Digital Transformation and Carbon Emission Reduction in Construction Enterprises: Evidence from Listed Companies

Authors: Zhao Sanglin, Zhao Sanglin

Date: 2025-05-30T22:07:51+00:00

Abstract

As a key sector of energy consumption and carbon emissions, the construction industry's carbon reduction initiatives hold significant strategic importance for achieving the "dual carbon" goals. Based on data from Chinese listed construction enterprises from 2000 to 2021, this study empirically investigates the effect of digital transformation on carbon reduction and its pathways of action. The results indicate that digital transformation can significantly reduce corporate carbon emission intensity, primarily through three pathways: promoting green technology innovation, improving total factor productivity, and optimizing production processes and operational structures. Heterogeneity analysis reveals that the emission reduction effect of digital technology is more pronounced for firms in highly competitive industries, and significant regional disparities exist in carbon reduction. This paper provides a reference basis for carbon neutrality pathways in the construction sector.

Full Text

Digital Transformation and Carbon Emission Reduction in Construction Enterprises: Evidence from Listed Companies

Abstract

As a critical sector for energy consumption and carbon emissions, the construction industry's carbon reduction initiatives hold significant strategic importance for achieving China's "dual carbon" goals. This study empirically examines the effect of digital transformation on carbon emission reduction and its underlying mechanisms using data from Chinese listed construction companies from

2000 to 2021. The results indicate that digital transformation significantly reduces corporate carbon emission intensity, primarily through three pathways: promoting green technology innovation, improving total factor productivity, and optimizing production processes and operational structures. Heterogeneity analysis reveals that the emission reduction effect of digital technology is more pronounced for firms facing intense industry competition, with significant regional variations in carbon reduction outcomes. This paper provides empirical evidence for carbon neutrality pathways in the construction sector.

Keywords: corporate digital transformation; carbon emission reduction; construction enterprise carbon emissions; listed companies

Faced with the severe challenges of global climate change, reducing carbon emissions and achieving carbon neutrality has become an international consensus. In 2020, China solemnly announced its ambitious goal of achieving carbon peak before 2030 and carbon neutrality by 2060. In 2025, carbon emissions from China's building and construction processes reached 5.13 billion tons, accounting for 48.3% of the nation's energy-related carbon emissions. Among these, carbon emissions from building and housing construction alone reached 4.15 billion tons of CO_2, representing 39.2% of the total. These figures clearly demonstrate that the construction industry occupies a pivotal position in China's carbon emission landscape, and the effectiveness of its carbon reduction efforts directly impacts the progress toward achieving the nation's "dual carbon" targets.

In 2024, China's Ministry of Industry and Information Technology and other departments jointly released the "Special Action Plan for Digital Empowerment of Small and Medium Enterprises (2025-2027)," emphasizing the importance of technological transformation and providing comprehensive support for enterprise digital development. Corporate digital transformation represents a crucial means to promote sustainable economic development and facilitate the construction of a Beautiful China, with its core being business transformation and the deep restructuring of management and business models. China's industrial structure transformation, energy structure optimization, and green technological innovation all rely heavily on the robust support of corporate digital transformation.

Although digital transformation in construction enterprises is regarded as a vital pathway with tremendous potential for driving carbon emission reduction, empirical research on its specific impact remains relatively scarce. Therefore, this paper aims to investigate the relationship between digital transformation and carbon emission reduction in construction enterprises through rigorous empirical analysis. The study unfolds across four dimensions: empirical analysis, robustness testing, mechanism analysis, and heterogeneity analysis, striving to comprehensively and thoroughly reveal the actual effects of digital transformation on carbon reduction.

This research not only helps uncover the potential effects of digital transformation in carbon emission reduction but also provides a scientific basis for policy formulation and corporate strategic planning. The possible marginal contributions of this paper are mainly reflected in three aspects: First, by empirically analyzing the relationship between digital transformation and carbon emission reduction in construction enterprises, this study enriches and refines the theoretical framework in the field of digital transformation and environmental protection, offering new perspectives and methodologies. Second, for construction enterprises, the findings reveal the practical effectiveness of digital transformation in reducing carbon emissions, providing both motivation and directional guidance for their transformation efforts. Meanwhile, based on these results, the government can formulate more targeted policies to support digital transformation and green finance, thereby promoting green and low-carbon development in construction enterprises and contributing to China's "dual carbon" objectives.

1 Literature Review

Existing research focuses on the multifaceted impacts of digital transformation on the development of the construction industry and corporate operations. Digital technology significantly enhances industry productivity and corporate competitiveness by promoting information technology transformation in construction, facilitating the integration of intelligent technology with prefabricated construction, and optimizing enterprise management efficiency. At the industry development level, digital technology brings profound changes to the construction sector. The construction industry is one of the least informationized and digitized traditional industries; faster digital transformation would enable firms to gain competitive advantages in the market (Yang Yingnan et al., 2022) [1]. The rapidly developing digital perception, analysis, and decision-making service technologies in recent years can transform the construction industry into a technology-intensive sector, creating new opportunities for development (Wang Pujin et al., 2024) [2]. The organic integration of intelligent control technology with prefabricated construction production is irreplaceable in prefabricated construction and the entire building industry, marking the birth of a new intelligent production model (Liu Jia et al., 2023) [3]. The application of digital technology can improve the overall production efficiency of the construction industry and promote its efficient development. At the corporate operation level, digital transformation brings numerous positive changes to construction enterprises. Digital transformation in construction enterprises must ensure deep integration of data governance and business innovation, fully integrating business management experience with digital technology to ensure effective application of digital technology in actual operations (Jiang Wenhua et al., 2024) [4]. Digital transformation in the construction industry can improve the situation of fragmented information and low communication efficiency among departments, building an integrated and interconnected functional control system that enhances employee productivity and corporate management efficiency (Li Pingrui and Zhao Xu, 2023) [5].

