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How the Institution of Big Data Experimental Zone Enhances the Digitalization of Manufacturing Enterprises? Empirical Evidence from China

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Abstract. In the wave of the digital economy, data, as a core production factor, is driving manufacturing enterprises toward digital transformation. However, because of the great complexity and systematical nature of such transformation, the national government has introduced and implemented multiple policies to provide fundamental support, expecting to accelerate the speed of digital transformation for manufacturing industries and enterprises. Utilizing data from Chinese listed companies spanning from 2011 to 2022, this paper employs the institution of the Big Data Comprehensive Experimental Zone (hereinafter referred to as " the Big Data Experimental Zone"), which is a national policy implemented in 2016, as a quasi-natural experiment to investigate the specific impacts of governmental policies on the digital transformation of manufacturing enterprises. The research findings indicate that the national institution of Big Data Experimental Zone has significantly promoted the digital transformation of manufacturing enterprises through three mechanisms which are government subsidy effects, human resource effects, and infrastructure effects, and this conclusion remains consistent after robustness testing. Furthermore, from the perspective of enterprise types, findings reveal that the institution of Big Data Experimental Zone has particularly facilitated the digital transformation of non-state-owned enterprises and smaller-sized enterprises. And, from the perspective of geographical areas, it demonstrates that this policy only has effectively driven the digitalization of manufacturing enterprises in eastern regions, megacities, as well as first-tier and new first-tier cities. While in regions with relatively backward industrial and technological development, the enhancement effect is not significant.

Keywords: Digitalization; Institution; National policy; the Big Data Experimental Zone; manufacturing enterprises

1. Introduction

Government actions, encompassing the series of activities and measures implemented by governments in fulfilling their statutory functions and exercising administrative powers, play a crucial role in the complex process of industrial development and enterprise transformation. Tingting and Jie [1] have emphasized that government subsidies significantly facilitate enterprises' green transformation. Furthermore, Guo and Zhang [2] have confirmed that tax policies promote enterprises' green transformation through optimizing finance, fostering innovation, and ensuring responsibility implementation, among other means. Liu et al. [3] have pointed out that the pilot policies for innovative cities significantly enhance the level of enterprises' digital transformation. Additionally, Zhang [4] has also discovered that the Policy of Specialized, Refined, Innovative, and Unique Firm Growth Plan significantly accelerates the progress of enterprises' digital transformation. However, despite the fact that numerous studies have already confirmed the significant impact of government behavior on enterprise transformation, the specific underlying mechanisms of this influence remain largely unexplored and require further in-depth investigation.

Recently, the transition towards digital and smart manufacturing has become a crucial strategic approach for countries to enhance the competitiveness and influence of their manufacturing sectors. However, compared to industrially developed countries such as the United States and Germany, China's manufacturing industry exhibits deficiencies in the area of smart development. Consequently, exploring effective strategies to promote the digital development of manufacturing enterprises is of great significance for elevating the overall competitiveness and international standing of China's manufacturing industry.

Existing research has conducted in-depth investigations into the various factors influencing the digital transformation of manufacturing enterprises from multiple perspectives, including internal factors such as enterprise innovation [5] enterprise performance [6], and enterprise value [7], as well as external environmental factors like government subsidies [8] and industrial internet platforms [9]. Specifically, Zhang and Wang [10], based on grounded theory, unequivocally identified core technological innovation, business model re-engineering, and organizational structure optimization as the primary drivers of digital transformation in manufacturing enterprises. Chen et al. [11] emphasized the central role of digital strategies and information technology in the digital transformation of enterprises. Besides the perspective of internal drivers, there are also some studies that focus on external factors, especially government-supporting policies. For example, Zhao et al. [12], through an analysis of data from Chinese manufacturing listed companies between 2016 and 2020, robustly demonstrated that government subsidies significantly incentivize the digital transformation of manufacturing enterprises. Liu et al. [9] argued that industrial internet platforms provide valuable technical support and potential opportunities for manufacturing enterprises to achieve digital business transformation through three key functions: resonance, collaboration, and adaptation. Furthermore, Zhao et al. [12], using China's low-carbon city pilot program as a natural experiment, found that this policy effectively promotes the digital transformation of manufacturing enterprises within the pilot cities. However, there is still a lack of in-depth research and clear explanations regarding the specific mechanisms through which a national policy exerts an impact on the enterprises' digital transformation. This hinders the understanding of policy formulation and implementation, as well as to discovery of the truly effective driving factors for manufacturing enterprises to implement digital transformation strategies.

