hidden high carbon." Emission factor calculation method is used to establish carbon emission model for building materials. Considering the effect of design optimization on the carbon emissions of the whole life cycle of the building, a low carbon level system is set up to optimize the target of low carbon design. In the construction phase, the carbon emission sources, emission boundary, and calculation model are determined according to the subdivisional engineering division method. Through a series of process decomposition, the total amount of carbon emissions at the embodied phase can be obtained, and the carbon emission quota list at the embodied phase can be compiled to provide technical support for the carbon trading mechanism of the building.

1. Introduction

Population growth, environmental pollution, and energy shortage are the three major problems to be faced now and in the future. "Green development" and "low carbon life" have gradually become the key words of the times. In 2009, the "Building and Climate Change" of United Nations Environment Programme (NNEP) reported that global buildings discharge 86 billion tons of CO_2 annually, and by 2030 emissions will increase to 156 million tons. At the regional level, a new tripartite cluster structure has been identified by the three gradually stabilized communities centered on USA, China, and Europe [1]. In the US, the construction industry is the third largest source of greenhouse gas (GHG) emissions [2]. In the European Union, buildings are the largest consumer of energy accounting for up to 40% of the total energy consumption and approximately 36% of the greenhouse gas emissions [3, 4]. Due to the rapid growth of social and economic development in China, the carbon emissions of building are greater than other countries, which have attracted the attention of the government. According to the research results of the Building Energy Saving Research Center of Tsinghua University (BESRCTU), in 2012, the total energy consumption of building amounted to 6.90 hundred million tons of standard coal, accounting for 19.1% of the total energy consumption in China [5]. At present, the international carbon emission trading system, except the Tokyo Metropolitan Trading System in Japan, does not include building emission reduction into the scope of mandatory trading control. This is mainly because of the transaction subject, emission boundary, emission reduction cost, and other factors, especially the difficulties and differences in building carbon emission data accounting, baseline determination, and so on, which are the primary problems to be solved in building carbon trading.

However, the energy consumption of building is influenced by many factors, such as climate zone difference, design type, construction method, building material, property, and energy management. The calculation of carbon emission is very complex. At present, the research on carbon emissions of buildings has made some achievements based on the Life Cycle Assessment (LCA) [6–12]. The LCA method is mainly used to calculate the carbon emissions of a product during the whole life cycle, including the raw materials, production, use, and demolition. We first determine the boundary of the research system, then calculate quantitatively the consumption of resources and the carbon emissions, and finally analyze the impacts on the environment. B. Steen, N. Itsubo, and A. Inaba evaluated the carbon emissions of buildings [13]. The existing basic methods of carbon emission quantification mainly include the measurement method, the process analysis method [14, 15], the input-output analysis method [16], and the hybrid method [17]. According to the different composition structure of the hybrid method, it can be divided into three categories: the tiered hybrid analysis (TH), the input-output based hybrid analysis (IOH), and the integrated hybrid analysis (IH) [18]. The hybrid analysis combines the advantages of the two methods and has been widely used in carbon emission quantification in recent years [19]. Lin Borong, Liu Nianxiong, and Pengbo use basic data of the Intergovernmental Panel on Climate Change (IPCC) to calculate the total carbon emissions, but the results can only represent the overall carbon emissions of the construction projects, which cannot subdivide direct and indirect emissions [20]. There are differences in carbon emissions in life cycle of a building, especially in the embodied phase where a large amount of materials, construction equipment, and equipment are used, and diesel, gasoline, electricity, and other energy are consumed. Research shows that building materials have the characteristics of high carbon emissions, and their indirect carbon emissions account for more than 92% [21]. Sharrard set up a hierarchical LCA model to calculate the energy consumption of the construction industry and environmental impact in the United States. The environmental impact of the materials is calculated by the IO-LCA, and the process analysis method is used to calculate the environmental impact of the construction phase [15, 22]. However, due to the complex calculation of carbon emissions during the embodied phase of the building, it has not become the focus of current research on building carbon emissions [23]. In the embodied phase, carbon emissions are important from the building life cycle, accounting for 20% [24, 25], and some research shows that they reach 40%–45% [26, 27]. Therefore, carbon emissions have an important impact on building carbon trading during the embodied phase.