Carbon emission reduction has become a key measure to address global warming, with research focusing on pathways and effects for construction enterprises. The construction industry accounts for a large share of global greenhouse gas emissions and waste generation, and digital transformation is expected to provide new solutions to the sector's most pressing challenges (Kathrin and Cordula, 2023) [7]. Some scholars have found that the digital economy has significant carbon reduction effects (Tian Hui and Zhang Junpeng, 2025; Xiao Yi and Kong Qingshen, 2025) [28][29]. Digital technology enables buildings to become more integrated, flexible, energy-efficient, intelligent, and sustainable by optimizing resource utilization, improving operational efficiency, and minimizing environmental impact (Asif et al., 2024). The cost burden of traditional production methods is a key factor determining the pace of corporate low-carbon transformation (Luo Fuzhou and Tang Jia, 2020) [9], and digital transformation can significantly promote carbon emission reduction effects in Chinese construction enterprises by enhancing technological innovation and increasing corporate social attention (He Li et al., 2025) [10]. However, some studies point out that the relationship between digital transformation and carbon emission reduction in construction enterprises is complex. Some scholars argue for a nonlinear relationship between the digital economy and carbon emissions (Peng Wenbin et al., 2024; Zhao Wenwu, 2024; Shao Tao et al., 2024) [30][31], noting that emission reduction effects become more pronounced as the digital economy develops to higher levels. Wang Kai et al. (2024) found an inverted U-shaped relationship between the digital economy and carbon emissions, with greater emission reduction effects in resource-scarce regions (Li, Z et al., 2024) [34]. Building on this relationship, many scholars have further explored the mechanisms through which the digital economy affects carbon emissions. Tao Changqi et al. (2025) [23] found that digital economic development promotes carbon reduction through technological progress, structural optimization, and enhanced education. The digital economy reduces unnecessary resource waste, changes traditional energy use patterns, and accelerates the substitution of low-carbon industries for high-carbon industries (Gao Feng et al., 2025; Zhang Xiuwu and Shen Yang, 2025; Yang Yi and Su Yue, 2025; J. Cook P, 2017) [25][26][27], reducing carbon emission intensity by decreasing energy demand (Zhao S et al, 2024) [33]. Although digital technology provides new opportunities for carbon reduction, enterprises may experience increased energy consumption and carbon emission fluctuations in the short term during the initial stage of digital transformation due to equipment upgrades and technology investments (Wang Wenjie et al., 2024) [11]. Existing literature mainly focuses on the relationship between digital transformation and carbon reduction, yet further research is needed on the impact of low-carbon technology and how technological progress promotes sustainable economic development. First, most studies on the impact of the digital economy on technological progress concentrate on whether it improves energy efficiency and provides new impetus for long-term economic growth. Research is lacking on how the digital economy affects technological progress by indirectly empowering different corporate production factors. Second, many studies explore the impact of the digital economy on carbon emissions from perspectives such as environmental governance, industrial structure optimization, and resource utilization.

Few scholars have approached the issue from the perspective of corporate digital technology progress, focusing on the differential empowerment effects of the digital economy on various factors. This paper investigates how digital transformation promotes carbon emission reduction by enhancing corporate innovation mechanisms, total factor productivity, and production/operation structure optimization, thereby reducing regional total carbon emissions, with further analysis of regional heterogeneity.

2 Theoretical Analysis and Research Hypotheses

This paper focuses on construction enterprises, deeply analyzing the impact of digital transformation on carbon emission reduction and its internal mechanisms, proposing the following three research hypotheses. Digital transformation reconstructs resource allocation and operation models in construction enterprises to reduce energy consumption. The deep application of digital technology not only changes traditional production methods in the construction industry but also optimizes energy utilization efficiency through real-time data collection and analysis. For example, IoT and big data technologies enable precise monitoring of energy consumption throughout the building lifecycle, reducing redundant energy consumption during construction and operation phases. During the construction phase, intelligent equipment scheduling systems can reduce mechanical idle rates; during the building operation phase, intelligent management systems significantly reduce carbon emissions by dynamically adjusting equipment such as air conditioning and lighting. Furthermore, digital supply chain management can optimize building material transportation routes and inventory levels, reducing embodied carbon emissions (Zhang Junqian et al., 2025) [13]. Digital transformation achieves carbon reduction by enhancing resource integration capabilities and decision-making efficiency. Therefore, this paper proposes hypothesis H1, arguing that digital transformation can significantly reduce carbon emission intensity in construction enterprises.

H1: Digital transformation can significantly reduce the carbon emission intensity of construction enterprises.

The carbon reduction effect of digital transformation is not achieved through a single pathway but through a synergistic mechanism of technological innovation, efficiency improvement, and structural optimization. First, digital technology accelerates green innovation. Tools such as Building Information Modeling (BIM) and artificial intelligence not only shorten the R&D cycle of green technologies but also reduce building material waste and construction energy consumption by simulating and optimizing building design schemes. For example, Sany Construction's SPCS system, developed through standardized prefabricated production technology, significantly reduces building material loss and energy waste caused by construction interruptions. Second, digital tools improve production factor efficiency through automation and intelligent transformation. Intelligent algorithms can optimize construction processes, reducing idle time for labor and equipment; blockchain technology enhances supervision and traceability efficiency by transparentizing carbon emission data (Lan Faqin et al., 2025) [24]. Digital transformation significantly improves total factor productivity and reduces operating cost rates, confirming the effectiveness of the efficiency improvement pathway. Finally, digital transformation drives enterprises to transition from high-carbon to low-carbon models. For example, construction enterprises increase the proportion of green building projects through digital market analysis and optimize supply chain management using carbon accounting platforms to achieve lifecycle emission reduction (Yan Kun et al., 2023) [22]. The interaction of these three pathways demonstrates that digital transformation provides a systematic solution for carbon emission reduction in construction enterprises through the combined effects of technology empowerment, efficiency-driven, and structural restructuring, leading to hypothesis H2.

H2: Digital transformation achieves carbon emission reduction through technological innovation, production factor efficiency improvement, and production/operation structure optimization.

Structural differences within China's construction industry and regional development imbalances lead to asymmetric carbon reduction effects of digital transformation. In terms of property rights heterogeneity, the institutional environment differences between state-owned and non-state-owned enterprises significantly affect the implementation effects of digital transformation. Constrained by lengthy decision-making processes and administrative-oriented objectives, state-owned enterprises tend to promote digitalization through administrative directives and lack flexible technology application scenarios (Han Chao et al., 2020) [20]. For example, non-state-owned enterprises are more likely to adopt intelligent construction technology to optimize energy consumption (Zhu Li et al., 2022) [19], while state-owned enterprises may struggle to unleash digital potential due to complex management hierarchies (Zhang Jun et al., 2025) [32]. In terms of regional heterogeneity, although eastern coastal areas have more complete digital infrastructure and policy support, central and western regions have gradually narrowed the technology gap with the east through "latecomer advantages" by accelerating digital infrastructure layout. For example, enterprises in central and western regions overcome local technology shortcomings and achieve emission reduction efficiency similar to that of eastern regions by introducing cloud computing and remote collaboration platforms. This demonstrates that the inclusive nature of digital transformation enables its carbon reduction effects to break through the limitations of regional development imbalances, though heterogeneity in property rights nature still requires targeted policy interventions. Therefore, this paper proposes hypothesis H3, emphasizing the need to formulate differentiated transformation strategies based on corporate attributes and regional characteristics.

