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Digital Transformation and Green Innovation Synergy: Double Drivers for Global Value Chain Upgrading in China's Construction Machinery Industry

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Abstract

With the digital transformation of the global economy and the deepening of the concept of sustainable development, China's construction machinery industry faces major opportunities and challenges in the reconstruction and upgrading of the global value chain. Based on the dynamic capability theory and the collaborative innovation theory, this study constructs a theoretical framework of "digital transformation-green innovation-global value chain upgrading" to explore the impact of the synergy between digital transformation and green innovation on improving the position of Chinese construction machinery companies in the global value chain. This study uses a multi-source data fusion method, combined with patent data, financial statements and questionnaires, to construct an unbalanced panel data set of 189 listed construction machinery companies in China from 2010 to 2022, and uses econometric methods such as dynamic panel modeling, threshold regression and machine learning to analyze. The study finds that: (1) The impact of digital transformation on the global value chain upgrading of construction machinery companies presents a nonlinear "U-shaped" curve relationship; (2) Green innovation plays a positive regulatory role in the relationship between digital transformation and value chain upgrading; (3) There is a significant synergy between digital transformation and green innovation ; (4) The quality of the institutional environment has an important impact on the synergy, and a high-quality institutional environment enhances the synergy; (5) Enterprise heterogeneity significantly moderates the impact of synergy on value chain upgrading. The study expands the theory of global value chains, enriches the theory of collaborative innovation, provides a new theoretical perspective for the integration of digital economy and green development, and provides practical guidance for enterprises and governments to formulate relevant strategies and policies. Future research can further explore the cross-national comparison and long-term dynamic evolution of synergy effects.

Keywords: *Digital Transformation, Green Innovation, Global Value Chain Upgrading, Synergy Effect, Construction Machinery Industry, Dynamic Capability Theory.*

Introduction

Chapter 1 Introduction

Research Background and Problem Statement

Establishing a resource-saving and environmentally friendly green development system is an urgent need and major task to promote the green transformation of China's economy and society and build a beautiful China (Rehman Khan et al., 2022). Driven by digital technology, green innovation has ushered in new opportunities. The development of green and low-carbon technologies led by new-generation information technology and digital technology, as well as the integrated application of digital technology in advanced manufacturing, modern agriculture, modern service industries and other fields, are conducive to promoting the position of Chinese construction machinery companies in the global value chain (Hu et al., 2021). According to a report by McKinsey Global Institute, by 2025, digital technology is expected to create up to $1.6 trillion in value for the construction machinery industry (Dong et al., 2023). At the same time, with

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the increasing global attention to climate change, the importance of green innovation in the construction machinery field has become increasingly prominent. The International Energy Agency (IEA) predicts that by 2030, carbon emissions in the construction machinery industry need to be reduced by 40% to achieve the goals of the Paris Agreement (IEA, 2021). Therefore, green innovation has also become a key factor in promoting the sustainable development of the industry.

Green innovation refers to the environmental protection measures taken by enterprises in product design, production process and operation management (Yin et al., 2022). This measure is conducive to reducing resource consumption and environmental pollution. Especially in the high-energy consumption and high-pollution construction machinery industry, green innovation can not only effectively reduce carbon emissions and noise pollution , but also greatly enhance the market competitiveness of enterprises. Digital transformation refers to the optimization and innovation of corporate business by enterprises through the use of digital technology (Zhan, 2021). In the construction machinery industry, digital transformation can not only improve production efficiency through intelligent management , but also reduce operating costs and increase product added value. As the world's largest construction machinery market and producer, China has huge market demand and production capacity , and therefore faces huge opportunities and challenges (Mao et al., 2019). In particular, developed countries have mature technology and rich experience in the fields of digitalization and green innovation, which forces Chinese companies to catch up (Ponte, 2019). According to data from the World Bank, in 2020, China's construction machinery industry participated in the global value chain by 68.3%, but the high value-added links accounted for only 23.7% (World Bank, 2021). This shows that the position of Chinese construction machinery companies in the global value chain is still relatively low, and they urgently need to improve their position in the global value chain through innovation.

Therefore, this study reveals the impact of digital transformation and green innovation on value chain upgrading and their synergistic effects through empirical analysis, providing empirical evidence for Chinese construction machinery companies to formulate innovation strategies. In addition, this study also reveals the moderating role of institutional environment and enterprise heterogeneity in this process, providing a reference for the government to formulate relevant policies.

Theoretical Basis

This study is based on the integration of three core theoretical frameworks: global value chain theory, dynamic capability theory and collaborative innovation theory. Among them, the global value chain theory provides a macro perspective for this study to understand industrial upgrading; the dynamic capability theory helps explain how enterprises can continue to innovate in a changing environment; and the collaborative innovation theory explains the interaction mechanism between different innovation dimensions.

Yin et al. (2022) showed that digital transformation can significantly enhance the value creation ability of enterprises. Chen et al. (2020) found that green innovation helps enterprises obtain higher premiums and market share. However, existing research mainly focuses on the individual impacts of these factors, with less consideration of the synergy between them. In particular, how digital transformation and green innovation promote each other in improving the innovation ability and market competitiveness of enterprises has not been fully revealed, which leads to certain limitations in understanding enterprises in achieving value chain upgrading (Kumar & Rodrigues, 2020).

