Empirical Study on Carbon Emission Estimation Indicators for the Life Cycle Analysis of Prefabricated Buildings

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Abstract: Based on the perspective of the life cycle of buildings, a carbon emission estimation model for prefabricated buildings (PC-LCA) is constructed, and conduct sensitivity analysis on the factors affecting carbon emissions. The results indicate that: (a) the accuracy of the PC-LCA model is within ± 10%, which is feasible and practical. (b) the ranking of sensitivity factor coefficients is: design life > building area > annual electricity consumption > carbon emission factor > annual heat consumption > annual cooling capacity. This study simplified the calculation process of carbon emissions and provided predictive suggestions for quantifying carbon emissions and optimizing carbon reduction measures in the early stages of construction.

Keywords: Prefabricated Buildings; Life Cycle Analysis; Carbon Emission; Regressive Analysis; Empirical Analysis

Introduction

China was the largest carbon dioxide emissions in the world. According to global counted that China's carbon emissions account for 32% of the total global carbon emissions in 2020. In 2020, the construction industry was one of the main areas of carbon emissions in China, accounting for 50.9% of the total carbon emissions. It can be seen that carbon emission reduction in the construction industry was a key measure to achieve China's "30-60" dual carbon goals. In order to effectively reduce the carbon emissions in the construction industry, prefabricated buildings have emerged. Prefabricated buildings utilize a factory production model, greatly reducing construction waste, reducing energy consumption and saving labor. Therefore, studying the estimation of carbon emissions from prefabricated buildings is of great scientific significance for promoting energy conservation and emission reduction in the construction industry.

With the advancement of China's "30-60" dual carbon goals, researchers have begun trying to reduce carbon emissions through prefabricated buildings strategies. Based on the existing research, it can be concluded that research on carbon emissions from prefabricated buildings mainly focused on three aspects: Firstly, researched on carbon emissions in various stages of the life cycle of prefabricated buildings, such as the construction phase, building construction phase, transportation phase, as well as the production and transportation phase of prefabricated components. Secondly, the carbon emission reduction effects of prefabricated buildings were studied, using comparative analysis and presence/absence analysis methods, to compare and analyze the carbon emissions of prefabricated buildings and cast-in-place buildings, as well as those using prefabricated and non-prefabricated methods. In addition, there were also studied on the influencing factors of carbon reduction in prefabricated buildings. This research has identified the key influencing factors of energy conservation and emission reduction in prefabricated buildings, and proposed optimization paths.

In summary, the carbon emission research system for prefabricated buildings has gradually been formed, but the existing carbon emission calculation research was based on validated calculations of existing or operating projects, and there was a lack of research that can be applied to estimate the carbon emissions of prefabricated buildings in the early stages of the project. The purpose of this study was to serve the estimation of carbon emissions in the early stages of the project. Based on the life cycle assessment method, and used the estimated data from China Northwest Architectural Design and Research Institute Co., Ltd. (China Northwest Architectural Design and Research Institute) from 2020 to present as the database, combined with the division of the life cycle stages of the building, a prefabricated building life cycle carbon emission estimation model (PC-LCA) was constructed. Through this study, providing decision-making and judgment basis for stakeholders such as decision-makers, designers, and property owners.

Theoretical Basis

Scope Definition

Life Cycle Assessment (LCA) is a tool for systematically evaluating the environmental impact of a building or product throughout its life cycle. Currently, most of the research on building carbon emissions at home and abroad was based on this theory. However, different researchers have different classifications of the life cycle stages that this theory, which can be mainly summarized into three stages, four stages, five stages, six stages and nine stages. This study defined the life cycle of a building as four stages: the production and transportation stage, the construction stage, the operation stage, and the demolition and recycling stage.

Evaluation system

Since the LCA was proposed, multiple research institutions have conducted research on LCA methods. Based on the life cycle assessment framework proposed by the International Society of Environmental Toxicology and Chemistry, this study proposed an LCA-based carbon emission and evaluation system based on the life cycle stages of building.

Model Structure

The prefabricated building life cycle carbon emission estimation model

Based on the whole life cycle carbon emission estimation system of prefabricated buildings, the prefabricated building life cycle carbon emission estimation model (PC-LCA) was constructed. The model includes four parts: model input, model calculation, model analysis, and model output.

The input section of model mainly inputs relevant content, clarifies the basic information of the project and independent variables that affect the estimation of carbon emissions of prefabricated buildings. Including project name, project location, building type, area and engineering investment.

