E3S Web of Conferences **725**, 02003 (2026) https://doi.org/10.1051/e3sconf/202672502003
ICSCER 2026

Analysis of influencing factors on carbon emissions in the building operation and maintenance phase

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Abstract. This study systematically identifies the key factors influencing carbon emissions during the operation and maintenance (O&M) phase of buildings in China. Using an exploratory sequential mixed methods design, we identify four core dimensions: equipment efficiency, O&M management, user behavior, and external environment. Importance analysis shows that O&M management exerts the strongest influence, with "management commitment" being the most critical factor. Equipment efficiency serves as the essential technological foundation, while external environment acts as the primary external driver. The direct impact of user behavior is perceived as relatively limited. Therefore, an integrated strategy is recommended, emphasizing management leadership, technological upgrades, improved policy and market mechanisms, and intelligent guidance of user behavior. The findings offer actionable insights to support China's "Dual Carbon" goals.

1 Introduction

Global warming and related environmental challenges have become increasingly severe, posing significant threats to human living conditions [1]. In response, countries worldwide are actively promoting energy conservation and emission reduction through policy instruments, technological innovation, and management measures. As one of the world's largest carbon emitters, China announced its "Dual Carbon" goals in September 2020, aiming to achieve carbon peaking by 2030 and carbon neutrality by 2060 [2]. Compared with developed economies such as the United States, Japan, and European Union, China faces a more compressed timeline and greater pressure due to its high total emissions [3].

The construction industry, as a typical energy-intensive sector, represents a major obstacle to achieving these goals. Across the building life cycle, the operation and maintenance (O&M) phase accounts for approximately 70%–90% of total carbon emissions, underscoring its critical role in emission reduction efforts. Carbon emissions during the O&M phase mainly arise from energy consumption associated with heating, cooling, ventilation, and lighting, manifesting as both direct and indirect emissions [4]. However, the advancement of emission reduction in China's building O&M phase remains constrained by factors such as a large existing building stock, outdated management practices, and uneven

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technological capabilities. Common challenges include low equipment efficiency, limited user awareness of energy conservation, and the absence of reliable carbon data traceability mechanisms. Moreover, insufficient policy incentives and weak cross-departmental coordination hinder the large-scale adoption of energy-saving technologies. Therefore, identifying the key factors influencing carbon emissions during the O&M phase is essential for promoting effective emission reduction in building sector.

2 Literature review

Existing studies on building carbon emissions largely adopt a life-cycle perspective, covering material production, construction, operation, and demolition stages. Research has been conducted from both macro- and micro-level perspectives.

At the macro level, factors such as economic development, policy incentives, and energy market reforms are commonly regarded as exogenous drivers of carbon emissions during the O&M phase [5]. The rapid expansion of China's construction industry has significantly contributed to GDP growth, while simultaneously leading to increased carbon emissions, indicating a strong coupling between economic growth and emissions [6]. Song et al. [7] found that purchase restriction policies can contribute to emission reduction by limiting population growth and freight demand. Given the dominance of coal in China's energy structure, adjustments toward cleaner energy sources play a crucial role in reducing building-related carbon emissions [8].

At the micro level, scholars have examined decarbonization pathways from the perspectives of construction technologies and materials. Prefabricated and steel structures exhibit advantages in reducing life-cycle emissions due to standardized production and assembly-oriented construction processes [9]. During the O&M phase, factors such as air-conditioning (HVAC) systems, lighting and electrical equipment, and building envelope performance are widely recognized as key determinants of energy consumption [10]. For instance, Litardo et al. [11] reviewed 41 studies on HVAC systems and reported that grid-connected vapor-compression heat pumps and chillers generate higher global warming potential than renewable-powered alternatives. Similarly, Albu et al. [12] found that 96% of greenhouse gas emissions from light-emitting diode (LED) systems occur during the O&M phase, and that natural lighting integration and intelligent dimming can reduce emissions by approximately 10%.

With recent technological advancements, digital tools such as Building Information Modeling (BIM) have facilitated data sharing throughout O&M process, contributing to improved energy efficiency and emission reduction [13]. Management factors function as intermediate mechanisms that shape actual performance of technical systems through operational procedures and monitoring practices [14]. In addition, user behavior, including HVAC use, lighting control, and equipment operation, has been identified as an important yet often underestimated factor in building emission reduction [15].

Despite substantial progress, existing research tends to emphasize the whole life cycle, with limited attention to the relative importance of factors specifically within the O&M phase. Therefore, this study focuses on identifying and prioritizing the key drivers of carbon emissions during building O&M phase in China, with the aim of informing targeted policy and management interventions.

