ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Sustainable building practices in contemporary Chinese urbanism: A low-carbon construction management perspective

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Abstract

China's transition toward a low-carbon economy has placed the building industry at the center of ecological modernization. This study examines sustainable building practices in contemporary Chinese urbanism through the lens of low-carbon construction management and ecological modernization theory (EMT). A dataset of 40 completed building projects across major Chinese provinces was analyzed to examine the interplay among technological innovation, managerial adaptation, and institutional incentives. The analyzed variables included operational energy performance, embodied carbon, renewable-energy integration, waste-reduction practices, certification level, managerial training, and policy support. The environmental and managerial determinants of the outcomes of the projects were assessed using descriptive and correlational analyses. The results indicate that the projects that combined prefabricated or hybrid construction systems, greater renewable-energy potential, and building information modeling had lower carbon intensity and greater reductions in carbon dioxide emissions. There was a positive correlation between managerial training and experience and the number of measures put in place to be sustainable, whereas policy incentives and green certifications were essential facilitators of modernization. On the other hand, cost sensitivity and skills shortages were still the main obstacles. From an EMT perspective, the findings suggest that China has followed a hybrid ecological modernization pathway characterized by the interaction of state guidance, technological diffusion, and managerial learning. By linking empirical evidence with EMT, the study demonstrates that innovation in construction management represents a key pathway for advancing the greening of China's urban development paradigm. This study provides policy recommendations to enhance capacity building, institutional alignment, and technology transfer to promote a systemic low-carbon transition.

Keywords: Sustainable construction; Ecological modernization theory; Low-carbon management; Chinese urbanism; Building performance; Renewable energy

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Citation: Zhong, J., & Mohd Shafiei, MW. (2026). Sustainable building practices in contemporary Chinese urbanism: A low-carbon construction management perspective. *Journal of Chinese Architecture and Urbanism*. 8(4):026090015. https://doi.org/10.36922/JCAU026090015

Received: February 27, 2026

Revised: April 9, 2026

Accepted: April 17, 2026

Published online: May 19, 2026

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1. Introduction

Over the past four decades, China's rapid urbanization has generated unprecedented demand for new buildings, infrastructure, and urban services. Although this has led to economic growth and improved quality of life, it has also increased the strain on the environment. Building operations and construction account for nearly 40 percent of

national energy consumption and over one-third of total carbon emissions (Huo *et al.*, 2022; Ma *et al.*, 2021; Xia *et al.*, 2024). As China seeks to peak its carbon emissions before 2030 and achieve carbon neutrality by 2060, the transformation of urban construction practices has become a cornerstone of the country's green transition.

Green building has evolved beyond a purely technical intervention and has become an important driver of institutional and managerial modernization. The construction management of low-carbon development requires a comprehensive strategy that includes design innovation, clean construction processes, and efficient project execution, alongside policy compliance and stakeholder awareness. In the last 10 years, the government has introduced a number of policies, including the Green Building Evaluation Standard (GB/T 50378-2019) and the 14th Five-Year Plan on Building Energy Efficiency, which have encouraged the spread of energy-saving technologies and green certifications. However, the conceptualization of the policy-to-practice transformation of such policies in on-site management practices remains inconsistent (He *et al.*, 2023; Q. Hu *et al.*, 2023; Zhang *et al.*, 2024).

An ecological modernization theory (EMT)-based analysis offers a valuable analytical framework for examining this change. EMT was developed in European environmental sociology and proposes that modernization does not necessarily impose a burden on environmental protection, but may instead act as one of its enabling conditions (Bush & Spaargaren, 2024). It highlights technological advancement, institutional change, and reflexive governance as reinforcing factors of ecological improvement (Bush & Spaargaren, 2024; S. S. Hu *et al.*, 2025). These concepts align with Chinese ambitions for high-quality development, which emphasize innovation-led and policy-directed modernization in the Chinese context (X. Yang & Liu, 2024).

Figure 1 presents the conceptual framework of the study based on EMT. The framework illustrates how technological innovation (e.g., prefabrication, building information modeling [BIM], and renewable energy), institutional transformation (e.g., policy incentives and certification systems), and managerial learning (e.g., experience and sustainability training) interact to influence low-carbon construction outcomes in urban building projects.

The use of EMT in the Chinese construction industry highlights three overlapping dynamics. First, technological modernization involves the increased use of prefabrication, modularization, digital design systems, and renewable-energy systems, which enhance eco-efficiency (Y. Y. Liu *et al.*, 2024; Sindhu Pradeep *et al.*, 2025; G. Yang *et al.*,

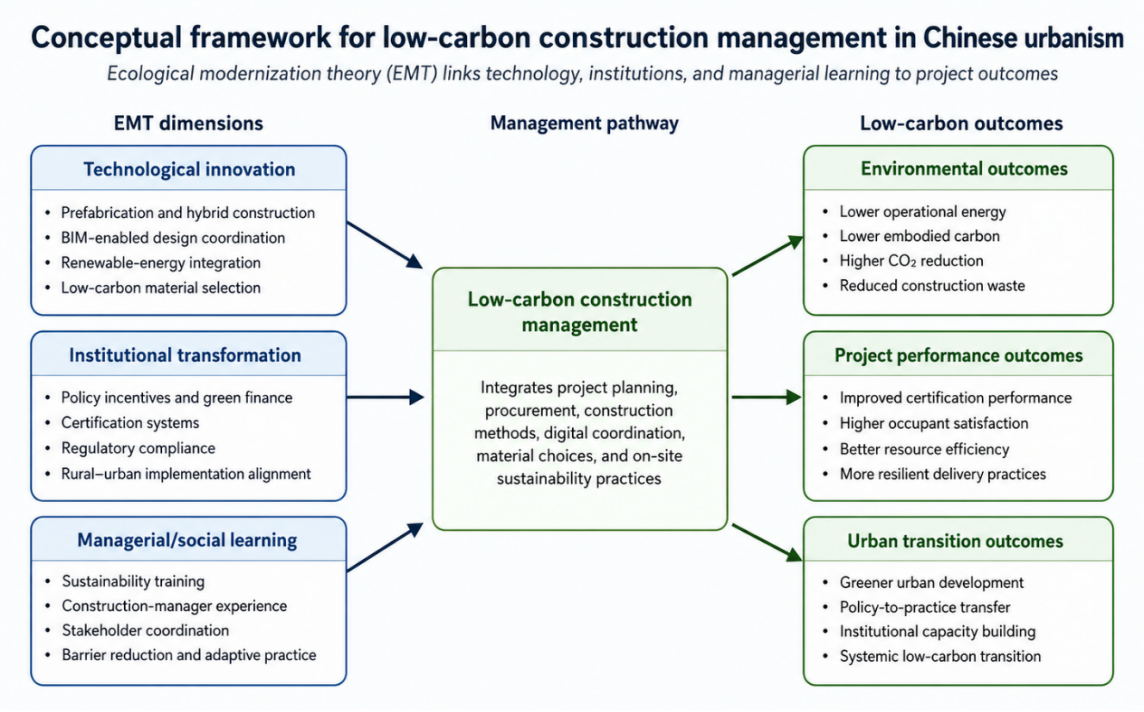


Figure 1. Conceptual framework linking ecological modernization theory dimensions—technological innovation, institutional transformation, and managerial learning—to low-carbon construction outcomes in Chinese urban building projects. Source: Diagram by the authors

2025). Second, policy incentives, certification regimes—including China Three-Star and Leadership in Energy and Environmental Design [LEED] systems—and evolving regulatory frameworks represent aspects of institutional modernization, integrating market mechanisms with environmental goals (Y. Hu & Lin, 2022; Q. Q. Hu *et al.*, 2023; Niu *et al.*, 2021). Third, social and managerial learning occurs through training programs, professional development, and shifts in sustainability perceptions among construction managers (Wu *et al.*, 2023; Qi *et al.*, 2023).