The analysis section mainly includes impact assessment and result interpretation, including analysis of total indicators and carbon emission intensity per unit building area, and sensitivity analysis of influencing factors.

Output section mainly exports the carbon emission estimation results table, carbon emission estimation analysis chart, sensitivity analysis table of influencing factors, and calculates and outputs the carbon emission estimation report analysis results based on the model.

The model analysis section is the core content of the PC-LCA model, which is divided into the database establishment and the data calculation. The model database establishment part is based on the prefabricated building budget data of China Northwest Architectural Design and Research Institute from 2020 to 2023. Through analyzing data, the consumption of each sub-project is determined, and an indicator library is constructed for building materials with cumulative mass accounting for 80% or more of the total building materials consumption and equipment systems with cumulative energy consumption accounting for 80% or more of the total energy consumption.

The data calculation process of PC-LCA

In the model data calculation section, based on the life cycle carbon emission calculation theory, carbon emission factor method, area index method, emission coefficient method, proportion estimation method, etc. are used for calculation. The specific calculation formula is as follows:

$$C_{sum} = C_{pt} + C_c + C_o + C_{dr}$$

In the formula: C_{sum} is the carbon emissions of life cycle($kgCO_2eq$); C_{pt} is the carbon emissions of the production and transportation stage($kgCO_2eq$); C_c is the carbon emissions of the construction stage($kgCO_2eq$); C_o is the carbon emissions of the operation stage($kgCO_2eq$);C_{dr} is the carbon emissions of the demolition and recycling stage($kgCO_2eq$).

First, the calculation of $\boldsymbol{C_{pt}}$:

$$C_{pt} = P_p + P_t + M_p + M_t$$

In the formula: P_p is the carbon emissions of material production($kgCO_2eq$); P_t is the carbon emissions of material transportation($kgCO_2eq$);M_p is the carbon emissions of component production($kgCO_2eq$); M_t is the carbon emissions of component transportation($kgCO_2eq$).

The calculation of $\boldsymbol{P_p}$:

$$P_p = \sum_{i=1}^{n} m \times m_i \times EF_i$$

In the formula: m is building area(m2); n is the number of materials; m_i is the material content per unit building area of i-th material(kg\t\m\m3/m2), the data is sourced from prefabricated building budget data of China Northwest Architectural Design and Research Institute from 2020 to 2023; EF_i is the carbon emission factor of i-th material($kgCO_2eq$ /kg\t\m\m^3/m^2), the carbon emission factor is determined according to Appendix D of the Building Material Carbon Emission Calculation Standard (GB/T51366-2019).

The calculation of $\boldsymbol{P_p}$:

$$P_t = \sum_{i=1}^{n}\sum_{j=1}^{z} m_{ij} \times D_{ij} \times K_y \times EF_j$$

In the formula: n is the number of materials; z is the number of transportation method; m_{ij} is the quality of i-th materials transported through the j-th transportation method(kg/t/m/m^3/m^2); D_{ij} is the average transportation distance of i-th materials transported through the j-th transportation method(km), the data is sourced from 2021 China Statistical Yearbook; K_y is correction coefficient for empty vehicle transportation, K_y =1.67; EF_j*is* the carbon emission factor per unit mass and transportation distance for the j-th transportation method($kgCO_2eq$ /(t.km)), the carbon emission factor is determined according to Appendix E of the Building Material Carbon Emission Calculation Standard (GB/T51366-2019).

The calculation of $\boldsymbol{M_p}$:

$$M_p = \sum_{i=1}^{n}\sum_{z=1}^{g} f_{z,i} \times m \times m_i \times EF_{z,i} + \sum_{i=1}^{n}\sum_{t=1}^{r} m \times m_i \times f_{t,i} \times EF_{t,i}$$

In the formula: m is building area(m2); n is the number of prefabricated component category; g is the number of types of prefabricated component materials in the i-th category; r is the number of energy types for the i-th prefabricated component category; m_i is the unit building area content of the i-th prefabricated components(m3/m2); $f_{z,i}$ is consumption of i-th prefabricated component's z-th materials(m3/m2); $f_{t,i}$ is consumption of i-th prefabricated component's t-th energy(L\kg/m3); $EF_{z,i}$ is the carbon emission factor for i-th prefabricated component's z-th materials($kgCO_2eq$ /kg\t\m\m3\m2); $EF_{t,i}$ is the carbon emission factor for i-th prefabricated component's t-th energy($kgCO_2eq$ /TJ).The data source is the same as P_p , and the energy carbon emission factors are from Appendix A of the Building Material Carbon Emission Calculation Standard (GB/T51366-2019).

