Comprehensive Evaluation of Carbon Emissions from Residential Buildings in Jiangsu Province's Prefectural-level Cities Based on the Entropy Weight-TOPSIS Method

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Abstract. This study aims to conduct a comprehensive evaluation of building carbon emissions based on the Entropy Weight-TOPSIS method. The construction industry is one of the primary sources of global greenhouse gas emissions, so evaluating the level of building carbon emissions is crucial for promoting sustainable development. The Entropy Weight-TOPSIS method combines the entropy weight method and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), allowing for a comprehensive assessment of building carbon emission performance considering multiple indicators. This research first identified a series of initial key indicators affecting building carbon emissions, then used the Delphi method to screen and finalize these indicators. Finally, the Entropy Weight-TOPSIS method was applied to rank and evaluate the carbon emission performance of different buildings. The research results can provide decision support for the construction industry to reduce carbon emissions and promote sustainable building development.

Keywords: Entropy Weight-TOPSIS Method, Delphi Method, Comprehensive Evaluation, Sustainable Building Development.

1 Introduction

In recent years, global climate change has drawn widespread attention to the issue of carbon emissions. As a primary component of greenhouse gases, the significant emissions of carbon dioxide have exacerbated the trend of global warming. Every industry is seeking ways to reduce carbon emissions. As one of the main sectors for energy consumption and carbon emissions, the construction industry plays a vital role in reducing greenhouse gas emissions and promoting sustainable development. Therefore, a scientific and reasonable evaluation of building carbon emissions is particularly important.

P. Xiang et al. (eds.), *Proceedings of the 2023 5th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2023)*, Atlantis Highlights in Engineering 26,
https://doi.org/10.2991/978-94-6463-398-6_61

Currently, there are numerous methods for evaluating carbon emissions. Pinghai and others have reviewed the carbon emission calculations during the industrialized construction phase[1]. Zhang Zhen and colleagues conducted research on the integrated calculation and carbon reduction technology of carbon emissions during transportation hub project construction[2]. Han Yuheng and his team estimated and analyzed the carbon emissions of prefabricated buildings with different assembly rates based on the carbon emission coefficient method[3]. Hu Haowei and others predicted and analyzed building carbon emissions based on the LEAP model and LMDI decomposition[4]. Zhou Yibing discussed the calculation methods for carbon emissions from newly constructed urban community buildings[5]. Luo Zhixing and his team studied the calculation method of carbon emissions for the life cycle of architectural landscape gardening projects, taking Xi'an residential communities as an example[6]. Huang Xiaoheng and others researched the measurement and influencing factors of urban residential building carbon emissions during the usage phase, using Chongqing as a case study[7]. Although some methods have been developed for studying building carbon emissions, most methods exhibit subjectivity or lack accuracy when considering indicator weights. To overcome these issues, studying residential building carbon emissions using the Entropy Weight-TOPSIS method is a new direction."

Based on the above background, this study employs the Entropy Weight-TOPSIS method, aiming to comprehensively evaluate the carbon emission performance of different buildings. Through the collection and processing of data on a series of key indicators, combined with the entropy weight method to determine the weights of the indicators, the TOPSIS method is then applied to rank the comprehensive performance of building carbon emissions. The research results are expected to provide scientific decision support for the construction industry in reducing carbon emissions and optimizing energy utilization, promoting sustainable building development.

2 Selection, Determination, and Explanation of Building Carbon Emission Indicators

2.1 Determination of Initial Indicators

First is the establishment of initial indicators. Based on the principles of indicator system construction and theories related to social stability, and referencing other relevant literature as well as opinions from experienced scholars, a preliminary framework for a building lifecycle carbon emission indicator system is established, as shown in Table 1.

