Digital Transformation and Enterprise Green Total Factor Productivity—Empirical Evidence Based on Text Analysis Methods

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Abstract. This study utilizes the Malmquist-Luenberger (ML) index to evaluate the Green Total Factor Productivity (GTFP) of manufacturing firms. The assessment is conducted on a data set encompassing Chinese manufacturing enterprises from the years 2011 to 2020. Additionally, the study employs a Python crawler for gauging the extent of digital transformation within these firms. The objective is to investigate and quantify the influence of digital transformation on the GTFP of manufacturing enterprises. Findings:(1) The results of the econometric model show that digital transformation can effectively enhance GTFP of manufacturing enterprises; (2)The extent to which digital transformation bolsters GTFP of manufacturing enterprises is influenced by the companies' ESG performance. Specifically, it is observed that higher ESG performance correlates with a more pronounced enhancement effect of digital transformation on the GTFP of these firms.

Keywords: Manufacturing companies; Digital transformation; Green total factor productivity; ESG performance.

1 Introduction

Pollution generated by manufacturing enterprises in the process of development, resulting in a serious environmental burden, carbon emissions accounted for as much as 20% of the global ratio, becoming the "third culprit" of carbon emissions[1]. Under the background of green development, manufacturing enterprises urgently need to enhance their GTFP and realize the coordination between green transformation and environmental resources, so as to ensure the sustainable development of enterprises. In the important stage of promoting green development and realizing energy saving and emission reduction, how manufacturing enterprises can continuously improve GTFP has become one of the main tasks of economic development at this stage.

As an important tool for realizing the "dual carbon" goal, digital transformation brings an opportunity for enterprises to realize GTFP improvement. Digital transformation is a series of economic activities centered on digital technology to reconfigure enterprise production processes and techniques and innovate enterprise management models[5], and its impact on GTFP of China's manufacturing industry shows a "marginal increment"[8]. Existing literature has empirically explored the relationship between digitalization and GTFP mainly at the industry and macro levels. At the industry level, digital industrialization enhances GTFP by optimizing

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industrial structure, promoting technological innovation and deepening marketization. The Digital Economy Can Significantly Boost GTFP in the Manufacturing Industry[9]. On a broader scale, the digitalization initiatives undertaken by municipalities can unlock the potential benefits of the digital economy. This, in turn, can stimulate the pursuit of environmentally sustainable and high-quality growth within urban areas[7].

Based on the above literature, it is found that most of the studies on the impact and mechanism of digitization on GTFP focus on the macroeconomic level, and there is a lack of analysis from the micro-enterprise level. Therefore, how does the digital transformation of manufacturing firms affect the GTFP of firms? Through what boundary mechanisms does it affect the empowerment of green total factors in enterprises? These are precisely the questions that will be explored in depth in this paper.

2 Theoretical analysis and hypothesis

2.1 Digital transformation and GTFP

Digital transformation augments the exchange, sharing, and creation of knowledge both within and beyond the enterprise. It expedites the concentration, optimization, and reorganization of resources for green technological innovation. This process facilitates the convergence of environmental protection technologies with production technologies, thereby maximizing the impact of green technological innovation. Furthermore, the advancement of digital technology enhances the transparency and visibility of managerial procedures and operational outcomes. This reduction in information asymmetry can mitigate the agency conflicts that may arise between shareholders and management. In addition, the integration of data and labor factors induces a shift in the labor demand structure and input ratio of manufacturing enterprises, and the mismatch rate of human resource allocation is significantly reduced, which is conducive to improving the GTFP of enterprises. Companies strategically distribute complementary resources, ensuring that the adaptive capabilities of skilled workers and state-of-the-art technology are fully leveraged. This approach increases the efficiency of highly skilled labor utilization and fosters the advancement of the human capital structure within manufacturing firms. To encapsulate these insights, the present study advances the following hypotheses:

Hypothesis 1: The degree of digital transformation can positively increase the GTFP of manufacturing firms.

