frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 25 June 2025
DOI 10.3389/fenvs.2025.1570182

OPEN ACCESS

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RECEIVED 03 February 2025
ACCEPTED 29 May 2025
PUBLISHED 25 June 2025

CITATION
Zhao S, Deng H, Cao J and Gustaf M (2025) Digital transformation of construction enterprises and carbon emission reduction: evidence from listed companies.
Front. Environ. Sci. 13:1570182.
doi: 10.3389/fenvs.2025.1570182

Digital transformation of construction enterprises and carbon emission reduction: evidence from listed companies

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As a key sector for energy consumption and carbon emissions, the construction industry's carbon reduction measures have important strategic significance for achieving the "dual carbon" goals. Based on data from Chinese listed construction companies from 2000 to 2021, this study empirically explores the effects and pathways of digital transformation on carbon reduction. The results indicate that digital transformation can significantly reduce the carbon emission intensity of enterprises, mainly through promoting green technology innovation, improving total factor productivity, and optimizing production processes and business structures. Heterogeneity analysis shows that digital technology has a more significant emission reduction effect on highly competitive enterprises in the industry, and there are significant differences in carbon emission reduction between regions. This study provides a reference for carbon neutrality pathways in the field of architecture.

KEYWORDS

digital transformation of enterprises, carbon emission reduction, carbon emission of construction enterprises, listed company, dual carbon targets

1 Introduction

With the severe challenge of global climate change, reducing carbon emissions and achieving carbon neutrality have become the focus of international attention. As one of the largest carbon emitters in the world, China announced to the world the grand goal of "achieving peak carbon dioxide emissions by 2030 and striving to achieve carbon neutrality by 2060". In this context, the construction industry is one of the main fields of energy consumption and carbon emission, and its carbon emission reduction actions have an important impact on achieving carbon emission reduction targets.

In recent years, with the rapid development of digital technology, the digital transformation of construction enterprises has become an important force to promote industry reform. At the same time, the wide application of digital technology in enterprises has promoted the sustainable development of the industry. Existing research shows that the digital transformation of enterprises has a significant role in promoting carbon emission reduction. Through digital transformation, enterprises can achieve structural optimization, resource integration, efficiency improvement and benefit increase, thus reducing carbon emissions (Zhang Zack et al., 2024). It is suggested that digital transformation has a significant inhibitory effect on urban carbon emissions, and carbon emission reduction is mainly achieved through internal optimization of enterprises and industrial integration, and the carbon emission reduction effects in different regions and economic agglomeration areas are heterogeneous (Chen and Zhang, 2024). It is pointed out that digital transformation is helpful to reduce the carbon emission intensity of enterprises, and energy conservation and emission reduction can be realized mainly by improving the effectiveness of internal control and promoting green technology innovation of enterprises. However, some scholars believe that if enterprises, governments and other subjects cannot take reasonable measures to promote digital transformation, it may be difficult to achieve sustainable development of carbon emission reduction (Zhang, 2023). It is considered that institutional pressure has a negative regulatory effect between digital transformation of construction enterprises and carbon emission of enterprises, that is, under high institutional pressure, certain economic compensation should be considered to improve the enthusiasm of construction enterprises to achieve carbon neutrality (Niu, 2023). It is believed that if the government does not encourage enterprises to actively adopt digital technology, the efficiency of digital transformation of the industry is very low, and it is not conducive to the sustainable development of the environment.

However, despite the great potential of digital transformation of construction enterprises, the empirical research on the specific impact of carbon emission reduction is not sufficient. Therefore, based on the evidence of listed companies, this paper explores the impact of digitalization of construction enterprises on carbon emission reduction through empirical analysis, robustness test, mechanism analysis and heterogeneity analysis, which not only helps to reveal the carbon emission reduction effect of digital transformation, but also provides scientific decision-making basis for the government to formulate relevant policies and enterprises to provide transformation strategies.

The marginal contributions of this paper are as follows: First, the empirical analysis of the relationship between digital transformation and carbon emission reduction of construction enterprises will help to enrich and improve the theoretical system in the field of digital transformation and environmental protection, and provide a new perspective and methodology for subsequent research. Secondly, for construction enterprises, it reveals the actual effect of digital transformation in reducing carbon emissions, and provides enterprises with the motivation and direction of transformation; At the same time, according to the research results, the government can formulate more accurate digital transformation support policies and green financial policies to promote the green and low-carbon development of construction enterprises; In addition, according to the research results, it can provide reference for other industries and promote the whole society to form a virtuous circle of digital transformation and carbon emission reduction.

2 Literature review

Related research focuses on the various impacts of digital transformation on the development of the construction industry and the operation of enterprises themselves. By promoting the information transformation of the construction industry, promoting the integration of intelligent technology and prefabricated buildings and optimizing the management efficiency of enterprises, digital technology has significantly improved the production efficiency of the industry and the core competitiveness of enterprises. At the level of industry development, digital technology has brought profound changes to the construction industry. Construction industry is one of the industries with the lowest informatization and digitalization in traditional industries. Whoever can realize digital transformation faster will occupy an advantageous position in market competition (Yang Yingnan et al., 2022). The rapid development of digital perception, analysis and decision-making service technology in recent years can transform and upgrade the construction industry to technology-intensive industries, and bring new opportunities for the development of construction projects (Wang Pujin et al., 2024). The organic integration of intelligent control technology and prefabricated building production is irreplaceable in prefabricated buildings and even the whole construction industry, and marks the birth of a new intelligent production mode of prefabricated buildings (Liu et al., 2023). The application of digital technology can improve the overall production efficiency of the construction industry and promote the efficient development of the industry. From the perspective of enterprise operation, digital transformation has brought many positive changes to construction enterprises. The digital transformation of construction enterprises should ensure the deep integration of data governance and business innovation, fully integrate business management experience and digital technology, and ensure that digital technology can be effectively applied in practical business (Cultur et al., 2024; Borozan and Pirgaip, 2024). The digital transformation of the construction industry can improve the scattered communication information and low communication efficiency of all departments of the enterprise, build a functional management and control system that is connected from top to bottom and linked internally and externally, and improve the work efficiency of employees and the management efficiency of enterprises (Pingru et al., 2023; Zhao et al., 2025; Lei, 2024; Zuo, 2023).

Carbon emission reduction has become a key measure to deal with global warming. For construction enterprises, the path and effect of carbon emission reduction are the focus of research. 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 for the most urgent challenges of this industry (Kathrin and Cordula, 2023). Some scholars have found that the digital economy has a significant carbon reduction effect (Hui and Zhang, 2025; Xiao and Kong, 2025; Huang et al., 2025a; Huang et al., 2025c). Digital technology makes buildings more integrated, flexible, energy-saving, intelligent and sustainable by optimizing resource utilization, improving operational efficiency and minimizing environmental impact (Asif et al., 2024). The cost borne by traditional production methods is the key factor to determine the speed of low-carbon transformation (Luo and Tang, 2020). After a variety of robustness tests, digital transformation can significantly promote the carbon emission reduction effect of China's construction enterprises, and can promote carbon emission reduction by enhancing technological innovation and increasing corporate social attention (He et al., 2025; Li et al., 2024; Huipeng et al., 2023; Xing and Zhu, 2025). However, some studies have pointed out that the relationship between digital transformation and carbon emission reduction of construction enterprises is complicated. Some scholars believe that there is a nonlinear relationship between digital economy and carbon emissions (Peng et al., 2024; Zhao et al., 2024; Shao et al., 2024). It is pointed out that with the development of digital economy to a higher level, the effect of emission reduction becomes more obvious (Wang et al., 2023). found that there is an inverted U-shaped relationship between digital economy and carbon emissions, and the emission reduction effect is greater in areas with scarce resources (Li et al., 2024; Huang et al., 2025b). Based on the study of this relationship, many scholars have further explored the mechanism of digital economy affecting carbon emissions. (Changqi et al., 2025). It is found that the development of digital economy promotes carbon emission reduction through technological progress, structural optimization and strengthening education. Digital economy reduces unnecessary waste of resources, changes the traditional energy use mode, and accelerates the replacement of high-carbon industries by low-carbon industries (Peak, 2025; Zhang and Yang, 2025; yi and Su, 2025-04; Cook, 2017) And reduce the intensity of carbon emissions by reducing energy demand (Zhao et al., 2024). Although digital technology provides new opportunities for carbon emission reduction, in the initial stage of digital transformation, enterprises may increase energy consumption and fluctuate carbon emissions in the short term due to equipment updating and technology investment (Wang Wenjie et al., 2024). Because the extensive use of related infrastructure may lead to higher power consumption, thus increasing emissions (Zhou and Chu, 2024). Existing literature on the impact of digital transformation on carbon emissions generally emphasizes the energy efficiency improvement and industrial structure optimization effects brought about by technological progress, but lacks attention to the potential "rebound effect" it may trigger (Mai et al., 2025; Han et al., 2025; Ying et al., 2024; Huang et al., 2025b; Huang et al., 2025c). The rebound effect theory suggests that when technological progress improves energy efficiency, the relative decrease in energy service costs may stimulate the growth of consumer demand, thereby partially or completely offsetting the expected emission reduction effect (Zhang Yuxin et al., 2024; Liu Haiying et al., 2024; Su et al., 2025). This controversy is particularly prominent in the context of digital transformation and requires theoretical analysis and empirical testing from multiple dimensions. For high carbon industries (Chen et al., 2024; Liu Bei et al., 2024; Shang Yuping et al., 2023), the initial stage of digital transformation may lead to a significant increase in carbon emissions due to equipment updates and capacity expansion (Wei et al., 2025; Zhang and Cui, 2025; Yang and Liu, 2024); But for low-carbon industries, the emission reduction effect achieved by optimizing supply chain management through digital technology is more significant (Yang et al., 2023; Yang Xiaoguang et al., 2022; Chen et al., 2022; Li et al., 2024; Wang, 2024). This industry heterogeneity requires that policy design should go beyond the unified model and adopt differentiated transformation strategies.