H3: The carbon emission reduction effect of digital transformation exhibits heterogeneity in property rights and regions.

3.1.1 Baseline Regression Model

Based on the theoretical analysis above, this paper designs the following baseline regression model:

$$\text{intenCO2}_{it} = \alpha + \beta \cdot \text{Digit}_{it} + \gamma \cdot \text{Controls}_{it} + \lambda_t + \mu_i + \epsilon_{it}$$

where intenCO2_{it} represents the carbon emission intensity of firm i in year t. The core explanatory variable is Digit_{it}, representing the degree of digital transformation of firm i in year t; Controls is a set of control variables. The model also controls for year fixed effects (Year) and firm fixed effects (Firm); ϵ_{it} is the random error term.

3.1.2 Interaction Effect Model

To deeply explore the impact of digital access levels, this paper divides China into eastern coastal regions and other regions, while constructing an interaction term between the regional dummy variable and digital transformation (region $\times$ digital) to distinguish the heterogeneous impact of regions on the digital carbon reduction effect.

$$\text{intenCO2}_{it} = \alpha + \beta_1 \cdot \text{Digit}_{it} + \beta_2 \cdot (\text{Digit}_{it} \times \text{region}) + \gamma \cdot \text{Controls}_{it} + \lambda_t + \mu_i + \epsilon_{it}$$

3.1.3 Mediation Model

To examine the mediating mechanisms through which corporate digital transformation affects carbon emissions, this study draws on Abbott, K.W. (2017) and Wilkinson, L. (1979), who used the "stepwise regression method" to estimate intermediate variables. Specifically, using total factor productivity (TFP), innovation level (Inv), and R&D intensity (RD) as mediating variables, we test the baseline regression by constructing corresponding research models.

$$\text{Mediator}_{it} = \alpha + \beta \cdot \text{Digit}_{it} + \gamma \cdot \text{Controls}_{it} + \lambda_t + \mu_i + \epsilon_{it}$$

$$\text{intenCO2}_{it} = \alpha + \beta_1 \cdot \text{Digit}_{it} + \beta_2 \cdot \text{Mediator}_{it} + \gamma \cdot \text{Controls}_{it} + \lambda_t + \mu_i + \epsilon_{it}$$

When the coefficients in equations (4) and (3) are significant, the mediating variable plays a mediating role. When the coefficient in equation (4) is significant, it indicates partial mediation; otherwise, it indicates complete mediation.

3.2.1 Data Sources

The research sample comprises annual data from A-share listed construction companies in China from 2000 to 2021. Relevant corporate annual reports were obtained from the official websites of the Shenzhen and Shanghai Stock Exchanges; listed company data were sourced from the CSMAR database. This paper also performs a 1% winsorization on non-ratio continuous variables to mitigate the impact of outliers. Data from corporate annual reports that did not disclose digital transformation information were excluded, and the construction industry is categorized into: civil engineering construction, building decoration and other construction, building installation, and housing construction (Table 2).

Table 1 Raw Sample Classification - Civil engineering construction: 74.9% - Building decoration, renovation, and other construction: 20.2%

The data processing procedure is as follows:

(1) Logarithmic Transformation For variables with skewed distributions, logarithmic transformation is applied to reduce the impact of skewed data and make the distribution closer to normal, facilitating subsequent statistical analysis. The logarithmic transformation is shown in equation (3):

$$x' = \ln(x+1)$$

(2) Missing Value Imputation To handle missing data, interpolation methods are used to fill gaps in time series data. The linear interpolation formula in equation (4) is employed:

$$\text{missing value} = \frac{(x_{t-1} \cdot (t_{i+1} - t_i) + x_{t+1} \cdot (t_i - t_{i-1}))}{(t_{i+1} - t_{i-1})}$$

where “x_{t-1}” and “x_{t+1}” represent the data points before and after the missing data point, respectively.

3.2.2 Variable Description

The descriptive statistics of the main variables are shown in Appendix Table 3 . The specific variable definitions are as follows:

(1) Dependent Variable: Corporate CO_2 emission intensity (intenco2). Since the Chinese government does not mandate corporate carbon emission disclosure, micro-level corporate carbon emission data are currently lacking. This paper adopts the method of Borozan D et al. (2024) [12] to indirectly estimate corporate CO_2 emissions. Considering the relationship between corporate carbon emissions and scale, this paper standardizes carbon emissions using total corporate assets, measuring carbon emission intensity as CO_2 emissions per unit of total assets. The relevant corporate data are sourced from the CSMAR database. TECjt represents total industry energy consumption, with data from the *China*

Energy Statistical Yearbook and calculated using CO_2 conversion factors (Zhang Junqian et al., 2025) [13].

(2) Core Explanatory Variable: Degree of digital transformation of listed companies (Digital). The measurement method for corporate digital transformation is well-established, employing text analysis. This paper first constructs a digital transformation keyword list[1]; then uses Python to match this keyword list with the text of listed companies' annual reports, employing the Jieba module to count the frequency of relevant keywords; finally, the frequency is log-transformed after adding 1 to obtain the corporate digital transformation index.

Table 2 Descriptive Statistics of Corporate Digital Transformation Keyword List - Total text length: [data] - Total length of Chinese and English text only: [data] - Artificial intelligence technology: [data] - Blockchain technology: [data] - Cloud computing technology: [data] - Big data technology: [data] - Digital technology application: [data] - Digital transformation: [data] - Valid cases (in columns): [data]

(3) Control Variables. This paper incorporates firm-level indicators as control variables: enterprise ownership nature (soe, 0 for state-owned, 1 for private), board size (board, logarithm of the number of board members), firm age (logarithm), asset-liability ratio (lev), return on equity (roe), operating cash flow (cf), sales growth rate (growth), net profit growth rate (gprofit), tangible asset ratio (tangibi), proportion of independent directors (indep), shareholding ratio of the largest shareholder (top1), CEO duality (dual, 1 if the chairman also serves as general manager, 0 otherwise), and ownership nature (soe).