2.2 The moderating role of EGS performance

According to stakeholder theory, the implementation of ESG practices by corporations leads to a gradual evolution in their business objectives. This shift moves away from the sole focus on profit maximization towards a more balanced approach that equally values economic and social benefits. The theory posits that ESG practices can help align the interests of various stakeholders, including managers, employees, suppliers, and customers. By doing so, it can facilitate the reintegration of corporate resources and relational networks. This reintegration is believed to contribute to an increased level of green innovation within the enterprise [3]. On the one hand, within the labor market, companies that excel in ESG performance often prioritize the interests of their employees. This approach not only makes them more appealing to poten-

tial job candidates, including researchers, but also serves to boost the motivation and productivity of their current workforce. On the other hand, a strong ESG performance can act as a form of market supervision and incentive for companies. It encourages them to proactively engage in green transformation initiatives and to improve the efficiency of their green innovation processes. In summary, this study proposes the following hypotheses:

Hypothesis 2: ESG performance positively moderates the relationship between digital transformation and GTFP of manufacturing firms. Specifically, the higher the ESG performance, the stronger the relationship; conversely, the weaker the relationship.

3 Measurement model setting and data description

3.1 Data collection

This study draws on sample data from a selection of Chinese manufacturing companies spanning the period of 2011 to 2020, sourced from the Huazheng database, China Urban Statistical Yearbook, and China Environmental Statistical Yearbook. Utilizing Python software for data disambiguation and counting, we analyze the corresponding annual reports of these companies. A panel regression model is then constructed to examine the influence of digital transformation on the GTFP of the enterprises, as well as the moderating role of their ESG performance. To process the initial data, the following steps are taken: initially, samples of companies labeled as ST or *ST are excluded; subsequently, any samples with missing key research variables are also excluded.

3.2 Variable selection

Outcome variable

The outcome variable is GTFP (gtfp). This research employs a non-parametric approach to evaluate the GTFP of firms within a sustainable context. Specifically, it utilizes the non-radial Slack-Based Measure-Malmquist-Luenberger (SBM-ML) index, which is also known as the "ML index," following the methodology established by Cui and Lin in 2019[2]. The data required for this assessment are extracted from the yearly financial statements of firms that are publicly traded on the A-share market. To determine the GTFP of these enterprises, the following approach is taken to measure the respective input and output indicators:

(1) Factor inputs: The labor input is represented by the total workforce count within the company; the capital input is indicated by the company's net fixed assets; and the energy input is determined by the industrial electricity usage in the city where the company operates. This energy input is then adjusted based on the ratio of the company's employee headcount to the total number of urban employees in that city； (2) Desired output: In this research, the revenue generated from business operations is utilized as an indicator to represent the company's desired output; (3) Undesired output: For the purpose of this analysis, the concept of "undesired output" is represented by the "three industrial wastes"—namely, sulfur dioxide, wastewater, and smoke and dust emissions from industrial processes. These wastes are measured in relation to the company's employee count as a proportion of the total urban workforce within the city where the company is headquartered.

Key explanatory variable

The key explanatory variable is digital transformation (digital). Drawing on Wu et al.'s study[6], the annual reports of A-share listed companies were organized by Python crawler and counting, and the whole contents of related texts were extracted by Java PDF box library. In addition, the word frequency statistics of all the digital transformation keywords are performed on the basis of eliminating the invalid text content of listed companies' annual financial reports, and this is used as a data pool for subsequent feature word selection.

Moderator variable

The moderating variable in the study is the firm's ESG performance, denoted (esgp). The research employs the ESG ratings from the Huazheng database, following the methodology established by Fang and Hu in 2023[4], to quantify the ESG performance of the companies. The ESG performance is categorized into nine tiers, ranging from AAA, which is the highest, to C, which is the lowest. For the purpose of analysis, each ESG rating tier is assigned a numerical value from 9 (for AAA) to 1 (for C), in descending order of sustainability performance.

Control variables

Drawing on existing research, the following control variables are selected: (1) corporate performance (roa); (2) enterprise size (size); (3) gearing (lev); (4) independent director ratio (rid); (5) the enterprise's sales capacity (sales); (6) the enterprise's ability to grow (growth).