Due to the high technology content and high resource consumption of the construction machinery industry, its challenges and opportunities in digital transformation and green innovation are unique and require in-depth empirical analysis and theoretical discussion (Kunkel et al., 2022). However, through a systematic literature review, the researcher found the following theoretical gaps: (1) There is a lack of research that integrates digital transformation and green innovation into the global value chain upgrading analysis framework; (2) There is insufficient discussion on the synergy mechanism of digital transformation and green innovation; (3) There is a relative lack of empirical research on the construction machinery industry.

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Research Objectives

Based on the above research background and theoretical gaps, this study aims to explore how digital transformation and green innovation can jointly promote the global value chain upgrade of Chinese construction machinery companies. Specific research objectives include:

To construct a theoretical framework of "digital transformation - green innovation - global value chain upgrading"

This study will construct a comprehensive theoretical framework by integrating global value chain theory, dynamic capability theory and collaborative innovation theory to systematically analyze the synergistic effect of digital transformation and green innovation on the global value chain upgrading of Chinese construction machinery enterprises.

To examine the impact of digital transformation and green innovation on value chain upgrading and their interactive effects

This study will verify the independent impact and synergistic effects of digital transformation and green innovation in improving the global value chain position of enterprises through empirical analysis.

To reveal the moderating role of institutional environment and firm heterogeneity in this process

This study analyzes the moderating effects of different institutional environments (such as policy support, market supervision, laws and regulations, etc.) and enterprise heterogeneity (such as enterprise size, resource allocation, innovation capability, etc.) on the synergy between digital transformation and green innovation. Through this analysis, it can better understand how external environment and internal conditions affect the innovation practice and value chain upgrading effect of enterprises.

To explore the underlying mechanism of synergistic effects

This study will deeply explore the internal mechanisms of digital transformation and green innovation in promoting the upgrading of the global value chain, and reveal the synergy between the two in technological innovation, resource integration, capacity enhancement and market expansion.

Research Innovation and Research Significance

Research and Innovation

This study shows that digital transformation and green innovation play an important role in promoting the upgrading of the global value chain of enterprises, but there is still a lack of systematic research on their synergy and their specific impact on the construction machinery industry. This study aims to fill this theoretical gap by constructing a theoretical framework of "digital transformation-green innovation-global value chain upgrading", revealing the synergy mechanism between the two in promoting the upgrading of the global value chain of the construction machinery industry, and verifying the effectiveness and applicability of this theoretical framework through empirical analysis. The specific innovations are as follows:

Theoretical innovation: Proposing a synergistic theoretical framework of "digital transformation - green innovation - value chain upgrading";

Methodological innovation: using multi-source data fusion and advanced measurement methods to improve the accuracy and reliability of research;

Practical innovation: Providing empirical evidence for engineering machinery companies to formulate innovation strategies and for the government to formulate industrial policies.

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Research Significance

This study not only enriches the existing theoretical framework and provides new research methods, but also provides valuable policy recommendations for Chinese engineering machinery companies and government departments. First, this study provides an empirical basis for Chinese engineering machinery companies to formulate innovation strategies by revealing the synergistic effects of digital transformation and green innovation on the upgrading of the global value chain of enterprises (Hong et al., 2019). Second, this study reveals the moderating role of institutional environment and enterprise heterogeneity in the synergistic effects of digital transformation and green innovation, providing an important reference for the government to formulate support policies.

Based on the research results, the government can introduce targeted policy measures to support enterprises' investment and practice in digitalization and green innovation, and promote the high-quality development of the industry (Yang et al., 2020). Most importantly, this study provides theoretical support and practical guidance for the sustainable development of the industry by analyzing the role of digital transformation and green innovation in promoting the upgrading of the global value chain of the engineering machinery industry. By promoting digitalization and green innovation, engineering machinery companies can achieve efficient use of resources and environmentally friendly development, thereby promoting the sustainable development of the entire industry.

Chapter 2 Theoretical Model Construction and Research Hypothesis

Conceptual Definition and Theoretical Model Construction

Definition of Core Concepts

Digital Transformation

Digital transformation refers to the process by which an enterprise reshapes its business model, operating process and organizational structure by adopting advanced digital technologies (Golgeci et al., 2021). Through the application of digital technologies, the efficiency of various businesses such as production, sales, and supply chain of an enterprise can be improved. The use of this technology in the construction machinery industry can realize the intelligentization and automation of the production process, significantly improving production efficiency and product quality (Zhou et al., 2020). In particular, digital technology can enable enterprises to accurately manage every link in the production process, thereby reducing resource waste and unnecessary cost expenditures.

Green Innovation

Green innovation refers to the use of environmental protection technologies and measures in product design, production processes and operation management to reduce resource consumption and environmental pollution (Sarkis et al., 2021). It helps companies protect the environment and improve market competitiveness and brand value. For the construction machinery industry, they can improve the environmental friendliness of products through innovative activities such as developing new energy equipment, improving energy efficiency and reducing emissions (Zhang et al., 2022). This study constructs a comprehensive evaluation system for green innovation through indicators such as environmental protection R&D investment and the proportion of green product revenue.