Table 1. Initial Indicators for Building Carbon Emissions

Primary Category	Secondary Category
Construction Phase Metrics	CO2 Emissions from Building Material Production (Tons CO2)
	CO2 Emissions from Building Material Transportation (Tons CO2)
	CO2 Emissions during Construction Activities (Tons CO2)
	Gross Floor Area (Square Meters)

Primary Category	Secondary Category
	Fossil Fuel Consumption in Building Material Production
	Waste Management and Recycling Rate in Construction
	Origin of Building Material Feedstock
Operational Phase Metrics	Total Energy Consumption (Tons of Standard Coal Equivalent)
	Energy Use Intensity (Tons CO2 per Square Meter)
	Carbon Intensity of Energy Source (Tons CO2 per Ton of Energy)
	Occupancy (Tens of Thousands)
	Lifestyle Carbon Footprint Index
	Building’s Operational Lifespan (Years)
	Carbon Impact of Building Retrofits and Renovations (Tons CO2)
	Carbon Emissions from Water Usage and Treatment in Buildings
	Carbon Footprint of HVAC Systems
	Carbon Footprint of Lighting Systems
	Carbon Footprint of Electronic Appliances
Demolition Phase Metrics	CO2 Emissions during Building Demolition (Tons CO2)
	Energy Consumption in Waste Management (Tons CO2)
	CO2 Emissions from Building Material Recycling Processes
	Rate of Building Material Reclamation

2.2 Selection of Indicators

In this study, the Delphi method was used for selection, with the specific steps shown in Table 2.

Table 2. Delphi method

Step1:Determine the Initial Indicators	By reviewing the literature of previous scholars and based on practical research, various factors that might lead to risks were summarized. On this basis, the initial indicators were proposed
Step2:Interview	Firstly, through expert interviews, necessary information and data were collected for questionnaire design, and the initially established indicator system was modified
Step3:Developing the Survey Questionnaire	After consulting with various experts, the first round of expert consultation questionnaires was developed
Step4:Distribution and Collection of Survey Questionnaires	Through face-to-face interviews, experts were once again brought together. Two days later, the results were collected and tabulated. Then, based on the results of the first round of screening, the second round of questionnaires was distributed and collected two days after. Based on the screening results of the first two rounds, the third round of questionnaires was prepared. The final indicator system was formed according to expert opinions.
Step5:Revision and Improvement of the Indicator System	In the process of determining the indicator system, there may be issues with the system due to oversights or other factors. Therefore, after each round of soliciting expert opinions, internal team communication is essential to identify and rectify deficiencies in the designed indicator system

2.3 Determination of the Indicator System

Through continuous improvement and revision, the final indicator system for carbon emissions throughout the building lifecycle was established, as shown in Table 3.

Table 3. The final index evaluation system

Primary Category	Secondary Category
Construction Phase Metrics	CO2 Emissions from Building Material Production (Tons CO2)
	CO2 Emissions from Building Material Transportation (Tons CO2)
	CO2 Emissions during Construction Activities (Tons CO2)
	Gross Floor Area (Square Meters)
Operational Phase Metrics	Total Energy Consumption (Tons of Standard Coal Equivalent)
	Energy Use Intensity (Tons CO2 per Square Meter)
	Carbon Intensity of Energy Source (Tons CO2 per Ton of Energy)
	Occupancy (Tens of Thousands)
	Lifestyle Carbon Footprint Index
	Building's Operational Lifespan (Years)
	Carbon Impact of Building Retrofits and Renovations (Tons CO2)
Demolition Phase Metrics	CO2 Emissions during Building Demolition (Tons CO2)
	Energy Consumption in Waste Management (Tons CO2)

3 Weighting of the Indicator System

3.1 Weighting of the Primary Indicator System

Based on domestic and international literature, for the primary indicators, since there are relevant literature descriptions both domestically and internationally, we used the literature review method to set the weights for the primary indicators as shown in Figure 1.

- Construction Phase Indicator: According to the research by Crawford et al.[8], carbon emissions during the construction phase account for 20%-40% of the total carbon emissions throughout the building's lifecycle. Therefore, we allocated a weight of 25% for the construction phase indicator and display it in a pie chart
- Operational Phase Indicator: The operational phase of a building is the longest and most critical stage in its entire lifecycle, involving aspects such as energy consumption, equipment maintenance, renovations, and updates. According to the research by Satori and Hestnes [9], carbon emissions during the building's operational phase typically account for 60%-80% of the entire building cycle. Therefore, we allocated a higher weight to the operational phase indicator, specifically 70%.
- Demolition Phase Indicator: The demolition phase indicator encompasses the carbon emissions produced during the building demolition and waste treatment processes. Even though the contribution of the demolition phase to the lifecycle carbon emissions of the building is relatively minor, it remains a point of concern. Based on the

research by Thormark [10], the carbon emissions during the demolition phase constitute 2%-10% of the entire building lifecycle. Considering the demolition phase's relatively small proportion in the complete building lifecycle, we assigned it a weight of 5%.

