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Construction and Empirical Study of the Quantitative Model of the Whole Process of Building Carbon Emissions

Ke Zhang[1*], Xiaogang Zhao[1]

[1] *School of Architecture and Art Design, Hebei University of Technology, Tianjin, China*
**Corresponding Author. Email:2458952291@qq.com*

Abstract. To enable systematic quantification and effective control of carbon emissions in the construction industry, this paper proposes a life cycle-based carbon emission model. Grounded in LCA principles, the model spans four stages: material production, construction, operation, and demolition. It integrates phased accounting with unified aggregation to ensure a closed-loop calculation process. Parameters are derived from the "Building Carbon Emission Calculation Standard" and the China Life Cycle Database (CLCD). Empirical validation on public buildings in Shanghai demonstrates the model's stability and its ability to identify high-emission stages and optimization opportunities. The model proves applicable to carbon verification, green building evaluation, and full-process carbon management, showing strong practical value and scalability.

Keywords: building carbon emissions, life cycle assessment, carbon factor model, full process accounting, empirical analysis

1. Introduction

Under the "dual carbon" strategy, full-lifecycle carbon management is essential, yet existing studies often focus on isolated stages and lack unified, practical frameworks. Liu and Leng [1]addressed early-stage embodied carbon; Lai et al. [2]detailed the construction process but lacked depth; Gao et al. [3] highlighted issues of consistency and adaptability; Yang et al. [4] showed structural type impacts; Lu et al. [5] emphasized model integration. This study develops and validates a comprehensive lifecycle model to enhance accuracy, applicability, and decision support in carbon management.

2. Logical framework of the entire process of building carbon emissions and extraction of modeling elements

2.1. Definition and boundary demarcation of the entire building carbon emission process

Building carbon emissions encompass all direct and indirect greenhouse gases from initiation to decommissioning. As shown in Figure 1,Based on LCA, the process is divided into five stages: raw material acquisition, transportation, construction, operation, and demolition. This paper adopts a

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cradle-to-grave boundary to ensure comprehensive, consistent, and comparable carbon accounting across the full building lifecycle.

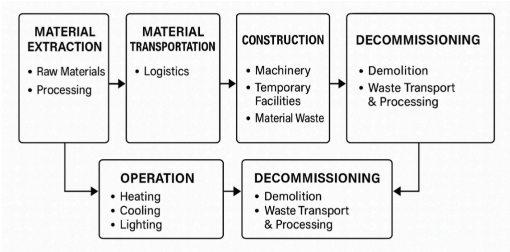

Figure 1: Schematic diagram of the entire process of building carbon emissions

2.2. Accounting objects and carbon factor system construction

Carbon emissions in construction include direct (Scope 1), indirect energy (Scope 2), and other indirect sources (Scope 3). To ensure accuracy, a stage-specific, traceable carbon factor database is required. Emissions are calculated using the unified formula from IPCC (2006) and GB/T 51366-2019 standards:

$$E = A \times EF \tag{1}$$

Among them, E is the carbon emission (unit: kg CO_2e), A is the activity level (such as cement usage, diesel consumption, etc.), EF and is the corresponding carbon emission factor (unit: kg CO_2e /unit activity)[7] . Typical carbon factors include: cement (0.856 kgCO_2/kg), steel (2.16 kg CO_2/kg), diesel (2.68 kgCO_2/L), electricity (0.524 kgCO_2/kWh), and waste disposal (0.07 kg CO_2/kg). All factors must be adjusted by location, grid mix, and source. A reliable, stage-specific carbon factor database is key to model accuracy and result comparability[8].

3. Method for constructing a quantitative model for the entire process of building carbon emissions

3.1. Overall logic and system structure of model construction

The model follows a "module decomposition–factor drive–integrated output" design, comprising input preprocessing, stage calculation, and result visualization. Based on IPCC algorithms and Chinese standards, it processes BIM and energy data, performs stage-wise emission calculations across five life cycle phases, and outputs integrated results. Developed in Python with CSV/Excel support, the model is scalable and can be embedded into carbon assessment platforms for full-process management.

3.2. Design of carbon emission accounting sub-models at each stage

3.2.1. Model of material acquisition and production stage

Carbon emissions during the material acquisition and production stages can be expressed as:

$$E_{mat} = \sum_{i=1}^{n} (A_i \times F_i) \tag{2}$$

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A_i is the processing amount of the i raw material (kg), F_i is the corresponding unit emission factor ($kgCO_2$ - e /kg), and n is the number of material types. The specific process includes: firstly, extracting the quantity of steel bars, cement, sand and gravel used in each component from the BIM component list; secondly, obtaining the carbon factor of F_i each material according to the carbon factor library of China's building materials industry , and combining the energy consumption rate in the actual production process, the original emission factor is corrected:

$$F_i^{'} = F_i \times \left(1 + \eta_{\text{proc}}\right) \tag{3}$$

η_{proc} is the incremental energy consumption coefficient (dimensionless) in the material production process. Finally, the total emissions of the stage are obtained by accumulating the corrected emissions of all materials.