Given this background, this paper selects the establishment of China's first digital economy pilot policy — the National Big Data Comprehensive Experimental Zone (hereinafter referred to as "the Big Data Experimental Zone") — as a quasi-natural experiment, so as to investigate how such national government policies influence the digital transformation of manufacturing enterprises. The expected functions of Big Data Experimental Zone include the following three aspects. Firstly, to explore innovative modes for data governance and big data applications, including cultivating new practices for big data trading, conducting market pilots for data trading, and promoting the formation of new business models. Secondly, to activate existing resources, promote data openness and sharing, and accelerate industrial development, through the layout and construction of comprehensive experimental zones. Thirdly, to promote technological innovation and application through the actions of "big data & intelligent manufacturing", enabling traditional industries to undergo digital upgrading. The implementation of Big Data Experimental Zone started in the year of 2015 in the city of Guizhou. Then the application of such policy extended to Beijing, Tianjin, Hebei, Inner Mongolia, Shenyang, Shanghai, Guangdong, and Chongqing in 2016. These eight Big Data Experimental Zones aim to promote digitalization, green development, and innovation, encompassing seven major tasks: data system innovation, data center integration, resource sharing and development, big data innovation applications, industrial agglomeration, resource circulation, and international cooperation [13]. So far, this policy has been implemented for nearly ten years. Related cities and local manufacturing enterprises have achieved differentiated performance in digital transformation. However, the mechanisms underlying the formation of different performances are still unclear. Therefore, we will attempt to discover the specific effects of relevant policies and explore the specific paths through which policies drive the digital transformation of enterprises.

2. Literature review

Currently, there has been extensive research on the impact of macroeconomic policies on micro-enterprises. Chen et al. [14], leveraging the quasi-natural experiment of the negative list system for the market access pilot, found that relaxing market access can facilitate the enhancement of firms' new quality productivity. Chen et al. [15] contended that the "Broadband China" pilot policy significantly promotes the formation and development of firms' new quality productivity. Gu and Liu [16] discovered that the national innovative city pilot policy can stimulate the creation of urban new quality productivity, with a notable increase in total factor productivity as its core. Jie and others [17] believe that after implementing the carbon emission trading pilot policy, the enterprise value in the pilot regions has significantly increased.

Meanwhile, the Big Data Experimental Zone, as a crucial initiative to explore new pathways for big data application and accelerate the development of the digital economy, has garnered significant attention from the academic community. Given the high value of the Big Data Experimental Zone, research on their related economic consequences has emerged continuously. At the cross-level dimension, scholars have explored the impact of the Big Data Experimental Zone on enterprise digital transformation [18,19], and enterprise innovation [20], and conducted in-depth analyses of the roles and effects of various factors in these processes. Specifically, Hou [19] believes that the construction of the Big Data Experimental Zone can significantly accelerate the process of firms' digital transformation; Dai [20] found that the establishment of the Big Data Experimental Zone significantly enhances the level of digital technological innovation among firms within the zones.

From an analysis of existed literature, it is evident that considerable research has been conducted on the Big Data Experimental Zone and the digital transformation of manufacturing enterprises. However, compared to the abundance of studies at the macro level, discussions on how the Big Data Experimental Zone specifically impact micro-enterprises and the economic and functional value they bring to these enterprises remain relatively scant. Furthermore, when examining the digital transformation of manufacturing enterprises, existing research has predominantly employed qualitative analysis methods. There is a lack of in-depth research and clear explanations regarding the mechanisms through which relevant policies specifically influence the digital transformation of enterprises. This gap hinders our comprehensive understanding of the pathways and processes involved in the digital transformation of enterprises. Therefore, based on data from the manufacturing industry in 30 provinces in China from 2011 to 2022, this paper treats the establishment of the Big Data Experimental Zone as a quasi-natural experiment to explore their role in the digital transformation of manufacturing enterprises and the underlying transmission mechanisms. This study aims to provide practical evidence for achieving higher levels of development in the manufacturing industry.

3. Theoretical mechanism and research hypothesis

Currently, industrial businesses face three significant challenges in their efforts to advance digital transformation. The primary issue is that capital constraints hinder the rational transformation of small and medium-sized firms. Digital transformation necessitates substantial capital investment, imposing significant strain on the comparatively limited financial resources of small and medium-sized firms. Secondly, the talent deficit poses a significant obstacle to sensible transition. Digital transformation necessitates a substantial pool of high-calibre talent; however, the market supply of such talent is inadequate. Furthermore, the labour market has entered a phase of negative growth normalization, exacerbating the talent issue. The deficiencies in digital infrastructure also hinder the advancement of enterprise’s digitalization. Despite China establishing the world's largest fibre-optic and mobile broadband network, significant deficiencies in digital infrastructure persist in certain regions and organizations, obstructing the effective execution of digital transformation.