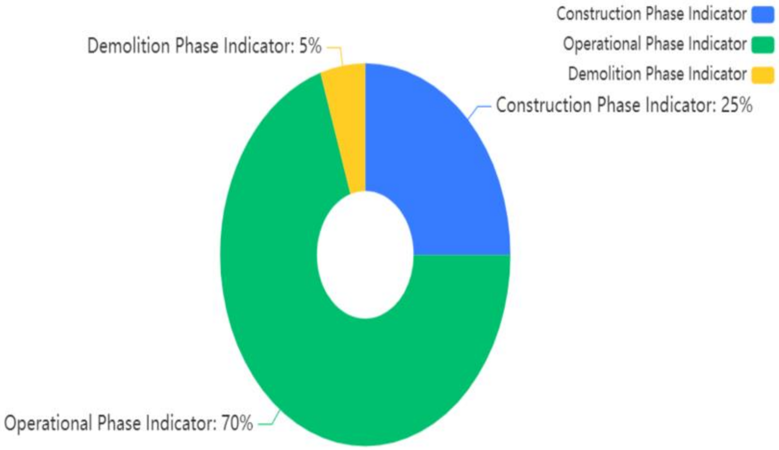

Fig. 1. Pie chart of primary indicator weights

It's important to note that these weight allocations are for reference only. In actual applications, adjustments may be required based on different building types, regions, and specific research contexts. Furthermore, with technological advancements and policy shifts, the structure and significance of building carbon emissions might change in the future, necessitating timely updates and optimization of these weights

3.2 Weighting of the Secondary Indicator System

In this study, data from 13 prefecture-level cities in Jiangsu Province in 2021 was collected, and the Entropy Weight Method (EWM) was used to calculate the weights of each indicator. The fundamental idea of the EWM is to determine objective weights based on the degree of variability of indicators. Generally speaking, if the information entropy of an indicator is smaller, it indicates a greater degree of variability in the indicator value, providing more information. As a result, it plays a more significant role in comprehensive evaluation, and its weight is higher. Conversely, if the information entropy of an indicator is larger, it means there's less variability in the indicator value, providing less information. Consequently, its role in comprehensive evaluation is lesser, and its weight is lower.

4 Sections, subsections and subsubsections

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

For each indicator, calculate its normalized entropy value. Suppose an indicator is $x_{ij,}$ where j=1,2,3,…,m and m is the number of indicators. Then, the normalized entropy value for this indicator can be expressed as:

$$E_i = -\frac{1}{\ln m}\sum_{j=1}^{m} p_{ij}\ln p_{ij} \tag{1}$$

For each indicator, calculate its weight. The weight for this indicator can be expressed as:

$$W_i = \frac{1-E_i}{m-\sum_{j=1}^{m} E_J} \tag{2}$$

Here, m represents the number of indicators.

After calculating the weights for each indicator, we can perform normalization to transform the data into values between 0 and 1. This facilitates comparison and evaluation. Next, we will normalize each indicator. The method used here is the Min-Max normalization:

$$X' = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \tag{3}$$

The calculation results are shown in Table 4.

Table 4. Weight of each indicator

Primary Category	Secondary Category	Weight
Construction Phase Metrics	CO2 Emissions from Building Material Production (Tons CO2)	0.33391
	CO2 Emissions from Building Material Transportation (Tons CO2)	0.19679
	CO2 Emissions during Construction Activities (Tons CO2)	0.27605
	Gross Floor Area (Square Meters)	0.19325
Operational Phase Metrics	Total Energy Consumption (Tons of Standard Coal Equivalent)	0.19901
	Energy Use Intensity (Tons CO2 per Square Meter)	0.15328
	Carbon Intensity of Energy Source (Tons CO2 per Ton of Energy)	0.08529
	Occupancy (Tens of Thousands)	0.18318
	Lifestyle Carbon Footprint Index	0.24107
	Building's Operational Lifespan (Years)	0.06366
	Carbon Impact of Building Retrofits and Renovations (Tons CO2)	0.0745
Demolition Phase Metrics	CO2 Emissions during Building Demolition (Tons CO2)	0.5744
	Energy Consumption in Waste Management (Tons CO2)	0.4256

To make the data more intuitive, we plotted a bar chart of the secondary indicator weights, as shown in Figure 2.

