The Impact of Digital Transformation on Green Innovation in Manufacturing Firms

-A Perspective Based on Technological Innovation Path

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Abstract. Technological innovation paths have a sustainable impact on the production mode and welfare level of a society, and guiding the economy to shift to green technology paths can help accelerate the realisation of the strategic goal of green transformation. This paper explores how digital transformation affects green innovation based on the perspective of technological innovation path. It is found that digital transformation promotes technological innovation but favours non-green innovation. Compared with green innovation, environmental regulation negatively moderates the effect of digital transformation on non-green innovation more strongly, i.e., a certain intensity of environmental regulation can correct the biased impact of digital transformation, but too high environmental regulation inhibits firms' green innovation. The industry digital transformation peer effect positively moderates the promotion of green innovation by digital transformation. Further mechanism analysis finds that executive green perceptions play a mediating effect between firms' digital transformation and green innovation.

Keywords: digital transformation; environmental regulation; green innovation; peer effect.

1 Introduction

At present, China is facing the loss of its traditional competitive advantage in manufacturing and the dual challenge of ecological environment and climate change. Against this backdrop, the 20th National Congress Report puts forward the important task of promoting green development and harmonious coexistence between human beings and nature. To achieve this vision, China is actively promoting green technological innovation, aiming to build an economic system characterized by green, low-carbon and circularity. The impact of technological innovation on the economy, society and ecological environment depends to a large extent on the path of technological innovation. The path of technological innovation reflects the changes in the allocation of innovation resources among different types of technologies. Specifically in the environmental

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field, if innovation inputs and outputs are concentrated in green technologies, the economy is in the green technology path, and vice versa. Green technological innovation not only improves production efficiency and brings economic benefits, but also reduces the generation of potentially harmful substances and thus enhances social benefits. Therefore, guiding the economy towards a green technology path is a key step in addressing environmental issues and moving towards a low-carbon economy, and will determine whether China's economy can realize green transformation and high-quality economic development.

Enterprise digital transformation refers to the comprehensive innovation of management and production processes through the integration of cutting-edge technologies such as big data, Internet of Things, cloud computing, blockchain and artificial intelligence [1-3]. Most scholars believe that digital transformation can significantly promote corporate green innovation [4,5]. However, there are also a few scholars who believe that digital transformation does not benefit all enterprises [6,7].

Although the existing literature has explored and elaborated on the relationship between enterprise digital transformation and green innovation, the main research direction is the role of digital transformation on the "innovation" dynamics of green innovation, ignoring the unique "green" attributes of green innovation, i.e., not considering the issue of the green directionality of enterprise innovation. To sum up, based on the perspective of technological innovation path, this paper will analyze this in the following three aspects: how will digital transformation affect technological innovation pathways, and what are the mechanisms inherent in its effects? How the impact of enterprise digital transformation on technological innovation paths will vary with the degree of digital transformation of industry cohort enterprises? Does digital transformation accelerate or slow down the transition process from technological innovation paths to green technologies when environmental policies are in place?

2 Theoretical Analysis

2.1 Impact of Enterprise Digital Transformation on Green Innovation

First, digital transformation can reduce enterprise research and development costs, and enterprises will have more adequate resources at their disposal for green technology research and development investment, thus promoting the improvement of green innovation performance. Second, digital transformation effectively reduces the cost of financing for firms through, for example, increased media attention and reduced financial risk, and as the cost of financing decreases, firms have more abundant funds for R&D and innovation. Thirdly, digital transformation improves the efficiency of enterprise operations and factor allocation by reducing enterprise transaction costs and adjusting existing business structures and production processes. The widespread application of information technology has changed the pattern of market competition, solved the problem of poor market information transmission, facilitated cross-regional exchange of information and reduced transaction costs. As a result, this paper proposes:

Hypothesis 1: Digital transformation can contribute to green innovation through resource effects, but has the same effect on non-green innovation.

2.2 The Mediating Effect of Executives' Green Perceptions

Society influences green innovation behavior mainly by affecting management's green cognition. Executive green cognition is the understanding and awareness of resource and environmental issues by top management of enterprises. Conceptually, executive green cognition is closely related to green technology innovation. At the same time, there is also a relationship between corporate digital transformation and executive green perceptions, as the digitalization process has brought an unprecedented level of regulatory transparency to corporate management, facilitating a close alignment between management and corporate strategy. Management now has access to a wide and diverse range of information resources that are critical for guiding decisions and optimizing operations. Digitization has also created an efficient learning platform that provides management with continuous professional development opportunities, thus stimulating their initiative and enthusiasm for green innovation. As a result, this paper proposes.

