Digital Transformation, Green Technology Innovation and Carbon Emission Reduction Performance in Manufacturing - The Moderating Role of Environmental Regulation

Yuan Liu[1] [a], Chunyan Dai[2,3*]

[a] liuyuan1@ctbu.edu.cn, *daichunyan@ctbu.edu.cn

[1]School of Business Administration, Chongqing Technology and Business University, Chongqing, 400067, China
[2]Research Center for Economy of Upper Reaches of the Yangtze River, Chongqing Technology and Business University, Chongqing 400067, China
[3]Chongqing Engineering Research Centre for Development Information Management

Abstract: Whether and how digital transformation affects the carbon emission reduction performance in manufacturing under the carbon neutral target has emerged as a significant concern. This paper investigates the issue by analyzing panel data extracted from manufacturing companies listed on the A-share market for the time span of 2015 to 2021. The study used a mediation effect model to examine the correlation among digital transformation, green technology innovation, and carbon emission reduction performance in manufacturing. Furthermore, it examines the impact of environmental regulation as a moderating factor. Research has shown that implenting digital transformation can greatly enhance the performance of carbon emissions reduction in manufacturing, green technology innovation somewhat mediates the process. Additionally, environmental regulation can enhance the beneficial effects of digital transformation on the advancement of green technology innovation.

Keywords: Digital transformation; Carbon emission reduction performance in manufacturing; Green technology innovation; Environmental regulation

1 Introduction

The Chinese government unveiled its goals of attaining “carbon peak” and “carbon neutrality” in September 2020. The 20th National Congress of the CPC report further emphasized the importance of advancing new industrialization, expediting the establishment of a robust manufacturing sector, a high-quality economy, and a digitally advanced China. The report also highlighted the need to implement projects for industrial infrastructure reconstruction and major technical equipment, support the growth of specialized and emerging enterprises, and promote the manufacturing industry's development towards high-end, intelligent, and environmentally friendly approaches. Manufacturing, as a key industry in the national economy, plays a crucial part in the economic growth of China. However, its rapid growth has resulted in over 50% of the country's carbon emissions. The prevailing high carbon emission development model poses challenge in accomplishing the “dual carbon” goals.

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In the era of digitalization, various economic sectors are experiencing a wave of development, as there is a growing trend towards integrating digital information technology to facilitate digital transformation. Digital transformation in manufacturing encompasses the utilization of digital technologies by firms to adjust to shifts in the business landscape and improve their processes for creating value (Su, Y et al., 2023)[1].

Existing studies have demonstrated that the implementation of digital transformation in the manufacturing sector yields substantial improvements in corporate performance. (Zhang, Y et al., 2023)[2], that firms that undergo digital transformation have better environmental, social, and governance performance than those that do not(Cai, C et al., 2023)[3], and that digital transformation can help to drive firms' green technology innovation (Dou, Q et al.,2023)[4]. The integration of the green development idea and technical innovation is crucial for addressing the current challenge of achieving coordinated economic and environmental development. Green technology innovation plays a significant role in this regard. (Quader M A et al.,2015)[5]. If enterprises want to achieve sustainable development and promote carbon emission reduction, they must pay attention to and improve their own green innovation ability. Enterprises are affected by a variety of factors in the process of green innovation, such as green credit policy , R&D subsidies and so on. The essence of environmental regulation is to transform specific environmental needs into standardised policy documents and to require enterprises to adopt behaviours conducive to the environment and green development of enterprises through coercive means, which plays an indispensable role in the implementation of green behaviours and green development of enterprises (Chen S et al.,2014)[6].

This study seeks to analyse the impact of digital transformation on the effectiveness of carbon emission reduction in the manufacturing sector, while considering the “dual carbon” target. The study also investigates the role of green technological innovation as a mediator and the impact of environmental regulation as a moderator. The study integrates these variables into a cohesive theoretical framework for empirical investigation to enhance comprehension of their interrelationships.