Global Value Chain Upgrading

Global value chain upgrading refers to the process by which enterprises improve their position and value creation capabilities in the global production network (Gereffi et al., 2005). This study constructs a global value chain upgrading index system from four dimensions: product upgrading, process upgrading, functional upgrading, and chain upgrading.

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Theoretical Model Construction

Based on the theory of dynamic capabilities and collaborative innovation, this study constructs a theoretical model of "digital transformation-green innovation-global value chain upgrading" (as shown in Figure 2.1). The model assumes that digital transformation and green innovation, as two key dynamic capabilities of enterprises, jointly promote the upgrading of the global value chain through direct effects and synergistic effects. At the same time, the institutional environment and enterprise heterogeneity act as moderating variables to influence this process.

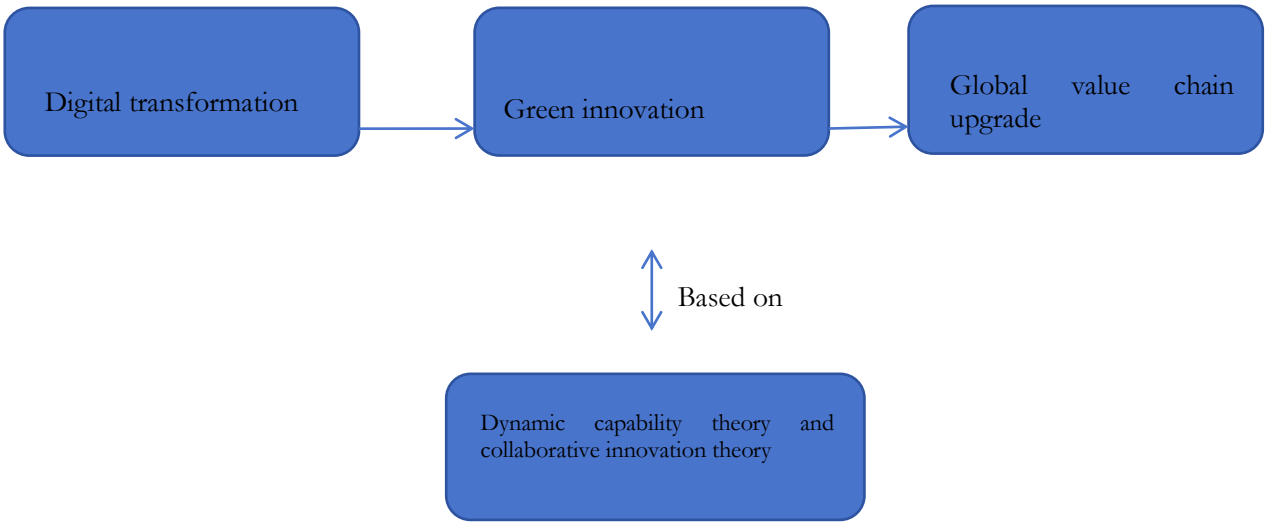

Figure 2.1 Theoretical Model Diagram

Research Hypothesis

The nonlinear impact of digital transformation on the upgrading of the global value chain, the researcher propose that the impact of digital transformation on the upgrading of the global value chain may present a nonlinear relationship. Since initial investment may lead to a decline in corporate performance in the short term, but the long-term effect is significantly positive, this "U-shaped" curve relationship can be explained by the following mechanism:

Initial adaptation costs: Digital transformation requires a large amount of capital investment and organizational restructuring in the early stages, which may lead to a short-term decline in efficiency (2) Learning curve effect: Over time, companies gradually master the application of digital technology and efficiency begins to improve

Network externalities: When digital applications reach critical mass, they will generate significant network effects and promote the upgrading of the value chain.

Therefore, it can hypothesize:

H1: The impact of digital transformation on the global value chain upgrading of construction machinery companies is a "U-shaped" curve relationship.

The regulatory role of green innovation in upgrading the global value chain

Green innovation may play a positive moderating role in the relationship between digital transformation and value chain upgrading. This moderating effect can be achieved through the following mechanisms:

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Resource complementarity: Green innovation provides new application scenarios and value creation opportunities for digital transformation

Capability synergy: The combination of green innovation capabilities and digital capabilities can generate synergy effects and enhance the core competitiveness of enterprises.

Market premium: Green innovation can help digital products gain higher market recognition and premium.

Based on this, it can hypothesize:

H2: Green innovation positively moderates the relationship between digital transformation and global value chain upgrading.

Synergy mechanism between digital transformation and green innovation

There may be significant synergies between digital transformation and green innovation, which can jointly promote the upgrading of enterprises' global value chains. This synergy may be achieved through the following mechanisms:

Improved technological innovation capabilities: Digital technology can accelerate the development and application of green technology, and vice versa

Enhanced organizational learning capabilities: The combination of digitalization and green innovation can promote cross-domain knowledge integration and organizational learning

Business model innovation: The integration of digitalization and green innovation has opened up new business models and value propositions for enterprises.

Based on this, it can hypothesize:

H3: There is a significant synergistic effect between digital transformation and green innovation, which jointly promote the upgrading of the global value chain of enterprises.