The existing literature mainly focuses on the relationship between digital transformation and carbon emission reduction, but the impact on low-carbon technology and how technological progress can promote low-carbon technology and sustainable economic development still need further study. First of all, the research on the influence of digital economy on technological progress mostly focuses on whether it can improve energy efficiency and provide new impetus for long-term economic growth. At present, there is a lack of research on how the digital economy affects technological progress by indirectly empowering different enterprise production factors. Secondly, many studies have discussed the impact of digital economy on carbon emissions from the perspectives of environmental governance, industrial structure optimization and resource utilization. Few scholars pay attention to the impact of digital economy on carbon emissions from the perspective of enterprise digital technology progress through the differential empowerment effect of digital economy on various factors. Most documents define technological progress as that technological progress improves the marginal productivity of one factor of production relative to another. However, technological progress is often tendentious, and not all forms of progress can bring about pollution reduction. When technological progress improves the marginal productivity of energy factors, it improves energy efficiency, thus reducing pollutant emissions. This paper studies the digital transformation to improve enterprise innovation mechanism, total factor productivity and optimization of production and operation structure to promote the reduction of enterprise carbon emissions, further reduce regional total carbon emissions, and further analyze regional heterogeneity.

3 Theoretical analysis and research hypothesis

This paper focuses on construction enterprises, deeply analyzes the impact of digital transformation on their carbon emission reduction and its internal mechanism, and puts forward the following three research hypotheses.

Digital transformation can reduce energy consumption by reconstructing the resource allocation and operation mode of construction enterprises. The deep application of digital technology not only changed the production mode of traditional construction industry, but also optimized the energy utilization efficiency through real-time data collection and analysis. For example, the Internet of Things and big data technology can accurately monitor the energy consumption in the whole life cycle of a building and reduce redundant energy consumption in the construction and operation stages. In the construction stage, the intelligent equipment scheduling system can reduce the mechanical idling rate; In the building operation stage, the intelligent management system can significantly reduce carbon emissions by dynamically adjusting the use of air conditioning, lighting and other equipment. In addition, digital supply chain management can optimize the transportation route and inventory level of building materials and reduce the implied carbon emissions (Jun-Qian and Yong-Kou, 2025). Digital transformation realizes carbon emission reduction by improving the ability of resource integration and decision-making efficiency. Therefore, this paper puts forward hypothesis H1, and thinks that digital transformation can significantly reduce the carbon emission intensity of construction enterprises.

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

The carbon emission reduction effect of digital transformation is not a single path, but is realized through the synergistic mechanism of technological innovation, efficiency improvement and structural optimization. First, digital technology has accelerated green innovation. Tools such as building information model (BIM) and artificial intelligence not only shorten the research and development cycle of green technology, but also optimize the architectural design scheme through simulation to reduce the waste of building materials and construction energy consumption. For example, the SPCS system developed by Sany Construction Engineering Co., Ltd. Significantly reduces the energy waste caused by building materials loss and construction interruption through standardized assembly production technology. Secondly, digital tools improve the efficiency of production factors through automation and intelligent transformation. Intelligent algorithm can optimize the construction process and reduce the idle time of manpower and equipment; Blockchain technology improves the efficiency of supervision and traceability through transparent carbon emission data (Lan and Zhou, 2025). Digital transformation significantly improves the total factor productivity and reduces the operating cost rate, which proves the effectiveness of the efficiency improvement path. Finally, digital transformation promotes the transformation of enterprises from high-carbon to low-carbon mode. For example, construction enterprises increase the proportion of green building projects through digital market analysis, and optimize supply chain management by using carbon accounting platform to achieve emission reduction in the whole life cycle (Yan et al., 2023). The interaction of the above three paths shows that digital transformation provides a systematic solution for carbon emission reduction of construction enterprises through the comprehensive effects of technology empowerment, efficiency drive and structural remodeling, so hypothesis H2 is proposed.

H2. Digital transformation realizes carbon emission reduction through technological innovation, improvement of production factor efficiency and optimization of production and operation structure.

The structural differences within China's construction industry and the unbalanced regional development lead to the asymmetric carbon emission reduction effect of digital transformation. In terms of heterogeneity of property rights, the difference of institutional environment between state-owned and non-state-owned enterprises significantly affects the implementation effect of digital transformation. State-owned enterprises are subject to lengthy decision-making processes and administrative goal orientation, and tend to promote digitalization through administrative instructions, but lack flexible technical application scenarios (Han and Marco, 2020). For example, non-state-owned enterprises are more likely to adopt intelligent construction technology to optimize energy consumption (Julie et al., 2022), and state-owned enterprises may be difficult to release the digital potential because of the complex management level (Zhang and Shen, 2024; hai et al., 2025; Fu and Pan, 2024; Guangmiao, 2023). In terms of regional heterogeneity, although the eastern coastal areas have more perfect digital infrastructure and policy support, it stems from the fact that the central and western regions have accelerated the layout of digital infrastructure through "late-comer advantage" and gradually narrowed the technological gap with the east. For example, by introducing cloud computing and remote collaboration platform, enterprises in the central and western regions have overcome the shortcomings of local technology and achieved emission reduction efficiency similar to that in the east. This shows that the inclusive characteristics of digital transformation enable its carbon emission reduction effect to break through the limitation of unbalanced regional development, but its heterogeneity in property rights still needs targeted policy intervention. Therefore, this paper puts forward hypothesis H3, emphasizing the need to formulate differentiated transformation strategies based on enterprise attributes and regional characteristics.

H3. The carbon emission reduction effect of digital transformation has property right heterogeneity and regional heterogeneity.

4 Analysis of carbon emission status of construction enterprises

4.1 Status of carbon emissions

With the increasingly severe global climate change, the construction industry, as an important field of energy consumption and carbon emission, has attracted much attention. According to the Report on the Status of Global Construction Industry in 2024–2025 issued by the United Nations Environment Programme and the Global Building and Construction Alliance, although the emissions of the construction industry will stop rising after 2020, the slow progress and insufficient funds put the global climate target at risk. According to the report, the construction industry is still the main driver of the climate crisis, consuming 32% of global energy and contributing 34% of global carbon dioxide emissions.

In China, according to "Research Report on Carbon Emissions in Urban and Rural Construction in China (2024 Edition)", the total carbon emissions of buildings and construction industry in China reached 5.13 billion tons of carbon dioxide in 2022, accounting for 48.3% of the national energy-related carbon emissions. Among them, the construction industry emits 2.82 billion tons of carbon dioxide, and the construction operation emits 2.31 billion tons of carbon dioxide. This data shows that the carbon emission of China's construction industry is huge, and the task of emission reduction is very arduous (Table 1).

4.2 Main emission sources

The carbon emissions of construction enterprises mainly come from the following aspects:

(1) Production of building materials: The production of building materials is one of the main sources of carbon emissions in construction. For example, in the production process of building materials such as cement, steel and wood, a large amount of carbon dioxide emissions will be generated. Cement production is one of the main sources of carbon emissions, and its carbon emissions account for a large proportion of the total.

(2) Construction process: During the construction process, mechanical equipment operation, transportation, and

TABLE 1 Carbon emission from construction process.

Classify		Energy consumption		Carbon dioxide emission	
		108 tce (Coal consumption for power generation)	Occupy the whole country proportion	108tCQ	Occupy the national energy phase Carbon emission ratio
Architecture and construction industry construction		**24.2**	**44.7%**	**51.3**	**48.3%**
Construction industry construction		**12.3**	**22.7%**	**28.2**	**26.6%**
Classification	Building construction	7.9		18.4	
	Infrastructure construction	4.4		9.8	
Subprocess	Building materials production and transportation	11.5		27.2	
	construct	0.8		1.00	
Building operation		**11.9**	**22.0%**	**23.1**	**21.7%**
Classification	Public building	4.9		9.4	
	Urban residential buildings	4.5		8.9	
	Rural residential buildings	2.5		4.8	
Separate sources	fossil energy	2.3		4.5	
	power	7.9		14.4	
	central heating	1.7		4.2	

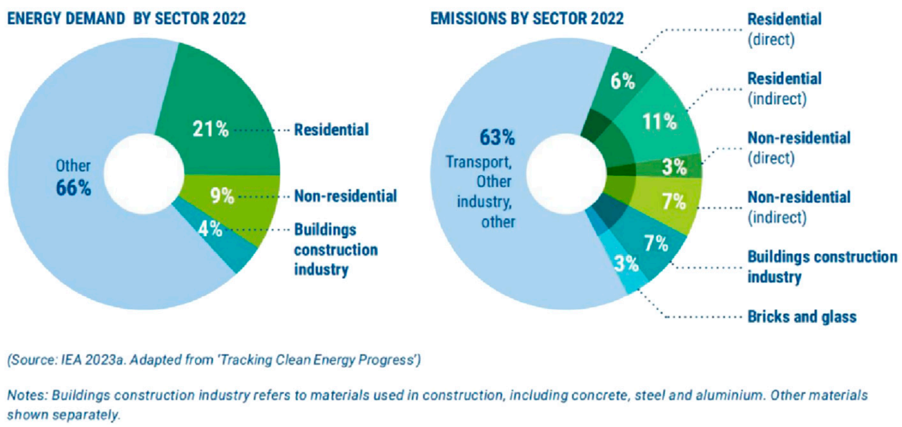

FIGURE 1
Schematic diagram of carbon emission in construction industry.

temporary facilities construction will all produce carbon emissions. In addition, waste disposal at the construction site and energy consumption during construction will also increase carbon emissions.