The key to the calculation of carbon emissions is to find all emission factors. The factors of the embodied phase are mainly energy carbon emission factors (coal, oil, natural gas, electricity, etc.), the material, and construction equipment carbon emission factors. If the emission factors can be found, the calculation of carbon emissions will follow the same rules, whether it is wood structure, steel structure, or concrete structure. Chinese Life Cycle Database (CLCD) is the only systematic and comprehensive database in China, covering the LCA data of China's major energy, raw materials, and transportation; covering resources, energy, water consumption, GHG, and major pollutants; and supporting the analysis of energy conservation and emission reduction (ECER); however, the basic parameters of this database are provided by the IPCC [28, 29].

The results show that the calculation of carbon emission in the embodied phase is a complex combination. According to the characteristics of each phase, different methods should be adopted to calculate the emissions, which is scientific and practical. However, the calculation of carbon emissions in this stage needs to first define the scope of this phase according to the division of building life cycle. Secondly, according to the contents contained in this phase, the carbon emissions are calculated separately. In the phase of material production and transportation, the carbon emissions of building materials are calculated by material balance method, and the total carbon emissions are obtained by determining the corresponding emission factors and carbon source consumption. In the design and preparation stage, the direct carbon emissions are less, but the design scheme and optimization have a great impact on the carbon emissions of the whole life cycle of the building. A low carbon level system should be established to effectively reduce the carbon emissions of the life cycle of the building through the optimization of different levels of layers. In the construction stage, according to the fuel emission factors, we define the emission factors of all kinds of mechanical shifts and calculate the corresponding carbon emissions of construction equipment. Through a series of process decomposition, the calculation of carbon emissions in the embodied stage is more scientific and reasonable.

2. Calculation Range of Carbon Emission at Embodied Phase

The boundary determination of a building life cycle is a necessary condition for the calculation of carbon emissions. This study does not consider the external policy and the natural climate change factors, mainly considering the inner system boundary of the building, which mainly refers to a series of processes of a building. The related research of the China Urban Science Research Association's Green Building and Energy Conservation Professional Committee (GBECPC) divided the building life cycle carbon emissions calculation into seven phases: materials production, materials transportation, construction, operation, maintenance, demolition, and waste recycling. However, this division does not take into account the owner's "three connections and one leveling," water connected, electric power and roads supplied, and the ground leveled in the preparatory phase of the construction. Therefore, in estimating the whole life cycle carbon emission of a low carbon building, it must be carried out according to the standards, which can be defined as "three connections and one leveling," building materials production, design optimization, materials transportation, construction process, low energy operation and maintenance, demolition, and materials recycling. These processes can be divided into three phases: materials processing, operation and utilization, and demolition and recycling. In this way, three items, materials processing, design optimization, "three connections and one leveling," and construction process compose the green building embodied phase.

2.1. Carbon Emission in the Materials Processing Phase. According to Adalbert's survey in Sweden, 20% of the energy consumption in the whole life cycle of building comes from materials [25]. The phase of material preparation is the second largest source of the whole life cycle carbon emissions [30–32]. This also fully shows that building materials have the characteristics of implication high carbon, and the calculation of their carbon emissions is very important. However, the characteristics of the building are unique, and the materials used and the construction methods are different. It is necessary to define the calculation range and the calculation method to estimate the carbon emissions in the embodied phase of a building. According to the law of conservation of mass, the carbon emission factor method is used to calculate the carbon dioxide emission model in the phase of materialization, based on the theoretical basis of the mass of the inputs and the mass of the output. It is assumed that the loss in the production process is not considered. The carbon emission factor method can be used to build the carbon dioxide emission model in the embodied phase [33]. The basic formula is as follows:

$$\text{carbon emissions} = \text{carbon emission factor} \times \text{carbon source consumption}. \quad (1)$$

According to formula (1), the key to calculate carbon emissions is to determine carbon emission factors.

2.1.1. Establish the Calculation Model of Carbon Source Consumption. First, we must determine Q_{jk}:

$$Q_{jk} = w_j \times q_k, \quad (2)$$

where j is a resource type, such as labor, materials, and construction equipment. k is the carbon source type of j resource consumption, fossil, such as electric carbon sources. Q_{jk} is the k carbon source consumption standard of category j resource.w_j is the unit input of j resource in the quota. q_k is the k carbon source consumption standard.