The paper outlines several contributions. Initially, it conducts an analysis of the effect of digital transformation on the efficacy of carbon emission reduction in manufacturing , thereby offering significant perspectives for future studies. In addition, this study assesses the impact of environmental regulations on the connection between digital transformation and the development of green technological innovation, by investigating it as a moderating element. This analysis deepens our comprehension of the correlation between these variables and establishes a basis for the establishment of efficient environmental policies by the government. Furthermore, this study presents innovative approaches to improve the carbon emission reduction effectiveness in the manufacturing sector by using the principles of sustainable development, green technical innovation, and Porter's Hypothesis. It offers valuable information to support the progress of environmentally-friendly and efficient development in the manufacturing industry.

2 Theoretical analysis and research hypothesis

2.1 Digital Transformation and carbon reduction performance in manufacturing

This study proposes that digital transformation has a direct impact on carbon emission reduction performance in manufacturing. Firstly, digital transformation facilitates energy management and enhances efficiency in manufacturing. By implementing smart energy management systems, manufacturing sectors can monitor and control energy consumption, identify and address energy waste issues in a timely manner, leading to reduced energy consumption (Shrouf F et al., 2015)[7] and subsequently lower carbon emissions. Secondly, digital transformation enables optimization of production processes and resource allocation, reducing waste of energy and materials while enhancing resource utilization efficiency (Massaro M et al. 2021)[8], ultimately contributing to carbon emission reduction. According to these observations, this study puts forward the hypothesis:

H1: Digital transformation can positively affect the carbon emission reduction performance in manufacturing

2.2 Digital transformation and green technology innovation

Digital transformation positively affects the carbon emission reduction performance in manufacturing through green technological innovation. Specifically, digital transformation offers enterprises with enhanced efficiency and flexibility in management methods and decision-making mechanisms, stimulate employees' motivation to innovate (Fischer M et al.,2020)[9], and promote green technological innovation. In addition, digital platforms and networks also promote cooperation and knowledge sharing between enterprises and external institutions (Aksin-Sivrikaya S et al.,2017)[10], accelerating cross-border integration and application. Studies have demonstrated that the innovation of green technology can successfully achieve a harmonious balance between economic growth and environmental management, mitigate the adverse effects of primary energy consumption (Onifade et al., 2022)[11], optimize resource utilization, facilitate the adoption of sustainable practices by businesses, and enhance their performance in reducing carbon emissions. As corporate digital transformation progresses, the amalgamation of digital resources and green innovation will strengthen further. This will boost the enterprise's ability to innovate green technologies and further drive improvements in carbon emission reduction performance. Thus, this paper puts forward the subsequent hypothesis:

H2:Digital transformation can positively influence green technology innovation

H3: Green technology innovation mediates the relationship between digital transformation and carbon reduction performance in manufacturing

2.3 The moderating role of environmental regulation

Environmental regulation can enhance the effect of digital transformation on the advancement of green technology innovation. The Porter hypothesis argues that rational environmental regulation can stimulate firms to innovate, especially through technology-led productivity and economic growth. On the one hand, environmental regulations motivate the manufacturing industry to invest more in green technology innovation (Saunila M et al., 2018)[12], driving

digital transformation to be more environmentally friendly. On the other hand, government incentives such as tax breaks and subsidy rewards reduce the costs and risks of business transformation and increase the incentive for digital and green technology innovation (Li M et al.,2022)[13]. In the face of environmental regulations, the manufacturing industry has an incentive to improve efficiency and reduce emissions through digitalisation in order to comply with the requirements and gain incentives. Given the information provided, this paper puts out the following hypotheis:

H4: Environmental regulations can positively moderate the positive impact of digital transformation on green technology innovation

3 Research design

3.1 Model construction

The model is designed to examine the impact of digital transformation on carbon emission reduction performance in manufacturing, while also considering the mediating effect of green technology innovation and the moderating effect of environmental regulation:

$$Cerp = \beta_0 + \beta_1 Dig_{it} + \sum \beta_m C_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (1)$$

$$GI = \beta_0 + \beta_1 Dig_{it} + \sum \beta_m C_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (2)$$

$$Cerp_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_2 GI_{it} + \sum \beta_m C_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (3)$$

$$GI_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_2 \left(Dig \times ER\right)_{it} + \beta_3 ER_{it} \sum \beta_m C_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (4)$$

Where i、t represents enterprises and years respectively, β_0 represents the constant term, $\beta_1 - \beta_m$ represents the degree of influence of the respective variables and control variables on the dependent variable, C_{it} represents each control variable, λ_i represents individual fixed effects, μ_t represents time fixed effects, and ε_{it} represents the random error term in the baseline model.