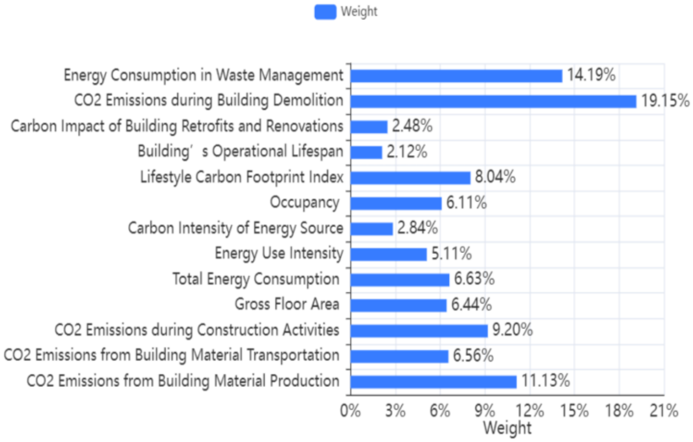

Fig. 2. Bar Chart of Secondary Indicator Weights.

5 Model Development

Establish a standardized matrix with n evaluation objects and m evaluation indicators (where n=13 and m=13):

$$Z=\begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nm} \end{bmatrix} \tag{4}$$

Define the maximum value:

$$Z^{+}=(Z_{1}^{+}\ ,\ Z_{2}^{+}\ ,\ \cdots\ Z_{m}^{+}) \tag{5}$$

$$=(\max\{z_{11},z_{21}\cdots z_{n1}\},\max\{z_{12},z_{22}\cdots z_{n2}\},\cdots,\max\{z_{1m},z_{2m}\cdots z_{nm}\})$$

Define the minimum value:

$$Z^{-}=(Z_{1}^{-}\ ,\ Z_{2}^{-}\ ,\ \cdots\ Z_{m}^{-}) \tag{6}$$

$$=(\min\{z_{11},z_{21}\cdots z_{n1}\},\min\{z_{12},z_{22}\cdots z_{n2}\},\cdots,\min\{z_{1m},z_{2m}\cdots z_{nm}\})$$

Define the distance between the evaluation object (where i=1,2,…,n) and the maximum value:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \omega_j \left(Z_j^+ - z_{ij}\right)^2} \tag{7}$$

Define the distance between the evaluation object (where i=1,2,…,n) and the minimum value:

$$D_i^- = \sqrt{\sum_{j=1}^{m} \omega_j \left(Z_j^- - z_{ij}\right)^2} \tag{8}$$

Calculate the unnormalized score for the evaluation object (where i=1,2,…,n):

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{9}$$

It's evident that $0 \leq S_i \leq 1$, and the larger the S_i, the smaller the D_i^+, meaning it's closer to the true value.

The scores can be normalized:

$$\widetilde{S}_i = S_i / \sum_{i=1}^{n} S_i \tag{10}$$

In this case:

$$\sum_{i=1}^{n} S_i = 1 \tag{11}$$

TOPSIS Solution Process as shown in Table 5:

Table 5. TOPSIS Solution Process

Step1	Establish the Decision Matrix
Step2	Normalize the Decision Matrix
Step3	Determine the Weights
Step4	Determine the Positive Ideal Solution and Negative Ideal Solution
Step5	Calculate the Distance
Step6	Calculate the Composite Score
Step7	Ranking

6 Model Solving

Presentation of TOPSIS Solution Results as shown in Table 6:

Table 6. TOPSIS Solution Results

Index Value	Distance to Positive Ideal Solution(D^+)	Distance to Negative Ideal Solution(D^-)	Comprehensive Score Index	Ranking
Nanjing City	0.68387626	0.62951849	0.47930638	8
Wuxi City	0.54650725	0.59191217	0.51994209	4
Xuzhou City	0.5928585	0.5011355	0.45807884	10
Changzhou City	0.49899296	0.58237139	0.53855242	3
Suzhou City	0.43605054	0.78035065	0.64152408	1
Nantong City	0.63325581	0.46883952	0.42540741	11
Lianyungang City	0.65758361	0.58266881	0.46979857	9
Huaian City	0.70978736	0.52207552	0.42380977	12
Yancheng City	0.63323601	0.45494106	0.41807631	13
Yangzhou City	0.57821855	0.58573594	0.50322925	6
Zhenjiang City	0.53452053	0.65736139	0.55153231	2
Taizhou City	0.58124776	0.58482208	0.50153264	7
Suqian City	0.65388637	0.6783514	0.50918193	5