2.1.2. Establish the Calculation Model of Carbon Emission Factor. Carbon dioxide emissions are mainly electricity consumption and gasoline, diesel, and other fossils. Analyzing the carbon emission guidelines published by the World Resources Institute (WRI), Intergovernmental Panel on Climate Change (IPCC), and Energy Research Institute of China National Development and Reform Commission, we can establish carbon emission factor calculation models for electric power and fossil fuels.

(1) The calculation model electric power emission factor formula:

$$C_{eR} = \frac{E_{m_R} + E_{m_{R,e}}}{E_R + E_{R,e}}, \quad (3)$$

where R is the area of the project. According to the climate zone types, C_{eR} is the average CO_2 emission factor of the R area electric power; E_{m_R} is CO_2 emissions of the R area electric power generation; $E_{m_{R,e}}$ is CO_2 emissions of other areas' electricity sent to the R area; G_R is the total power generation of the R area; $G_{R,e}$ is the total power generation of other areas' electricity sent to the R area.

(2) The calculation model fossil fuels emission factor:

$$C_{fCO_2,T} = FF_T \times CC_T \times CF_{T,\text{tec}} \times \beta \times \frac{44}{12}, \quad (4)$$

where $T$is the fossil fuel type; $C_{fCO_2,T}$ is the CO_2 emission factor based on mass or volume of the T fuel; $FF_T$is the carbon oxidation rate of the T type fuel during combustion(%); CC_T is the carbon content of unit calorific value of the T type fuel (tc/MJ); $CF_{T,\text{tec}}$ is the reference conversion standard factor of the T type fuel in "Energy Use Situation Report" of important energy use enterprises. β is the calorific value of per-ton standard coal (tcal), 29307 MJ. (44/12) is the molecular weight conversion factor (carbon dioxide and carbon).

2.1.3. Establish the Calculation Model of Carbon Emissions

(1) Calculation model of unit carbon emissions:

$$U_{ij} = \sum_{jk} C_{fjk} \times Q_{jk}, \quad (5)$$

where i is the item type with the construction project budget quota corresponding; C_{fjk} is the $k$emission factor of j and can be get by formula (3) or (4); and U_{ij} is the unit carbon emission of j in i.

(2) Calculation model of total carbon emissions:

$$TQ_{CO_2} = \sum_{i=1}^{n} Q_i \times U_{ij}, \quad (6)$$

where $Q_i$is the estimated quantity of i in embodied phase (determined by the construction drawings). TQ_{CO_2} is the total carbon dioxide emission in embodied phase.

According to all kinds of building materials and machine-teams in the construction project budget quota and the bill of quantities, the carbon source consumption standard and the carbon emission standard can be determined by formulas (2) and (5), and the carbon emissions calculation budget quota of various building materials can also be compiled. Then, using this quota, we can directly calculate the carbon emissions in the process of material production and transportation [34].

2.2. Carbon Emissions at Design and Preparation Stages. In the embodied phase, an important factor of the carbon emission is the low carbon of the building itself. The traditional architectural design stage is generally based on the

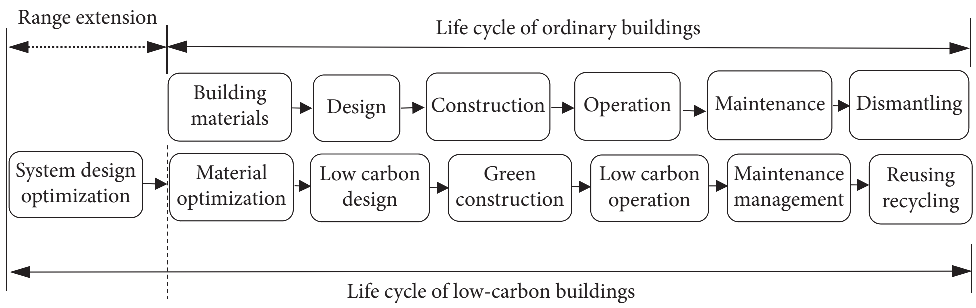

Figure 1: Life cycle division of low carbon buildings.

active or passive energy saving measures based on the existing building design scheme. The defect is that the low carbon concept and the building scheme are not integrated in the early stage of the architectural design, which makes the carbon emissions in the design and preparation stage not fully considered. Low carbon buildings need to be considered from the system design of the program. When we divide the life cycle of low carbon buildings, we should consider the forward movement of the starting point, as shown in Figure 1 [35].