(3) Building operation stage: During the operation of the building, such as lighting, air conditioning, heating, etc., a lot of energy will be consumed, and then carbon emissions will be generated. The carbon emissions in the operation stage of a building account for a large proportion of the carbon emissions in the whole life cycle of the building.

4.3 Influencing factors

The carbon emissions of construction enterprises are affected by many factors, mainly including the following aspects (Figure 1):

Population and urbanization rate: the total population and urbanization rate are important factors affecting building energy consumption and carbon emissions. With the growth of population and the improvement of urbanization rate, the carbon emissions in the construction sector may increase accordingly.

Building area and type: the expansion of building area and the diversification of building types will also lead to the increase of carbon emissions. For example, large public buildings and high-rise residential buildings usually have high energy consumption and carbon emissions.

Energy intensity and structure of buildings: Changes in energy intensity and energy structure of buildings will also affect carbon emissions. For example, the use of energy-efficient building equipment and materials can reduce the energy intensity of buildings, thus reducing carbon emissions.

Urban construction land: The expansion of urban construction land will bring higher energy consumption and carbon dioxide emissions. Therefore, rational planning of urban construction land is of great significance for reducing building carbon emissions. Climate factors: Climate factors will also have an impact on building carbon emissions. For example, areas with cold weather in winter need more heating energy, thus increasing carbon emissions.

To sum up, the current situation of carbon emissions of construction enterprises is not optimistic. In order to reduce carbon emissions and achieve green and low-carbon development, construction enterprises need to start from many aspects, including optimizing the selection of building materials, improving energy utilization efficiency, and promoting the application of renewable energy. At the same time, the government and all walks of life also need to work together to promote the low-carbon transformation and sustainable development of the construction industry through policy guidance, technological innovation and social supervision.

5 Research data and model design

5.1 Model assumptions

5.1.1 Benchmark regression model

According to the above theoretical analysis, this paper designs a benchmark regression model (Equation 1):

$$\text{int}enco_{2it} = \alpha_0 + \alpha_1 Digit_{it} + \sum \alpha_k Controls_{it} + year + firm + year + \xi_{it} \tag{1}$$

In which intenCO2it represents the carbon emission intensity of enterprise I in the t year. The core explanatory variable is digitalit, which represents the degree of digital transformation of enterprise I in T year; Controls is the control variable set model, which also controls the time-fixed effect Year and the enterprise-fixed effect Firm; ξ_{it} is a random error term.

5.1.2 Interaction effect model

In order to deeply explore the impact of digital access level, this paper divides all regions in China into eastern coastal areas and other regions, and at the same time constructs an interactive term (region × digital) of regional virtual variables and digital transformation, so as to distinguish the heterogeneous impact of regions on the digital carbon emission reduction effect (Equations 2).

$$\text{int}enco_{2it} = \alpha_0 + \alpha_1 Digit_{it} + \alpha_1 \left(Digit_{it} \times \text{region}\right) + \sum \alpha_k Controls_{it} + year + firm + year + \xi_{it} \tag{2}$$

5.1.3 Intermediary variable model

To examine the mediating mechanism of the impact of enterprise digital transformation on carbon emissions, this study draws on Abbott, K. W. (2017) and Wilkinson, L. (1979), who estimated intermediate variables using the "stepwise regression method". Specifically, taking Total factor productivity (TF), innovation level (Inv), and R&D intensity (RD) as intermediate variables, the benchmark regression is tested, and the corresponding research model is constructed.

$$M\text{edia}_{\text{i,t}} = \beta_0 + \beta_1 Digit_{it} + \sum \beta_{\text{x}}\text{Control}_{\text{i,t}} + \sum Code + \sum Year + \varepsilon_{i,t} \tag{3}$$

$$\text{int}enco_{2\text{i,t}} = \delta_0 + \delta_1 DT_{\text{i,t}} + \delta_2 M\text{edia}_{\text{i,t}} + \sum \delta_{\text{x}}\text{Control}_{\text{i,t}} + \sum Code + \sum Year + \varepsilon_{i,t} \tag{4}$$

The mediating variable plays a mediating role when the coefficients in Equation 4 and Equation 3 are significant. When and the coefficient in Equation 4 is significant, it indicates that the mediating effect is partial, and *vice versa*. β_1, δ_2 all significant, This means that the mediation variable plays a mediating role. When and in Equation 4 δ_1 coefficients are significant when, This indicates that the mediation effect is partial mediation effect and otherwise complete mediation effect.

5.2 Data source and variable description

5.2.1 Data sources

The research sample of this paper comes from the annual data of China A-share listed construction companies from 2000 to 2021. The annual reports of relevant enterprises were obtained from official website of Shenzhen and Shanghai Stock Exchanges; Relevant data of listed companies come from CSMAR database. At the same time, the non-ratio continuous variables are truncated by 1% to reduce the influence of outliers. In this paper, the data of digital transformation that has not been disclosed in the annual report of enterprises are excluded, and the construction industry is divided into industry categories: civil engineering construction, architectural decoration, decoration and other construction industries, construction and installation industries, and housing construction industries (Table 2) (Sanglin, 2025).

The data processing process in this paper is as follows:

5.2.1.1 Logarithmic transformation

In the second step, the variables with skewed distribution are logarithmically transformed to reduce the influence of skewed data and make the data distribution closer to normal distribution, which

TABLE 2 Original sample classification.

Industry classification	Count	Proportion
Civil engineering construction industry	837	74.9%
Architectural decoration, decoration and other construction industries	226	20.2%
Construction and installation industry	28	2.5%
housing industry	27	2.4%

is beneficial to subsequent statistical analysis. Logarithmic transformation is shown in Formula 5

$$y = log(x + 1) \tag{5}$$

5.2.1.2 Missing value filling

In order to deal with missing data, interpolation method is used to fill the blank values in time series data. The linear interpolation formula of Equation 6 is adopted.

$$x_{miss} = x_{after} + \frac{x_{after} - x_{before}}{2} \tag{6}$$

"indicates missing data", and indicate data before and after missing data points, respectively. $x_{miss} x_{before} x_{after}$

5.2.2 Description of variables

Descriptive statistics of the main variables in this paper are shown in Table 3. Specific descriptions of related variables are as follows:

(1) Explained variable: enterprise carbon dioxide emission intensity (intenco2).

The carbon emissions, fossil energy consumption, electricity and heat consumption used in this article were manually collected from annual social responsibility reports, sustainable development reports, and environmental reports disclosed by companies, and further calculated according to the methods published by the National Development and Reform Commission (NDRC) to obtain partial carbon emission data. The sample year span is from 2000 to 2021. The accounting of greenhouse gases by enterprises needs to be based on the internationally recognized standards of the Greenhouse Gas Protocol, and the calculation method published by the National Development and Reform Commission is also the same. According to the greenhouse gas accounting system, a company's carbon emissions can be divided into three categories. Scope one refers to the direct greenhouse gas emissions generated by emission sources owned or controlled by enterprises, such as combustion emissions from boilers, furnaces, vehicles, etc. Owned or managed by enterprises; Emissions generated from chemical production using owned or controlled process equipment. Scope 2: Accounting for indirect greenhouse gas emissions generated by the consumption of electricity and heat purchased by the company. Scope 1 and Scope 2 carbon emissions are mandatory disclosures required by the greenhouse gas accounting system and are also the focus of this article. The total carbon emissions typically disclosed by companies refer to the sum of Scope 1 and Scope 2 emissions. Scope three emissions consider all other indirect emissions that are the result of company activities but not generated by emission sources owned or controlled by the enterprise. For example, raw materials used for mining and production procurement, fuels used for transportation procurement, the use of products and services sold, and transportation vehicles used by employees and customers. This article does not consider Scope 3 emissions. The regional carbon emissions (CO2) data used in this article is from the China Energy Statistical Yearbook.

(2) Core explanatory variable: Digital transformation degree of listed companies.

The measurement method of digital transformation of the company has been relatively mature, and the measurement method adopts text analysis. Firstly, this paper constructs a digital transformation keyword list; Then use Python software to match the glossary with the annual report text of listed companies, and use Jieba function module to count the word frequency of related keywords in the annual report file of listed companies; Finally, after adding 1 to the word frequency for logarithmic processing. Get the enterprise digital transformation index.

Note: Referring to Zhao Chenyu (2021), this paper makes statistics on 99 digital related word frequencies in four dimensions: digital technology application, Internet business model, intelligent manufacturing and modern information system.

(3) Control variables. In this paper, the enterprise-level indicators are included in the control variables: the nature of enterprise property rights (soe, state-owned enterprises take 0, private enterprises take 1), the board size (board, Logarithmic number of board members), logarithm of enterprise age (AGE), asset-liability ratio (lev), return on net assets (roe), operating cash flow (cf), sales growth rate (growth), net profit growth rate (gprofit), tangible assets ratio (tangibi), independent directors ratio (indep), shareholding ratio of the largest shareholder (top1), chairman and chairman.

Descriptive statistical analysis shows that (Table 4), the research sample covers 737 observation objects, and the core variables show multi-dimensional distribution characteristics. In terms of financial performance, the average return on equity (ROE) of enterprises is only 0.023%, but the standard deviation is 1.343%, reflecting the significant differentiation of the profitability of sample enterprises. The concentration of cash flow (Cflow) is relatively high, with the median value of 0.014 close to the average value of 0.008, but the lower limit of negative value (−3.224) reveals the financial liquidity risk of some enterprises. Finlev is distributed to the right, indicating that most

TABLE 3 Construction of enterprise digital transformation index and key words selection.