3 Research design

This study adopts an exploratory sequential mixed methods design, consisting of three main phases, as illustrated in Figure 1. First, a systematic literature review was conducted, drawing on relevant works and considering China's actual context to develop a preliminary scale. In the second phase, semi-structured interviews were carried out with 16 executives from the Chinese building industry to identify key influencing factors and theoretical foundations for carbon reduction during building O&M stage. Finally, in the third phase, a questionnaire survey was administered to professionals in building industry. A non-probability purposive sampling method was used to target individuals with direct experience in building O&M. The survey was distributed through professional networks and project teams. After screening for completeness and consistency, 126 valid responses were retained for analysis. The sample included project managers, engineering technicians, design consultants and construction workers. Exploratory factor analysis was performed using SPSS to extract underlying structures, and relative importance indices were calculated to identify the significance of each influencing factor.

Fig. 1. Research methodology framework.

4 Results and discussion

4.1 General information

Table 1 summarizes characteristics of the 126 valid samples. Among respondents, 14.29% were project managers, 26.98% were engineering technicians, 34.13% were construction workers, and 24.60% were design consultants. Regarding work experience, 16.67% had 0–5 years, 26.19% had 6–10 years, 41.27% had 11–15 years, and 15.87% had over 15 years. In terms of education, 58 respondents (46.03%) held bachelor's degrees, 40 (31.75%) held master's degrees, and 28 (22.22%) held doctoral or higher degrees.

Table 1. Demographic profile of the sample data.

Characteristics	Category	Percentage
Occupation	Project manager	14.29%
	Engineering technician	26.98%
	Construction worker	34.13%
	Design consultant	24.60%
Years of service	0-5	16.67%
	6-10	26.19%
	11-15	41.27%
	16 or above	15.87%
Education level	Bachelor degree	46.03%
	Master's degree	31.75%
	Doctoral degree or above	22.22%

4.2 Exploratory factor analysis

This study aims to identify factors influencing carbon emissions during the O&M phase of building industry. Exploratory factor analysis (EFA) was conducted on the questionnaire data using SPSS. Common factors with initial eigenvalues greater than 1 were extracted via principal component analysis, and the factor matrix was refined using varimax rotation. The results of KMO and Bartlett's test are shown in Table 2. A KMO value of 0.887 (>0.6) indicates that the original variables are suitable for EFA, and the significant Bartlett's test result confirms the data's suitability for factor analysis.

Table 2. KMO and Bartlett test.

Number of KMO sample tangents	Bartlett's sphericity test		
	Approximate chi square	Degree of freedom	Statistical significance
0.887	2049.434	231	<0.001

The cumulative variance contribution rate of four components with eigenvalues greater than 1 is 74.267% (>60%), indicating a relatively clear factor structure. The distribution of variable loadings aligns with theoretical expectations, suggesting that the model effectively captures the underlying data structure. The rotated component matrix is detailed in Table 3.

Table 3. Factor load matrix after rotation.

Attributes	Components			
	1	2	3	4
A1	0.870			
A2	0.826			
A3	0.854			
A4	0.798			
A5	0.857			
A6	0.876			
A7	0.854			
B1				0.825
B2				0.808
B3				0.822
B4				0.824
B5				0.811
C1			0.867	
C2			0.849	
C3			0.813	
C4			0.769	

Table 3. (Continued).

Attributes	Components			
	1	2	3	4
C5			0.856	
D1		0.863		
D2		0.835		
D3		0.834		
D4		0.862		
D5		0.832		

Note: A1–A7: Equipment efficiency; B1–B5: O&M management; C1–C5: User behavior; D1–D5: External environment.

The rotated component matrix shows four categories of influencing factors: equipment efficiency, O&M management, user behavior, and external environment. These comprise 22 items in total: 7 under equipment efficiency, and 5 each under O&M management, user behavior, and external environment.

4.3 Relative importance indices

To determine each factor's relative importance, we used a method combining average scores and the relative importance index (RII). The RII for each factor was calculated from questionnaire responses using the following formula:

$$RII = (\Sigma W)/(A*N) \quad (1)$$

Where W represents the weight assigned to each factor (ranging from 1 to 5), A is the highest possible weight (5), and N is the total number of valid responses. The RII for each dimension was computed as the arithmetic mean of its constituent items. The results are presented in Table 4.

Table 4. Relative importance indices of influencing factors.