Therefore, low carbon design should take into account all phases of building life cycle. The above research shows that building materials have a great impact on carbon emissions. The low carbon level system can be set up, and the scheme and technology are integrated into the low carbon design system by superposition and optimization of different levels of the system, so as to avoid the design defects.

In this system, factors can be categorized into three different levels: building reality, envelope, and units (Table 1). For comparative analysis, we can set standard values and variable values of simulation factors at each level and divide building information into small simulation factors. Simulations factors can be single, combined, or simulate the design system. The carbon emission difference between the variable value and the standard value of the change part can be obtained by comparing the changes in each part with the design standards.

First of all, as regards analysis of design, we can compare the single-factor carbon emission standard value and the change value from the building reality level. By comparing conditions, forms, and values of factors $(C_{A_0}, C_{A_1}, C_{A_2}, \ldots)$, we can get the change value $(C^0_{A_n}, C^1_{A_n}, C^2_{A_n}, \ldots)$ of carbon emissions caused by the change of each factor itself. We also can get the change value $(C^0_{B_n}, C^1_{B_n}, C^2_{B_n}, \ldots)$, $(C^0_{C_n}, C^1_{C_n}, C^2_{C_n}, \ldots)$. The standard value is the set value of the simulation factor and the change value is the range of the values used by the building code. Through the change of each factor, the influence on the total carbon emission is analyzed. The factor value of the minimum carbon emission is the optimal value.

It is feasible to analyze the influence of single factor in theory, but the factors are influenced by each other between the three levels. For example, the ratio of window/wall will be increased, the energy consumption in indoor lighting will be reduced, and the thermal insulation performance will also be reduced, but this will result in increasing the energy consumption of the HVAC, so it is necessary to consider the enclosure at the same time. Moreover, the structures and components can also influence carbon emissions; so, the interaction of multiple factors in the optimization design of carbon emissions must be considered. Therefore, the interaction of multiple factors must be considered in the optimization design of carbon emissions. Through the analysis, a low carbon analysis system can be set up to optimize the various factors according to different regions and types of buildings. Through the selection of different factors in all levels, the carbon emission in the design can be kept in a controllable range, so that the system design is more technical, reasonable, and scientific. Finally, we can achieve the best energy saving and emission reduction effect.

2.3. Carbon Emissions at Building Construction Phase. Various kinds of construction equipment are used during the building construction phase, which consume diesel, gasoline, electricity, and other kinds of energy. In this phase, since carbon emissions are involved in complex construction process, carbon emission is complicated by theoretical calculation.

We can put the site leveling into the building construction phase, calculated in accordance with the amount of construction equipment. We can divide the construction into four phases: pile foundation, main structure, roof, and decoration engineering. Combined with the cost quota, each stage can be subdivided according to the CWBS method, which is divided into pile foundation, concrete, steel bar, vertical transportation, doors and windows, exterior wall decoration, and so on. Then classify these subitems, determine the carbon emission boundary, and divide the carbon emission sources, so that they can be calculated according to the above emission types [23, 36].

2.3.1. Classification of Carbon Emission Sources. The resource types are divided into diesel, gasoline, coal, electricity, and so on. The resources consumed by each subdivision project have both differences and commonness, but there are certain differences between different phases. Based on the PAS2050 code, the boundary is divided into foundation, main structures, roofing, and decoration according to the carbon emission source (Figure 2). In the foundation, the mechanical carbon emissions from site leveling and

Table 1: The low carbon level system.

Level system	Building reality (A0-n)					Envelope (B0-n)									Structural component (C0-n)				
Simulation factor	Plan form	Building shape	Shape coefficient	Orientation	Other factors	Wall heat transfer coefficient	Insulation thickness	Peripheral color	Window/wall	Windows heat transfer coefficient	Roof form	Roof heat transfer coefficient	Shading coefficient	Other factors	Sun shade	Solar energy	Wind energy	Heat pump	Other factors
Type	Square	Specification	Building size	Best orientation	Other types	K value	Design energy saving rate	Design color	Within the scope of the specification	K value	Different type	Within the scope of the specification	Within the scope of the specification	Other types	Roofing facade mixed type	Solar energy optic-electric photo-thermal	Wind turbine vertical axis turbine	Ground-source/water source heat pump	Other components
Carbon emission change value	C_{A_0}	C_{A_1}	C_{A_2}	C_{A_3}	C_{A_n}	C_{B_0}	C_{B_1}	C_{B_2}	C_{B_3}	C_{B_4}	C_{B_5}	C_{B_6}	C_{B_7}	C_{B_n}	C_{C_0}	C_{C_1}	C_{C_2}	C_{C_3}	C_{C_n}