Dimension	Classified words	Text combinations with high frequency of occurrence	Word segmentation dictionary
Numeric technique app; application	Data, numbers, digitization	Data management, data mining, data network, number According to the platform, data center, data science, digital Control, digital technology, digital communication, digital network Network, digital intelligence, digital terminal, digital marketing, digitization	Data management, data mining, data network, data platform Data center, data science, digital control, digital technology Digital communication, digital network, digital intelligence, digital terminal Digital Marketing, Digitalization, Big Data, Cloud Computing, Cloud IT, Cloud Ecology, cloud services, cloud platforms, blockchain, Internet of Things, machines study
Internet business model	Internet, e-commerce	Mobile Internet, Industrial Internet and Industrial Interconnection Network, Internet solutions, Internet technology Internet thinking, Internet action, Internet industry Service, Internet mobile, Internet application and interconnection Internet marketing, Internet strategy, Internet platform Internet model, Internet business model, interconnection Network ecology, e-commerce, e-commerce	Mobile internet, industrial internet, industrial internet, interconnection Network solution, Internet technology, Internet thinking, interconnection Network action, Internet business, Internet mobile and Internet should Use, Internet marketing, Internet strategy, Internet platform Internet model, Internet business model, Internet ecology E-commerce, e-commerce, Internet. “internet plus”, online Offline, online to offline, online and offline, 020, B2B C2C、B2C、C2B
smart manufacturing	Intelligent, intelligent Automatic, numerical control, one Systematization and integration	Artificial intelligence, high-end intelligence, industrial intelligence, mobile Dynamic intelligence, intelligent control, intelligent terminal, intelligence Mobile, intelligent management, intelligent factory, intelligent things Flow, intelligent manufacturing, intelligent warehousing, intelligent technology Intelligent equipment, intelligent production, intelligent networking, intelligence Can be systematic, intelligent, automatic control and automatic monitoring Measurement, automatic monitoring, automatic detection, automatic production Numerical control, integration, integration and integration solution Case, integrated control, integrated system	Artificial intelligence, high-end intelligence, industrial intelligence, mobile intelligence Intelligent control, intelligent terminal, intelligent mobile, intelligent management Intelligent factory, intelligent logistics, intelligent manufacturing, intelligent warehousing Intelligent technology, intelligent equipment, intelligent production, intelligent networking, intelligence Can be systematic, intelligent, automatic control, automatic monitoring and automatic supervision Control, automatic detection, automatic production, numerical control, integration, integration Chemistry, integrated solutions, integrated control, integrated systems, industry Cloud, future factory, intelligent fault diagnosis, life cycle management Manufacturing execution system, virtualization, virtual manufacturing
Contemporary information system	Information, informatization, networking	Information sharing, information management, information integration and information communication Information software, information system, information network, information Terminal, information center, informationization and networking	Information sharing, information management, information integration, information software Information system, information network, information terminal, information center Informatization, networking, industrial information and industrial communication

enterprises maintain a moderate level of leverage, but there are a few cases of high leverage operation.

6 Empirical analysis

6.1 Benchmark regression

Table 4 reports the results of fitting regression according to Formula 1. Column (1) gives the results of adding only the core explanatory variables, and it can be found that the digital transformation of enterprises can significantly reduce the carbon emission intensity of enterprises; On this basis, columns (2) and (3) control the fixed effect of the industry and region where the enterprise is located, and the digital coefficient is still significantly negative; Finally, (4) regression with control variables shows that the higher the degree of digital transformation of enterprises, the better the effect of carbon emission reduction. Thus, the regression results in Table 5 prove that the digital transformation of enterprises can promote enterprises to reduce carbon emissions. That is, to verify the research hypothesis H1.

6.2 Robustness test

6.2.1 Replacing core explanatory variables

In order to further verify the robustness of the conclusion, the core explanatory variables are replaced to test the robustness. Firstly,

10.3389/fenvs.2025.1570182

TABLE 4 Variable declaration.

Variable type	Symbol	Variable declaration
Explained variable	intenco2	Carbon emission intensity of enterprises
Explanatory variable	digtial	Enterprise digital transformation, ln (related word frequency of enterprise digital transformation +1)
Control variable	age	Enterprise age
	lev	Asset-liability ratio
	roe	Rate of Return on Common Stockholders' Equity
	cflow	Operating cash flow
	growth	Sales growth rate
	gprofit	net profit growth rate
	Tangibi	Proportion of tangible assets
	board	Board size
	indep	Proportion of independent directors
	Top1	Proportion of shares held by the largest shareholder
	dual1	The value of chairman and general manager is 1, otherwise it is 0
	soe	Property right nature, state-owned enterprises take 0, private enterprises take 1

TABLE 5 Descriptive statistic.

Name	Sample size	Min	Max	Mean	Std	Median
age	1,118	−1.000	28.000	8.474	6.764	7.000
Region id	1,118	0.000	1.000	0.384	0.487	0.000
roe	1,118	−13.949	29.725	0.023	1.343	0.070
cflow	1,118	−3.224	0.325	0.008	0.139	0.014
Finlev	1,118	0.000	0.908	0.359	0.232	0.357
growth	1,118	−0.747	82.792	0.511	3.742	0.108
gprofit	1,118	−1,058.374	4254.917	4.980	179.507	0.123
size	1,118	16.185	26.282	22.358	1.313	22.237
Board size	1,118	0.000	18.000	9.075	1.723	9.000
Number of independent directors	1,118	0.000	5.000	3.170	0.860	3.000
Proportion of independent directors	1,118	0.000	0.571	0.357	0.090	0.333
top1	1,118	4.420	87.460	34.285	14.331	33.670
Nature of equity	1,118	1.000	6.000	3.467	1.535	2.000
Carbon emission intensity	1,118	14.005	547,276.396	19,274.929	44,711.957	5962.537
soe	1,118	0.000	1.000	0.517	0.500	1.000
intenco2	1,118	32.248	1260150.472	44,382.164	102,953.085	13,729.249
Does the chairman concurrently serve as the general manager?	1,118	0.000	1.000	0.199	0.400	0.000
Enterprise carbon emission lg	1,118	2.449	7.152	5.158	0.673	5.120
Regional carbon emission lg	1,118	2.693	3.814	3.530	0.199	3.579
Digital transformation level	1,118	0.000	4.000	1.128	1.675	0.000
Frequency proportion of words in digital transformation (10E-5)	1,118	0.000	3.135	0.240	0.675	0.000
Digital transformation	1,118	0.000	13.000	0.474	1.689	0.000

this paper uses (Wu et al., 2021) to measure the digital transformation of enterprises, which is recorded as Dig1 and Dig2. The results are shown in columns (1) and (2) of Table 6, and Wu Fei (2021) is used as the second one (Wu et al., 2021; Jun-qian and Yong-kou, 2025). Others' digital transformation rating index (Dig3) is used to measure the degree of digital transformation of enterprises. As shown in column (3), the result is still remarkable. Secondly, the regression results obtained by using sulfur dioxide emissions (SO2) of fossil fuels instead of carbon emissions of enterprises are shown in column (4) (Zhu et al., 2023; Kathrin and Cordula, 2023; Cultur et al., 2024), which shows that the results are still significant, and the digital transformation has effectively reduced carbon emissions of enterprises and other pollutants.

6.2.2 Substitution sample regression

After excluding municipalities directly under the central government, this study uses the fixed effect (FE) model to empirically analyze the relationship between digital transformation of construction enterprises and carbon emissions. The overall significance of the model is extremely high, and the F statistic is 300.989 ($p = 0.000$), which shows that the model has a good fitting effect on the data and can well explain the variation of the dependent variable. The value of r is 0.118 and R^2 (within) is 0.367, which shows that the model has strong explanatory power within the group (that is, after excluding municipalities directly under the central government).

This study further verifies the negative impact of digital transformation on carbon emissions of construction enterprises through panel regression analysis after excluding municipalities directly under the central government. The results are shown in Table 7. This is consistent with the research conclusions on the relationship between digital transformation and carbon emission reduction in the existing literature. (Zhou and Chu, 2024; Zhu et al., 2023; Zhao et al., 2024; He et al., 2024; Liu et al., 2025; Qian et al., 2024; Guangqing et al., 2022). Digital transformation has significantly reduced the carbon emission intensity of construction enterprises by promoting the research and application of green technologies, improving resource utilization efficiency and optimizing production processes. In addition (Yang and Wang, 2021; Jing et al., 2018), this study also found that other variables, such as the nature of property rights, the proportion of tangible assets, and the size of the board of directors, have no significant impact on carbon emissions after excluding municipalities directly under the central government, which may be due to the particularity of municipalities in terms of economic development level and policy environment. After eliminating these particularities, the impact of these variables on carbon emissions is no longer obvious.

6.2.3 Endogenous problems

This paper adopts the following two methods to deal with endogenous problems. One is instrumental variable method. In this paper, the number of post offices in each prefecture-level city in 1984 is selected as the tool variable (iv) of enterprise digital transformation, which reflects the early informatization development level of each prefecture-level city and the active degree of folk information exchange. (Zhu et al., 2023). As shown in column (1) of Table 8, in the first stage of regression,

TABLE 6 Influence of digital transformation on carbon emissions of construction enterprises.

Variable	(1)	(2)	(3)	(4)
Digital	intenCo2	intenCo2	intenCo2	intenCo2
const	−0.0001***	−0.0001***	−0.0001***	−0.0001***
age				0.031
roe				0.011
inlev				0.110
cflow				0.658
gprofit				0.005
growth				−0.005
board				0.165
indep				1.169
Top1				0.006
Tangibi				−2.523
equity				−0.187
dual				−0.231
Time-fixed effect	YES	YES	YES	YES
Regional fixation effect	No	YES	YES	YES
Firm fixed effect	No	No	YES	YES
sample size	805	805	805	805
R2	0.184	0.183	0.182	0.083

TABLE 7 Excluding the regression results of municipalities directly under the central government.