3.3 Model design

$$\ln gtfp_{i,t} = \beta_0 + \beta_1 digital_{i,t} + \varepsilon_{i,t} \tag{1}$$

$$\ln gtfp_{i,t} = \beta_0 + \beta_1 digital_{i,t} + \beta_2 roa_{i,t} + \beta_3 size_{i,t} + \beta_4 lev_{i,t} + \beta_5 rid_{i,t} + \beta_6 sales_{i,t} + \beta_7 grow_{i,t} + \varepsilon_{i,t} \tag{2}$$

GTFP (lngtfp) is the explanatory variable, digital transformation (digital) is the explanatory variable, and the rest are control variables; i denotes firms; t denotes year; ε is the residual.

4 Empirical results and analysis

4.1 descriptive statistics

Table 1 displays the findings from the descriptive statistics and correlation analysis for each variable under study. The data reveal a notable correlation among the variables, yet the correlation coefficients are observed to be moderate in size. Specifically, regarding the extent of digital transformation in enterprises, denoted as 'digital', the maximum observed value is 4.554, the minimum is 0.000, and the mean value stands at 1.132. These statistics suggest a considerable variation in digitalization levels across the sampled companies, pointing to an uneven distribution of digital transformation capabilities among them.

Table 1. Descriptive statistics and correlation analysis

Var	lngtfp	digital	lnsize	lev	rid	grow	sales	roa	esgp
lngtfp	1								
ditigal	0.317***	1							
lnsize	0.131***	0.110***	1						
lev	0.023***	-0.014*	0.456***	1					
rid	0.062***	0.077***	-0.020**	-0.014*	1				
grow	0.014*	0.103***	-0.033**	0.00700	0.017**	1			
sales	-0.038**	-0.004	0.0120	-0.361**	0.023***	0.018**	1		
roa	-0.015*	0.020***	0.080***	0.277***	-0.020**	0.013*	0.734***	1	
esgp	0.0130	0.051***	0.166***	-0.125**	0.054**	0.037**	0.211***	0.0130	1
Mean	0.986	1.132	22.01	0.403	37.54	0.240	0.0540	0.0460	4.043
p50	0.994	0.693	21.87	0.392	33.33	0.114	0.0630	0.0620	4
SD	0.0780	1.240	1.154	0.199	5.359	0.601	0.192	0.161	1.083
Max	1.116	4.554	25.46	0.985	57.14	4.241	0.449	0.341	6
Min	0.832	0	19.57	0.0530	33.33	-0.735	-1.404	-1.087	1

4.2 Benchmark regression analysis

Table 2 presents the outcomes of the benchmark regression analysis examining the impact of digital transformation on GTFP of manufacturing companies. The findings indicate a significantly positive correlation between digital transformation and GTFP at the 1% confidence level. This suggests that the implementation of digital transformation strategies has led to an enhancement in the GTFP among manufacturing enterprises.The reason may be: digital transformation promotes the digital change of the traditional industrial production mode, realizes the reduction of production cost, improves the output efficiency, and provides motivation and objective conditions for the enhancement of enterprise GTFP.

Table 2. Regression test results

	lngtfp	lngtfp	lngtfp
digital	0.050***	0.026***	0.023***
	(0.001)	(0.001)	(0.001)
lnsize		0.087***	0.090***
		(0.001)	(0.001)
lev		-0.062***	-0.066***
		(0.005)	(0.005)
rid		0.002***	0.002***
		(0.000)	(0.000)
grow		-0.004***	-0.004***
		(0.001)	(0.001)
sales		-0.062***	-0.059***
		(0.004)	(0.004)
roa		-0.004	-0.007
		(0.004)	(0.005)

esgp·digital			0.001***
			(0.000)
_cons	0.929***	-0.995***	-1.045***
	(0.001)	(0.023)	(0.024)
N	17220	17220	17220