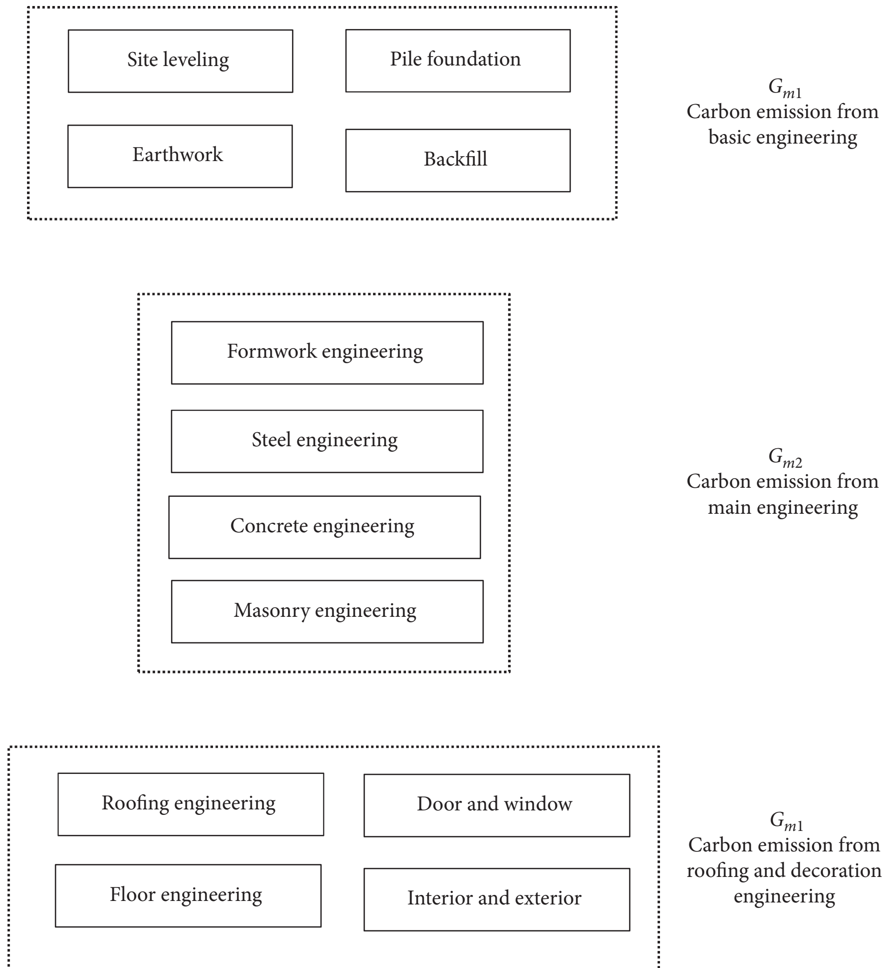

Figure 2: Carbon emission boundary divisions.

earthwork engineering are mainly the consumption of diesel and gasoline. The carbon emission of construction equipment is mainly derived from the consumption of diesel and electric power according to the category of piles. The main structure mainly includes the construction process of steel making, concrete, formwork, masonry, and so on. There are many kinds of construction equipment used in this phase, which involve a lot of use of power, diesel, and gasoline. The total amount of carbon emissions is also large. Roofing and decoration engineering construction equipment consumption is relatively small, but at these phases, a variety of horizontal and vertical transport construction equipment was used, and there are more carbon sources.