Issues of higher cost, lack of technical skills, and fragmented coordination among stakeholders remain key barriers to the wider adoption of low-carbon practices (B. B. Li *et al.*, 2025). Therefore, the empirical analysis of the impact of managerial experience, training, and policy incentives on project performance is important to understand the actual trajectory of ecological modernization in the Chinese building industry.

The present study adds to the existing literature in that it links empirical project-level data with EMT theoretical constructs. In this study, 40 sustainable building projects across major provinces, including residential, office, industrial, public, and mixed-use, were analyzed. The variables grouped in the dataset include technical variables, such as the intensity of operational energy, installation share of renewable energy, and the share of BIM, as well as managerial and institutional variables, which comprise training, experience, level of certification, perceived obstacles, and the presence of policy incentives. By combining these factors, the study provides a multidimensional view of the process of ecological modernization in terms of day-to-day construction management decision-making.

Theoretically, this study extends EMT into a practical management framework, in which sustainability outcomes are not merely technological outputs, but reflections of institutional capacity and organizational learning. From a policy perspective, it highlights how national and city-level programs such as ultra-low-energy building projects and industrialization through BIM can be translated into actual on-site performance outcomes.

This study aims to provide empirical evidence supporting the view that the building industry in China is an ecological modernization laboratory: state policies, technological development, and advanced management practices collectively contribute to the national low-carbon agenda.

1.1. Research questions

(i) How do technological, institutional, and managerial variables jointly influence low-carbon outcomes in Chinese building projects?
(ii) Which technology practices (e.g., prefabrication, BIM, and renewable-energy integration) are the most effective in minimizing operational-energy consumption and embodied-carbon emissions?
(iii) How well do institutional supports (e.g., policy incentives, green-building certifications, and managerial training) facilitate the adoption and effectiveness of sustainable construction management practices?

1.2. Research hypothesis

(i) The use of advanced construction technologies (e.g., prefabrication, BIM, and renewable energy) is positively related to carbon dioxide (CO_2) reduction rates.
(ii) There is a significant improvement in overall project sustainability performance associated with policy incentives and higher levels of certification.
(iii) Managerial experience and formal sustainability training have a positive impact on the implementation and performance of low-carbon construction practices.

1.3. Literature review

1.3.1. Sustainable and low-carbon building practices in China

Chinese research on sustainable building has increased at an accelerated pace since the 2010s due to decarbonization pressures and the increasing maturity of building governance systems. Many researchers indicate that buildings are central to achieving the country's dual-carbon goals (Cao *et al.*, 2022; Ma *et al.*, 2021; S. Hu *et al.*, 2025). The construction sector of China accounts for approximately 38–40 percent of the total energy consumption and 30 percent of carbon emissions (J. J. Li *et al.*, 2024; You *et al.*, 2023; Zhang *et al.*, 2024). As a result, the government has heightened its attention on energy-efficient technologies, enforcement of building codes, and green building certification systems.

Several green building frameworks, such as the China Three-Star Rating System (launched in 2006), LEED, and the International Finance Corporation Excellence in Design for Greater Efficiencies (IFC EDGE), have provided quantifiable measures of environmental performance (Cao *et al.*, 2022; Y. Hu & Lin, 2022; Wang, 2022). According to recent studies, certified buildings achieve an average of 20–30 percent improvement in operational energy efficiency compared with conventional buildings (Sindhu Pradeep *et al.*, 2025; Q. Q. Hu *et al.*, 2023). Nonetheless, certification diffusion is unequal: major cities such as

Shanghai and Shenzhen have achieved near-universal certification in public projects, whereas secondary urban centers show lower certification uptake because of financial constraints and technical barriers (He *et al*., 2023).

Prefabrication and modularization have taken center stage. The Ministry of Housing and Urban-Rural Development has set a target that the proportion of prefabricated buildings in new urban areas should exceed 30 percent by 2025 (MOHURD, 2022). The empirical data demonstrate that the use of prefabricated structures can reduce construction waste by 60 percent and embodied carbon by up to 20 percent (Huang *et al*., 2023; Sindhu Pradeep *et al*., 2025; Zhao *et al*., 2025). Likewise, BIM solutions improve design accuracy, optimize resource scheduling, and support life-cycle carbon accounting (Y. Liu *et al*., 2024). However, their implementation still faces challenges related to fragmented supply chains and a lack of managerial expertise (B. B. Li *et al*., 2025; Wu *et al*., 2023).

According to managerial literature in construction management, technical performance is not sufficient in achieving sustainability improvements. Project outcomes are highly dependent on organizational learning, leadership behavior, and skill development (Wu *et al*., 2023; Qi *et al*., 2023). In the Chinese context, which is characterized by both state-owned enterprises and private contractors, heterogeneous performance outcomes may be attributed to differences in training, incentive schemes, and decision-making authority (S. S. Hu *et al*., 2025; X. Yang & Liu, 2024).

1.3.2. Low-carbon construction management and policy instruments

Low-carbon management (LCM) is not merely about energy-saving technology, but also encompasses psychological, institutional, and financial aspects of project delivery. Luo *et al*. (2022) and Hewa *et al*. (2024) indicate that LCM brings together four essential functions: carbon goal setting, carbon auditing, stakeholder coordination, and continuous learning processes. These should be incorporated into the daily management of construction processes by following international standards such as ISO 14064 and the embodied carbon quantification framework under EN 15978.

The Chinese government at the national and provincial levels has implemented various policy tools that are in line with LCM principles. These include the *14th Five-Year Plan for Building Energy Efficiency and Green Building Development* (MOHURD, 2022) and the *Implementation Plan for Carbon Peaking in Urban and Rural Construction* (MOHURD & NDRC, 2022). Empirical evidence indicates that there are significant regional variations in implementation: eastern provinces have more developed financing systems and stronger institutional capacity for policy implementation, whereas western provinces face constraints in capital availability and technical knowledge (Niu *et al*., 2021).

According to Kong and He (2021), the most frequently cited obstacle to low-carbon construction practices is cost perception. However, advances in digital monitoring technologies and mass production techniques are gradually transforming cost-efficiency. Research also highlights the complementary relationship between BIM and energy modeling software in forecasting carbon trajectories prior to the commencement of construction (Y. Y. Liu *et al*., 2024).

In the present dataset, projects receiving policy incentives reported a 12.2 percentage-point higher renewable-energy share and an 8.1 percentage-point higher CO_2-reduction rate than non-incentivized projects, indicating that institutional support mechanisms can strengthen low-carbon construction outcomes. Nevertheless, longitudinal evidence remains limited, making it difficult to determine the long-term efficacy of such programs.

1.3.3. Ecological modernization theory and its adaptation in China

Ecological modernization theory, initially formulated in Western Europe in the 1980s, proposes that environmental reform can be achieved through the modernization of technology, industry, and governance, rather than through radical societal restructuring (Bush & Spaargaren, 2024; S. S. Hu *et al*., 2025). It emphasizes four main processes: technological innovation, institutional adaptation, market rationalization, and social learning (Bush & Spaargaren, 2024).

Western literature tended to view EMT in a liberal-state framework and focused on corporate self-regulation and policy networks (Bush & Spaargaren, 2024). Nonetheless, its application in developing and transition economies has necessitated conceptual redefinition. In China, ecological modernization is highly state-centered, involving hierarchical policy structures and deliberate techno-economic planning (S. S. Hu *et al*., 2025; X. Yang & Liu, 2024). Ecological civilization, a policy narrative introduced in the early 2010s, incorporates EMT principles into a distinctive ideological framework that positions technological innovation and environmental protection as mutually reinforcing objectives (He *et al*., 2023; Q. Q. Hu *et al*., 2023).

Recent studies have integrated EMT with sociotechnical transition theories to examine how institutional and

managerial reforms facilitate sustainable innovation in China. For example, Q. Q. Hu *et al.* (2023) found that green certification systems have become reflexive governance mechanisms, enhancing information transparency and professional accountability. S. S. Hu *et al.* (2025) also suggest that the Chinese context is characterized by a dual dynamic within EMT: state-facilitated market-oriented modernization. In this paradigm, innovation is generated by state-sponsored pilot projects rather than pure market competition, a configuration also observed in the building industry.