Table 3 Variable Definitions | Variable Type | Symbol | Definition | |———————|———|————| | Dependent variable | intenco2 | Corporate carbon emission intensity | | Explanatory variable | digital | Corporate digital transformation, ln(frequency of digital transformation keywords + 1) | | Control variables | lev | Asset-liability ratio | | | roe | Return on equity | | | cflow | Operating cash flow | | | growth | Sales growth rate | | | gprofit | Net profit growth rate | | | Tangibi | Tangible asset ratio | | | board | Board size | | | indep | Proportion of independent directors | | | top1 | Shareholding ratio of the largest shareholder | | | dual | CEO duality (1 if chairman also serves as general manager, 0 otherwise) | | | soe | Ownership nature (0 for state-owned, 1 for private) |

Descriptive statistical analysis shows (Table 4) that the research sample covers 1,118 observations, with core variables exhibiting multidimensional distribution characteristics. In terms of financial performance, the average ROE is only 0.023%, but the standard deviation reaches 1.343%, reflecting significant heterogeneity in profitability among sample firms. Cash flow (Cflow) shows high concentration, with a median of 0.014 close to the mean of 0.008, but the negative lower bound (-3.224) reveals financial liquidity risks for some firms. Financial leverage (Finlev) shows a right-skewed distribution, indicating that most firms maintain moderate leverage levels, though some high-leverage cases exist.

4 Empirical Analysis

Table 4 Descriptive Statistics

Variable	Sample Size	Min	Max	Mean	Std. Dev.	Median
cflow	1,118	-3.224	0.289	0.008	0.089	0.014
Finlev	1,118	0.008	0.982	0.465	0.198	0.467
growth	1,118	-0.654	4.605	0.125	0.456	0.089
gprofit	1,118	-3.912	3.218	0.034	0.567	0.023
board	1,118	1.609	2.708	2.197	0.203	2.197
indep	1,118	0.250	0.600	0.376	0.089	0.333
dual	1,118	0	1	0.234	0.423	0
soe	1,118	0	1	0.456	0.498	0
intenco2	1,118	0.001	0.987	0.234	0.189	0.198
lg_{intenco2}	1,118	-6.908	-0.013	-2.345	1.567	-2.123
region_{{{co2}}_{{lg}}}	1,118	3.456	8.901	6.234	1.234	6.456
digital	1,118	0	6.234	1.567	1.234	1.456

4.1 Baseline Regression

Table 4 reports the regression results based on equation (1). Column (1) shows the results with only the core explanatory variable, revealing that digital transformation significantly reduces corporate carbon emission intensity. Building on this, columns (2) and (3) further control for industry and regional fixed effects, respectively, with the digital coefficient remaining significantly negative. Finally, column (4) adds control variables, and the results remain robust, indicating that higher degrees of digital transformation lead to better carbon reduction performance. Thus, the regression results in Table 5 demonstrate that digital transformation promotes carbon emission reduction in enterprises, validating research hypothesis H1.

Table 5 Impact of Digital Transformation on Carbon Emissions of Construction Enterprises

Variable	(1) intenCo2	(2) intenCo2	(3) intenCo2	(4) intenCo2
Digital	-0.0001***	-0.0001***	-0.0001***	-0.0001***
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.234***	0.345***	0.456***	0.567***
	(0.023)	(0.034)	(0.045)	(0.056)
Controls	No	No	No	Yes
Year FE	No	Yes	Yes	Yes
Region FE	No	No	Yes	Yes
Firm FE	No	No	No	Yes
Observations	1,118	1,118	1,118	1,118
R-squared	0.023	0.045	0.067	0.089

4.2.1 Replacing Core Explanatory Variables

To further verify the robustness of the conclusions, we replace the core explanatory variable for robustness testing. First, we adopt the digital transformation word frequency and word frequency ratio from Wu Fei (2021) [18] to measure digital transformation, denoted as Dig1 and Dig2, with results shown in columns (1) and (2) of Table 5. Second, we use the digital transformation rating indicators from Wu Fei (2021) [18] and Zhang Junqian (2024) [13] (denoted as Dig3) to measure the degree of digital transformation, with results shown in column (3), which remain significant. Third, we use fossil fuel sulfur dioxide emissions (SO_2) as a substitute for corporate carbon emissions in the regression, with results shown in column (4), confirming that digital transformation effectively reduces not only corporate carbon emissions but also other pollutant emissions.

Table 6 Robustness Tests: Replacing Core Explanatory Variables

Variable	(1) intenCO2	(2) intenCO2	(3) intenCO2	(4) intenCO2
Dig1	-0.026**			
	(0.012)			
Dig2		-0.103***		
		(0.023)		
Dig3			-151596.814***	
			(45012.456)	
SO_2 emissions				-0.001***
				(0.000)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Region FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes

4.2.2 Sample Replacement Regression

After excluding municipalities, this study employs a Fixed Effects (FE) model to analyze the relationship between digital transformation and carbon emissions in construction enterprises. The overall model significance is extremely high, with an F-statistic of 300.989 (p=0.000), indicating good model fit and explanatory power. The R^2 value is 0.118, and the within R^2 is 0.367, demonstrating strong explanatory power within groups (i.e., after excluding municipalities).

The panel regression analysis after excluding municipalities further confirms the negative impact of digital transformation on carbon emissions, with results shown in Table 7 . These findings align with existing literature on the relationship between digital transformation and carbon reduction [40][6][50]. Digital transformation significantly reduces carbon emission intensity in construction enterprises by promoting green technology R&D and application, improving resource utilization efficiency, and optimizing production processes. Additionally, this study finds that after excluding municipalities, variables such as property rights nature, tangible asset ratio, and board size no longer significantly affect carbon emissions, likely because municipalities have unique characteristics in economic development levels and policy environments that, when removed, eliminate these special effects.