3.2 Description of variables

1. Explained variable

Carbon emission reduction performance in manufacturing (Cerp). Referring to the measurement method of the existing research (Li J et al.,2023)[14], the data of carbon emissions of manufacturing industries are collected from the CEADs database, and then the carbon emissions are estimated, and the business revenue corresponding to each unit of carbon emissions is used as a proxy variable for carbon emission reduction performance (Cerp), and the larger the value of this index, the better the carbon emission reduction performance in manufacturing is, and the specific formula is shown in the following:

$$Cerp = \left(\frac{\text{Manufacturing operating income}}{(\frac{\text{Manufacturing carbon emissions}}{\text{Manufacturing main operating costs}} + 1) \times \text{Manufacturing operating costs}} \right) \quad (5)$$

2. Explanatory variable

Digital transformation (Dig) pertains to the systematic implementation of digital technologies with the intent of essentially altering and enhancing diverse facets of an institution or community.The measurement method used in this study is derived from prior study carried by Liao, K *et al*.(2023)[15]. Using a text analysis technique and Python crawler technology, the yearly reports of publicly traded manufacturing companies' text pertaining to "digital transformation" is extracted. The occurrence of words containing the use of digital technology and other characteristic words appearing in the financial statements is incremented by 1, and then the natural logarithm is applied to reflect the degree of digital transformation.

3. Mediating variable

Green technology innovation (GI) pertains to the development and implementation of new and advanced technologies that are environmentally friendly and sustainable. The measurement method used in this study is derived from prior research conducted by Dou, Q *et al*. (2023)[4]. The logarithm of the count of green patent applications by manufacturing businesses is used as a measure of green technical innovation in the manufacturing industry.To prevent the presence of null values, a logarithmic transformation is performed on the original data by appending 1 prior to applying the logarithm. The specification information was acquired from the China Research Data Service Platform. (CNRDS).

4. Moderating variable

Environmental regulation (ER) refers to the set of rules and laws implemented by governments or other regulatory bodies to control and manage human activities that may have an impact on the environment. The research conducted by Ben Kheder *et al*. (2008) [16]utilises the ratio of regional GDP to total regional energy consumption as a measure of the level of environmental regulation intensity. At a specific level of GDP, the efficacy of environmental control concerning energy conservation and emission reduction becomes more evident as the ratio grows. This indicates a higher intensity of environmental regulation.

5. Control variables

This study utilises previous research and selects firm size (Size:the natural logarithm of the firm's year-end total assets.), gearing ratio (Debt: the ratio of year-end total liabilities to year-end total assets.), profitability level (Roa: the ratio of after-tax net profit to total asset), shareholding concentration (Top1: percentage of shares retained by the majority shareholder), two-job unity (Dual: a value of 1 signifies complete agreement between the chairman and the general manager, whereas a value of 0 shows complete disagreement between them.), and regional economic development level (GDP: logarithm of per capita GDP of the region where the firm is located) as control variables.

3.3 Sample selection and data sources

This analysis samples China's A-share listed manufacturing enterprises from 2015 to 2021, using data from the Wanderlust (Wind) database, Cathay Pacific database (CSMAR), and China Statistical Yearbook. The provided data is processed in the following manner: (1) Companies labelled as ST or *ST, as well as those with substantial missing data in the statistical year, are not included. (2) All continuous variables are adjusted by a 1% increase or decrease. Data processing and analysis are performed utilising the software applications Excel 2021 and Stata 17.0. Table 1 displays the descriptive statistics for each variable. The highest value for carbon emission reduction performance in manufacturing is 3.885, the lowest value is 0.137, and the standard deviation is 0.945. The results demonstrate substantial variation in the carbon emission reduction performance among manufacturing enterprises in China.