1.3.4. The association of ecological modernization theory with construction management

Scholars have increasingly considered construction management as a technical and institutional domain in which EMT processes are operationalized (Bush & Spaargaren, 2024; G. Yang *et al.*, 2025; Y. Y. Liu *et al.*, 2024). Managerial learning is a form of reflexive modernization: project actors respond to environmental policies by adjusting organizational practices and technical standards. As an illustration, Wu *et al.* (2023) showed that sustainability training directly leads to increased project team cohesion and willingness to innovate. Qi *et al.* (2023), in a comparative study of 180 projects, established a statistically significant correlation between management experience and key sustainability indicators such as waste reduction and occupant satisfaction.

Governance structures are not independent of technological diffusion in the Chinese building industry. Local authorities tend to promote or even mandate BIM adoption, renewable-energy installation, and waste reduction measures, thereby integrating technological and institutional modernization (Niu *et al.*, 2021; Q. Q. Hu *et al.*, 2023). This interdependence demonstrates the argument that EMT posits environmental innovation as socially constructed within specific policy and cultural contexts.

In practice, EMT should be incorporated in construction management research to contribute to three analytical goals:

(i) It does not present sustainability as a compliance issue, but as a means of enhancing efficiency and fostering innovation.
(ii) It exposes the interdependencies of governance, depicting how state policy, corporate strategy, and managerial learning co-evolve.
(iii) It connects micro-level practices (e.g., training and decision-making) and macro-level outcomes (e.g., carbon reduction and urban decarbonization).

Quantifying these linkages at the project level remains empirically limited. Most EMT analyses are based on national or industry-level data, and they do not disaggregate outcomes by technological or managerial factors (Ai *et al.*, 2024; Kong & He, 2021). Limited comparative studies have been conducted on how specific construction methods or managerial capacities can be translated into actual carbon outcomes across different institutional environments. To overcome this limitation, the present study—based on project-level survey data—aims to examine whether the synergy predicted by EMT, encompassing technological innovation, institutional transformation, and managerial learning, can be empirically confirmed.

1.3.5. Research gaps and framework

There are three research gaps that motivate the contribution of this study:

(i) Quantitative integration of EMT with building-level data: The majority of EMT research in China is theoretical or qualitative; quantitative project-level analysis remains limited.
(ii) Managerial–institutional interface: Although the role of technological innovation has been widely studied, the influence of managerial training, experience, and perceived barriers on quantified carbon performance remains underexplored (Huang *et al.*, 2023).
(iii) Policy–practice consistency: There is a dearth of empirical analyses on the effectiveness of incentives and certification schemes in translating into operational sustainability performance.

Therefore, this study explores how the interaction of managerial, technological, and institutional factors determines low-carbon outcomes in urban buildings. These relationships are conceptualized in the framework (Figure 1) through the three EMT dimensions, including technological innovation, institutional transformation, and managerial/social learning, which are operationalized using the measurable indicators.

The construction sector of China operationalizes EMT by providing a new set of evidence that environmental reform can be structurally institutionalized within industrial processes. Such a view is a complement to the international literature on EMT as it demonstrates a form of directive eco-modernization, in which policy guidance replaces market spontaneity (S. S. Hu *et al.*, 2025; X. Yang & Liu, 2024). This study is positioned not as an entirely new theory of ecological modernization, but as an empirical refinement and contextual reinterpretation of EMT for state-led urban transitions. EMT provides the primary macro-theoretical lens, while sociotechnical transitions thinking helps explain how low-carbon practices diffuse across project routines, technologies, and regulatory

niches, and institutional theory clarifies how certification systems, policy incentives, and managerial norms stabilize these practices across organizations.

Within this integrated framework, prefabrication, BIM, and renewable-energy adoption represent technological transition mechanisms; certification and incentive schemes function as institutional carriers; and managerial training and experience reflect organizational learning mechanisms through which sustainability becomes embedded in project delivery. The contribution of the study therefore lies in demonstrating that, in the Chinese construction context, ecological modernization is best understood as a state-steered, institutionally mediated, and managerially enacted transition, rather than a purely market-driven technological shift.

2. Methodology

2.1. Data collection

This study surveyed 40 completed building projects in 21 cities across 16 provinces in China. The database covers all types of projects: residential (35%), office (27%), public and institutional projects (20%), industrial buildings (10%), and mixed-use projects (8%). The years of project completion range from 2013 to 2023, representing 10 years of policy changes and technological diffusion in the Chinese construction industry.

The structured interviews and questionnaire surveys conducted in 2023 and 2024 involved project managers, and the data were verified against public-domain certification records (e.g., China Three-Star, LEED, IFC EDGE) and documentation of municipal green-building databases. There were four categories of variables:

(i) Technical characteristics: Floor area, the main construction technique (e.g., traditional, prefabricated, hybrid), primary material, type of insulation (or no insulation), installed renewable energy capacity (as a percentage of total energy consumption), operational energy intensity (kWh/m^2/year), and embodied carbon (kg CO_2e/m^2).
(ii) Managerial indicators: Construction manager experience (years), training conducted (yes/no), sustainability cost premium (%), and waste reduction (%).
(iii) Institutional measures: Type of certification, use of local materials and sourcing (yes/no), policy incentive (yes/no), and perceived barriers (e.g., costs, skills, supply chain constraints).
(iv) Outcome measures: The rate of CO_2 reduction (%) and occupant satisfaction (scale: 1–5).

Although policy incentives were operationalized as a binary variable (presence or absence) for statistical modeling purposes, the dataset also recorded the type of incentive mechanisms, including direct subsidies, expedited administrative approvals, floor-area-ratio bonuses, and preferential access to green financing programs. The binary variable was used in regression models to ensure statistical stability given the limited sample size. However, future research could operationalize policy incentives using multidimensional indicators reflecting incentive magnitude and duration.

Building information modeling was reported to be used in approximately 60 percent of projects for design coordination and/or on-site management purposes. The average renewable-energy integration was 15.8 percent of total energy supply, and the average operational energy intensity was 82.5 kWh/m^2/year. The survey was also intentionally designed to capture diversity rather than scale, so as to reflect the heterogeneity of China regarding climate zones, resource endowments, and policy focus (S. S. Hu *et al*., 2025).

To enhance data reliability, multiple validation procedures were implemented. Approximately 65 percent of the project-level responses were cross-checked against external documentation, including municipal green-building databases, certification records (China Three-Star, LEED, and IFC EDGE), and publicly available project reports. Where discrepancies were identified, follow-up clarification was obtained from project managers.

This triangulation procedure reduces the potential bias associated with self-reported survey responses and strengthens the internal validity of the dataset.

All responses were anonymized in order to safeguard proprietary data. The sample was considered representative of modern building practices in Chinese cities, including high-income regions (e.g., Shanghai, Shenzhen, Guangzhou) and developing inland provinces (e.g., Shaanxi, Sichuan, Hubei).

2.1.1. Carbon accounting boundaries

To improve transparency and comparability of the environmental indicators, the study explicitly defines the carbon accounting boundaries used in the analysis. Embodied carbon values were calculated following the methodological principles outlined in GB/T 51366-2019. The accounting boundary includes three stages:

(i) Production of construction materials.
(ii) Transportation of materials to the construction site.
(iii) On-site construction processes.

Embodied carbon values were derived from life-cycle inventory coefficients available in the Chinese Life Cycle Database (CLCD), the China Products Carbon Footprint

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Factors Database (CPCD), and the China Carbon Database (CCDB), and were cross-checked with green-building certification documentation where available.