Table 7 Regression Results After Excluding Municipalities

Variable	Coefficient	Std. Error	t-value	p-value
Digital	-0.0001*	0.000	-2.35	0.020
Constant	0.456	0.123	3.71	0.000
Controls	Yes			
Year FE	Yes			
Firm FE	Yes			
Observations	987			

4.2.3 Endogeneity Issues

This paper addresses endogeneity issues through two approaches. First, the instrumental variable method. We select the number of post offices in each prefecture-level city in 1984 as an instrumental variable (iv) for corporate digital transformation, reflecting early-stage information development levels and the vitality of civilian information exchange [6]. As shown in column (1) of Table 8 , in the first-stage regression, the iv coefficient is 0.0001, significant at the 1% level, indicating a strong correlation between the instrumental variable and the endogenous variable, satisfying the relevance requirement. As shown in column (2) of Table 3, in the second-stage regression, the Dig coefficient is -0.001, indicating that digital transformation significantly reduces carbon emissions, supporting hypothesis H1. Since the primary function of post offices is information transmission, which has no direct connection with construction enterprises' carbon reduction performance, the exogeneity requirement is also satisfied. As shown in columns (3) and (4) of Table 7, in the pilot policy regression analysis, the interaction term (du×Dig) coefficient reaches 161.637, reflecting that pilot policies may weaken the emission reduction effect of digital transformation due to high-energy-consuming industry expansion; while the interaction term (lag1_{du}×dig) coefficient is 148.335, indicating that this pilot policy impact has some persistence.

Table 8 Endogeneity Test Results

	2SLS Regression		Pilot Policy Regression	
Variable	(1) First Stage	(2) Second Stage	(3) Region CO_2	(4) Region CO_2
iv (post offices)	0.0001** (7.688)	-0.001** (-2.786)		
du×Dig			161.637** (6.727)	
Lag1_{du}×dig				148.335** (6.080)
Constant	-4.082** (-15.499)	4595.951** (3.438)	4277.729** (3.170)	
Controls	Yes	Yes	Yes	Yes
Observations	1,118	1,118	1,118	1,118

Meanwhile, based on the history of digital economy development, Shenzhen and Hangzhou are considered the birthplaces of China's digital economy. Following the relevance and exogeneity conditions for instrumental variables, this study selects the natural logarithm of the nearest spherical geographic distance from each enterprise to Shenzhen and Hangzhou (lndis) as an instrumental variable for corporate digital transformation to further test endogeneity.

To control for sufficient fixed effects, time-varying instrumental variables are also constructed. An interaction term between lndis and the time trend (lndis × year) is created, and two-stage least squares (2SLS) estimation continues to be used for instrumental variable regression (Table 9). The Wald F statistics are all greater than the 10% critical value in the Stock-Yogo test, indicating that the instrumental variables are reasonable and reliable. The regression coefficient of the corporate digital transformation index is significantly negative, still confirming the robustness of the conclusions.

Table 9 Endogeneity Test Results (lndis)

Variable	(1) IV1: lndis	(2) IV2: lndis×Year	(3) Iv1: lnDis (Hangzhou)	(4) Iv2: lndis×Year
Digital	-0.134* (-1.83)	-0.038*** (-2.786)	-0.002*** (-3.638)	-15.95*** (-15.950)
Constant	315.691*** (36.426)	4277.729** (3.170)		
Wald F statistic	Wald=8450.151 P=0.000***	Wald=785.396 P=0.000***		

4.3 Mechanism Analysis

The preceding empirical analysis demonstrates that digital transformation significantly reduces carbon emissions in construction enterprises, supporting the carbon reduction perspective of digital transformation. This section analyzes the carbon reduction mechanisms of digital transformation from three dimensions: corporate innovation, efficiency improvement, and production/operation structure optimization.

4.3.1 Innovation Mechanism of Digital Transformation

First, digital transformation in construction enterprises positively impacts carbon reduction by promoting green technology innovation. With the widespread application of digital technology, construction enterprises can more effectively integrate internal and external resources, accelerating R&D and application of new technologies. Green patents, as important outcomes of corporate technological innovation, directly reflect enterprises' investment and achievements in environmental protection and energy-saving technologies. This paper uses the logarithm of green patent count (lngpat) to measure the level of green technology innovation. As shown in column (1) of Table 9, digital transformation is positively correlated with green patent quantity, indicating that digital transformation helps improve the output efficiency of green patents, promotes their application in actual construction production, and stimulates green innovation capabilities, thereby reducing carbon emission intensity. Second, increased R&D investment is also an important manifestation of digital transformation driving technological innovation. As shown in column (2) of Table 9, digital transformation is significantly positively correlated with R&D investment, meaning that digital transformation provides more R&D resources and motivation for construction enterprises, promoting the development and application of energy-saving and emission-reduction technologies. Digital transformation enables construction enterprises to more accurately grasp market demands and construction technology trends, thereby allocating R&D resources more efficiently. This increased investment not only promotes the birth of new technologies but also accelerates the optimization and upgrading of existing technologies, further advancing carbon reduction.

4.3.2 Efficiency Improvement Mechanism of Digital Transformation

Based on previous empirical research, digital transformation in construction enterprises not only improves total factor productivity but also enhances production efficiency through operational optimization and reduced production interruptions, thereby helping reduce carbon emissions. This paper uses total factor productivity calculated by the OP method and LP method as proxy variables for corporate production efficiency. According to the regression results, as shown in columns (3) and (4) of Table 4, digital transformation is significantly positively correlated with total factor productivity, indicating that digital transformation helps improve production efficiency in construction enterprises. Improved production efficiency means that enterprises consume fewer resources and generate less carbon emissions for the same output. Sany Construction's innovatively developed SPCS system for prefabricated concrete buildings simplifies construction processes, achieving "full prefabrication of walls, columns, beams, and slabs + full assembly above and below ground." This technical system offers overall advantages of "cavity connection with post-casting, equivalent heterogeneous structure, good performance, speed, and cost savings," directly addressing pain points such as structural safety, water leakage, external wall insulation, labor shortages, low efficiency, and high costs, significantly improving total factor productivity, reconstructing the construction industry ecosystem, and achieving low-carbon, high-quality development [5].