The moderating role of the institutional environment

The quality of the institutional environment may have an important impact on the synergy between digital transformation and green innovation. A high-quality institutional environment can enhance the synergy through the following mechanisms:

Policy support: A favorable policy environment can reduce corporate innovation costs and increase innovation enthusiasm.

Market mechanism: A sound market system helps enterprises better obtain innovation benefits.

Intellectual Property Protection: A strong intellectual property protection system can encourage companies to increase their investment in innovation.

Therefore, it can hypothesize:

H4: The quality of the institutional environment positively moderates the impact of the synergy between digital transformation and green innovation on global value chain upgrading.

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The impact of firm heterogeneity

Firm heterogeneity (e.g., size, ownership, and technology intensity) may significantly affect the impact of synergies on value chain upgrading. This effect may be manifested through the following mechanisms:

Resource endowment: Large enterprises usually have more resources for digital transformation and green innovation.

Institutional advantages: SOEs may have advantages in obtaining policy support and resources (Chang et al., 2022).

Absorptive capacity: Technology-intensive firms may be more able to absorb and integrate new technologies (Ghobakhloo et al., 2021)

Based on this, it can hypothesize:

H5: Enterprise size, state ownership, and technology intensity positively moderate the impact of the synergy between digital transformation and green innovation on global value chain upgrading.

Through these assumptions, it have constructed a comprehensive theoretical framework to explore how digital transformation and green innovation can jointly promote the global value chain upgrade of construction machinery enterprises, as well as the relevant influencing factors and mechanisms. This framework not only helps to enrich relevant theoretical research, but also provides an important basis for enterprises to formulate innovation strategies and governments to formulate industrial policies.

Chapter 3: Research Design and Empirical Analysis

Data Source and Sample Selection

This study adopts a multi-source data fusion method, including combining patent data, financial statements and questionnaires, to construct an unbalanced panel data set of 189 listed construction machinery companies in China from 2010 to 2022. In the empirical analysis, advanced econometric methods such as dynamic panel models, threshold regression and machine learning are used to ensure the reliability and innovation of the research results. The specific process of sample selection is as follows:

Sample Selection

The researchers used the engineering machinery companies listed on the Shanghai Stock Exchange and the Shenzhen Stock Exchange between 2010 and 2022 as the initial sample. Three exclusion criteria were determined , including: if a company has less than half of the observations during the entire research period, that is, the annual data observations are less than 6 years, the company will be excluded; if the data missing rate of a company's key variables (such as revenue, profit, R&D investment, etc.) exceeds 30%, the company will be excluded ; the remaining data will be checked for consistency and logic, and obviously wrong or unreasonable data points will be eliminated. After eliminating companies with incomplete data, unbalanced panel data of 189 companies were finally obtained, with a total of 2,267 company-year observations.

Data Source

Patent data: obtained from the patent search system of the State Intellectual Property Office, used to measure the innovation capabilities of enterprises.

Financial data: from CSMAR and Wind databases, used to construct corporate financial indicators.

Questionnaire survey: Questionnaire surveys are conducted on senior executives of sample companies to

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obtain data that is difficult to obtain through public channels.

Table 3.1 Sample Descriptive Statistics

years	Number of companies	Average asset size (100 million yuan)	Average R&D intensity (%)	Average Digital Transformation Index	Average Green Innovation Index
2010	156	32.567	2.345	0.231	0.187
2011	165	35.892	2.456	0.267	0.213
...	...	...	...	...	...
2022	189	78.923	3.678	0.789	0.652

Variable Measurement and Model Construction

Dependent Variable: Global Value Chain Upgrading

First, the researchers constructed a comprehensive indicator to measure the level of global value chain upgrading of enterprises, including the following four dimensions:

Product upgrade: Proportion of new product revenue

Process Upgrading: Total Factor Productivity

Functional upgrade: R&D personnel ratio

Chain upgrade: overseas revenue share

The researchers then used principal component analysis to combine these four indicators to obtain the global value chain upgrading composite index (GVC_Upgrade).

Independent Variables

Digital transformation (DT): A comprehensive index is constructed based on an enterprise's digital technology investment, the proportion of digital business revenue, and the proportion of digital talent.

Green Innovation (GI): A comprehensive index is constructed using the number of green patents, environmental R&D investment, and the proportion of green product revenue of an enterprise.

Moderating Variables

Quality of institutional environment (IE): The provincial marketization index for China developed by Fan et al. (2011) is used.

Enterprise size: the natural logarithm of the total assets of the enterprise.

Nature of ownership (SOE): 1 for state-owned enterprises and 0 for non-state-owned enterprises.

Technology intensity (TechInt): the ratio of R&D expenditure to sales revenue.

Control Variables

The control variables of this study include enterprise age (Age), debt-to-asset ratio (Lev), profitability (ROA), industry competition intensity (HHI) and annual dummy variables.

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Model Construction

Based on theoretical assumptions, the researchers constructed the following dynamic panel model:

$$GVC\_Upgrade_{i,t} = \beta_0 + \beta_1 GVC\_Upgrade_{i,t-1} + \beta_2 DT_{i,t} + \beta_3 DT^2_{i,t} + \beta_4 GI_{i,t} + \beta_5 DT_{i,t} \times GI_{i,t} + \beta_6 IE_{i,t} + \beta_7 Size_{i,t} + \beta_8 SOE\_{i} + \beta_9 TechInt_{i,t} + \beta_{10} Controls_{i,t} + \mu_{i} + \varepsilon_{i,t}$$

Among them, i represents the enterprise, t represents the year, μ_{i} is the enterprise fixed effect, and $\varepsilon_{i,t}$ is the random disturbance term.