2.1.2. Scope of construction management variables

Although this study examined both embodied carbon and operational energy indicators, the analytical focus remains on construction management practices that influence these outcomes during the project development process. Specifically, the study evaluates construction-phase management measures such as prefabrication adoption, BIM-based design coordination and construction planning, material selection strategies, and waste-reduction practices. Operational energy performance is included as an outcome indicator because construction management decisions made during the design and construction phases significantly affect long-term building performance. This approach allows the study to assess how management decisions during project delivery influence life-cycle environmental outcomes while maintaining a primary focus on construction-phase management practices.

2.2. The use of ecological modernization theory

Ecological modernization theory focuses on transforming production and governance models through technological innovation, institutional reform, and social learning (Bush & Spaargaren, 2024; S. S. Hu *et al.*, 2025).

Technological innovation is defined through the variables of prefabrication, hybrid construction types, BIM usage, and the percentage of renewable-energy installation. These are based on the EMT assumption that modernization and eco-optimization can be advanced simultaneously due to technological advancements (G. Yang *et al.*, 2025; Sindhu Pradeep *et al.*, 2025).

Institutional change is represented by policy incentives, the type of certification, and the use of local materials. These aspects indicate a shift in regulatory and market models that integrate environmental performance into construction governance (Niu *et al.*, 2021; Q. Q. Hu *et al.*, 2023; Wang, 2022).

Managerial and social learning are captured by variables such as training, managerial experience, and perceived barriers. Their inclusion is consistent with the EMT concept of reflexive modernization, in which stakeholders internalize sustainability norms into organizational behavior (Qi *et al.*, 2023; Wu *et al.*, 2023).

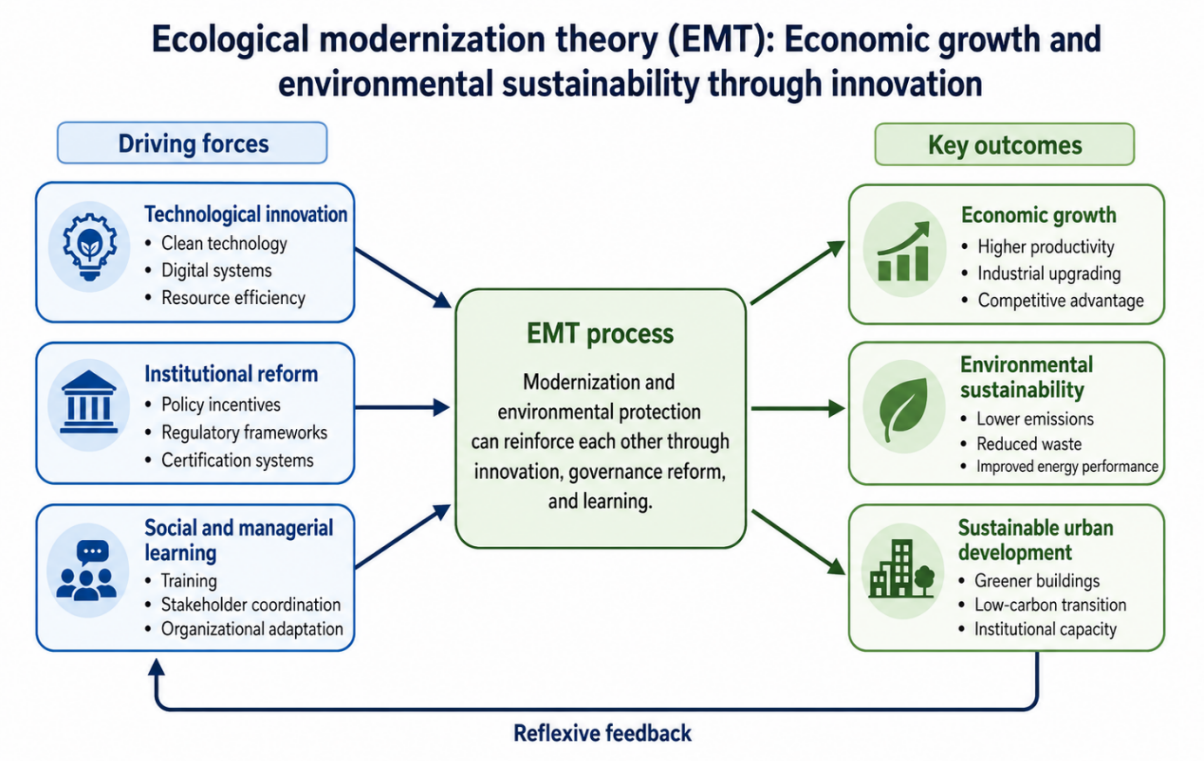


Figure 2. Ecological modernization theory (EMT): Economic growth and environmental sustainability through innovation. Source: Diagram by the authors

This three-pronged framework enables the simultaneous assessment of technological, institutional, and cognitive dimensions in shaping sustainable outcomes. All dimensions were empirically tested against the measured CO_2 reduction rate, which was treated as the primary dependent variable.

2.3. Analytical methods

The analysis employed descriptive statistics, comparative analysis, and correlation analysis to examine the relationships between sustainability practices and project outcomes.

The distribution of variables was summarized by descriptive statistics, including averages, ranges, and standard deviations, to determine adoption trends and performance levels. Variables related to technology usage (e.g., the percentage of renewable energy, BIM adoption) were compared across project types and regions to identify heterogeneity in the adoption of sustainability practices (Sindhu Pradeep *et al.*, 2025).

Comparative analysis was performed to assess differences in mean values between certified and non-certified projects, as well as between projects with and without policy incentives. An independent samples *t*-test was conducted to determine whether there were statistically significant differences in operational energy use and carbon intensity between the groups.

Pearson's correlation coefficient (r) was used to examine the relationships between managerial and institutional factors and carbon-related outcomes. For example, relationships were evaluated among (i) construction-manager experience and measured CO_2 reduction; (ii) training provision and prefabrication or BIM adoption; and (iii) the presence of policy incentives and the share of renewable energy.

In cases where there were sufficient samples, several linear regression models were then estimated in which the measured CO_2 reduction rate was taken as the dependent variable. Predictor variables included the percentage of renewable energy, certification level (ordinal), years of managerial experience, and policy incentive dummy variable. Multicollinearity was assessed using variance inflation factors (<5). All statistical analyses were conducted in SPSS version 27.0 (IBM, USA), and $p < 0.05$ was considered statistically significant.

Missing data were addressed using multiple imputation techniques, which preserve the variance structure of the dataset and provide more reliable parameter estimates compared with simple mean substitution. The proportion of missing observations was below 2 percent, and the imputation procedure produced stable estimates across iterations.

To reduce potential omitted variable bias, additional control variables were incorporated into the regression models. These include gross floor area, project type (e.g., residential, office, public, industrial, mixed-use), year of completion, and regional classification (coastal vs. inland). These variables capture differences in building scale, functional energy demand, temporal policy evolution, and regional disparities in technological diffusion and institutional support.

In addition to quantitative analysis, qualitative interpretation of open-ended survey responses provided a contextual understanding of managers' perception of barriers (e.g., cost, skills, supply chain) and motivations (e.g., client demand, policy compliance). The findings contributed to the EMT interpretation by demonstrating how actors cognitively respond to environmental modernization pressures (Hewa *et al.*, 2024; Wu *et al.*, 2023).

2.4. Statistical and validity issues

Considering the relatively small sample size ($n = 40$), the results are exploratory but reflect major trends in the sector. The analysis focuses on identifying relational patterns rather than population-level generalization. Cross-checking of project data with certification records and government reports supports internal validity, whereas the diversity in geographic distribution and project typologies strengthens external validity.

Although the use of self-reported data introduces potential response bias, triangulation with secondary documentation mitigates this limitation (Q. Q. Hu *et al.*, 2023). Sensitivity analyses, conducted under the exclusion of extreme outliers (e.g., large industrial facilities), showed consistent correlations between renewable energy integration and CO_2 reduction, as well as between policy incentives and innovation uptake.

Ethical approval was obtained from the research ethics committee of Universiti Sains Malaysia in 2023, and informed consent was obtained from all participants.