4.3.3 Production and Operation Structure Optimization

First, the widespread application of digital technology can significantly improve resource utilization efficiency throughout the entire lifecycle of construction enterprises, thereby reducing emissions of various polluting construction waste. This paper uses the operating cost ratio (cost) (operating cost/operating revenue) as a negative indicator to measure the degree of production/operation optimization. Second, we improve operational efficiency through internal controls to achieve diversified and multi-level development strategies. We adopt the widely recognized "Dibo China Listed Company Internal Control Index" (InnCt) as a measure of internal control level, which comprehensively covers internal environment, risk assessment, control activities, information communication, and internal supervision. The regression results, as shown in columns (5) and (6) of Table 9, indicate that digital transformation is negatively correlated with the operating cost ratio, with significant coefficients, suggesting that digital transformation helps reduce operating costs. This cost reduction may stem from improved production efficiency and optimized resource utilization, thereby contributing to carbon emission reduction. Combined with previous analysis, this verifies research hypothesis H2. Construction enterprises can achieve automated and intelligent production by applying big data, artificial intelligence, and other digital technologies, reducing repetitive and low-value manual tasks and significantly lowering labor and time costs, thus achieving cost reduction and efficiency gains. Intelligent building management systems optimize energy use, reducing consumption and emissions. Meanwhile, construction enterprises can use digital technology to improve carbon accounting accuracy, enhance compliance and transparency of carbon emission information disclosure, promote carbon market trading, and achieve sustainable development.

Table 10 Mechanism Analysis Results

Variable	(1) Production/Operation Structure Optimization	(2) Lngpat	(3) TEP_{OP}	(4) TFP_{LP}	(5) Innct
digital	0.001** (0.009)	0.053* (0.026)	0.001*** (0.0001)	0.003*** (0.0001)	-0.001* (0.0031)
Constant	-0.001*** (0.0001)				

4.3.4 Mediation Effect Analysis

This study constructs a mediation effect model to deeply explore three pathways through which digital transformation affects corporate carbon emission intensity: the R&D innovation pathway, total factor productivity (TFP) improvement pathway, and operation cost optimization pathway.

1. **R&D Innovation Pathway**
   Mediation test results show that digital transformation significantly promotes corporate R&D innovation activities (regression coefficient of dig on R&D is 0.0009, $p<0.01$) (Table 10). Increased R&D intensity significantly reduces corporate carbon emission intensity (regression coefficient of R&D on intCO_2 is -0.0003, $p<0.01$). This indicates that digital transformation can indirectly reduce carbon emission intensity by promoting green technology R&D, validating the theoretical logic of achieving environmental benefits through technology empowerment.

2. **TFP Improvement Pathway**
   Although the direct impact of digital transformation on TFP is not significant (regression coefficient of dig on TFP is -0.0004, $p>0.05$), TFP significantly reduces carbon emission intensity (regression coefficient of TFP on intCO_2 is 0.0003, $p<0.01$) (Table 11). This suggests that digital transformation can indirectly suppress carbon emissions by optimizing factor allocation efficiency. The economic interpretation is that digital transformation improves resource utilization efficiency through data-driven decision-making and intelligent production scheduling, thereby reducing energy consumption and carbon emissions while maintaining the same output level.

3. **Operation Cost Optimization Pathway**
   Digital transformation significantly reduces corporate operating costs (regression coefficient of dig on cost is -0.0001, $p<0.01$), and cost optimization is positively correlated with carbon emission intensity (regression coefficient of cost on intCO_2 is 0.0013, $p<0.01$) (Table 12). This indicates that digital transformation indirectly reduces carbon emission intensity through lean management and supply chain collaboration mechanisms. The underlying logic is that cost optimization is typically accompanied by improved energy efficiency and waste reduction, such as reducing transportation energy consumption through intelligent logistics systems or decreasing equipment idle time through predictive maintenance.

Table 11 Mediation Model Results (R&D Investment)

Variable	(1) intenco2	(2) RD	(3) intenco2
Digital	-1.4879* (-2.2040)	0.0009** (3.9934)	-5.2209** (-17.8752)
RD			-0.0003** (-3.4576)
Constant	-5.0849** (-17.6881)	-0.0004** (-4.3140)	0.0914** (4.4187)
F-test	F(14,419)=92.8990, p=0.000	F(14,419)=499.5128, p=0.000	F(15,418)=488.1262, p=0.000

Table 12 Mediation Model Results (Total Factor Productivity)

Variable	(1) TFP_{FE}	(2) intenco2	(3) intenco2
Digital	-12.9142** (-4.7034)	-0.0003** (-3.5680)	-5.0106** (-17.1286)
TFP			-0.0003** (-3.5247)
Constant	-5.2544** (-18.1002)	0.0189** (3.9470)	
F-test	F(13,474)=29.6959, p=0.0000	F(13,474)=535.6878, p=0.0000	F(14,473)=513.8367, p=0.0000

Table 13 Mediation Model Results (Corporate Operating Cost Ratio)

Variable	(1) Cost	(2) intenco2	(3) intenco2
Digital	0.0014** (5.3725)	0.0013** (5.2536)	
Cost			-1.2285
Constant	0.4198	0.5008	
F-test	F(10,477)=11.5274, p=0.0000	F(10,477)=36.2380, p=0.0000	F(11,476)=33.1160, p=0.0000

4.4 Heterogeneity Tests

Given the varying attributes of construction enterprises, the carbon reduction effects of digital transformation may exhibit asymmetric characteristics. To address this, this paper thoroughly examines digital transformation practices in construction enterprises, conducting detailed discussions based on regional differences, property rights nature, and types of digital technology adopted.

4.4.1 Regional Heterogeneity

China's vast territory features varying levels of digital development across regions, which may create digital "access barriers." To further explore the impact of digital access levels, this paper divides all Chinese regions into eastern, central, western, and northern areas, analyzing listed companies by province. Eastern regions typically refer to a series of provinces and municipalities in China's administrative divisions. The eastern region listed companies covered in this paper include six provinces/municipalities: Anhui, Fujian, Jiangsu, Shandong, Shanghai, and Zhejiang. Eastern regions are usually economically developed with high levels of industrialization and urbanization, occupying the forefront of China's opening-up and economic development. They are rich in natural resources, have convenient transportation networks, highly concentrated scientific and educational resources, relatively complete market systems, and hold important positions in China's economic development. Table 13 shows that carbon reduction effects differ significantly across regions during enterprise digitalization, supporting research hypothesis H3 regarding regional heterogeneity in carbon reduction effects. The carbon reduction effect of digital transformation is significant in eastern regions, while coefficients in central and southern regions are positive but insignificant.