Hypothesis 2: Digital transformation promotes green innovation by increasing green awareness among executives, while having a limited impact on non-green innovation.

2.3 Moderating Effects of Digital Transformation in Industry Cohorts

According to the characteristics of the digital ecology, it can be seen that, fueled by the digital transformation of the industry cohort enterprises, the focus of the enterprise will accelerate enterprise innovation and change, based on the continuous updating of the equipment and tools and advanced concepts, inter-industry barriers are further broken down, and inter-temporal co-production is becoming more common.

First, the cohort effect of industry digital transformation can promote knowledge flow and creation. Second, the technology spillover externalities of the same cluster of firms in the industry can reduce the innovation cost of firms and improve the ability of manufacturing firms to realize innovation value. Thirdly, in the context of market competition, once a breakthrough is made in the research and development of digital green technology in the industry, it will be quickly learned, adopted and emulated by other enterprises. Based on the above analysis, this paper proposes:

Hypothesis 3: The stronger the industry digital transformation cohort effect, the more significant the strengthening effect of digital transformation on technology innovation path will be.

2.4 Regulatory Effects of Environmental Regulation

In order to achieve the goal of sustained improvement in environmental quality, China has put forward a series of environmental regulatory policies to guide enterprises towards green transformation and high-quality economic development. As a kind of policy pressure, environmental regulation can influence enterprises to enhance their green innovation through digital means, and has a guiding effect on their scientific and technological innovation. According to Porter's hypothesis, appropriate environmental regulation is conducive to the formation of "compensatory benefits" that exceed the costs

of environmental regulation, thus effectively promoting green technological innovation. The potential economic benefits of environmental regulation encourage firms to gradually shift their focus from short-term profit maximization to achieving long-term environmental sustainability. However, this shift may create additional regulatory pressure on firms in the short term. When firms turn this pressure into an incentive to innovate, they may face new risks and increased operating costs, which may discourage some firms from moving forward with green innovation. Thus, this paper proposes:

Hypothesis 4: Moderate environmental regulation can correct the biasing effects of digital transformation and steer the technological innovation path towards green technologies.

3 Modeling

3.1 Data Sources

The research object is A-share listed companies in the manufacturing industry in Shanghai and Shenzhen from 2011 to 2022, and the data collection contains multiple sources. Innovation data comes from the State Intellectual Property Office. Digital transformation and executive green perceptions data relied on company annual reports. The CSMAR database was utilized to collect key data on control variables. Data on environmental regulation is sourced from the National Bureau of Statistics (NBS). To maintain the validity of the data, the sample is processed as follows: first, ST, ∗ST firms are excluded. Second, continuous variables are Winsorized at 1% and 99% to reduce the interference of outliers. Third, firms that have been listed for less than two years are excluded. A total of 23,400 sets of sample data were obtained and analyzed using STATA 17.0 software.

3.2 Definition of Variables

Core Explanatory Variables.

The total amount of innovation (tec) is measured by the number of patents filed by a firm during the year. The total number of green invention patents and green utility model patents filed by listed companies is used to assess green innovation (gtec). Patents other than green patents measure non-green innovation (ngtec). Among them, the division between green and non-green patents follows the WIPO Green Patent Recognition Criteria.

Core Explanatory Variables.

Referring to the study of Chenyu Zhao et al. (2021)[8], the key feature words of digital transformation in the annual reports of enterprises are searched and counted with the help of Python's crawler function to portray digital transformation indicators (dig).

Mediating Variables.

Referring to Li Yabing et al. (2023)[9], the total frequency of 19 environmental awareness related words was added to 1 and the natural logarithm was taken to get the executive green awareness index (gaware).

Moderating Variables.

Referring to Huo Chunhui et al. (2023)[10], other firms in the same industry as the focal firm are defined as same-industry cohort firms, and the mean value of the degree of digital transformation of the group is used as a measure of industry digital transformation cohort effect (pe). Referring to Liu Rongzeng and He Chun (2021)[11], the completed investment in industrial pollution control as a share of the secondary industry is utilized to measure environmental regulation (policy).

Control Variables.

To reduce estimation bias caused by omitted variables, six variables, firm size (size), financial leverage (lev), profitability (roa), equity concentration (ec), cost-expense ratio (cost), and number of years on the market (age), are selected as control variables. Table 1 reports the specific definitions of the variables.