Table 1. Descriptive statistics.

Variables	Mean	Std	Min	Max
Cerp	1.138	0.945	0.137	3.885
Dig	2.970	1.070	0.223	5.768
GI	1.134	1.280	0.000	4.865
ER	1.161	1.326	0.126	3.615
Size	20.692	1.160	17.697	23.573
Debt	0.420	0.187	0.008	0.976
Roa	0.071	0.087	-0.122	0.265
Dual	0.246	0.431	0	1
Top1	32.710	13.930	2.431	70.828
GDP	9.442	0.382	8.593	10.321

4 Empirical results and analysis

4.1 Correlation analysis

Table 2 demonstrates a significant and favorable correlation between digital transformation and the effectiveness of carbon emissions reduction performance in manufacturing. The correlation value of 0.170 indicates a statistically meaningful link at a 1% level of significance. This implies that a higher level of digital transformation is linked to a larger capacity for facilitating the carbon emissions reduction performance in manufacturing. Moreover, there is a strong and positive relationship between the development of green technology and the carbon emissions reduction performance in manufacturing. The correlation value of 0.034 indicates a statistically significant link at a 1% level of significance. This suggests that an increased degree of innovation in green technology is beneficial for enhancing the performance of reducing carbon emissions in manufacturing. Furthermore, there is a strong and statistically meaningful correlation between digital transformation and the development of green technological innovation. This correlation is significant at a level of 1%, with a correlation coefficient of 0.313. These findings indicate that a greater degree of digitalization is linked to a rise in green innovation endeavours, hence expediting the swift advancement of green technology innovation.

Table 2. Correlation analysis.

	Cerp	Dig	GI	ER	Size	Debt	Roa	Dual	Top1	GDP
Cerp	1									
Dig	0.170***	1								
GI	0.034***	0.313***	1							
ER	-0.564***	-0.216***	0.018	1						
Size	-0.068***	0.204***	0.520***	0.101***	1					
Debt	-0.176***	0.102***	0.305***	0.092***	0.425***	1				
Roa	0.082***	0.092***	0.104***	-0.003	0.212***	-0.12***	1			
Dual	0.097***	0.060***	-0.036***	-0.085***	-0.083***	-0.059***	0.013	1		
Top1	0.057***	-0.001	0.043***	-0.004	0.169***	0.005	0.145***	-0.042***	1	
GDP	0.123***	0.110***	0.057***	-0.270***	0.025**	-0.077***	0.039***	0.083***	0.048***	1

4.2 Regression analysis

The regression analysis is offered in table 3 and yields the subsequent results. The model (1) supports hypothesis H1, demonstrating a substantial positive correlation between digital transformation (Dig) and the performance of reducing carbon emissions in the manufacturing sector (Cerp) (β=0.028, P<0.01). Model (2) also confirms hypothesis H2, showing a statistically significant and favorable relationship between digital transformation (Dig) and green technological innovation (GI) (β = 0.081, P<0.01). In Model (3), the introduction of green technological innovation (GI) is considered as a mediating variable. The analysis shows a significant positive link between GI and Cerp, with a beta coefficient of 0.017 and a p-value of less than 0.01. Furthermore, the strong connection between Dig and Cerp is diminished, suggesting that the introduction of green technology has a partial role in mediating the influence of digital transformation on the performance of reducing carbon emissions in manufaturing. This finding supports hypothesis H3. Model (4) incorporates environmental regulation (ER) and the Dig×ER interaction term. This reveals that the positive correlation between Dig and GI is favourably influenced by environmental regulation, hence confirming hypothesis H4.

Table 3. Regression analysis.