The calculation of $\boldsymbol{M_t}$:

The calculation formula is the same as P_p .

Second, the calculation of $\boldsymbol{C_c}$:

The carbon emissions of the construction stage are generated by the energy consumption of mechanical equipment and the work of construction personnel during the construction process. Due to the long calculation cycle and heavy workload of carbon emissions during this stage, but the proportion of carbon emissions is relatively small, according to Xu et. Al, this study calculated that carbon emission during the construction stage accounts for 2.55% of the production and transportation stage.

Third, the calculation of $\boldsymbol{C_o}$:

$$C_o = N \times (\sum_{i=1}^{n} \alpha \times E_i \times EF_i - \sum_{i=1}^{n} R_i \times EF_i - C_p$$

In the formula: N is design service life; n is the number of energy category; á is usage load; Ei is annual consumption of the i-th energy(kg\L\m3/year); EFi is the carbon emission factor of i-th energy ($kgCO_2eq$ /TJ); R_i is annual savings of the i-th energy; C_p is annual carbon reduction of building green space carbon sequestration system(t).

Fourth, the calculation of $\boldsymbol{C_{dr}}$:

Due to the difficulty in obtaining actual consumption data during the dismantling and recycling stage, there is relatively little analysis of this stage in relevant research cases. This study is based on Wang's research and calculated at 1% of the total life cycle carbon emissions.

Empirical analysis

This study selected residential cases from researches to verify the accuracy and applicability of the model. The specific case analysis results were shown in Table 1. The analysis results showed that the deviation of the PC-LCA model constructed in this study was within ± 10%.

Table 1 Empirical case analysis results

No.	Author	Research results ($kgCO_2e/m^2$)	Model results ($kgCO_2e/m^2$)	Error ratio
1	Wei Guanglong	3472.01	3272.84	5.74%
2	Liu Binjin	4400.85	4161.96	5.43%
3	Ma Kangwei	5310.47	4990.48	6.03%
4	Zou Yining	4854.87	4695.45	3.28%
5	Zhang Huan et al.	2878.5	2943.08	-2.24%

Measured the sensitivity of each influencing factor to carbon emissions by increasing or decreasing (-20%~20%), design service years, building area, annual electricity consumption, annual heat consumption, and annual cooling capacity. By calculating the sensitivity coefficients of various influencing factors, the order of influence from large to small was as follows: design service life > building area > annual electricity consumption > carbon emission factor > annual heat consumption > annual cooling capacity. Among them, building area has a negative impact on carbon emissions, while the rest have a positive impact on carbon emissions. The specific analysis results were shown in Table 2.

Table 2 Sensitivity analysis results

No.	Carbon emission factor	Design service life	Building area	Annual electricity consumption	Annual heat consumption	Annual cooling capacity	Ref.
1	0.253	0.725	-0.604	0.428	0.204	0.093	[6]
2	0.199	0.784	-0.653	0.202	0.128	0.064	[7]
3	0.290	0.702	-0.585	0.432	0.197	0.073	[8]
4	0.114	0.890	-0.742	0.454	0.317	0.119	[9]
5	0.380	0.592	-0.494	0.286	0.227	0.080	[10]

Conclusion

This study was based on the theory of LCA, and used the estimated data of China Northwest Architectural Design and Research

Institute in the past three years as the database to construct a PC-LCA model. Empirical analysis was conducted on existing research cases. The results showed that: (1) the PC-LCA model has operability and feasibility, the total carbon emissions indicators and unit indicators output by this model were consistent with existing research, with a calculation accuracy of ± 10%. (2) The sensitivity coefficients of various influencing factors on carbon emissions, in descending order were: design service years, building area, annual electricity consumption, carbon emission factor, annual heat consumption, annual cooling capacity. Design service years and building area have the greatest impact on carbon emissions, with building area having a negative correlation and the rest having a positive correlation.

The PC-LCA model constructed in this study simplifies the carbon emission calculation process of prefabricated buildings, provides judgment conditions for government decision-making, design scheme comparison, material selection and utilization, investment environmental benefit analysis in the early stage of building design, and provides an operational implementation path for energy conservation and carbon reduction in construction projects.

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