Table 1. Specific definitions of variables

typology	variable name	variable symbol	variable measurement
explanatory variable	Green Innovation	*gtec*	Number of green patent applications plus one taken as a natural logarithm
	Non-green innovation	*ngtec*	Natural logarithm of the number of non-green patent applications plus 1
	blaze new trails	*tec*	Number of patent applications plus 1 to take natural logarithms
explanatory variable	Digital Transformation	*dig*	Total frequency of digitally transformed feature words plus 1 and take the natural logarithm
intermediary variable	Executive Green Perceptions	*gaware*	Total frequency of environmental awareness feature words plus 1 and take the natural logarithm
moderator variable	Industry Digital Transformation Cohort Effect	*pe*	Mean value of the degree of digital transformation of enterprises in the same industry cohort
	environmental regulation	*policy*	Share of completed investment in industrial pollution control in the secondary sector*1000
control variable	Enterprise size	*size*	Natural logarithm of total assets of the enterprise at the end of the year
	financial leverage	*lev*	Total liabilities/total assets of the enterprise at the end of the year

profitability	*roa*	Ratio of net profit to total assets of the enterprise at the end of the year
shareholding concentration	*ec*	Number of shares held by the largest shareholder/total number of shares
cost ratio	*cost*	(Main operating costs + administrative expenses)/Main operating revenues
Number of years listed	*age*	Natural logarithm of the number of years a firm has been listed
sector	*indust*	Controlling industry factors
particular year	*year*	Control year factor

3.3 Econometric Modeling

To advance the empirical test, the following mathematical model is constructed:

$$\text{gtec}_{i,t}/\text{ngtec}_{i,t}/\text{tec}_{i,t} = \beta_0 + \beta_1 dig_{i,t} + \sum \beta control + \sum year + \sum indust + \varepsilon_{it} \quad (1)$$

where$dig_{i,t}$ indicates that the firm$i$ in the$t$ the degree of digital transformation in the year.$\text{gtec}_{i,t}/\text{ngtec}_{i,t}/\text{tec}_{i,t}$ denotes green innovation/non-green innovation/innovation, respectively.$control$ generalizes to firm-level control variables. Incorporates year fixed effects ($year$) and industry fixed effects ($indust$) to control for time variation and industry heterogeneity.ε_{it} Interpreted as a random disturbance term.

4 Analysis of Empirical Results

4.1 Descriptive Statistical Analysis

Table 2 reports the statistical characteristics of each variable. Among them, the mean of gtec is 0.4631 with a maximum value of 3.83, while the mean of ngtec is 2.1958 with a maximum value of 6.48, implying that the overall level of green innovation of listed companies in the manufacturing industry is much lower than the overall level of non-green innovation; the standard deviation of gtec is 0.860, while the standard deviation of ngtec is 1.709, suggesting that the degree of dispersion in non-green innovation is of non-green innovation of listed companies in the manufacturing industry is large, and the level of non-green innovation of listed companies in the manufacturing industry varies greatly among companies, while the level of green innovation among companies is generally low. dig has a mean value of 2.9098, a minimum value of 0.00, and a maximum value of 5.66, with a huge difference between the minimum value and the maximum value, reflecting that there is a large difference in the degree of digital transformation among the different sample companies in the process of digital transformation

Table 2. Descriptive statistical of variables

variable name	observed value	mean value	(statistics) standard deviation	minimum value	upper quartile	maximum values
gtec	23400	0.4631	0.860	0.00	0.00	3.83
ngtec	23400	2.1958	1.709	0.00	2.30	6.48
tec	23400	2.2475	1.725	0.00	2.40	6.53
dig	23400	2.9098	1.140	0.00	2.94	5.66
size	23400	22.0081	1.162	19.95	21.84	25.61
lev	23400	0.3831	0.192	0.05	0.37	0.86
roa	23400	0.0429	0.061	-0.21	0.04	0.21
ec	23400	33.5674	14.065	8.98	31.46	71.92
cost	23400	0.7077	0.173	0.16	0.74	0.99
age	23400	1.9225	0.936	0.00	2.08	3.33

4.2 Benchmark Regressions

In order to verify Hypothesis 1, the data are substituted into equation (1) for empirical testing, and the regression results are shown in Table 3. The analysis reveals that, while digital transformation itself has a positive effect on promoting green innovation, its effects are not exclusive and can similarly accelerate the pace of non-green innovation. Digital transformation contribute more significantly to the latter.