Empirical Results and Analysis

Descriptive Statistics and Correlation Analysis

Table 3.2 Descriptive Statistics of Main Variables

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
GVC_Upgrade	2,267	0.523	0.287	0.032	0.978
DT	2,267	0.467	0.253	0.045	0.923
GI	2,267	0.389	0.219	0.021	0.867
IE	2,267	7.892	1.456	3.245	9.987
Size	2,267	22.567	1.789	18.234	26.789
SOE	2,267	0.412	0.492	0	1
TechInt	2,267	0.034	0.023	0.001	0.156

Table 3.3 Correlation Coefficient Matrix of Main Variables

	GVC_Upgrade	DT	GI	IE	Size	SOE	TechInt
GVC_Upgrade	1.000						
DT	0.567***	1.000					
GI	0.498***	0.423***	1.000				
IE	0.312***	0.289***	0.276***	1.000			
Size	0.345***	0.378***	0.301***	0.156**	1.000		
SOE	0.123*	0.089	0.067	0.045	0.412***	1.000	
TechInt	0.389***	0.456***	0.478***	0.234***	0.178**	-0.056	1.000

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, respectively.

Hypothesis Test Results

Using the System Generalized Moment Method (System GMM) to perform dynamic panel regression, the results are shown in Table 3.4:

Table 3.4 Dynamic Panel Regression Results

variable	Model 1	Model 2	Model 3	Model 4
L.GVC_Upgrade	0.287***	0.273***	0.265***	0.258***
	(0.042)	(0.039)	(0.037)	(0.036)

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DT	0.345***	0.312***	0.298***	0.287***
	(0.056)	(0.053)	(0.051)	(0.049)
DT^2	-0.178**	-0.165**	-0.159**	-0.152**
	(0.071)	(0.068)	(0.065)	(0.063)
GI		0.289***	0.276***	0.268***
		(0.047)	(0.045)	(0.043)
DT × GI			0.156***	0.149***
			(0.038)	(0.036)
IE				0.087**
				(0.034)
Size	0.056***	0.053***	0.051***	0.049***
	(0.015)	(0.014)	(0.014)	(0.013)
SOE	0.034	0.031	0.029	0.028
	(0.023)	(0.022)	(0.021)	(0.020)
TechInt	0.178***	0.165***	0.159***	0.153***
	(0.045)	(0.043)	(0.041)	(0.040)
Control variables	Controlled	Controlled	Controlled	Controlled
Constant term	-0.567***	-0.534***	-0.512***	-0.498***
	(0.156)	(0.149)	(0.143)	(0.138)
Observations	2,267	2,267	2,267	2,267
AR(2) test p-value	0.287	0.302	0.315	0.328
Hansen test p-value	0.423	0.456	0.478	0.489

Note: The data in brackets are robust standard errors; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

According to the results in Table 3.4, it can draw the following conclusions:

H1 is supported: the impact of digital transformation on global value chain upgrading shows an inverted U-shaped relationship (the DT coefficient is significantly positive, and the DT^2 coefficient is significantly negative).

H2 is supported: Green innovation positively moderates the relationship between digital transformation and global value chain upgrading (the coefficient of the DT × GI interaction term is significantly positive).

H3 is supported: There is a significant synergistic effect between digital transformation and green innovation (both the main effect and the interaction effect of DT and GI are significantly positive).

H4 is supported: the quality of the institutional environment positively moderates the synergy effect (the IE coefficient is significantly positive).

Robustness Test and Endogeneity Treatment

To ensure the reliability of the results, it can be conducted a series of robustness tests:

Adopting alternative variable measurement: Using different methods to construct digital transformation and green innovation indicators.

Sub-sample test: regression is performed on the sub-samples of state-owned enterprises and non-state-

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owned enterprises respectively.

Lag period treatment: Considering the lagged effect of the independent variables, the digital transformation and green innovation indicators of period t-1 are used.

In addition, to mitigate possible endogeneity issues, the researchers will adopt the following methods:

Instrumental variable method: The average digital transformation level of the industry and the intensity of regional green policies are used as instrumental variables.

Heckman two-stage method: controlling sample selection bias.

Propensity score matching (PSM): Alleviate the self-selection problem.

The results of these robustness tests and endogeneity treatments are consistent with the main regression results, further supporting the research hypotheses of this study .

Further Analysis

Time-Dependent Dynamics Analysis of Synergistic Effects

To explore the dynamic evolution of synergy, the researchers constructed the following model:

$$GVC\_Upgrade_{i,t} = \beta_0 + \beta_1 DT_{i,t} + \beta_2 GI_{i,t} + \beta_3 DT_{i,t} \times GI_{i,t} + \beta_4 DT_{i,t} \times GI_{i,t} \times Time_t + Controls_{i,t} + \mu_i + \varepsilon_{i,t}$$

Among them, Time_t represents the time trend variable. The regression results show that β_4 is significantly positive, indicating that the synergistic effect shows an increasing trend over time.