Table 1 summarizes the analytical structure of the study by linking the three dimensions of EMT—technological innovation, institutional transformation, and managerial/social learning—to their empirical indicators and expected low-carbon outcomes. This table clarifies how the conceptual framework was operationalized in the empirical analysis and shows that the study evaluated sustainability performance as a multidimensional process rather than a purely technical outcome.

Table 1. Summary

EMT dimension	Empirical variables (indicators)	Expected influence on low-carbon performance
Technological innovation	Prefabrication, hybrid methods, BIM adoption, renewable energy share	↓ Operational energy, ↓ embodied carbon
Institutional transformation	Policy incentive, certification level, local material utilization	↑ Innovation adoption, ↑ CO_2 reduction
Managerial/social learning	Training, experience, perceived barrier	↑ Sustainability compliance, ↑ stakeholder awareness

Abbreviations: BIM: Building information modeling; EMT: Ecological modernization theory

This combined methodological approach allows for a rigorous evaluation of the interplay of technological, institutional, and managerial dynamics in shaping the performance of sustainable urban construction in China. It operationalizes EMT as both a conceptual and empirical framework, serving as a bridge between sociotheoretical analysis and quantifiable project outcomes. Given the modest sample size, the regression findings should be interpreted as exploratory and indicative of directional relationships rather than as robust population-level estimates.

Although multicollinearity was within the acceptable threshold used in this study, the limited number of observations constrains statistical power and may reduce coefficient stability in multivariate models. Therefore, the study emphasizes consistency of relationships across descriptive, comparative, correlational, and regression analyses rather than relying on regression outputs alone. In addition, because the design is cross-sectional, the statistical models are not intended to establish definitive causal relationships among certification, policy incentives, managerial capacity, and carbon performance. Future studies should report a more comprehensive set of regression diagnostics and evaluate the model using larger longitudinal datasets to assess the stability of the observed relationships more rigorously.

3. Results

3.1. Overview of project distribution and characteristics

The sample of 40 surveyed projects covers a broad range of regions and typologies, reflecting the diversity of modern Chinese urban development. Table 2 presents the geographic and categorical stratification of the data.

The temporal range from 2013 to 2023 reflects the acceleration of technological and policy change, with 70 percent of the projects implemented after 2018, corresponding to the adoption of the 13th and 14th Five-Year Plans, which provide specific support to low-carbon urbanization (S. S. Hu *et al.*, 2025; X. Yang & Liu, 2024).

As shown in Table 3, residential projects formed the largest functional category in the sample (35.0%), followed by office buildings (27.5%), public/institutional projects (20.0%), industrial buildings (10.0%), and mixed-use projects (7.5%). The average gross floor area was 28,500 m^2, with approximately half of the projects adopting hybrid or prefabricated construction techniques.

3.2. Technological practices and construction methods

3.2.1. Construction methods

Prefabricated projects recorded lower embodied carbon than traditional construction projects. Based on the average embodied-carbon values reported in Table 4, prefabricated projects showed 25.8 percent lower embodied carbon than traditional projects (487.5 vs. 657.2 kg CO_2e/m_2). They also showed lower operational energy intensity (73.1 vs. 95.4 kWh/m^2/year), equivalent to a 23.4 percent reduction. These findings are consistent with national-level evaluations (Huang *et al.*, 2023; J. Liu *et al.*, 2023; Sindhu Pradeep *et al.*, 2025) and support the technological-innovation dimension of EMT.

Prefabricated projects recorded 25.8 percent lower embodied carbon and 23.4 percent lower operational energy intensity than traditional construction projects. Hybrid projects also performed better than traditional projects, with 20.4 percent lower embodied carbon. These findings support the technological-innovation dimension of EMT by showing that industrialized and hybridized construction methods are associated with improved carbon performance.

Building information modeling was used during the design and/or implementation phases of 24 projects, representing 60.0 percent of the sample. As shown in Table 5, BIM-enabled projects achieved a higher average CO_2-reduction rate than non-BIM projects. BIM adoption was also positively associated with measured CO_2 reduction ($r = 0.62$, $p < 0.01$), suggesting that digital coordination and energy modeling support improved low-carbon project performance.

Table 2. Project distribution by province and type

Province (n = 16)	Sample share (%)	Predominant type	Key cities included
Guangdong	15	Office/institutional	Guangzhou, Shenzhen
Jiangsu	10	Residential	Nanjing, Suzhou
Shanghai (municipality)	12	Mixed-use/office	Shanghai
Sichuan	10	Industrial/residential	Chengdu
Shaanxi	8	Office/industrial	Xi'an
Tianjin (municipality)	7	Residential	Tianjin
Hubei	8	Residential/mixeduse	Wuhan
Zhejiang	6	Institutional	Hangzhou
Others (n = 8)	24	Mixed-use	Multiple cities (n = 8)

Table 3. Project distribution by functional category

Project type	Projects (n)	Share (%)
Residential	14	35.0
Office	11	27.5
Public/institutional	8	20.0
Industrial	4	10.0
Mixed-use	3	7.5
Total	40	100.0

Table 4. Construction method distribution and associated performance indicators

Method type	Projects (n)	Share (%)	Average operational energy (kWh/m²/year)	Average embodied carbon (kg CO_2e/m²)	BIM adoption (%)	Measured CO_2 reduction (%)	Embodied-carbon reduction vs. traditional (%)
Traditional	13	32.5	95.4	657.2	38.0	8.6	Reference
Prefabricated	15	37.5	73.1	487.5	80.0	19.8	25.8
Hybrid	12	30.0	81.7	523.4	67.0	14.2	20.4
Weighted mean/total	40	100.0	82.9	553.4	62.5	14.5	—

Notes: The mean row reports weighted means calculated according to the number of projects in each construction-method group. Embodied-carbon reduction was calculated relative to the traditional construction group

Table 5. Building information modeling (BIM) adoption and measured CO_2 reduction

BIM status	Projects (n)	Share (%)	Average CO_2 reduction (%)
BIM-enabled projects	24	60.0	18.0
Non-BIM projects	16	40.0	9.0

3.2.2. Building information modeling adoption and digitalization

As shown in Table 5, the findings revealed that BIM was used during the design and implementation phases of 24 projects. The findings suggest that digital design coordination and construction-planning tools reduce design conflicts and enable more accurate energy and resource planning.

These results support the view that digitalization enhances coordination efficiency and enables more

accurate energy modeling, as demonstrated by J. Liu *et al.* (2024) and Y. Liu *et al.* (2024).

3.3. Energy and carbon performance

3.3.1. Operational energy use

Based on Table 6, the mean operational energy intensity of the dataset is 82.5 ± 25.1 kWh/m²/year. Residential projects exhibit the lowest energy use (mean = 76.1 kWh/m²/year), whereas industrial facilities record the highest (mean = 112.8 kWh/m²/year).

One-way ANOVA analysis demonstrated a significant difference in operational energy intensity across project types ($F = 5.73$, $p < 0.01$). Post-hoc Tukey tests confirm that industrial and residential buildings differ significantly. These differences also correspond to sector-specific end-use demands and are consistent with national statistics (You *et al.*, 2023; Zhang *et al.*, 2024).

Based on Table 6, operational energy intensity varies significantly across project types. Industrial buildings exhibit the highest average energy consumption, whereas residential projects show the lowest values, confirming that building function remains an important determinant of energy performance and should be accounted for when evaluating low-carbon construction outcomes.

3.3.2. Embodied carbon

As shown in Table 7, embodied-carbon intensity ranged from 388.3 kg CO_2e/m² for timber/engineered wood structures to 661.4 kg CO_2e/m² for reinforced-concrete structures. Material selection was therefore a major determinant of life-cycle carbon performance. Compared with reinforced concrete, timber/engineered wood projects recorded 41.3 percent lower embodied carbon, while composite/hybrid projects recorded 21.6 percent lower embodied carbon. These findings indicate that material substitution can substantially reduce embodied emissions when supported by appropriate design and construction-management decisions.