Variable	(1)
	intenCo2
Digital	−0.0001* (0.020)
Control variable	YES
Time-fixed effect	YES
Regional fixation effect	YES
Firm fixed effect	YES
sample size	738
R2	0.118

the iv coefficient is 0.0001, which is significant at the level of 1%, indicating that instrumental variables are strongly correlated with endogenous variables, meeting the requirements of correlation. As shown in column (2) of Table 9, in the second-stage regression, the Dig coefficient is −0.001, which indicates that digital transformation significantly reduces carbon emissions and supports the H1 hypothesis. Because the main function of post office is

TABLE 8 Robustness test: replacing core explanatory variables and explanatory variables.

Variable	(1)	(2)	(3)	(4)
	intenCO2	intenCO2	intenCO2	SO2
Dig1	−0.026**			
Dig2		−0.103***		−151596.814***
Dig3			−0.001***	
Time-fixed effect	YES	YES	YES	YES
Regional fixation effect	YES	YES	YES	YES
Firm fixed effect	YES	YES	YES	YES
sample size	1,118	1,118	1,118	1,118
R2	0.072	0.060	0.177	0.008

TABLE 9 Endogenous test results.

Variable	2SLS regression		Pilot policy regression	
	Dig	CO2	Regional CO2	Regional CO2
Iv Telephone * Number of Internet users in the last year	0.0001** (7.688)			
Dig		−0.001** (−2.786)		
du*Dig			161.637** (6.727)	
Lag1_du*dig				148.335** (6.080)
cons	200.672 (1.727)	−4.082** (−15.499)	4595.951** (3.438)	4277.729** (3.170)
Time-fixed effect	no	no	no	no
Regional fixation effect	no	no	no	no
sample size	478	478	292	292
R^2	0.317	0.937	0.190	0.169

information transmission, it is not directly related to the carbon emission reduction performance of construction enterprises, so it also meets the exogenous requirements. As shown in columns (3) and (4) of Table 9, in the regression analysis of the pilot policy, the coefficient of du*Dig reached 161.637, which reflected that the pilot policy may weaken the emission reduction effect of digital transformation due to the expansion of high energy-consuming industries; The coefficient of interaction term (lag1_du*dig) is 148.335, which indicates that the pilot policy has a certain persistence to this impact.

Meanwhile, based on the development history of the digital economy, Shenzhen and Hangzhou are considered the birthplaces of China's digital economy. Based on the correlation and exogenous conditions of instrumental variables, this study selects the natural logarithm of the nearest spherical geographic distance (lndis) from each enterprise to Shenzhen and Hangzhou as the instrumental variable for enterprise digital transformation, further testing endogeneity (Shang Y. et al., 2023).

In order to control for sufficient fixed effects, time-varying instrumental variables were also constructed. Construct the interaction term between lndis and the time trend term (lndis x year), and continue to use two-stage least squares estimation (2SLS) for instrumental variable regression (Table 10). The WaldF statistics are all greater than the critical value of 10% in the Stock Logo test, indicating that the instrumental variables are reasonable and reliable. The regression coefficients of the enterprise digitalization index are significantly negative, which still proves the robustness of the conclusion.

The lagged regression results show that when regressing on the explanatory variable of enterprise digital transformation lagging behind by one period, the results are also significant (Table 11). (Coefficient less than 0, $R^2 > 0.75$).

6.3 Mechanism analysis

According to the previous empirical analysis results, digital transformation can significantly reduce the carbon emissions of construction enterprises, that is, it supports the view of carbon emission reduction of digital transformation. So this part will analyze the carbon emission reduction mechanism of digital transformation from three dimensions: enterprise innovation,

TABLE 10 Endogenous test results.

Variable	IV1:lndis		IV2:lndis × Year	
	Dig	CO2	Dig	CO2
Iv1:lnDis (HangZhou)	−0.134* (−1.83)			
Dig		−0.038*** (−2.786)		
Iv2:lndis × Year			−0.002*** (−3.638)	
Cons	−11.128 (−6.572)	−15.95*** (−15.950)	315.691*** (36.426)	4277.729** (3.170)
Time-fixed effect	No	No	No	No
Regional fixation effect	YES	YES	YES	YES
sample size	1,118	1,118	1,118	1,118
Wald F statistic	Wald = 8450.151 P = 0.000***		Wald = 785.396 P = 0.000***	
R^2	0.859	0.88	0.163	0.169

TABLE 11 Lag regression results.

Variable	Lagged regression
Constant	−4.157** (−3.703)
Lag1_dig	−0.0001* (−2.405)
R^2	0.766
N	208
F	F (14,160) = 15.561,p = 0.000
Code	*YES*
Year	*YES*

efficiency improvement and optimization of production and operation structure.

Innovative mechanism of digital transformation.

6.3.1 Innovative mechanism of digital transformation

First of all, the digital transformation of construction enterprises has a positive impact on the carbon emission reduction effect of construction enterprises by promoting green technology innovation. With the wide application of digital technology, construction enterprises can integrate internal and external resources more effectively and accelerate the development and application of new technologies. As an important achievement of technological innovation of construction enterprises, the increase in the number of green patents directly reflects the investment and effectiveness of construction enterprises in environmental protection and energy-saving technologies. In this paper, the logarithm of the number of green patents (lngpat) is used to measure the green technology innovation level of enterprises. The empirical analysis shows that the degree of digital transformation is positively correlated with the number of green patents, which shows that digital transformation helps to improve the output efficiency of green patents, promote the application of green patents in actual construction production, and stimulate the green innovation ability of construction enterprises, thus reducing the intensity of carbon emissions. Second, the increase in R&D investment of construction enterprises is also an important embodiment of digital transformation to promote technological innovation. As shown in column (2) of Table 4, there is also a significant positive correlation between the degree of digital transformation and the R&D investment of construction enterprises, which means that digital transformation provides more R&D resources and motivation for construction enterprises and promotes the R&D and application of energy-saving and emission-reduction technologies. Digital transformation enables construction enterprises to more accurately grasp the construction market demand and construction technology trends, thus rationally allocating R&D resources and improving R&D efficiency. This increase in investment not only promotes the birth of new technologies, but also accelerates the optimization and upgrading of existing technologies, further promoting the realization of carbon emission reduction.

6.3.2 Efficiency improvement mechanism of digital transformation

According to the previous empirical analysis, the digital transformation of construction enterprises is not only conducive to improving the total factor productivity, but also may improve the production efficiency by optimizing the production process and reducing the production interruption of construction products, so as to help construction enterprises reduce the carbon emission effect. In this paper, the total factors measured by OP method and LP method are used as proxy variables of enterprise production efficiency. According to the results of correlation regression analysis, as shown in columns (3) and (4) of Table 4, there is a significant positive correlation between the degree of digital transformation and total factor productivity, indicating that digital transformation is helpful to improve the production efficiency of construction enterprises. The improvement of production efficiency means that under the same output, the resources consumed by construction enterprises and the carbon emissions generated will be reduced. The SPCS system of prefabricated concrete building innovatively developed by Sany Construction Company simplifies the construction process and realizes "full prefabrication of wall column beam slab + full assembly on the ground and underground". This technical system has the overall advantages of "cavity overlapping and post-pouring, equivalent heterogeneity is fast and economical", which directly hits the pain points of building structure safety, water leakage, external wall insulation, labor shortage, low efficiency and high cost, significantly improves the production efficiency of all factors, reconstructs the ecology of construction industry, and realizes the low-carbon and high-quality development of construction enterprises (Pingru et al., 2023).

6.3.3 Optimization of production and operation structure

First of all, the wide application of digital technology can significantly improve the utilization efficiency of resources in the whole life cycle of construction enterprises, thus reducing the discharge of various polluting construction wastes. In this paper, the operating cost ratio (cost/revenue) is used to measure the negative index of the optimization degree of enterprise production and operation. Secondly, we improve the operating efficiency of construction enterprises through internal control and realize the diversified and hierarchical development strategy of enterprises. We adopt the "Internal Control Index of listed companies in Dibo China" (InnCt for short) widely recognized by academic circles as an indicator to measure the level of internal control, which comprehensively covers many key dimensions such as internal environment, risk assessment, control activities, information communication and internal supervision. The results of correlation regression analysis show that, as shown in columns (5) and (6) of Table 12, the degree of digital transformation is negatively correlated with the operating cost rate, and the coefficient is significant, indicating that digital transformation is helpful to reduce the operating cost of construction enterprises. This cost reduction may come from the improvement of production efficiency and the optimization of resource utilization, which will help to reduce carbon emissions. Combined with the above, the research hypothesis H2 can be verified. By using digital technologies such as big data and artificial intelligence, construction enterprises can realize automatic and intelligent production, reduce repetitive and low-value manual tasks, and greatly reduce labor costs and time costs, thus achieving cost reduction and efficiency improvement. Use intelligent building management system to optimize energy use and reduce energy consumption and emissions. At the same time, construction enterprises can also use digital technology to improve the accuracy of carbon accounting, enhance the compliance and transparency of carbon emission information disclosure, promote carbon market transactions, and achieve sustainable development.

6.3.4 Analysis of intermediary role

This study explores in depth the three pathways through which digital transformation affects corporate carbon emission intensity by constructing a mediation effect model, namely, the R&D innovation pathway, the total factor productivity (TFP) improvement pathway, and the operational cost optimization pathway.

1. R&D Innovation (R&D) Path

The results of the mediation effect test indicate that digital transformation significantly promotes the R&D innovation activities of enterprises (the regression coefficient of dig on R&D is 0.0009, $p < 0.01$) (Table 13) The increase in R&D intensity significantly reduces the carbon emission intensity of enterprises (the regression coefficient of R&D on intCO2 is −0.0003, $p < 0.01$)。 This indicates that digital transformation can indirectly reduce carbon emission intensity by promoting green technology research and development. Verified the theoretical logic of digital transformation achieving environmental benefits through technological empowerment.