Considering the carbon emission boundary based on the PAS2050 code, combined with the general formula, the three phase models are identified:

$$I_C = \sum_{n=1}^{3} G_{mn} \times P_q, \quad (7)$$

where I_C is the carbon emission index; G_{mn} is the quality of GHG produced by the m building at its n phase $(n = 1, 2, 3)$ (foundation, main structures, roofing, and decoration). P_q is the potential value of global warming effects of GHG ($kgCO_2/kg$).

$$G_{mn} = G_{m1} + G_{m2} + G_{m3}, \quad (n = 1, 2, 3). \quad (8)$$

According to the classification of energy and combined with $C_{fCO_2,T}$ of formula (4),

$$G_{m1} = C_d \times Q_{M_1} + C_o \times Q_{M_2} + C_e \times Q_{M_3}. \quad (9)$$

In the same way, G_{m2} and G_{m3} can be obtained, where C_d is the diesel carbon emission factor ($kgCO_2/kg$). C_o is the gas carbon emission factor ($kgCO_2/kg$). C_e is the electric power carbon emission factor ($kgCO_2/kg$). Q_{M_1}, Q_{M_2}, and $Q_{M_3}$are the corresponding energy consumption.

Because the carbon emission from the construction equipment is derived from the consumption of diesel, gasoline, and electricity, the carbon emission factors of several of construction equipment can be determined by the unit energy consumption and carbon emission factor:

$$G_{mn} = \sum_{n=1}^{3} Q_{M_k} \times C_{\mathrm{Mk}}, \quad (10)$$

where k is the construction equipment number ($k = 1, 2, 3, \ldots$), C_{Mk} is the construction equipment emission factor, and Q_{M_k} is the construction equipment consumption.

2.3.2. Parameter Determination. According to the energy carbon emission factor, combined with the national unified construction equipment cost quota (NUCMCQ, 2013), the unit carbon emissions of each machine are determined:

$$C_{\mathrm{Mk}} = S \times Q_{M_k}, \tag{11}$$

where S is the construction equipment cost composition.

Then, $G_{mn} = \sum_{n=1}^{3} Q_{M_k} \times C_{\mathrm{Mk}}$.

Through calculation, we can get all kinds of carbon emission factors of construction equipment.

3. Discussion

In the life cycle of building, there are many kinds of construction and use activities, and the system boundary is complex. The carbon emission in the embodied phase of buildings is a complex combination, the calculation method is complex, the boundary division standard is not uniform, and the calculation results are very different. In the material production stage, there are mainly raw materials mining, processing, and storage; in the production stage, the main resource and energy flow are the input of raw materials and energy and the output of materials and components. In the construction stage, the research idea is to classify carbon emission sources, decompose by Construction Work Breakdown Structure (CWBS), and calculate by quota and inventory. Considering the characteristics of the building stage, this study adopts different methods and ideas to calculate the carbon emission of the embodied phase and applies a variety of indicators, which have wide applicability. Carbon emission factor is an important parameter to represent the characteristics of greenhouse gas emissions of a substance. In the study of carbon emissions in the life cycle of buildings, CO_2 is usually the focus of research, and the corresponding conversion coefficient can be reported according to IPCC AR5 [37]. In this study, for the calculation of carbon emissions of building materials, we can estimate the carbon emissions in the production and transportation of materials according to the quota and bill of quantities [38, 39]. Combined with the results of case studies, it is helpful to combine theory with practice and provide a basis for the calculation of carbon emissions in the embodied phase.

In view of the complexity of the analysis of carbon emissions in the embodied phase and the inconsistency of calculation methods, in the future, we should constantly supplement, improve, and enrich the existing carbon emission factor database of the existing Chinese Life Cycle Database (CLCD) and establish a special building carbon emission database, so as to change the inaccurate or missing of the existing carbon emission factors on the results.

The scientific accounting method of carbon emissions is to accurately calculate carbon emissions. At present, the calculation method of carbon emission in the stage of building based on inventory has good applicability, but the calculation method based on BIM is simpler than inventory method and will become the main development direction.

4. Conclusion

In this paper, considering the characteristics of carbon emission in the embodied phase, the calculation range of carbon emission is determined, and the carbon emission factor method is used to calculate the carbon emission in the embodied phase. It is proposed to move forward the life cycle of buildings, consider the impact of design optimization on carbon emissions, establish a low carbon hierarchical system of buildings, and consider the comprehensive effect of single factor and multifactor. Through optimization, the carbon emission in the design can be kept in a controllable range, which makes the system design more technical, reasonable, and scientific and achieves the optimal energy saving and emission reduction effect.

The construction process is divided into three stages, and the carbon emission boundary of each stage is determined. According to the characteristics of each stage, the carbon source is classified, and the emission factors of various machinery teams are determined according to the fuel consumption and fuel emission factors. The total carbon emission of mechanical equipment in the construction process can be calculated.