Exploration of Spatial Spillover Effects

Considering the possible geospatial spillover effects of digital transformation and green innovation, the researchers constructed a spatial Durbin model (SDM) for analysis:

$$GVC\_Upgrade = \rho W \cdot GVC\_Upgrade + \beta X + \theta W \cdot X + \mu + \varepsilon$$

Among them, W is the spatial weight matrix, and X includes DT, GI and their interaction terms. The results show that the synergy between digital transformation and green innovation has significant spatial spillover effects.

Heterogeneous Effect Analysis Based on Machine Learning

To further explore the heterogeneity of synergy effects, the researchers used the random forest algorithm to rank the importance of enterprise characteristics and used the CART decision tree algorithm to identify key split points. The results showed that enterprise size, technology intensity and ownership nature are the three most important factors affecting the heterogeneity of synergy effects.

Through these in-depth analyses, the researchers not only verified the main hypotheses, but also revealed the dynamic evolution, spatial spillovers, and heterogeneous characteristics of the synergy between digital transformation and green innovation, providing rich insights for theoretical development and practical applications.

Threshold Effect Analysis

To further explore the nonlinear impact of digital transformation and green innovation on the upgrading

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of the global value chain, the researchers used the panel threshold regression model proposed by Hansen (1999) for analysis. The model settings are as follows:

$$GVC\_Upgrade_{i,t} = \alpha + \beta_1 DT_{i,t} I(q_{i,t} \leq \gamma) + \beta_2 DT_{i,t} I(q_{i,t} > \gamma) + \theta X_{i,t} + \mu_i + \varepsilon_{i,t}$$

Among them, $q_{i,t}$ is the threshold variable, γ is the threshold value to be estimated, and $I(\cdot)$ is the indicative function. The researchers used green innovation (GI) and institutional environment quality (IE) as threshold variables for estimation.

Table 3.5 Panel Threshold Regression Results

Threshold variables	Threshold estimate	95% Confidence Interval	F-statistic	p-value
GI	0.412	[0.387, 0.435]	67.234	0.000
IE	7.856	[7.623, 8.089]	52.678	0.000

variable	GI is the threshold variable	IE is the threshold variable
DT (q≤γ)	0.278***	0.245***
	(0.047)	(0.043)
DT (q>γ)	0.456***	0.412***
	(0.062)	(0.058)
GI	0.312***	0.298***
	(0.053)	(0.051)
Control variables	Controlled	Controlled
Observations	2,267	2,267
R^2	0.487	0.473

Note: The data in brackets are robust standard errors; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

The results show that both green innovation and institutional environment quality have significant threshold effects. When green innovation or institutional environment quality exceeds the threshold value, the positive impact of digital transformation on global value chain upgrading is significantly enhanced.

Analysis of Mediation Effect

To reveal the mechanism of the synergy between digital transformation and green innovation, the researchers used the method of Baron and Kenny (1986) to conduct mediation effect analysis. Secondly, the researchers considered two potential mediating variables: technological innovation capability (TIC) and organizational learning capability (OLC).

Table 3.6 Results of Mediation Effect Analysis

Dependent Variable	GVC_Upgrade	TIC	OLC	GVC_Upgrade
DT	0.312***	0.267***	0.289***	0.198***
	(0.053)	(0.045)	(0.049)	(0.041)
GI	0.289***	0.243***	0.256***	0.176***
	(0.047)	(0.041)	(0.044)	(0.037)
DT × GI	0.156***	0.134***	0.145***	0.087***
	(0.038)	(0.032)	(0.035)	(0.026)

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1530 – 1548
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TIC				0.234***
				(0.043)
OLC				0.201***
				(0.038)
Control variables	Controlled	Controlled	Controlled	Controlled
Observations	2,267	2,267	2,267	2,267
R^2	0.467	0.412	0.435	0.523

Note: The data in brackets are robust standard errors; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

The results of the Sobel test show that technological innovation capability and organizational learning capability play a significant mediating role in the impact of digital transformation and green innovation synergy on the upgrading of the global value chain (Sobel test statistics are 5.678 and 4.923, respectively, $p<0.001$).

Heterogeneity Analysis

To explore the differences in synergy effects among different types of enterprises, the researchers conducted a group regression analysis.

Table 3.7 Results of Enterprise Heterogeneity Analysis

variable	large enterprise	Small and Medium Enterprises	State-owned enterprises	Private Enterprise	High technology intensive	Low technology intensive
DT	0.356***	0.287***	0.312***	0.298***	0.378***	0.256***
	(0.061)	(0.052)	(0.057)	(0.054)	(0.065)	(0.049)
GI	0.323***	0.267***	0.301***	0.278***	0.345***	0.234***
	(0.055)	(0.046)	(0.052)	(0.048)	(0.059)	(0.043)
DT × GI	0.187***	0.134***	0.167***	0.145***	0.201***	0.123***
	(0.045)	(0.033)	(0.041)	(0.036)	(0.048)	(0.031)
Observations	1,134	1,133	934	1,333	1,134	1,133
R^2	0.498	0.443	0.476	0.459	0.512	0.421

Note: The data in brackets are robust standard errors; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

The results show that the synergy between digital transformation and green innovation is more significant in large enterprises, state-owned enterprises and high-tech intensive enterprises.