Type	Items	Factor loading	RII%	Overall RII%	Rankings
Equipment efficiency	Efficiency of HVAC system	0.870	67.60%	69.23%	16
	Efficiency of lighting system	0.826	69.80%		8
	Envelope performance	0.854	72.60%		2
	Renewable energy adoption	0.798	70.60%		5
	Monitoring and metering systems	0.857	67.40%		19
	Smart control systems	0.876	67.80%		15
	Digital infrastructure	0.854	68.80%		11
Operation and maintenance management	O&M strategy	0.825	71.20%	70.60%	3
	Data-driven decision making	0.808	68.00%		14
	Team competence	0.822	70.60%		5
	Management commitment	0.824	75.80%		1
	Green procurement management	0.811	67.40%		19
User behavior	Space utilization intensity	0.867	67.40%	67.84%	19
	Time-of-use patterns	0.849	69.80%		8
	Energy-saving	0.813	70.60%		5

	awareness				

Table 4. (Continued).

Type	Items	Factor loading	RII%	Overall RII%	Rankings
User behavior	Equipment usage habits	0.769	63.80%	67.84%	22
	Information feedback & engagement	0.856	67.60%		16
External environment	Policies and regulations	0.863	69.40%	69.00%	10
	Economic incentives	0.835	68.80%		11
	Electricity mix	0.834	68.40%		13
	Market and professional services	0.862	70.80%		4
	Industry and social pressure	0.832	67.60%		16

4.4 Discussion

Based on the data analysis, this study provides a detailed interpretation of how each specific questionnaire item contributes to carbon emissions during the building O&M phase.

O&M management emerged as the most influential dimension, with an overall RII of 70.60%. Within this dimension, management commitment (Item B4, RII = 75.80%) ranked first among all 22 indicators, highlighting that top-level managerial attention and leadership are decisive for implementing effective carbon reduction measures. Similarly, O&M strategy (Item B1, RII = 71.20%) ranked third overall, indicating that the formulation of clear operational strategies directly affects the performance of energy-saving measures. These findings suggest that management-related items play a critical coordinating role by translating technical potential into actual emission reduction outcomes.

In the equipment efficiency dimension, envelope performance (Item A3, RII = 72.60%) ranked second overall, underscoring its fundamental role in reducing energy demand during building operation. In addition, renewable energy adoption (Item A4, RII = 70.60%) and lighting system efficiency (Item A2, RII = 69.80%) also demonstrated high importance, confirming that improvements in physical infrastructure and energy systems remain the technological foundation for carbon reduction in the O&M phase.

Regarding the external environment, market and professional services (Item D4, RII = 70.80%) ranked fourth overall, suggesting that access to specialized energy services and professional support significantly facilitates emission reduction practices. Meanwhile, policies and regulations (Item D1, RII = 69.40%) further emphasize the role of regulatory frameworks in guiding industry behavior and accelerating low-carbon transitions.

The user behavior dimension exhibited the lowest overall RII (67.84%). Although energy-saving awareness (Item C3, RII = 70.60%) showed moderate importance, equipment usage habits (Item C4, RII = 63.80%) ranked last among all items. This indicates that while user-related factors are necessary components of carbon reduction strategies, their direct and short-term impact is perceived as more limited compared to management and technical factors, particularly in large-scale and institutional buildings.

Compared with previous studies that primarily emphasized technological upgrades or policy interventions, the present findings reveal that management-related items—especially management commitment and strategic O&M planning—play a more decisive role during the building O&M phase. This reflects a shift from "technology-driven" to "management-enabled" emission reduction pathways under existing technological conditions.

5 Conclusion

This study focuses on the building O&M phase, using an exploratory sequential mixed methods approach to identify four key dimensions influencing carbon emissions: equipment efficiency, O&M management, user behavior, and external environment. The relative importance indices analysis shows O&M management is currently the most influential dimension, equipment efficiency serves as the technological foundation, external environment provides important drivers, and the direct impact of user behavior appears relatively limited.

Therefore, promoting carbon reduction in building O&M phase requires a systemic strategy: strengthening management-led governance frameworks, prioritizing key energy-efficient technological retrofits, improving policy incentives and market mechanisms, and guiding user behavior through intelligent solutions. Only by deeply integrating management, technology, policy, and behavior can the full emission reduction potential of the O&M phase be realized, thereby providing robust support for China's "Dual Carbon" goals.

Thanks to all respondents who participated in the survey and interviews for their valuable contributions to this research.

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