The summary calculation of various carbon emissions at the embodied phase of buildings can not only theoretically obtain the total carbon emissions, but also compile the carbon emission quota list. It is suitable for the calculation of carbon emissions at all kinds of building phases, which is beneficial to the precise calculation of carbon emissions in the building life cycle. It will provide technical support for the formulation and implementation of carbon trading mechanism.

Data Availability

All data used, generated, or analyzed to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors would like to express their sincere thanks to the authors of all the papers. This research was funded by the Ministry of Housing and Urban Rural Development, Science and Technology Project (2015-K4-023).

References

[1] Y. L. Li, B. Chen, and G. Q. Chen, "Carbon network embodied in international trade: global structural evolution and its policy implications," *Energy Policy*, vol. 139, p. 111316, 2020.

[2] US EPA, *Potential for Reducing Greenhouse Gas Emissions in the Construction Sector*, Environmental Protection Agency, Washington, DC, USA, US EPA archive document, 2009.

[3] J. J. V. Díaz, M. Ri. Wilby, and A. B. Ro. González, "Setting up GHG-based energy efficiency targets in buildings: the Ecolabel," *Energy Policy*, vol. 59, pp. 633–642, 2013.

[4] J. Grözinger, T. Boermans, A. John et al., *Overview of Member States Information on NZEBs: Background Paper-Final Report*, ECOFYS GmbH, Cologne, Germany, 2014.

[5] Building Energy Efficiency Research Center of Tsinghua University, *Annual Report on China's Building Energy Efficiency*, China Construction Industry Press, Beijing, China, 2016.

[6] X. K. Mao, L. X. Wang, J. W. Li et al., ""Comparison of regression models for estimation of carbon emissions during building's lifecycle using designing factors: a case study of residential buildings in Tianjin, China," *Energy & Buildings*, vol. 204, pp. 1–11, 2019.

[7] S. W. Choi, B. K. Oh, and H. S. Park, "Design technology based on resizing method for reduction of costs and carbon dioxide emissions of high-rise buildings," *Energy and Buildings*, vol. 138, pp. 612–620, 2017.

[8] X. Wu, B. Peng, and B. Lin, "A dynamic life cycle carbon emission assessment on green and non-green buildings in China," *Energy and Buildings*, vol. 149, pp. 272–281, 2017.

[9] M. K. Dixit, "Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 390–413, 2017.

[10] W. Pan, K. Li, and Y. Teng, "Rethinking system boundaries of the life cycle carbon emissions of buildings," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 379–390, 2018.

[11] Y. J. Zhan, W. Liu, F. Wu, Z. Li, and C. Wang, "Life cycle energy consumption and greenhouse gas emissions of urban residential buildings in Guangzhou city," *Journal of Cleaner Production*, vol. 194, pp. 318–326, 2018.

[12] D. Trabucco and A. Wood, "LCA of tall buildings: still a long way to go," *Journal of Building Engineering*, vol. 7, pp. 379–381, 2016.

[13] N. Itsubo and A. Inaba, "A new LCIA method: LIME has been completed," *The International Journal of Life Cycle Assessment*, vol. 8, no. 5, p. 305, 2003.

[14] L. Z. Bribián, A. V. Capilla, and A. A. Usón, "Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and valuation of the eco-efficiency improvement potential," *Building and Environment*, vol. 46, pp. 1133–1140, 2011.

[15] Y. L. Li, M. Y. Han, S. Y. Liu, and G. Q. Chen, "Energy consumption and greenhouse gas emissions by buildings: a multi-scale perspective," *Building and Environment*, vol. 151, pp. 240–250, 2019.

[16] Y. A. Huang, C. L. Weber, and H. S. Matthews, "Categorization of scope 3 emissions for streamlined enterprise carbon footprinting," *Environmental Science & Technology*, vol. 43, no. 22, pp. 8509–8515, 2009.

[17] J. Guan, Z. Zhang, and C. Chu, "Quantification of building embodied energy in China using an input-output-based hybrid LCA model," *Energy and Buildings*, vol. 110, pp. 443–452, 2016.

[18] S. Suh and G. Huppes, "Methods for life cycle inventory of a product," *Journal of Cleaner Production*, vol. 13, no. 7, pp. 687–697, 2005.