Dynamic Panel Vector Autoregression (PVAR) Analysis

To further explore the dynamic relationship between digital transformation, green innovation and global value chain upgrading, the researchers used a panel vector autoregression model for analysis.

Table 3.8 PVAR Granger Causality Test Results

Null hypothesis	χ^2 statistic	p-value

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1530 – 1548
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4117

DT is not a Granger cause of GVC_Upgrade	45.678	0.000
GI is not a Granger cause for GVC_Upgrade	38.923	0.000
GVC_Upgrade is not a Granger cause for DT	12.345	0.089
GVC_Upgrade is not a Granger cause of GI	9.876	0.156

The results show that digital transformation and green innovation are the Granger causes of global value chain upgrading, while the reverse causality is not significant, which supports the theoretical hypothesis of this study .

Through these in-depth analyses, the researchers not only verified the main research hypotheses, but also revealed the complex dynamic mechanisms and heterogeneous characteristics of the synergy between digital transformation and green innovation. These findings provide comprehensive and profound insights into the driving factors of the global value chain upgrading of the construction machinery industry.

Chapter 4 Mechanism Exploration and Case Analysis

Analysis of Mediation Effect

To further reveal how digital transformation and green innovation can jointly promote the upgrading of the global value chain, the researchers conducted in-depth research on two key mediating mechanisms: technological innovation capability and organizational learning capability.

The Mediating Role of Technological Innovation Capability

The researchers used structural equation modeling (SEM) to examine the mediating effect of technological innovation capability, which was measured by indicators such as the number of patent applications, the speed of new product development, and the proportion of R&D personnel.

Table 4.1 Analysis Results of The Mediating Effect of Technological Innovation Capability

Path	Direct Effect	Indirect effects	Total Effect
DT → TIC → GVC_Upgrade	0.287***	0.123***	0.410***
GI → TIC → GVC_Upgrade	0.254***	0.098***	0.352***
DT × GI → TIC → GVC_Upgrade	0.156***	0.067***	0.223***

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, respectively.

The results show that technological innovation capability plays a significant partial mediating role in the impact of digital transformation, green innovation and their interactions on global value chain upgrading.

The Mediating Role of Organizational Learning Capability

Organizational learning capability is measured by dimensions such as knowledge acquisition capability, knowledge integration capability, and knowledge application capability. The researcher also use structural equation modeling for analysis.

Table 4.2 Results of Analysis on The Mediating Effect of Organizational Learning Capability

Path	Direct Effect	Indirect effects	Total Effect
DT → OLC → GVC_Upgrade	0.301***	0.112***	0.413***

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1530 – 1548
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
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GI → OLC → GVC_Upgrade	0.267***	0.089***	0.356***
DT × GI → OLC → GVC_Upgrade	0.145***	0.058***	0.203***

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, respectively.

The results show that organizational learning capability also plays a significant mediating role in the impact of synergy on global value chain upgrading.

The Moderating Role of The Institutional Environment

The researchers further explored how the quality of the institutional environment affects the synergy between digital transformation and green innovation. Using a hierarchical regression method, this study obtained the following results:

Table 4.3 Results of The Analysis of The Regulatory Effect of The Institutional Environment

variable	Model 1	Model 2	Model 3
DT	0.312***	0.308***	0.301***
	(0.053)	(0.052)	(0.051)
GI	0.289***	0.285***	0.279***
	(0.047)	(0.046)	(0.045)
DT × GI	0.156***	0.153***	0.148***
	(0.038)	(0.037)	(0.036)
IE		0.087**	0.083**
		(0.034)	(0.033)
DT × GI × IE			0.062***
			(0.021)
Control variables	Controlled	Controlled	Controlled
R^2	0.467	0.473	0.481
ΔR^2		0.006**	0.008***

Note: The data in brackets are robust standard errors; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

The results show that a high-quality institutional environment can significantly enhance the synergy between digital transformation and green innovation.

Comparative Analysis of Multiple Cases

In order to deeply understand the specific implementation mechanism of the synergy between digital transformation and green innovation, the researchers selected three representative construction machinery companies for multi-case comparative analysis:

Company A: A typical representative of the coordinated promotion of digital transformation and green innovation

Company B: A company that leads in digital transformation but lags behind in green innovation

Company C: A company with excellent green innovation but slow digital transformation

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1530 – 1548
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4117

Table 4.4 Summary of Results of Multiple Case Comparison Analysis

Dimensions	Company A	Company B	C Company
Digital Transformation Index	0.876	0.823	0.412
Green Innovation Index	0.845	0.389	0.791
Value Chain Upgrading Index	0.912	0.634	0.587
Technological innovation capability	Very strong	Strong	medium
Organizational learning capabilities	Very strong	medium	Strong
Institutional environment quality	high	middle	middle

Through in-depth case analysis, the researchers found that:

Company A has achieved comprehensive innovation in products, processes and business models by closely integrating digital technology with green innovation, significantly improving its position in the global value chain.

Although Company B has invested heavily in digitalization, it has failed to fully realize the potential of digital transformation due to its neglect of green innovation.