4.3 Moderating effect test of ESG performance

To delve deeper into the moderating influence of ESG performance on the relationship between digital transformation and GTFP of manufacturing firms, the study introduces an interaction term between ESG performance and the digital transformation of these enterprises into Model (1). The ensuing regression analysis outcomes are presented in Table 2.

$$\ln \mathrm{gtfp}_{i,t} = \beta_0 + \beta_1 \mathrm{digital}_{i,t} + \beta_2 \mathrm{esgp} \cdot \mathrm{digital}_{i,t} + \beta_3 \mathrm{roa}_{i,t} + \beta_4 \mathrm{size}_{i,t} + \beta_5 \mathrm{lev}_{i,t} + \beta_6 \mathrm{rid}_{i,t} + \beta_7 \mathrm{sales}_{i,t} + \beta_8 \mathrm{grow}_{i,t} + \varepsilon_{i,t} \quad (3)$$

The regression results in Table 2 show that the coefficient of the interaction term (esgp·digital) is significantly positively correlated at the 1% level, indicating that ESG performance can positively regulate the effect of digital transformation on the enhancement of GTFP of enterprises. The underlying rationale could be attributed to the progressive improvement in ESG information disclosure. As ESG ratings and associated data are increasingly made public, corporate transparency is significantly bolstered. This development helps to ameliorate, to a certain extent, the challenges posed by adverse selection issues. It also promotes a more efficient allocation of resource factors. Furthermore, the enhanced transparency facilitates the direction of spillover resources stemming from digital transformation initiatives towards the company's green development initiatives.

4.4 Robustness check

To mitigate the potential influence of the intensive roll out of the digital economy strategy on the study's findings, the research excludes data from the years 2017 and 2018 before re-executing the regression analysis. The updated results in Table 3 indicate that the coefficient for the digital transformation of the comprehensive manufacturing firm sample remains significantly positive even after accounting for the exclusion of the two years heavily impacted by national policies. This outcome serves to reinforce the robustness of the research conclusions.

Table 3. Results of robustness test.

	lngtfp	lngtfp
ditigal	0.033***	0.039***
	(0.001)	(0.002)
lnsize	0.078***	0.081***
	(0.001)	(0.001)
lev	-0.045***	-0.058***
	(0.005)	(0.006)
rid	0.002***	0.002***
	(0.000)	(0.000)
grow	-0.003**	-0.003***
	(0.001)	(0.001)
sales	-0.067***	-0.064***

	(0.004)	(0.004)
roa	0.002	-0.001
	(0.005)	(0.005)
esgp·ditigal		0.002***
		(0.000)
_cons	-0.822***	-0.888***
	(0.027)	(0.028)
N	13323	13323

5 Conclusion

The research focuses on manufacturing companies that are listed on the A-share market in China, using them as subjects for analysis over a period spanning from 2011 to 2020, constructs digital transformation indicators and GTFP indicators, empirically tests the relationship between digital transformation and GTFP of manufacturing enterprises, and obtains the following conclusions:(1) Enterprise digital transformation can effectively enhance GTFP of manufacturing enterprises.;(2) The study reveals that ESG performance exerts a beneficial moderating effect on the link between digital transformation and GTFP of manufacturing firms. Specifically, it suggests that improved ESG performance intensifies the positive association between digital transformation initiatives and the GTFP of these enterprises. By expanding the research scope on corporate GTFP, the paper not only underscores the significance of digital transformation but also offers insights aimed at guiding manufacturing companies in boosting their GTFP. Considering the findings discussed above, the following recommendations are proposed: (1) Strengthen green technological innovation and release the effect of digital technological innovation. With the help of digital technology, integrate enterprise production factors, enhance the depth and breadth of digital technology embedded in green technology R&D and innovation, promote the transformation of enterprise green technology achievements; (2) Actively practicing ESG development concepts and continuously improving ESG management level. Based on the findings of this study, it is evident that ESG performance of companies acts as a significant positive moderator, enhancing the beneficial impact of digital transformation on GTFP of the firms. This moderating effect is instrumental in fostering the green and sustainable development trajectory of the enterprises.

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