Table 14 Grouped Regression Results

Variable	Eastern Region	Central Region	Western Region	Northern Region
Constant	16.949* (2.271)	-0.054** (-3.049)	0.139*** (0.003)	-0.038*** (0.000)
Digital	-0.054** (-3.049)	0.128 (0.082)	0.030 (0.109)	-0.011*** (0.010)
Controls	Yes	Yes	Yes	Yes
F-test				

F(16,336)=99.415, p=0.00 | F(16,141)=71.567, p=0.0 | F(16,43)=32.732, p=0.0 | F(16,86)=24.205, p=0.0 |

- **Eastern region** (coefficient -0.054, $p<0.01$): Digital transformation has a significant inhibitory effect on carbon emissions, consistent with theoretical expectations. This may be due to strong technological foundations in eastern enterprises, where digital transformation focuses on optimizing energy structure and iterating green technologies.
- **Central region** (coefficient 0.128, $p=0.082$): The positive effect is marginally significant, possibly because central region enterprises are in a critical period of industrialization, where digital transformation is accompanied by short-term capacity expansion, leading to increased carbon emissions.
- **Southern region** (coefficient 0.030, $p=0.109$): The positive effect is insignificant, possibly related to the export-oriented economic characteristics of southern regions, where digital transformation focuses on market responsiveness rather than production-side emission reduction.

Further grouped regression results show that digital transformation in eastern region enterprises demonstrates significant carbon reduction dividends, while central and western regions require complementary structural reforms to unleash the potential of digital technology. Enterprises in central regions are in a critical period of industrialization, where the initial stage of digital transformation may be accompanied by capacity expansion to meet market demands and enhance competitiveness. During this process, equipment upgrades, technology investments, and production scale expansion may temporarily increase energy consumption and carbon emissions, masking the long-term potential carbon reduction effects of digital transformation. Although central regions are accelerating digital infrastructure layout, their digital technology applications may still be in relatively early stages compared to eastern regions. If digital transformation remains superficial without deep promotion of green technology innovation and optimization of production processes and management structures, it will be difficult to achieve significant carbon reduction effects.

4.4.2 Property Rights Heterogeneity

Different ownership construction enterprises adopt different strategies when facing digital transformation due to varying policy environments and incentive structures. To investigate how ownership differences affect digital transformation's carbon reduction effectiveness, this paper constructs an interaction term between ownership dummy variables and digital transformation (digital×soe) to test whether significant differences exist between state-owned and non-state-owned construction enterprises. The results in column (1) of Table 15 show a significant interaction term coefficient, indicating that digital transformation in state-owned construction enterprises may be less effective in reducing carbon emission intensity than in non-state-owned enterprises, or may even increase carbon emission intensity, validating hypothesis H3 regarding property rights heterogeneity. First, state-owned construction enterprises may struggle to fully utilize the emission reduction potential of digital transformation due to complex decision-making processes, traditional management models, and slow operational efficiency improvements. In contrast, non-state-owned construction enterprises, with greater autonomy and flexibility, can more quickly adopt new technologies and models such as BIM and intelligent construction to achieve rapid operational efficiency improvements and more effectively reduce carbon emission intensity. Second, non-state-owned construction enterprises have higher carbon content than state-owned enterprises, and after digital transformation, the marginal benefits of emission reduction are higher for non-state-owned enterprises. Finally, state-owned construction enterprises tend to achieve energy-saving goals through production reduction, while non-state-owned enterprises focus more on improving energy efficiency.

4.4.3 Digital Technology Heterogeneity

Wu Fei (2021) [18] demonstrates that various digital technologies contribute to carbon reduction. Therefore, we divide digital transformation indicators into two major categories: "underlying technology level" and "practical application level," including five key sub-items: AI, blockchain (BC), cloud computing (CC), big data (DT), and applied digital technology (ADT). Empirical results in columns (3)-(7) of Table 15 show that AI, blockchain, cloud computing, and big data all have significant negative impacts on carbon emission intensity. These technologies optimize building energy consumption through intelligent control and management, ensure accurate tracking and management of carbon emission data using blockchain, improve data center energy efficiency and enable remote monitoring through cloud computing, and deeply analyze energy consumption data to formulate optimization strategies using big data. Moreover, these technologies play crucial roles throughout the entire lifecycle of prefabricated buildings, including design, production, transportation, installation, and operation/maintenance, through digital management. Particularly in prefabricated construction, digital technology optimizes production planning and logistics, reduces energy consumption and emissions, and achieves precise prediction and optimization of building energy consumption through intelligent control and management systems. Meanwhile, big data applications provide rich energy consumption data support for construction enterprises, helping them formulate more scientific carbon reduction strategies. The deep integration of these digital technologies with prefabricated construction jointly drives the green transformation of the construction industry, laying a solid foundation for achieving sustainable development goals. In summary, these digital technologies collectively promote carbon reduction practices in construction enterprises through multiple approaches, driving sustainable development in the industry, particularly demonstrating remarkable effectiveness in key areas such as prefabricated construction and digital management.

Table 15 Heterogeneity Test Results | Variable | Property Rights Heterogeneity | Digital Technology Heterogeneity | |———-|——————————|——————————-| | | (1) Intenco | (2) Intenco | (3) AI | (4) BC | (5) CC | (6) DT | (7) ADT | | Digital | -0.006 (0.580) | 0.42*** (0.000) | -0.031*** (0.002) | 0.139*** (0.003) | -0.038*** (0.000) | -0.011*** (0.010) | -0.013*** (0.001) | | Controls | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

5 Conclusions and Recommendations

5.1 Research Conclusions

Based on the empirical analysis results, this paper draws the following conclusions:

(1) As a major source of carbon emissions, construction enterprises bear significant responsibility in achieving China's "dual carbon" goals. Despite data availability limitations that have constrained past research, this paper, through detailed data processing and analysis of Chinese listed companies from 2000 to 2021, not only confirms the positive impact of digital transformation on carbon reduction but also deeply analyzes the underlying transmission mechanisms, filling an important gap in this research field. The results show that digital transformation significantly reduces carbon emission intensity in construction enterprises, a conclusion strongly supported by various robustness tests, further proving its stability and reliability.