D+ and D- values, these two values represent the distance (Euclidean distance) between the evaluation object and the optimal or worst solution (ie A+ or A-), the actual meaning of these two values is that the distance between the evaluation object and the optimal or worst solution, the larger the value, the farther the distance, the larger the value of the research object D+, the farther away from the optimal solution; D-The higher the value, the farther away from the worst solution. The most understood object of study is that the smaller the D+ value, the larger the D- value. The synthesis score C value, C = (D-) / (D+ + D-), the calculation formula, the numerator is the D- value, and the denominator is the sum of D+ and D-; The larger the D-value, the farther away the research object is from the worst solution, the better the research object; the larger the C value, the better the research object. To validate the authenticity and reliability of this study, we obtained the ranking of environmental air quality in Jiangsu Province from the Jiangsu Provincial Department of Ecology for the year 2021, as shown in Table 7. Building lifecycle carbon emissions refer to the total carbon emissions generated throughout the entire lifecycle of a building, including construction, use, and demolition. On the other hand, air quality is one of the important indicators reflecting the environmental quality of a city. While building lifecycle carbon emissions and air quality are two different indicators, their outcomes are influenced by the same environmental factors, such as energy consumption, industrial emissions, and traffic conditions. Building lifecycle carbon emissions mainly involve carbon emissions from aspects like building materials, construction, use, and demolition. During the building's use phase, a large amount of pollutants such as carbon dioxide, nitrogen oxides, and particulate matter are generated. These pollutants have a significant impact on air quality. Therefore, there is a certain correlation between building lifecycle carbon emissions and air quality.

Table 7. Ranking of Environmental Air Quality in Jiangsu Province

City	Comprehensive Air Quality Index	Rank
Suzhou City	3.92	1
Wuxi City	3.93	2
Nantong City	3.94	3
Nanjing City	4.01	4
Taizhou City	4.1	5
Yancheng City	4.16	6
Yangzhou City	4.45	7
Huaian City	4.46	8
Zhenjiang City	4.5	9
Changzhou City	4.64	10
Lianyungang City	4.69	11
Suqian City	4.84	12
Xuzhou City	5.61	13

The disparities between rankings of architectural carbon emissions and air quality across various cities in Jiangsu Province stem from a confluence of multiple underlying factors. These encompass disparate focuses on carbon emissions and other pollutants across cities, the spread of pollutants influenced by climatic and geographical conditions, varied governmental policies and their enforcement, heterogeneous industrial structures and urban development stages, along with differences in technological applications and societal environmental awareness. For instance, while architectural carbon emissions primarily concern carbon dioxide, the quality of air is often impacted by various pollutants, potentially leading to scenarios where some cities may maintain decent air quality despite high carbon emissions, and vice versa. Moreover, the policies and enforcement from the government, as well as the industrial structure and development stage of a city, also shape the status of a city's carbon emissions and air quality to a certain extent. A profound exploration and understanding of the fundamental reasons behind these differences will assist in formulating more precise and effective environmental policies and measures, also providing beneficial references and insights for environmental protection and sustainable development across the province—and even in a broader context.

7 Conclusion

Through analyzing the rankings for building lifecycle carbon emissions and air quality standards, Suzhou and Wuxi in Jiangsu Province notably excel in both metrics, validating the reliability of our comprehensive evaluation model. This research can guide policymakers, urban planners, and the construction industry in formulating precise, targeted policies, and developing sustainable urban plans and eco-friendly building practices. Implementing the findings may encounter challenges, such as technological innovation costs and policy compliance, which can be navigated through strategies like providing financial incentives, establishing collaborative platforms, and enhancing environmental awareness and engagement through educational campaigns. This alignment and practical application of research findings and actionable strategies could pave the way for tangible improvements in managing building carbon emissions.

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