Table 7 highlights the strong effect of material choice on sustainability outcomes. Timber and engineered wood projects record substantially lower embodied carbon and higher waste-reduction performance than reinforced concrete buildings, indicating that material substitution is a key strategy for reducing life-cycle environmental impacts in construction management.

3.4. Institutional drivers: Policy incentives and certifications

Policy incentives, including subsidies, additional floor area ratio allowances, and expedited approval, were present in 45 percent of the total sample (18 out of 40 projects).

As shown in Table 8, incentivized projects demonstrate higher renewable energy adoption and lower operational energy intensity compared to non-incentivized projects. These patterns are consistent with EMT, which posits that institutional mechanisms can facilitate eco-innovation and performance improvements in the built environment (Bush & Spaargaren, 2024; Q. Q. Hu *et al.*, 2023).

Table 6. Operational energy intensity by project type

Project type	Mean (kWh/m²/year)	Standard deviation	Minimum (kWh/m²/year)	Maximum (kWh/m²/year)
Residential	76.1	22.4	48.0	115.5
Office	85.9	19.7	60.2	122.0
Public (e.g., school, hospital)	88.5	17.5	63.1	111.4
Industrial	112.8	27.8	78.0	142.2
Mixeduse	83.6	23.1	50.8	120.4

Table 7. Comparison between primary material, embodied carbon, and waste reduction

Primary material	Projects (*n*)	Average embodied carbon (kg CO_2e/m²)	Average waste reduction (%)	Average CO_2 reduction (%)
Reinforced concrete	21	661.4	6.5	9.7
Timber/engineered wood	9	388.3	19.8	24.2
Composite/hybrid	10	518.7	12.3	16.1

Table 8 indicates that policy incentives are associated with improved project-level environmental performance. Compared with non-incentivized projects, incentivized projects exhibit higher renewable energy installation, lower operational energy intensity, and greater CO_2 reduction, suggesting a positive relationship between institutional support mechanisms and low-carbon construction outcomes.

In addition to statistical significance, the magnitude of these differences is notable from a practical perspective. Specifically, incentivized projects show a 12.2 percentage-point increase in renewable energy installation, a reduction of 13.8 kWh/m²/year in operational energy intensity, and an 8.1 percentage-point increase in CO_2 reduction relative to non-incentivized projects.

3.4.1. Green certification influence

The findings revealed that 30 out of 40 projects hold national or international green certifications. Their performance is presented in Table 9.

Certification level is negatively correlated with operational energy intensity (r = 0.59, p = 0.01) and positively correlated with CO_2 reduction (r = 0.63, p = 0.01). These results suggest that standards-based governance, which is central to the institutionalization of EMT, may enhance environmental performance through improved transparency and benchmarking mechanisms (Q. Q. Hu *et al.*, 2023; Wang, 2022).

Table 9 reveals a consistent relationship between certification level and environmental performance. Projects with higher levels of green certification (China 3-Star, LEED) demonstrate lower operational energy use, lower embodied carbon, higher CO_2 reduction rates, and greater occupant satisfaction, indicating that certification systems function as effective governance mechanisms for improving sustainability outcomes.

3.5. Managerial and organizational factors

3.5.1. Managerial experience and training

The dataset recorded a mean managerial experience of 13.1 years (SD = 5.9), with sustainability-related training reported in 52.5 percent of the projects. The comparative performance impact is summarized in Table 10 (Qi *et al.*, 2023; Wu *et al.*, 2023).

Table 10 demonstrates that managerial capacity has a measurable influence on low-carbon performance. Projects led by more experienced managers and those in which sustainability training was provided achieved higher average CO_2 reduction and greater renewable-energy integration, highlighting the importance of organizational learning and professional competence in sustainable construction management.

Projects led by experienced managers achieved 5.5 percentage points higher CO_2 reduction than those led by early-career managers, while projects with sustainability

Table 8. Effect of policy incentives on project performance

Variable	Incentivized projects (n = 18)	Non incentivized (n = 22)	t	p
Renewable energy installed (%)	22.6	10.4	3.11	0.004 **
Operational energy (kWh/m²/year)	74.8	88.6	−2.57	0.015 *
CO_2 reduction (%)	18.9	10.8	2.88	0.006 **
Waste reduction (%)	12.4	7.1	1.99	0.056

Note: *p < 0.05 and **p < 0.01 indicate statistical significance

Table 9. Green certification level versus sustainability outcomes

Certification type	Average operational Energy use (kWh/m²/year)	Average embodied carbon (kg CO_2e/m²)	Average CO_2 reduction (%)	Average occupant satisfaction (scale: 1–5)
China 1-Star	88.2	621.5	12.4	3.4
China 2-Star	80.3	562.9	15.6	3.9
China 3-Star	72.7	509.7	19.8	4.1
LEED Silver/Gold	71.1	497.3	21.0	4.3
No certification	91.4	647.6	9.2	3.1

Abbreviation: LEED: Leadership in Energy and Environmental Design

training achieved 6.6 percentage points higher CO_2 reduction than projects without training.

3.5.2. Perceived barriers to low-carbon adoption

Projects reporting cost-related barriers achieved the lowest average CO_2 reduction among the barrier categories shown in Table 11, with an average reduction of 9.8 percent. Skills-related barriers and supply-chain barriers were also associated with comparatively lower CO_2-reduction performance, whereas projects identifying client demand as the main barrier reported a higher average CO_2 reduction. These findings suggest that financial constraints remain the most prominent perceived obstacle to the wider adoption of low-carbon construction practices, while technical skills and supply-chain limitations also continue to restrict implementation (Bush & Spaargaren, 2024; Kong & He, 2021).

Based on Table 11, cost is identified as the most frequently reported barrier to the implementation of sustainable construction practices, followed by skills shortages and policy-related constraints. The lower CO_2 reduction performance among projects reporting cost barriers suggests that financial concerns remain a major obstacle to the wider diffusion of low-carbon innovations.

Projects reporting cost-related barriers achieved an average CO_2 reduction of 9.8 percent, compared with 16.7 percent among projects that did not report cost as the primary barrier (Table 12; $t = 3.02$, $p = 0.004$). This result highlights persistent economic constraints in the implementation of low-carbon construction practices.

3.6. Integrated statistical models

To test the interaction effects between different dimensions of EMT, two multiple regression models were developed (Table 13). The dependent variable was the percentage CO_2 reduction. Model 1, which included only technological factors, explained 51 percent of the variance, whereas Model 2, which incorporated institutional and managerial variables, increased the explanatory power to 68 percent. This improvement supports the EMT proposition that technological modernization alone is insufficient, while institutional and managerial capacities provide additional explanatory power for environmental performance.

Table 10. Managerial attributes and performance

Attribute	*n*	Average CO_2 reduction (%)	Average renewable energy share (%)	*t*	*p*
Years of experience					
≤10 (early career)	18	11.3	10.7	2.78	0.008**
>10 (experienced)	22	16.8	18.9	–	–
Training provided					
Yes	21	17.5	19.2	2.03	0.049*
No	19	10.9	11.8	–	–

Note: *$p < 0.05$ and **$p < 0.01$ indicate statistical significance

Table 11. Perceived barriers to sustainable practices

Barrier type	Frequency (*n*)	Percentage (%)	Average CO_2 reduction (%)
Cost	16	40	9.8
Skills	9	22.5	13.6
Policy	6	15	14.1
Client demand	5	12.5	18.4
Supply chain	4	10	12.3

Table 12. Binary comparison of cost-related barriers and CO_2 reduction

Barrier comparison	Projects (*n*)	Average CO_2 reduction (%)	*t*	*p*
Cost barrier reported	16	9.8	3.02	0.004**
No cost barrier reported	24	16.7	—	—

Notes: The "no cost barrier reported" group includes all projects that did not identify cost as the primary barrier. **$p < 0.01$

In addition to statistical significance, the regression analysis reports standardized beta coefficients,

Table 13 confirms that technological, institutional, and managerial variables jointly explain variation in project-level CO_2 reduction. While Model 1 shows that technological factors alone have substantial explanatory power, Model 2 demonstrates that adding policy incentives, certification level, managerial experience, and training significantly improves model performance, thereby supporting the integrated framework of EMT.