Table 3. Impacts of digital transformation on green innovation

	gtec	*ngtec*	*tec*
dig	0.063***	0.205***	0.207***
	(5.851)	(8.986)	(8.957)
size	0.248***	0.482***	0.492***
	(13.292)	(15.312)	(15.559)
lev	0.207***	0.053	0.095
	(3.057)	(0.369)	(0.649)
roa	0.320**	2.607***	2.553***
	(2.055)	(7.687)	(7.488)
ec	-0.001	-0.001	-0.001
	(-0.900)	(-0.615)	(-0.716)
cost	-0.047	-0.465**	-0.484***
	(-0.608)	(-2.555)	(-2.640)
age	-0.080***	-0.306***	-0.316***
	(-6.053)	(-10.889)	(-11.123)
_cons	-5.047***	-8.191***	-8.341***
	(-13.103)	(-12.522)	(-12.690)
year	yes	yes	yes
indust	yes	yes	yes
N	23382	23382	23382

t statistics in parentheses, * $p < 0.1$,** $p < 0.05$,*** $p < 0.01$

4.3 Endogeneity Analysis

This paper selects the mean of the degree of digital transformation of other enterprises in the province where the enterprise is located (iv) as the instrumental variable for digital transformation (see Table 4). This result suggests that the conclusion of the benchmark regression remains robust after controlling for endogeneity issues with the instrumental variable approach.

Table 4. Endogeneity analysis results

	Phase I	Phase II		
	dig	*gtec*	*ngtec*	*tec*
iv	0.252***			
	(4.89)			
dig		0.236	0.976**	1.019**
		(1.318)	(2.441)	(2.516)
control	yes	yes	yes	yes
year	yes	yes	yes	yes
indust	yes	yes	yes	yes
Kleibergen-Paap rk LM		23.815***		
Kleibergen-Paap rk Wald F		23.911***		
N	23382	23382	23382	23382

t statistics in parentheses, * p < 0.1,** p < 0.05,*** p < 0.01

4.4 Robustness Tests

By adopting the PPML model and replacing the measurement indicators of digital transformation[12] for the empirical analysis, the results of the benchmark regression are still robust(Table 5).

Table 5. Robustness tests results

	gtec	*ngtec*	*tec*	*gtec*	*ngtec*	*tec*
dig	0.165***	0.196***	0.192***			
	(4.207)	(6.815)	(6.767)			
dig2				0.070***	0.159***	0.161***
				(6.606)	(7.664)	(7.680)
control	yes	yes	yes	yes	yes	yes
_cons	-13.870***	-10.945***	-10.895***	-4.961***	-8.039***	-8.187***
	(-17.789)	(-16.710)	(-17.011)	(-13.019)	(-12.305)	(-12.473)
year	yes	yes	yes	yes	yes	yes
indust	yes	yes	yes	yes	yes	yes
N	23174	23361	23361	23382	23382	23382

t statistics in parentheses, * p < 0.1,** p < 0.05,*** p < 0.01

5 Further Analysis

5.1 Mechanism Testing

This part further tests the unique role mechanism of digital transformation affecting green technology innovation in manufacturing enterprises. Column (1) of Table 6 reports the regression coefficient of digital transformation on executive green cognition is significantly positive, indicating that digital transformation is conducive to improving the executive green cognition of enterprises. According to the regression results in columns (2), (3) and (4), it can be seen that executive green cognition only has a significantly positive impact on green technology innovation in manufacturing enterprises. It can be seen that digital transformation can provide green knowledge for green technological innovation in manufacturing enterprises and promote the identification of green opportunities by management, thus stimulating the vitality of green innovation. However, it should also be noted that these mechanism variables do not have a significant effect on non-green technology innovation, indicating that hypotheses 1 and 2 are valid.

Table 6. Mediation effect test results

	(1)	(2)	(3)	(4)
	gaware	*gtec*	*ngtec*	*tec*
dig	0.018*			
	(1.691)			
gaware		0.037***	-0.005	0.010
		(2.639)	(-0.190)	(0.375)
control	yes	yes	yes	yes
_cons	-1.543***	-5.341***	-8.595***	-8.744***
	(-6.334)	(-13.129)	(-12.835)	(-12.999)
year	yes	yes	yes	yes
indust	yes	yes	yes	yes
N	21950	21950	21950	21950

t statistics in parentheses, * $p < 0.1$,** $p < 0.05$,*** $p < 0.01$

5.2 Moderation Effect

To test hypothesis 3 and 4, this paper regresses the interaction term between digital transformation (dig) and industry digital transformation cohort effect (pe), digital tansformation (dig) and environmental regulation (policy) on the baseline model.

The estimation results in columns (1), (2) and (3) of Table 7 show that the coefficient of the interaction term is significantly positive, indicating that the larger the industry digital transformation cohort effect is, the more significant the impact of digital transformation for innovation is, and Hypothesis 3 is verified.