2. Path to Total Factor Productivity (TFP) Improvement

Although the direct impact of digital transformation on total factor productivity is not significant (the regression coefficient of dig on TFP is −0.0004, $p > 0.05$), However, the significant improvement in total factor productivity has reduced carbon emission intensity (the regression coefficient of TFP for intCO2 is −0.0003, $p < 0.01$) (Table 13). This indicates that digital transformation can indirectly suppress carbon emissions by optimizing the efficiency of factor allocation. Its economic explanation is that digital transformation improves resource utilization efficiency through data-driven decision-making, intelligent production scheduling, and other functions, thereby reducing energy consumption and carbon emissions while maintaining the same output level.

3. Optimization path for operating costs

Digital transformation significantly reduces the operating costs of enterprises (the regression coefficient of dig for cost is −0.0001, $p < 0.1$), And there is a positive correlation between cost optimization and carbon emission intensity (the regression coefficient of Cost to intCO2 is 0.0013, $p < 0.01$) (Table 13). This indicates that while digital transformation reduces operating costs through mechanisms such as lean management and supply chain collaboration, it also indirectly reduces carbon emission intensity. The inherent logic is that cost optimization often accompanies the improvement of energy efficiency and the reduction of waste, such as reducing transportation energy consumption through intelligent logistics systems or reducing equipment idle through predictive maintenance.

6.4 Heterogeneity test

Under the background of different attributes of construction enterprises, the carbon emission reduction effect brought by their digital transformation may show asymmetric characteristics. In view of this situation, it is helpful to formulate more accurate and differentiated policy guidance to deeply discuss and distinguish the carbon emission reduction effects of digital transformation of

TABLE 12 Mechanism analysis results.

Variable	Enterprise innovation		Efficiency improvement		Optimization of production and operation structure	
	Lngpat	RD	TEP_OP	TFP_LP	Cost	Innct
	(1)	(2)	(3)	(4)	(5)	(6)
digital	0.001**(0.0094)	0.053*(0.0264))	0.001***(0.0001)	0.003***(0.0001)	−0.001*(0.0031)	−0.001***(0.0001)
Control variable	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES
Regional fixation effect	YES	YES	YES	YES	YES	YES
Sample size	1,118	1,118	1,118	1,118	1,118	1,118
R^2	0.126	0.234	0.344	0.124	0.231	0.365

TABLE 13 Intermediary model results (RD).

Variable	R&D	intenco2	intenco2
Constant	−1.4879* (−2.2040)	−5.2209** (−17.8752)	−5.0849** (−17.6881)
dig	0.0009** (3.9934)	−0.0003** (−3.4576)	−0.0004** (−4.3140)
R&D			0.0914** (4.4187)
N	434	434	434
R^2	0.7563	0.9435	0.9460
F	F (14,419) = 92.8990,p = 0.0000	F (14,419) = 499.5128,p = 0.0000	F (15,418) = 488.1262,p = 0.0000
Variable	**TFP_FE**	**intenco2**	**intenco2**
Constant	−12.9142** (−4.7034)	−5.2544** (−18.1002)	−5.0106** (−17.1286)
dig	−0.0004 (−0.5329)	−0.0003** (−3.5680)	−0.0003** (−3.5247)
TFP			0.0189** (3.9470)
N	488	488	488
R^2	0.4489	0.9363	0.9383
F	F (13,474) = 29.6959,p = 0.0000	F (13,474) = 535.6878,p = 0.0000	F (14,473) = 513.8367,p = 0.0000
Variable	**Cost**	**intenco2**	**intenco2**
constant	0.1457 (1.4562)	0.3209 (0.4198)	0.3835 (0.5008)
digi	−0.0001 (−1.8354)	0.0014** (5.3725)	0.0013** (5.2536)
Cost			−0.4295 (−1.2285)
N	488	488	488
R^2	0.1946	0.4317	0.4335
F	F (10,477) = 11.5274,p = 0.0000	F (10,477) = 36.2380,p = 0.0000	F (11,476) = 33.1160,p = 0.0000

*p < 0.05 **p < 0.01.

different construction enterprises. In order to achieve this goal, this paper will comprehensively examine the digital transformation practice of construction enterprises, and make detailed classification discussions according to regional differences, property rights and digital technologies adopted.

6.4.1 Regional heterogeneity

China has a vast territory, and the level of digital development varies among different regions, which may lead to digital "access barriers". In order to further explore the impact of digital access level, this article divides all regions of China into eastern, central, western, and northern regions, and analyzes listed companies based on provinces. The eastern region usually refers to a series of provinces and municipalities directly under the central government in China's administrative divisions. The listed companies in the eastern region covered in this article include six provinces and cities: Anhui, Fujian, Jiangsu, Shandong, Shanghai, and Zhejiang. The eastern region is usually economically developed, with high levels of industrialization and urbanization. At the same time, it is also at the forefront of China's opening-up and economic development. Rich in natural resources, convenient transportation network, highly concentrated scientific and educational resources, and relatively complete market system, it occupies an important position in China's economic development. The results in Table 10, Figures 2, 3 indicate that there are significant differences in carbon reduction effects among different regions of China during the digitalization process of enterprises, and also demonstrate the regional heterogeneity of carbon reduction effects in H3 digital transformation. The carbon reduction effect of enterprise digital transformation is significant in the eastern region, while the coefficient is positive but not significant in the central and southern regions. Figure 1 Bubble map of digital transformation degree in 2012.

Eastern region (coefficient −0.054, $p < 0.01$): Digital transformation has a significant inhibitory effect on carbon emissions, consistent with theoretical expectations (Table 14). This may be due to the strong technological foundation of enterprises in the eastern region, where digital transformation focuses more on optimizing energy structure and iterating green technologies; Central region (coefficient 0.128, $p = 0.082$): The positive effect is close to significant, or due to the fact that central enterprises are in a critical period of industrialization, digital transformation is accompanied by capacity expansion in the short term, leading to an increase in carbon emissions; Southern region (coefficient 0.030, $p = 0.109$): The positive effect is not significant and may be related to the outward oriented economic characteristics of the southern region. Digital transformation focuses on market response rather than production side emission reduction. Further grouping regression results indicate that the digital transformation of enterprises in the eastern region has shown significant carbon emission reduction dividends, while the central and western regions need supporting structural reforms to unleash the potential of digital technology.

Enterprises in the central region are in a critical period of industrialization, and digital transformation may be accompanied by capacity expansion in the early stages to meet market demand and enhance competitiveness. During this process, equipment updates, technological investments, and expansion of production scale may temporarily increase energy consumption and carbon emissions, thereby masking the long-term potential carbon reduction effects of digital transformation. Although the central region is accelerating its digital infrastructure layout, compared to the eastern region, its digital technology application may still be in a relatively early stage. If digital transformation only stays on the surface and fails to deeply promote green technology innovation, optimize production processes and management structures, it will be difficult to achieve significant carbon reduction effects.

6.4.2 Heterogeneity of property rights

Faced with technological innovation in digital transformation, construction enterprises of different ownerships often adopt different response strategies due to different policy environments and target incentives. In order to explore the impact of ownership differences on carbon reduction in digital transformation, this paper constructs an interaction term (digital × soe) between the ownership logic variables of construction enterprises and digital transformation, to test whether there are significant differences in the impact of different property rights on carbon reduction in the process of digital transformation. Further classify state-owned

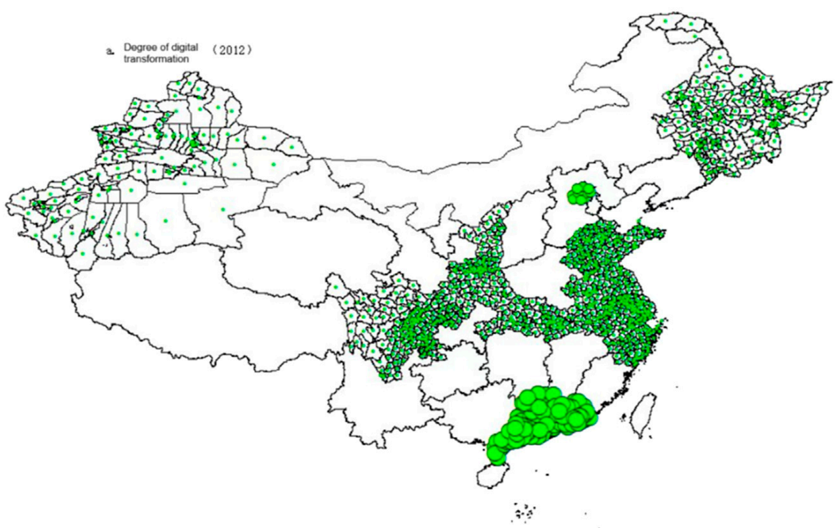

FIGURE 2
Bubble map of digital transformation degree in 2012.

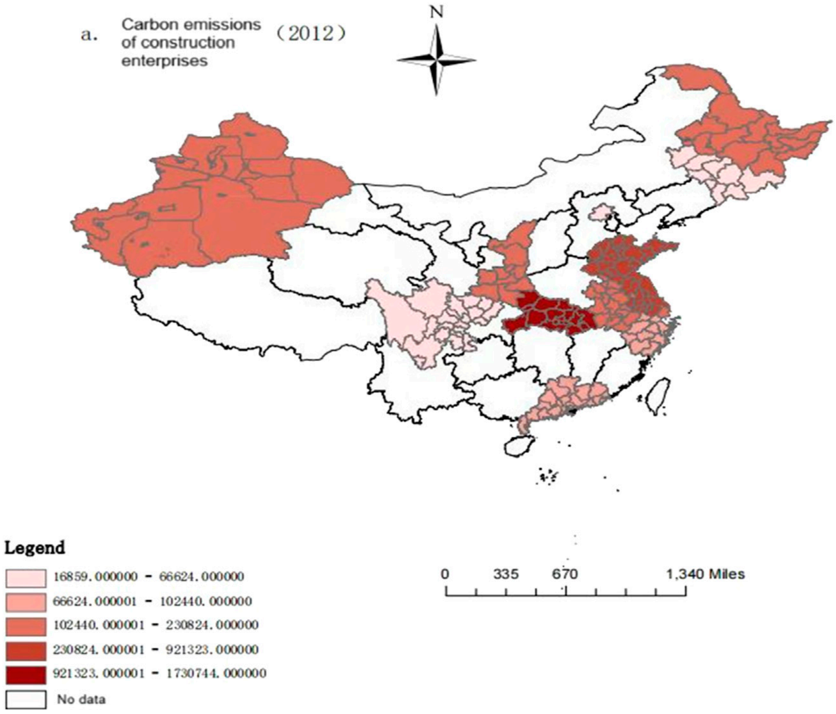

FIGURE 3
Thermal map of carbon emission of construction enterprises in 2012.