3.7. Robustness tests

To ensure that the regression results were not sensitive to model specification, several robustness checks were conducted. First, stepwise regression procedures were applied to assess the stability of predictor selection. Second, alternative model specifications excluding individual predictors were estimated to test the robustness of key relationships involving renewable energy integration, certification level, managerial experience, and CO_2 reduction.

Finally, sensitivity analyses were performed by excluding potential outliers, particularly industrial projects with unusually high operational energy intensity. The main coefficients remained stable across these alternative specifications, suggesting that the reported results are not driven by extreme observations or specific model specifications.

3.8. Regional and temporal trends

The cross-tabulation of region (coastal and inland) shows clear regional differences in low-carbon construction performance. As shown in Table 13, coastal projects reported lower average operational energy intensity than inland projects (78.2 vs. 87.4 kWh/m^2/year), higher renewable-energy adoption (20.3% vs. 11.4%), higher BIM adoption (75% vs. 47%), and higher average CO_2 reduction (16.9% vs. 11.2%). These results indicate that coastal regions demonstrate stronger low-carbon construction performance, which may reflect more advanced technological diffusion, stronger implementation capacity, and greater exposure to green-building practices.

Policy-incentive rates were also higher in coastal areas than in inland areas (60.0% versus 30.0%), and BIM adoption was more frequent in coastal projects (75.0% versus 47.0%). Table 14 demonstrates clear regional disparities in low-carbon construction performance. Coastal projects report lower operational energy intensity, higher renewable-energy integration, greater BIM adoption, and higher CO_2 reduction, suggesting that regional policy capacity and technological diffusion are important factors shaping sustainability performance.

As shown in Table 15, average CO_2 reduction improved from 10.2 percent among projects completed during 2013–2019 to 17.8 percent among projects completed during 2020–2023. This pattern suggests that recent projects benefited from stronger policy implementation, technological diffusion, and accumulated managerial learning.

3.9. Synthesis of ecological modernization theory dimensions in the dataset

To provide a synthesized overview of the integrated analysis, Table 16 presents a summary of performance indicators across the three EMT dimensions. The findings suggest that projects scoring highly across multiple dimensions tend to achieve higher CO_2 reduction outcomes, supporting the argument that ecological modernization in construction is driven by the interaction of technological, institutional, and managerial factors.

Table 13. Regression models predicting carbon reduction

Predictor	Model 1 (technological)		Model 2 (full EMT)	
	β	*p*	β	*p*
Renewable energy (%)	0.41	0.002**	0.32	0.008**
BIM adoption (dummy)	0.28	0.015*	0.22	0.032**
Policy incentive (dummy)	–	–	0.29	0.006**
Certification level (ordinal)	–	–	0.31	0.004**
Experience (years)	–	–	0.25	0.018*
Training (dummy)	–	–	0.21	0.041*
Constant	7.6		6.2	
Adjusted R^2	0.51		0.68	

Abbreviations: BIM: Building information modeling; EMT: Ecological modernization theory

3.10. Interpretive summary

Managerial and social learning is reflected in the statistically significant associations between managerial experience, sustainability training, and CO_2 reduction, suggesting that eco-efficiency is shaped not only by technical systems but also by organizational knowledge and managerial capability.

Table 17 summarizes the key correlations among the principal variables in the study. The results show that renewable-energy integration, BIM adoption, policy incentives, managerial experience, and certification level are positively associated with sustainability outcomes, whereas cost barriers are negatively associated with CO_2 reduction performance.

4. Discussion

It is important to note that the empirical analysis identifies associative relationships rather than strict causal effects. Given the cross-sectional nature of the dataset, the results should be interpreted as correlations between technological adoption, institutional support, managerial learning, and carbon emission performance. Potential endogeneity may exist; for instance, projects that are already environmentally oriented may be more likely to pursue certification or qualify for policy incentives. From a theoretical perspective, the findings also invite reflection on the nature of ecological modernization in the Chinese context. Classical EMT literature often assumes pluralistic governance structures where environmental innovation emerges through interactions between markets, civil society, and regulatory institutions. In contrast, the Chinese case appears to represent a state-driven form of ecological modernization, in which policy planning, regulatory mandates, and strategic pilot programs guide technological diffusion. This suggests that ecological modernization may follow multiple institutional pathways depending on political and economic structures. From a construction management perspective, these findings highlight that project-level managerial decisions

Table 14. Regional comparison of selected indicators

Region	Average operational energy intensity (kWh/m²/year)	Renewable energy adoption (%)	BIM adoption rate (%)	Policy incentive present (%)	CO_2 reduction (%)
Coastal (n = 20)	78.2	20.3	75.0	60.0	16.9
Inland (n = 20)	87.4	11.4	47.0	30.0	11.2

Abbreviation: BIM: Building information modeling

Table 15. Temporal comparison of CO_2-reduction performance

Project completion period	Average CO_2 reduction (%)
2013–2019	10.2
2020–2023	17.8

Table 16. Performance summary across ecological modernization theory dimensions

EMT dimension	Key variables	Highscoring projects (%)	Average CO_2 reduction (%)	Interpretive notes
Technological innovation	Prefabrication, hybrid construction, BIM adoption, renewable energy integration	42.5	18.6	Ecoefficiency gains validated
Institutional transformation	Certification level, policy incentive, local material utilization	45.0	17.9	Governance drives compliance and market learning
Managerial/social learning	Project experience, training, barrier reduction	52.5	16.2	Cultural shift toward a low-carbon mindset
Integrated model (average)	Projects scoring high in more than two EMT dimensions	60.0	20.1	Synergistic effects validate the EMT framework

Abbreviations: BIM: Building information modeling; EMT: Ecological modernization theory

Table 17. Performance summary across ecological modernization theory dimensions

Relationship pair	*r*	*p*	Interpretation
Renewable energy–CO_2 reduction	0.69	<0.001	Strong positive association; key technological driver
BIM adoption–CO_2 reduction	0.62	<0.01	Digital management associated with improved outcomes
Policy incentive–renewable energy share	0.55	<0.01	Institutional support associated with higher adoption
Manager experience–CO_2 reduction	0.46	<0.01	Positive managerial learning effect
Certification level–occupant satisfaction	0.58	<0.01	Higher certification associated with perceived quality
Cost barrier–CO_2 reduction	–0.48	<0.01	Economic constraints negatively associated with performance

Abbreviation: BIM: Building information modeling

during design coordination, technology adoption, and construction planning play a decisive role in shaping long-term environmental performance outcomes.

4.1. Technological modernization and eco-efficiency

The use of prefabricated or hybridized construction techniques, coupled with BIM-driven design and a strong emphasis on renewable energy integration, yields the greatest environmental benefits, including reductions in both operational energy use and embodied carbon. These results empirically support the technological innovation aspect of EMT (Bush & Spaargaren, 2024; S. S. Hu *et al.*, 2025).

The 23 percent reduction in embodied carbon in prefabricated buildings compared with conventional construction is consistent with Sindhu Pradeep *et al.* (2025), J. J. Liu *et al.* (2023), and Huang *et al.* (2023), who report that modular manufacturing reduces material waste and improves resource efficiency. The synergistic role of BIM further supports the findings of Y. Y. Liu *et al.* (2024), who characterize digital integration as a key infrastructural component of modernization, enabling energy simulation, precise quantity take-off, and waste reduction.

From an EMT perspective, these advances reflect technological rationalization—a process in which ecological considerations are systematically integrated into production logic (Bush & Spaargaren, 2024).