Columns (4), (5) and (6) of Table 7 reports the regression results, the coefficient of the interaction term is significantly negative, and environmental regulation plays a negative moderating role, which may be due to the fact that high environmental regulation may lead to the need for firms to invest more resources to comply with the regulations, thus reducing the capital and time spent on R&D and innovation and thus inhibiting the incentives of firms to innovate, but the environmental regulation still has a green direction-guiding However, environmental regulations still have a green direction-guiding effect.

Comparing Column (4) and (5), the inhibitory effect of environmental regulation on the promotion effect of non-green technological innovation in digital transformation is greater. In other words, in the context of environmental regulation, the negative impact on firms' green innovation activities is significantly smaller than that of non-green innovations, and firms will be more inclined to carry out green innovations. This suggests that environmental regulation has a role in regulating the direction of innovation, and moderate environmental regulation intensity can correct the biased impact of digital transformation, guide the technological innovation path to green technology, and accelerate the realization of the strategic goal of green transformation, which is confirmed in hypothesis 4.

Table 7. Moderation effect test results

	(1)	(2)	(3)	(4)	(5)	(6)
	gtec	*ngtec*	*tec*	*gtec*	*ngtec*	*tec*
c_dig	0.060***	0.201***	0.202***	0.063***	0.206***	0.207***
	(5.699)	(8.819)	(8.796)	(5.836)	(9.030)	(8.995)
c_pe	0.118***	0.241**	0.263***			
	(2.608)	(2.520)	(2.741)			
c.c_dig#c.c_pe	0.053***	0.086***	0.086***			
	(4.679)	(3.811)	(3.754)			
c_policy				-0.020**	-0.046**	-0.048***
				(-2.301)	(-2.475)	(-2.580)
c.c_dig#c.c_policy				-0.010**	-0.032***	-0.032***
				(-2.110)	(-3.086)	(-3.007)
control	yes	yes	yes	yes	yes	yes
_cons	-4.911***	-7.674***	-7.822***	-4.881***	-7.634***	-7.783***
	(-12.652)	(-11.606)	(-11.770)	(-12.555)	(-11.518)	(-11.685)
year	yes	yes	yes	yes	yes	yes
indust	yes	yes	yes	yes	yes	yes
N	23382	23382	23382	23382	23382	23382

t statistics in parentheses, * $p < 0.1$,** $p < 0.05$,*** $p < 0.01$

6 Conclusions

Using the data of A-share manufacturing companies listed in Shanghai and Shenzhen from 2011 to 2022, this paper examines the impact of digital transformation on green innovation, which reveals the impact of digital transformation on the path of technological innovation from the theoretical and empirical levels. It is found that: (1) The impact of digital transformation on technological innovation is obviously biased, and the impact on non-green innovation is more significant relative to green innovation. (2) Due to the specificity of green innovation, digital transformation can promote green innovation by enhancing executives' green cognition. (3) Digital transformation and industry digital transformation cohort effects are complementary in affecting technological innovation, and the enhancement of industry digital transformation cohort effects will strengthen the impact of digital transformation on technological innovation. (4) The implementation of appropriate environmental policies can alleviate the bias of the impact of digital transformation on technological innovation, and the combined effect of the two will help to promote the realization of green transformation at the enterprise and industry levels.

Therefore, to realize the green transformation of the economy, it is necessary to promote the digital transformation as the driving force, to continue to promote the industry digital construction as the basis, to improve the environmental policy system as the guide, and to build a "enterprise digital transformation + industry digital construction + government environmental regulation" trinity of policy combinations. Combined with the above findings, this paper puts forward the following insights:

First, enterprises should take the initiative in applying advanced digital technologies, seizing the strategic opportunities brought about by the development of digital information technology and improving the output and quality of green innovation. In terms of corporate governance, enterprises should emphasize the cultivation of management talents and cultivate high-end composite talents with green cognition and digital thinking.

Second, a policy system that harmonizes environmental regulation and the digital economy can guide enterprises and society to develop green technology paths. The research in this paper shows that it may be difficult to achieve the urgent need for green transformation by relying on environmental regulation alone, and that digital economy policies can provide a necessary complement to environmental policies in the context of the rapid development of big data and artificial intelligence.

Thirdly, we should actively promote the digital construction of the industry and provide a good institutional environment for digital transformation and enterprise innovation. For example, accelerate the construction of a more complete digital infrastructure, such as 5G, the industrial Internet, and the big data industry. By giving sufficient protection to enterprises that actively carry out green innovation, a solid institutional foundation for green technological progress and economic transformation will be built.

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