[19] M. Y. Han, L. Shao, J. S. Li et al., "Emergy-based hybrid evaluation for commercial construction engineering: a case study in BDA," *Ecological Indicators*, vol. 47, pp. 179–188, 2014.

[20] B. R. Lin, N. X. Liu, B. Peng et al., "International comparative study on building life-cycle energy consumption and CO_2 emission," *Building Science*, vol. 29, pp. 22–27, 2013.

[21] J. Z. Song, X. Y. Yuan, and X. P. Wang, "Analysis on influencing factors of carbon emission intensity of construction industry in China," *Environmental Engineering*, vol. 36, pp. 178–182, 2018.

[22] A. L. Sharrard, H. S. Matthews, R. J. Ries et al., "Estimating construction project environmental effects using an input-output-based hybrid life-cycle assessment model," *Journal of Infrastructure Systems*, vol. 14, no. 4, pp. 327–336, 2008.

[23] X. Li, Y. Zhu, and Z. Zhang, "An LCA-based environmental impact assessment model for construction processes," *Building and Environment*, vol. 45, no. 3, pp. 766–775, 2010.

[24] S. J. Qi, J. Q. She, and Y. B. Zhang, "Research on life cycle carbon emission and its reduction sensitivity of public building on the basal of system dynamics: a case study in hot summer and warm winter area," *Xi'an University of Architecture and Technology (Natural Science Edition*, vol. 48, pp. 101–108, 2016.

[25] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples," *Building and Environment*, vol. 32, no. 4, pp. 321–329, 1997.

[26] W. L. Jin and Z. J. Wang, "Life-cycle green index of building structure and green construction analysis," *Building Construction*, vol. 38, pp. 1322–1325, 2016.

[27] H. Ma, N. Du, S. Yu et al., "Analysis of typical public building energy consumption in northern China," *Energy and Buildings*, vol. 136, pp. 139–150, 2017.

[28] X. L. Liu, H. T. Wang, J. Chen et al., "Method and basic model for development of Chinese reference life cycle data base," *Acta Scientiae Circumstantiae*, vol. 30, pp. 2136–2144, 2010.

[29] S. Marinova, S. Deetman, E. Voet et al., "Global construction materials database and stock analysis of residential buildings between 1970–2050," *Journal of Cleaner Production*, vol. 247, pp. 1–13, 2020.

[30] F. You, D. Hu, H. Zhang et al., "Carbon emissions in the life cycle of urban building system in China-A case study of residential buildings," *Ecological Complexity*, vol. 8, no. 2, pp. 201–212, 2011.

[31] D. Ma, J. X. Zhang, H. Y. Duan et al., "Reutilization of gangue wastes in underground backfilling mining: overburden aquifer protection," *Chemosphere*, vol. 264, pp. 1–13, 2021.

[32] D. Ma, H. Duan, Q. Zhang et al., "A numerical gas fracturing model of coupled thermal, flowing and mechanical effects," *Computers, Materials & Continua*, vol. 65, no. 3, pp. 2123–2141, 2020.

[33] C. W. Wang and Z. D. Ma, "Quota estimation method and application prospect of carbon emission in construction project," *Construction Economy*, vol. 37, pp. 59–61, 2016.

[34] C. Ji, T. Hong, and H. S. Park, "Comparative analysis of decision-making methods for integrating cost and CO_2 emission - focus on building structural design," *Energy and Buildings*, vol. 72, pp. 186–194, 2014.

[35] M. Liu, X. R. Ge, W. S. Li et al., "The impact factor of low carbon building in early design stages," *Journal of Dalian*

University of Technology (Social Sciences), vol. 37, pp. 119–123, 2016.

[36] R. J. Cole, "Energy and greenhouse gas emissions associated with the construction of alternative structural systems," *Building and Environment*, vol. 34, pp. 335–348, 1999.

[37] Intergovernmental Panel on Climate Change, *Climate Change 2014: Synthesis Report, Summary for Policymakers*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2014.

[38] X. C. Zhang, *Research on the Quantitative Analysis of Building Carbon Emissions and Assessment Methods for Low-Carbon Buildings and Structures*, Harbin Institute of Technology, Harbin, China, 2018.

[39] Y. J. Cang, *Study on Accounting Methods of Building Carbon Emission in Embodied Stage*, Xi'an University of Architecture and Technology, Xi'an, China, 2018.