TABLE 14 Group regression results.

Variable	Whole	East	North	Central	South
Constant	16.949* (2.271)	12.030 (1.186)	42.412 (1.164)	−861.647 (−1.387)	−9.930 (−0.884)
Digital	−0.013 (−1.020)	−0.054** (−3.049)	−0.020 (−0.423)	0.128 (1.821)	0.030 (1.635)
N	1,118	473	307	71	267
R^2	0.826	0.890	0.924	0.980	0.818
F	F (16,336) = 99.415,p = 0.000	F (16,141) = 71.567,p = 0.000	F (16,43) = 32.732,p = 0.000	F (16,15) = 46.166,p = 0.000	F (16,86) = 24.205,p = 0.000
Code	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES

*p < 0.05 **p < 0.01.

enterprises and non-state-owned enterprises based on their controlling nature, and conduct group regression analysis. As shown in the first column of Table 15, the cross-term coefficient is significant, which indicates that the effect of digital transformation of state-owned construction enterprises on reducing carbon emission intensity may not be as significant as that of non-state-owned construction enterprises, or it may even lead to an increase in carbon emission intensity. The carbon reduction coefficient of state-owned enterprises is positive and not significant, while that of non-state-owned enterprises is negative and significant, further indicating that the carbon reduction effect of state-owned construction enterprises is not as significant as that of non-state-owned construction enterprises. The verification study assumes that the carbon emission reduction effect of H3 digital transformation has property rights heterogeneity. First of all, it is difficult for state-owned construction enterprises to make full use of the emission reduction potential brought by digital transformation due to complicated decision-making process, traditional management mode and slow improvement of operational efficiency. In contrast, non-state-owned construction enterprises may be able to adopt new technologies and modes such as BIM and intelligent construction more quickly because of their higher autonomy and flexibility, so as to achieve rapid improvement of operational efficiency and thus reduce carbon emission intensity more effectively. Secondly, the carbon emission content of non-state-owned construction enterprises is higher than that of state-

TABLE 15 Property rights grouping regression results.

Variable	Whole	State controlled	Non-state-owned holding
Constant	−5.9998** (−18.3964)	−6.9356** (−5.1078)	−6.1830** (−18.0836)
dig	−0.0004** (−2.6079)	0.0009 (1.3301)	−0.0003* (−2.2062)
N	316	39	277
R^2	0.8133	0.8772	0.8195
F	F (12,303) = 109.9699,p = 0.0000	F (12,26) = 15.4760,p = 0.0000	F (12,264) = 99.8825,p = 0.0000
Code	*YES*	*YES*	*YES*
Year	*YES*	*YES*	*YES*

*$p < 0.05$ **$p < 0.01$.

owned construction enterprises. After digital transformation, the marginal benefit of carbon emission of non-state-owned construction enterprises is higher than that of state-owned construction enterprises, so the carbon emission reduction effect of state-owned construction enterprises may not be as good as that of non-state-owned construction enterprises. Finally, state-owned construction enterprises use more ways to reduce production to achieve energy-saving goals, while non-state-owned construction enterprises use more ways to improve energy efficiency.

6.4.3 Heterogeneity of digital technology

Through Wu Fei's research (2021), we found that various digital technologies are helpful to promote carbon emission reduction. Therefore, we divide the indicators of digital transformation into two categories: "the bottom technology level" and "the practical application level", including five important sub-projects: AI, (BC) blockchain, CC, big data (DT) and (ADT). The empirical analysis results are shown in columns (3)–(7) of Table 16. By comparing the data of various indicators, it can be seen that digital technologies such as artificial intelligence, blockchain, cloud computing and big data have a significant negative impact on carbon emission intensity. These technologies not only optimize building energy consumption through intelligent control and management, but also use blockchain technology to ensure accurate tracking and management of carbon emission data. They also use cloud computing technology to improve the energy efficiency of data centers and realize remote monitoring. At the same time, big data technology digs deep into energy consumption data to formulate optimization strategies. In addition, through digital management, these technologies have played a key role in the whole life cycle of prefabricated buildings, such as design, production, transportation, installation and operation and maintenance. Especially in the field of prefabricated buildings, digital technology not only optimizes production planning and logistics transportation, reduces energy consumption and emissions, but also realizes accurate prediction and optimization of building energy consumption through intelligent control and management systems. At the same time, the application of big data technology provides rich energy consumption data support for construction enterprises to help them formulate more scientific carbon emission reduction strategies. The deep integration of these digital technologies and prefabricated buildings has jointly promoted the green transformation of the construction industry and laid a solid foundation for achieving the goal of sustainable development. To sum up, these digital technologies have jointly acted on the carbon emission reduction practice of construction enterprises in various ways, which has promoted the sustainable development of the industry, especially in key links such as prefabricated buildings and digital management.

6.4.3.1 Analysis of the effects of dual carbon policy

In September 2020, China proposed a policy of dual carbon targets, requiring carbon peaking by 2030 and carbon neutrality by 2060. To explore the actual impact of the policy on construction enterprises, this article sets 2021 as a segmented time point to study the effect of digital transformation and carbon reduction on construction enterprises before and after 2021. And perform a double difference test (Figure 4).

The control group represents that the enterprise has not undergone digital transformation. After refers to 2022–2023, and before refers to 2000–2021 (Tables 17–19).

Table 18 shows the grouping of sample enterprises before and after policy implementation ("Before" for 2000–2021 and "After" for 2022–2023). Before the implementation of the policy, the average carbon emission intensity (intCO2) of the control group and the experimental group were 3.2094 and 3.1469, respectively (Table 18), with no significant difference (t = −1.0734, p = 0.2841). This indicates that before policy intervention, the carbon emission intensity of the two groups of enterprises was at a similar level, meeting the prerequisite for the parallel trend assumption of the DID model. After the implementation of the policy, there was a significant change in the carbon emission intensity between the control group and the experimental group. The mean experimental value decreased to 0.6494, while the mean of the control group increased to 2.1852, and the inter group difference reached a significant level (t = 8.7548, p = 0.0000). This preliminary result suggests a correlation between digital transformation and changes in carbon emission intensity.

Trend item x Grouping variable Policy interaction term: The coefficient of this interaction term is −1.5708 (p = 0.000) and is significant at the 1% level. This indicates that after the implementation of the policy, the carbon emission intensity of

TABLE 16 Heterogeneity test results.

Variable	Heterogeneity of property rights	Regional heterogeneity	Heterogeneity of digital technology				
	Intenco2	Intenco2	Intenco2	Intenco2	Intenco2	Intenco2	Intenco2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Digital	−0.006 (0.580)	−0.031***(0.002)					
Digital × soe	0.42***(0.000)						
Digital × region		0.139***(0.003)					
AI			−0.038***(0.000)				
BC				−0.011***(0.010)			
DT					−0.013***(0.001)		
CC						−0.014***(0.004)	
ADT							−0.013***(0.001)
Control variable	YES	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES	YES
Regional fixation effect	YES	YES	YES	YES	YES	YES	YES
Sample size	1,118	1,118	1,118	1,118	1,118	1,118	1,118
R^2	0.072	0.031	0.028	0.006	0.045	0.031	0.045

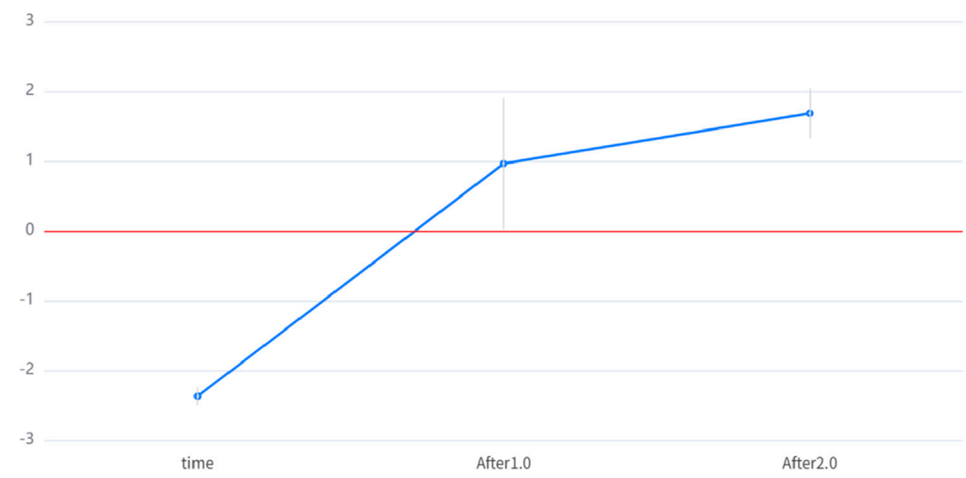

FIGURE 4
Event study method result chart.

the experimental group decreased by 1.5708 units compared to the control group. This result contradicts the expected hypothesis, and further decomposition of policy effects reveals that before policy implementation, there is no significant difference in carbon emission intensity between the experimental group and the control group (Diff = −0.0315, p = 0.6242), further validating the parallel trend hypothesis.