Variables	Cerp	GI	Cerp	GI
Dig	0.028***(3.62)	0.081***(5.42)	0.027***(3.44)	0.035*(1.88)
GI			0.017***(2.68)	
Dig*ER				0.036***(3.94)
ER				-0.116***(-2.70)
Control Variables	YES	YES	YES	YES

Variables	Cerp	GI	Cerp	GI
Ind	YES	YES	YES	YES
Year	YES	YES	YES	YES
Cons	-3.331***(-2.90)	-6.934***(-3.13)	-3.214***(-2.79)	-7.020***(-3.15)
N	7,924	7,924	7,924	7,924
R^2	0.592	0.151	0.593	0.153

4.3 Robustness test

This study utilises a metric known as Dig_T to evaluate digital transformation. Dig_T is determined by dividing the fraction of intangible assets directly linked to digital transformation by the total intangible assets reported in the financial statements of manufacturing companies. This measure substitutes the digital transformation metrics (Dig) that were used in the benchmark regression model. The results obtained from this rigorous test, as displayed in Table 4, validate the assertions made in this study.

Table 4. Robustness test.

Variables	Cerp	GI	Cerp	GI
Dig_T	0.878***(4.46)	0.737*(1.94)	0.865***(4.40)	0.309*(0.68)
GI			0.018***(2.81)	
Dig_T*ER				0.526*(1.65)
ER				-0.046(-1.23)
Control Variables	YES	YES	YES	YES
Ind	YES	YES	YES	YES
Year	YES	YES	YES	YES
Cons	-3.230***(-2.81)	-6.911***(-3.11)	-3.108***(-2.70)	-8.027***(-3.61)
N	7,924	7,924	7,924	7,924
R^2	0.593	0.148	0.593	0.148

5 Conclusion

This study explores the correction between digital transformation, green technology innovation, and carbon emission reduction performance in manufacturing. It also explores the influence of environmental regulation as a moderator. The research focuses on Chinese manufacturing companies listed on the A-share market from 2015 to 2021. The following findings have been derived: (1) Digital transformation can enhance the carbon emission reduction performance in manufacturing , green technology innovation somewhat mediates the process. (2) Digital transformation can greatly boost green technology innovation. In other words, the more advanced the digital transformation, the more it facilitates the innovation and development of green technology. Environmental regulation can effectively govern the relationship between the two.

Stemming from the aforementioned facts, this study proposes the following recommendations:

Firstly, enhance the development of digital economic infrastructure. The government should furnish financial subsidies and other incentives to manufacturing businesses in order to

encourage the adoption of digital technology, which can enhance governance effectiveness and support the reduction of carbon emissions. Manufacturing companies should proactively establish favourable conditions for digital transformation, focusing on creating a conducive environment both internally and externally to ensure the seamless implementation of digital transformation. Additionally, they should prioritise environmental protection and assume greater environmental responsibility while leveraging digital technology to enhance the company's capabilities.

Secondly, it is imperative for governments and corporations to prioritise the significance of green technology innovation. The government ought to provide and enforce incentives, such as subsidies for green innovation, loans, and tax benefits, in order to motivate manufacturing businesses to actively adopt digital technology for the purpose of enhancing green innovation. Manufacturing enterprises should incorporate the digital economy into all aspects of their daily business operations, facilitate the comprehensive integration of digital technology and green technological innovation, enhance the efficiency of the green economy, and strengthen carbon emission reduction efforts.

Thirdly, considering the regulatory function of environmental regulations. Local governments should systematically and logically establish the intensity of environmental regulation, and employ a variety of regulatory methods to actively guide and stimulate manufacturing enterprises. This will encourage them to utilise digital resources to improve their capacity for green innovation and facilitate the high-quality advancement of the economy. Manufacturing firms must acknowledge the significance of digital transformation for their green innovation within the framework of environmental legislation. Manufacturing enterprises also need to fully recognise the importance of digital transformation for their green innovation in the context of environmental regulation.

The study is restricted by the absence of more sophisticated empirical techniques, such as structural equation modelling, to explore the relationship between variables. Additionally, there is a dearth of discussion on the various types of green technological innovation, including inventive and improved green technological innovation, as well as other influencing factors such as green credit policy and R&D subsidies. Subsequent research should address these limitations. The research can be improved by the utilisation of advanced technical methodologies and in-depth conversations.

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