(2) Digital transformation effectively promotes carbon reduction primarily through its multiple roles in technological innovation, production efficiency improvement, and production/operation structure optimization. Specifically, digital transformation stimulates corporate green innovation capabilities, promotes R&D and application of green technologies such as intelligent building design and energy efficiency management systems, significantly improves resource utilization efficiency, and reduces unnecessary energy consumption. Simultaneously, digital transformation indirectly reduces carbon emissions by optimizing production processes, improving total factor productivity, and reducing operating cost ratios.

(3) The carbon reduction effects of digital transformation exhibit heterogeneity across construction enterprises with different property rights natures. Due to differences in resource endowments and management mechanisms, state-owned and private enterprises demonstrate different carbon reduction effects during digital transformation. However, from a regional perspective, digital transformation's carbon reduction effects do not show significant regional differences, indicating that the green and low-carbon effects of digital transformation have universal applicability.

5.2 Policy Recommendations

This study proposes specific measures to promote corporate digital transformation and carbon reduction from multiple perspectives:

(1) **Increase R&D investment in digital green building technology.** Construction enterprises should leverage digital technology to identify innovation opportunities and improve energy efficiency. In terms of technological innovation, they should continue increasing investment in digital technology R&D, 攻克 low-energy consumption and high-efficiency technologies, promote technology transformation and application, and use digital technology to identify innovation opportunities in building energy conservation and renewable energy utilization. For example, optimize building design schemes through digital simulation technology to improve energy efficiency; use IoT technology for real-time building energy consumption monitoring to achieve precise management. Further enhance the promotion effect of listed companies' digitalization on total factor productivity. Accelerate the upgrading and application of digital technology, deepen its application in R&D design, production manufacturing, warehousing logistics, and marketing services to achieve digitalization from production to sales. Second, enterprises should accelerate the construction of digital and smart factories, increase investment in intelligent equipment such as AI, robotics, interconnected platforms, and smart sensors, precisely control production efficiency and quality, and gradually transform toward intelligent manufacturing. Enterprises should shift their operational mindset, enhance IT awareness, and further expand investment in software and hardware and digitalization. Finally, we should innovate traditional self-operated models, continuously explore new business models such as live-streaming sales through internet and e-commerce platforms, and keep pace with consumer demand and market changes.

(2) **Optimize processes using digital tools and energy management systems, and introduce intelligent technology for efficient energy utilization.** To improve operational efficiency, enterprises should make full use of digital project management tools and energy systems to optimize construction processes, allocate resources reasonably, and reduce energy waste and carbon emissions during construction. Simultaneously, introduce intelligent equipment and technology to transform and upgrade high-energy-consuming equipment, achieving efficient energy utilization.

(3) **Strengthen exchanges and cooperation among construction enterprises, and use digital finance to promote green supply chain construction.** In terms of improving the business environment, we will share experiences and technologies for energy conservation and emission reduction, jointly promoting green supply chain construction. Additionally, we should make full use of digital finance support to apply for low-interest green loans, providing financial security for green building projects and

digital transformation.

(4) **Pilot a digital carbon supervision exemption mechanism in free trade zones**, granting a 3-year carbon emission quota exemption period to enterprises applying new technologies such as blockchain traceability and AI energy efficiency management. Introduce smart contract technology to achieve automatic settlement and cross-chain mutual recognition of carbon trading, reducing transaction costs. Establish a "data sandbox" regulatory model, piloting blockchain carbon data certification platforms in central provinces such as Hubei and Hunan. Through smart contracts, achieve hierarchical management of data access rights among government regulatory nodes, corporate data nodes, and third-party identity verification nodes, ensuring a balance between data sharing and trade secret protection. Drawing on the "regulatory chain" model from the financial sector, construct a construction carbon chain responsibility traceability network, requiring high-emission enterprises to obtain and achieve full-chain permeable supervision of carbon emission data from design and construction to operation and maintenance, with blockchain certification and accountability for data fraud.

5.3 Limitations and Future Research

5.3.1 Research Limitations Despite systematically analyzing the impact of digital transformation on carbon reduction in construction enterprises and its mechanisms, this study still has the following limitations:

(1) **Limited data coverage:** The research sample only covers Chinese listed construction enterprises, excluding small and medium-sized unlisted companies and local construction firms. Due to significant differences in management mechanisms, resource endowments, and technology applications between unlisted enterprises, the generalizability of conclusions may be limited. Additionally, carbon emission data relies on indirect estimation methods that may not fully reflect actual emission levels.

(2) **Limitations in measuring digital transformation:** Although the text analysis method is used to construct digital transformation indicators, this approach mainly relies on keyword frequency in annual reports and cannot comprehensively measure the actual depth and implementation effectiveness of digital transformation. For example, some enterprises may only engage in superficial digital promotion without substantively advancing technology transformation.

(3) **Insufficient depth in regional heterogeneity analysis:** Although regional differences are found to be insignificant, the study does not further explore specific pathways for central and western regions to achieve "latecomer advantages" through policy subsidies or technological progress, nor does it quantify the moderating role of regional policy environments on digital transformation effects.

(4) **Inevitable data robustness issues in this study.** It is widely believed that CO_2 is the main atmospheric pollutant, making it difficult to use CO_2 as a dependent variable for substitution. In this study, SO_2 is used as a substitute to demonstrate data robustness due to inherent errors. Future research can improve CO_2 measurement and data collection.

5.3.2 Future Research Directions Addressing the above limitations, future research can expand in the following directions:

(1) **Expand data dimensions and sample scope:** Integrate data from unlisted enterprises and micro-level project-specific carbon emission data, combine field research or IoT sensor data to improve carbon emission estimation accuracy, and extend the research time span to capture the long-term dynamic relationship between digital transformation and carbon reduction.

(2) **Deepen the digital transformation measurement system:** Construct multi-dimensional indicators covering technology application intensity (such as BIM usage rate), employee digital skills, supply chain collaboration levels, etc., combined with case studies to validate indicator effectiveness.

(3) **Explore policy and technology synergy mechanisms:** Analyze the interaction effects between carbon trading markets, green finance policies, and digital transformation, such as investigating how carbon price signals incentivize enterprises to adopt intelligent emission reduction technologies.

---

[1] The corporate digital transformation keyword list follows Wu Fei (2021), categorizing digital transformation into artificial intelligence technology, blockchain technology, etc.

Note: Figure translations are in progress. See original paper for figures.