TABLE 17 DID model description statistics.

Variable	Before	After	All	
Control		238	31	269
Treated		35	9	44
ALL		273	40	313

TABLE 18 Comparison before and after the dual carbon policy.

T-test (Before)					
	Treated *N* = 238	Control *N* = 35	Diff	*t*	*p*
intco2	3.2094	3.1469	−0.0625	−1.0734	0.2841
***T*-test (After)**					
	Treated *n* = 31	Control *n* = 9	Diff	*t*	*p*
intco2	0.6494	2.1852	1.5358	8.7548	0.0000**

*p < 0.05 **p < 0.01.

After policy implementation: The carbon emission intensity of the experimental group significantly increased compared to the control group (Diff = −1.5393, p = 0.0000), consistent with the results of the interaction term. Double difference estimator (Diff in Diff): The net effect is −1.5708 (p = 0.0000), indicating that after policy implementation, digital transformation resulted in an additional reduction of 1.5708 units in carbon emission intensity in the experimental group compared to the control group. Therefore, the dual carbon policy can promote enterprises to implement digital transformation and reduce carbon emissions.

7 Conclusions and suggestions

7.1 Research conclusion

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

(1) As the main source of carbon emissions, construction enterprises bear a decisive responsibility in the process of realizing the goal of "double carbon" in China. Although limited by the difficulty of data acquisition, relevant research was relatively scarce in the past, through the detailed data processing and analysis of listed companies in China from 2000 to 2021, this paper not only verified the positive impact of digital transformation of construction enterprises on carbon emission reduction, but also deeply analyzed the transmission mechanism behind it, which filled an important gap for the research in this field. The research results show that digital transformation not only significantly reduces the carbon emission intensity of construction enterprises, but also strongly supports this conclusion in various robustness tests, further proving its stability and reliability.

(2) The reason why digital transformation can effectively promote carbon emission reduction is mainly due to its multiple functions in technological innovation, production

TABLE 19 DID model results.

OLS regression analysis results		
Variable	β	95% CI
constant	2.4669** (6.0250)	1.6611–3.2726
Trend items (with or without digital transformation)	−0.0315 (−0.4904)	−0.1578–0.0949
Grouping Variables - Policy	−2.5938** (−40.2377)	−2.7206 ~ −2.4669
Trend item (with or without digital transformation) × Grouping variable - Policy	−1.5708** (−11.4118)	1.2999–1.8416
N	313	
R^2	0.8594	
F	*F* (15,297) = 121.0542,*p* = 0.0000	
Dependent variable: intCO2		

Grouping variables - policy	Item	Efect value intco2	Standard error	*t*	*p*
Before	Control	2.4669			
	Treated	2.4354			
	Diff (T − C)	−0.0315	0.0642	−0.4904	0.6242
After	Control	−0.1269			
	Treated	1.4124			
	Diff (T − C)	−1.5393	0.1226	−12.5603	0.0000**
Diff-in-Diff		−1.5708	0.1376	−11.4118	0.0000**
R^2 = 0.8594					

*p < 0.05 **p < 0.01.

efficiency improvement and optimization of production and operation structure. Specifically, digital transformation has stimulated the green innovation ability of enterprises, promoted the research and development and application of green technologies, such as intelligent building design, energy efficiency management system, etc., significantly improved the utilization efficiency of resources and reduced unnecessary energy consumption. At the same time, digital transformation also reduces the operating cost rate of enterprises by optimizing production processes and improving total factor productivity, thus indirectly reducing carbon emissions.

(3) The effect of digital transformation on carbon emission reduction of construction enterprises with different property rights is heterogeneous. Due to the differences in resource endowment and management mechanism, state-owned enterprises and private enterprises have shown different carbon emission reduction effects in the process of digital transformation. However, from a regional perspective, the carbon emission reduction effect of digital transformation does not show obvious regional differences, which shows that the green and low-carbon effect of digital transformation has universal applicability.

7.2 Policy recommendations

This study also puts forward specific measures to promote the digital transformation of enterprises and carbon emission reduction from many angles.

(1) Construction enterprises should increase investment in research and development of digital green building technology, use digital technology to tap innovative points and improve energy efficiency. In terms of technological innovation, we should continue to increase investment in research and development of digital technology, continue to attack low-energy and high-efficiency technologies, promote the transformation and application of technological achievements, and use digital technology to tap innovative points in the fields of building energy conservation and renewable energy utilization. For example, through digital simulation technology to optimize the architectural design scheme, improve the energy efficiency of buildings; Using Internet of Things technology to monitor building energy consumption in real time and realize accurate management. Further leverage the promotion effect of digitalization of listed companies on total factor productivity. We should accelerate the upgrading and application of digital technology, deepen the application of digital technology in research and development design, production and manufacturing, warehousing and logistics, and marketing services, and achieve digitization from the production end to the sales end. Secondly, enterprises should accelerate the establishment of digital factories and smart factories, increase investment in intelligent equipment such as artificial intelligence, robots, interconnected platforms, and smart sensors, accurately control product production efficiency and quality, and gradually transform towards intelligent manufacturing. Enterprises should transform their operational thinking, enhance their IT awareness, further expand their investment in software and hardware, and increase their digital investment. Finally, we should innovate the traditional self support model, constantly explore new business models through the Internet and e-commerce platforms, such as the current emerging live broadcast sales, and keep up with consumer demand and market changes.

(2) Using digital tools and energy management system to optimize the process, and introducing intelligent technology to realize efficient use of energy. In improving operational efficiency, we should make full use of digital project management tools and energy management systems, optimize the construction process, rationally arrange resources, and reduce energy waste and carbon emissions during construction. At the same time, the introduction of intelligent equipment and technology, the transformation and upgrading of high energy-consuming equipment, to achieve efficient use of energy.

(3) Strengthen exchanges and cooperation among construction enterprises, and use digital financial support to promote the construction of green supply chain. In improving the business environment, we will share the experience and technology of energy conservation and emission reduction, and jointly promote the construction of green supply chain. In addition, we should make full use of the support of digital finance and apply for low-interest green loans to provide financial guarantee for green building projects and digital transformation.

(4) Pilot a digital carbon regulatory exemption mechanism in the free trade zone, granting a 3-year carbon emission quota exemption period to enterprises that apply new technologies such as blockchain traceability and AI energy efficiency management. Introduce smart contract technology to achieve automatic carbon trading clearing and cross chain mutual recognition, reducing transaction costs.

Establish a “data sandbox” regulatory model and pilot a blockchain carbon data certification platform in central provinces such as Hubei and Hunan. Through smart contracts, achieve hierarchical management of data access permissions between government regulatory nodes, enterprise data nodes, and third-party authentication nodes, ensuring a balance between data sharing and trade secret protection. Referring to the “regulatory chain” model in the financial field, a construction carbon chain responsibility traceability network is constructed, requiring high annual emission enterprises to access and achieve full chain penetration supervision of carbon emission data from design, construction to operation and maintenance, and implementing blockchain certification and accountability for data fraud.

7.3 Research limitations and future prospects

7.3.1 Research limitations

Although this study systematically analyzes the impact of digital transformation of construction enterprises on carbon emission reduction and its mechanism, there are still the following limitations:

(1) Limited data coverage: The research sample only covers listed construction enterprises in China, excluding small and medium-sized unlisted enterprises and local construction companies. Due to the significant differences in management mechanism, resource endowment and technology application of unlisted enterprises, the universality of the research conclusions may be limited. In addition, carbon emission data depends on indirect measurement methods, which may not fully reflect the actual emission level of enterprises.
(2) Limitations of digital transformation measurement: Although text analysis method is used to construct digital transformation indicators, this method mainly relies on the frequency of keywords in annual reports, and it is difficult to comprehensively measure the actual depth and technology landing effect of digital transformation of enterprises. For example, some enterprises may only carry out superficial digital publicity without substantially promoting technology application.
(3) The depth of regional heterogeneity analysis is insufficient: although the regional differences are not significant, the specific path of realizing "late-comer advantage" through policy subsidies or technological advancement in the central and western regions has not been further explored, and the regulatory role of regional policy environment on the digital transformation effect has not been quantified.
(4) There are unavoidable data robustness issues in this article. It is generally believed that carbon dioxide is the main atmospheric pollutant, so it is difficult to replace the sample with carbon dioxide as the dependent variable. In this study, sulfur dioxide was used as a substitute to demonstrate the robustness of the data, which has inherent errors. Subsequent research can improve the measurement and data collection of carbon dioxide.

7.3.2 Future outlook

In view of the above limitations, future research can be expanded in the following directions:

(1) Expand the data dimension and sample range: integrate the data of unlisted enterprises and micro-project-level carbon emission data, and improve the accuracy of carbon emission measurement by combining field research or sensor data of the Internet of Things. At the same time, extend the research time span to capture the long-term dynamic relationship between digital transformation and carbon emission reduction.
(2) Deepen the measurement system of digital transformation: construct multi-dimensional indicators, covering the intensity of technology application (such as BIM utilization rate), employees' digital skills, supply chain collaboration level, etc., and verify the effectiveness of the indicators with case studies.
(3) Explore the synergistic mechanism of policy and technology: analyze the interactive effects of carbon trading market, green financial policy and digital transformation, for example, explore how the carbon price signal encourages enterprises to adopt intelligent emission reduction technology.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SZ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. HD: Conceptualization, Data curation, Formal analysis, Writing – original draft. JC: Writing – original draft, Writing – review and editing. MG: Conceptualization, Data curation, Formal analysis, Software, Writing – original draft, Visualization.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. Key Support Project of Hunan Province College Students' Innovation and Entrepreneurship Training Program (S20241,1532001). National College Students' Innovation and Entrepreneurship Training Program (S20241,1532005) (S20231,1532004). Hunan Provincial Social Science Fund (2022ZDB089).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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