4.2. Institutional change: Policy and government

In line with the second pillar of EMT (institutional transformation), empirical findings indicate that governance structures are decisive in shaping sustainability outcomes. The average rate of CO_2 reduction in projects with policy incentives is 70 percent higher than in non-incentivized projects (Table 6). This finding underscores the critical role of state direction, fiscal instruments, and regulatory mechanisms.

This interpretation is consistent with broader international evidence showing that sustainability transitions in complex urban settings depend not only on technical interventions but also on governance capacity, planning coordination, and institutional alignment (S. S. Hu *et al.*, 2025; Zhang *et al.*, 2024).

Such impacts are consistent with the findings of X. Yang and Liu (2024), who report that ecological modernization in China differs from Western models, as it is grounded in hierarchical administrative coordination. In contrast, classical EMT emphasizes pluralistic governance and corporate voluntarism; the Chinese pathway can be characterized as directive modernization, where environmental innovation occurs through diffusion rather than market self-correction (S. S. Hu *et al.*, 2025).

There is also a significant correlation between the degree of certification and carbon reduction, which demonstrates governance through standards as a core principle of EMT. Ecological modernization has been formalized through certification systems such as China Three-Star and LEED, which provide measurable benchmarks and market credibility (Q. Q. Hu *et al.*, 2023; Wang, 2022). The results of this study show that certification level is positively correlated with performance ($r = 0.63$, $p < 0.01$), supporting prior findings by Q. Q. Hu *et al.* (2023) and He *et al.* (2023), who reported similar trends in national datasets.

4.3. Causality, governance mechanisms, and transferability

The findings of the present study should be interpreted with caution with respect to causal direction. Reverse causality remains plausible because projects with stronger environmental performance, greater financial capacity, or more experienced management teams may be more likely to pursue certification, adopt BIM, or qualify for policy incentives. Similarly, managers with a stronger sustainability orientation may self-select into projects that are already predisposed toward low-carbon innovation. Accordingly, the present analysis should be read as evidence of systematic associations rather than proof of unidirectional causal effects. Future research could

address this limitation through panel data, matched project comparisons, quasi-experimental policy designs, or instrumental-variable strategies based on staggered policy adoption across provinces.

From a governance perspective, the results suggest that low-carbon construction performance is shaped not by technology alone but by the alignment of regulatory incentives, certification systems, and organizational learning structures. Policy incentives play a critical role because they lower adoption barriers and make renewable-energy integration and digital coordination more feasible at the project level. Certification systems are important because they convert broad sustainability goals into visible performance benchmarks and standardized compliance routines. Managerial training is essential because it translates institutional expectations into operational decisions during design coordination, procurement, and site management.

These findings generate several practical implications. First, local governments should move beyond generic green-building promotion and adopt targeted policy bundles that connect subsidies, floor-area-ratio bonuses, or expedited approvals to verified outcomes such as renewable-energy installation, BIM-enabled carbon monitoring, and waste-reduction thresholds. Second, certification should be linked to implementation support rather than treated only as an *ex ante* approval mechanism; municipalities and clients could require mid-project sustainability audits and training modules for teams pursuing higher certification levels. Third, the coastal–inland gap observed in the dataset suggests that transferability is conditional rather than automatic. The findings are most directly applicable to urban regions with moderate to strong administrative capacity, functioning certification systems, and access to digital and prefabrication supply chains. In lower-capacity regions, a phased pathway that prioritizes managerial training and policy coordination before advanced technological deployment may be more realistic than the immediate replication of high-capacity coastal models.

4.4. Limitations and future research directions

Despite providing valuable exploratory insights, this study has several limitations. The dataset includes 40 building projects, which is smaller than the large-scale sustainability datasets used in international studies. Consequently, the statistical results should be interpreted as exploratory associations rather than generalizable causal relationships.

Additionally, the geographical distribution of projects is not entirely balanced. Coastal regions such as Guangdong, Jiangsu, Zhejiang, and Shanghai account for a relatively higher proportion of the sample, reflecting their stronger policy support and higher adoption of green-building technologies. While inland regions are represented, the dataset may not fully capture the diversity of construction practices in less developed western provinces. Future research should expand the sample to include more projects across a broader geographical range, thereby strengthening statistical robustness and national representativeness.

Future research should build on this exploratory analysis by incorporating larger datasets and longitudinal monitoring of building performance. Comparative international studies could examine whether the state-driven modernization pathway observed in China differs from governance models in Europe or East Asia. Additionally, integrating life-cycle assessment methods with construction-management datasets would enable more precise evaluations of embodied carbon and long-term operational performance.

4.5. Theoretical synthesis

The findings suggest that China's construction sector reflects a hybrid pathway of ecological modernization in which technological upgrading, administrative steering, and organizational learning reinforce one another. Rather than treating EMT as a retrospective label, the study operationalizes its core mechanisms through observable project-level variables and shows how those mechanisms interact in practice. In this sense, the study offers a contextual extension of EMT: under state-led urban transition, ecological modernization is mediated less by spontaneous market adjustment and more by the coordinated action of policy incentives, certification systems, and managerial capability.

This interpretation also helps explain why the full EMT model outperforms the technology-only model and why projects that perform strongly across multiple dimensions achieve superior carbon reduction outcomes. The Chinese case therefore contributes to broader sustainability transition scholarship by showing that low-carbon construction modernization can proceed through a directive institutional pathway while still relying on firm-level learning and technical innovation. The study thus contributes not only empirical evidence on sustainable building performance but also a more differentiated explanation of how ecological modernization is enacted in a non-Western, policy-intensive urban development context.

5. Conclusion

This study evaluated 40 completed building projects across major Chinese provinces to assess how technological innovation, institutional support, and managerial learning

shape low-carbon construction outcomes. Prefabrication, BIM adoption, renewable-energy integration, certification level, policy incentives, and managerial capability were all positively associated with enhanced sustainability performance, including reduced operational energy intensity, lower embodied carbon, and greater CO_2 reduction. The findings indicate that the strongest-performing projects were not those relying on a single green technology, but those integrating technological, institutional, and organizational capacities within the same project-delivery system.

The study also contributes theoretically by refining EMT in the context of state-directed urban transition. The Chinese case suggests a hybrid pathway in which ecological modernization is driven by the interaction of regulatory guidance, certification-based governance, digital and material innovation, and project-level managerial learning. In practical terms, the results imply that governments and industry actors should prioritize targeted incentives, rigorous certification enforcement, BIM-enabled carbon management, and structured sustainability training for construction managers.

At the same time, the findings should be interpreted with caution because the evidence is based on a relatively small cross-sectional sample and therefore identifies associations rather than definitive causal effects. Future research should extend this line of inquiry through larger longitudinal datasets, comparative regional studies, and stronger causal designs capable of testing how policy, technology, and management jointly shape low-carbon construction transitions over time. Despite these limitations, the study provides a useful project-level foundation for understanding how sustainable urban construction can be advanced through the combined action of technological modernization, institutional coordination, and managerial learning.

Acknowledgments

The authors acknowledge the support from the Centre for Global Sustainability Studies, Universiti Sains Malaysia, for providing the academic environment in which this study was completed, as well as for the constructive discussions and valuable suggestions of colleagues and peers during the development of this research. The authors also thank the anonymous reviewers for their insightful comments and suggestions, which have significantly improved the quality, clarity, and rigor of the manuscript.

Funding

This research received no external funding.

Conflict of interest

The authors declare that they have no conflict of interest.

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Ethics approval and consent to participate

This study used anonymized project-level data and professional responses from construction managers. No personally identifiable information, sensitive personal data, medical data, or vulnerable-participant data were collected. Participation was voluntary, and informed consent was obtained from all respondents before data collection. Therefore, no formal ethics approval number is available for this study.

Consent for publication

All participants provided written/electronic informed consent prior to participation, including consent for the use of anonymized survey/interview responses and project-level data for research publication. No identifiable personal data or participant images are included in this article.

Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Access may be limited in order to protect the confidentiality of project-level and respondent information.

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