3.2.2. Construction phase model

Emissions during the construction phase consist of two parts: fuel consumption of construction machinery and electricity use on the construction site:

$$E_{\text{cons}} = \sum_{j=1}^{m} \left(C_j \times EF_{\text{fuel}}\right) + P_{\text{elec}} \times EF_{\text{elec}} \tag{4}$$

In the formula, C_j is the fuel consumption of the j- th construction machine (L), EF_{fuel} is the unit emission factor of fuel ($kgCO_2$ - e /L); P_{elec} is the total electricity consumption on site (kWh), EF_{elec} and is the electricity emission intensity ($kgCO_2$ - e /kWh).

3.2.3. Using the operation stage model

The carbon emissions during operation adopt a dynamic integral model:

$$E_{\text{op}} = \int_0^T \left[P_{\text{heat}}(t)EF_{\text{heat}} + P_{\text{cool}}(t)EF_{\text{cool}} + P_{\text{elec}}(t)EF_{\text{elec}}\right]\mathrm{d}t \tag{5}$$

$P_{heat}(t)$,$P_{cool}(t)$,$P_{elec}(t)$ are the heating, cooling and other power consumption (kW) at time t; EF_{heat}, EF_{cool} and EF_{elec} are the corresponding energy emission factors. The module obtains the power curve with a 5-minute resolution through the building energy consumption monitoring platform, and calculates the daily and annual total emissions by numerical integration.

3.2.4. Estimation model for demolition and abandonment stage

Waste classification parameters are determined through disassembly plans and on-site surveys. Different disposal methods (landfill, incineration, and reuse) correspond to different parameters. At the same time, the energy consumption of mechanical crushing is considered:

$$E_{\text{crush}} = P_{\text{crush}} \times T_{\text{crush}} \times EF_{\text{elec}} \tag{6}$$

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P_{crush} and T_{crush} are crusher power (kW) and operation time (h), respectively. After adding up all items, the carbon emission estimate for this stage is obtained.

4. Model verification and typical building empirical research

4.1. Empirical objects and experimental data sources

To verify the model's applicability and accuracy, "Shanghai Book City" was selected as a case study —a 15,000 m^2 public building built in 2003 and renovated for carbon neutrality in 2023. Data came from official sources, including the 2023 energy and carbon report and the city's supervision platform. Preprocessing followed GB/T 51366-2019 and GB/T 50378-2019, involving unit standardization, missing value estimation, and outlier removal.

4.2. Display and analysis of carbon emission results

In Table 1,Based on the model applied to "Shanghai Book City," lifecycle emissions totaled 782.0 $kgCO_2e/m^2$, with the operation phase accounting for 62.7% and material production 27.9%. High-emission sources such as cement, rebar, and electricity were identified, and optimization paths proposed, including material substitution and renewable energy use.

Table 1: Carbon emissions by stage and optimization suggestions

Stage	Emissions ($kgCO_2e/m^2$)	Main Sources	Optimization Suggestions
Material Production	218.4	Cement, Rebar, Glass	Low-carbon cement, recycled steel, low-e glass
Construction	47.2	Machinery, Electricity	Efficient equipment, reduce temporary loads
Operation	490.8	Electricity, Gas	Photovoltaics, improve energy efficiency
Demolition	25.6	Transport, Treatment	Reuse materials, optimize disposal logistics
Total	782.0	—	—

4.3. Model performance analysis

To verify model accuracy, the "Shanghai Book City" project was tested and compared with manual results and a third-party tool. Outputs included stage emissions, unit intensity, and total lifecycle emissions. Manual results based on GB/T 51366-2019 served as the benchmark, with tool data used for cross-validation.

Table 2: Comparison and analysis of model results and other calculation methods (unit: t CO_2 e)

Calculation method	Material stage	Construction Phase	Operational stage	Demolition phase	total
Output of this model	3276.0	708.0	7362.0	384.0	11730.0
Manual calculation	3304.5	687.3	7501.2	410.5	11903.5
eToolLCD tool output	3441.2	752.0	7219.3	395.7	11808.2
Deviation rate (with manual)	-0.86%	+3.01%	-1.86%	-6.45%	-1.45%

Table 2 shows that model results deviate less than ±5% from manual calculations, within acceptable industry limits. Compared to eToolLCD, this model reports slightly lower emissions in construction and demolition due to localized carbon factor settings.

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5. Conclusion

This study develops and validates a full-process quantitative model for building carbon emissions, covering all life cycle stages with clear boundaries and phased sub-models. Applied to public building cases, the model demonstrates strong adaptability and accuracy, effectively identifying emission hotspots and optimization paths. It offers technical support for green design and carbon reduction. Future work will enhance its regional applicability and dynamic response to climate and policy changes, supporting low-carbon development under the "dual carbon" strategy.

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