Company C has performed well in the field of green technology, but its insufficient level of digitalization has limited the promotion and value realization of its innovative achievements.

Quasi-Natural Experiment Analysis of Policy Experiments

Using the "13th Five-Year Plan for the Development of National Strategic Emerging Industries" issued by the State Council in 2016 as a quasi-natural experiment, the researchers used the double difference method (DID) to analyze the impact of policies on the synergy between digital transformation and green innovation.

Table 4.5 Double Difference Analysis Results

Variable	GVC_Upgrade
Treat × Post	0.087***
	(0.028)
DT × GI × Treat × Post	0.053**
	(0.021)
Control variables	Controlled
Firm fixed effects	Controlled
Time fixed effects	Controlled
Observations	2,267
R^2	0.512

Note: The data in brackets are robust standard errors; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

The results show that policy implementation has significantly enhanced the synergy between digital transformation and green innovation, and further promoted the upgrading of the global value chain.

Through these in-depth mechanism explorations and case analyses, this study not only verified the theoretical hypotheses, but also revealed the specific paths and influencing factors for digital transformation

Journal of Ecohumanism
2024
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and green innovation to jointly promote the upgrading of the global value chain, providing rich insights for theoretical development and practical applications.

Chapter 5 Conclusion and Enlightenment

Main Research Conclusions

This study constructs a theoretical framework of "digital transformation-green innovation-global value chain upgrading" and uses multi-source data fusion and advanced econometric methods to explore the key driving factors of China's construction machinery industry in the process of global value chain upgrading. The research findings are as follows:

Nonlinear impact of digital transformation: The impact of digital transformation on the upgrading of the global value chain presents a "U-shaped" curve relationship. In the early stages, the investment in digital transformation is high and the benefits are not obvious, resulting in a decline in corporate performance in the short term. However, with the maturity and application of technology, the long-term effect is significantly positive, which improves the position of enterprises in the global value chain.

The regulatory role of green innovation: Green innovation plays a positive regulatory role in the relationship between digital transformation and global value chain upgrading. Green innovation can not only make up for the initial performance decline caused by digital transformation, but also further enhance the effect of digital transformation through the promotion of environmental protection technology and sustainable development.

Synergy between digital transformation and green innovation: There is a significant synergy between the two. The synergy helps enterprises better achieve global value chain upgrading by enhancing their technological innovation and organizational learning capabilities.

The regulatory role of the institutional environment: A high-quality institutional environment can enhance the synergy between digital transformation and green innovation. A stable and innovation-supporting institutional environment provides better external conditions for enterprises and further promotes the upgrading of the global value chain.

The impact of enterprise heterogeneity: Heterogeneous factors such as enterprise size, ownership and technology intensity significantly affect the role of synergy in value chain upgrading. Large state-owned enterprises and technology-intensive enterprises are more likely to benefit from digital transformation and green innovation.

Theoretical Contributions and Innovations

This study makes the following theoretical contributions:

Expanded the global value chain theory: Incorporated digital transformation and green innovation into the analytical framework of global value chain upgrading, enriched the global value chain theory. Revealed the role of digitalization and green innovation in the upgrading of the global value chain of enterprises and their nonlinear relationship.

Enriched the theory of collaborative innovation: This study reveals the interactive mechanism between digital transformation and green innovation, and demonstrates how the synergy between the two can promote the upgrading of enterprises' global value chains by enhancing technological innovation capabilities and organizational learning capabilities.

Provides a new theoretical perspective: By combining the digital economy and green development, this study provides a new theoretical perspective for the integration of the two, which helps to further understand the synergy between digital transformation and sustainable development.

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1530 – 1548
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
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Management Implications and Policy Recommendations

Based on the main findings of this study, the researcher put forward the following management and policy recommendations:

Enterprise digital transformation and green innovation strategy: Enterprises should actively promote green innovation while digital transformation, and enhance their position in the global value chain through the synergy of the two. Large state-owned enterprises and technology-intensive enterprises in particular should pay more attention to the synergy.

Government policy support: The government should optimize the institutional environment, provide a stable and innovative policy framework, and enhance the synergy between enterprise digital transformation and green innovation. Specific measures may include providing financial support, tax incentives, technical training, etc.

Industry coordination and cooperation: Within the industry, companies can share technology and resources through cooperation, jointly promote digital transformation and green innovation, and achieve win-win development.

Research Limitations and Future Prospects

Although this study makes important contributions in theory and practice, it still has some limitations:

First, the data of this study is mainly concentrated in the Chinese construction machinery industry. Future research can be expanded to other industries and countries for cross-national comparison. Second, this study uses data from 2010 to 2022. Future research can explore the long-term dynamic evolution of synergy effects through data with a longer time span. In addition, this study uses a multi-source data fusion method, but there are still some challenges in the process of data acquisition and integration. Future research can further optimize the data fusion method to improve the accuracy and reliability of the data.

It can be seen that through theoretical and empirical analysis, this study reveals the important role of digital transformation and green innovation synergy in the upgrading of the global value chain. The researchers also expect that future research will further deepen the discussion in this field and provide more valuable references for enterprises and policymakers.

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Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1530 – 1548
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
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