This paper utilizes resource-based theory to thoroughly investigate the influence of the Big Data Experimental Zone on the digital transformation of manufacturing enterprises, focusing on three dimensions: the effect of government subsidies, the impact of human resources, and the role of infrastructure. The government support effect may mitigate financial pressures on enterprises through financial support; the human resource effect examines how the Big Data Experimental Zone can attract and develop high-quality talent to satisfy the demands of digital transformation; and the infrastructure effect investigates the contribution of the Big Data Experimental Zone to enhancing digital infrastructure, facilitating the seamless advancement of digital transformation.

Therefore, this paper proposes corresponding research hypotheses based on two aspects: the promotion effect of the Big Data Experimental Zone on the digital transformation of manufacturing enterprises and the mechanisms underlying this effect.

3.1. Promotion effect

Digitization can facilitate the transformation of manufacturing production methods, reduce transaction costs for manufacturing businesses [21], and drive changes in the manufacturing sector's organizational structure. Currently, China's manufacturing enterprises encounter several challenges in their pursuit of digital transformation, including a deficiency in core technology, cost pressures, insufficient talent supply, and other issues, making the transition from conceptualization to practical application a protracted endeavor.

The creation of the Big Data Experimental Zone seeks to overcome obstacles to data resources, enhance infrastructure integration, and foster the advancement of sophisticated big data products [22], thereby nurturing significant big data enterprises and developing specialized big data professionals. This effort simultaneously fosters pertinent institutional and technological advances to leverage data resources, facilitating the digital transformation of the manufacturing sector. On one hand, industrial internet platforms enable organizations to tightly integrate components such as factories, equipment, products, suppliers, and consumers, facilitating the efficient exchange of various basic resources throughout the product life cycle [23]. Data integration allows organizations to consolidate and manage various database types, facilitating data storage and dynamic adjustment. On the other hand, the implementation of intelligent technology facilitates automation and intelligence within the manufacturing process, significantly improving production efficiency. Utilizing big data, the production and operational technologies of manufacturing firms will progressively advance towards visualization. Visualization technology employs sophisticated charts, maps, and other tools to exhibit and evaluate diverse data created during the manufacturing process [24], facilitating a more intuitive comprehension of varied scenarios, ultimately enhancing quality and efficiency. This study contends that the creation of the Big Data Experimental Zone will facilitate the digital transformation of manufacturing businesses.

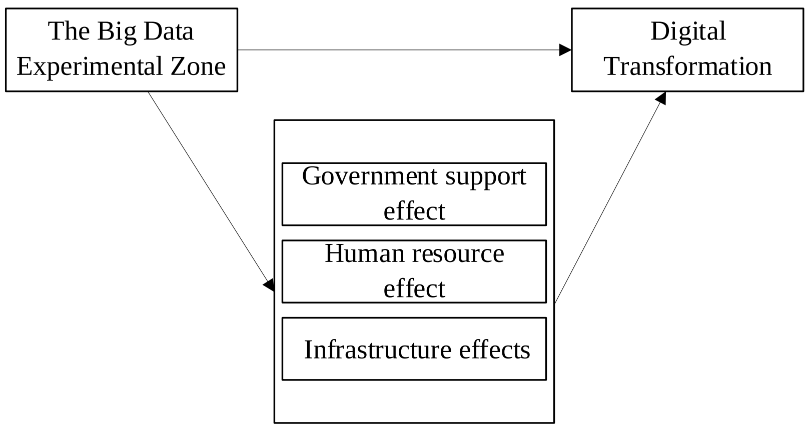

Figure 1: Theoretical mechanism analysis framework

H1: The institution of Big Data Experimental Zone significantly accelerates the digital transformation of manufacturing enterprises.

3.2. Government support effect

The impact of government support as a policy tool to encourage enterprises in intelligent manufacturing transformation is evident in two key areas. The primary objective is to minimize the costs and risks associated with transformation. Digital transformation necessitates that enterprises undertake technological upgrades, equipment modifications, and other investments that entail significant costs and associated risks [25]. The primary objective is to minimize the cost and risk associated with transformation. Supportive policies may include capital subsidies, tax incentives, and additional measures aimed at alleviating financial burdens on enterprises and decreasing transformation costs [26]. The goal is to lessen the financial strain on businesses and reduce the risks associated with technological progress. The decrease in transformation costs and risks promotes greater enterprise engagement in digital transformation and expedites the transformation process. Additionally, it conveys a more robust transformation signal to the investment community. Signal theory posits that government financial subsidies to manufacturing enterprises are perceived as "signals," indicating a shift towards digital transformation. When businesses receive project subsidies, this signal conveys a more compelling message to investors, thereby facilitating the successful implementation of digital transformation in manufacturing enterprises. Subsidy policies enable enterprises to demonstrate their willingness and commitment, reflecting their determination and capability in digital transformation [27]. These signals can bolster investor confidence and recognition of firms, thereby enhancing their capacity to secure capital in the financial market.

The establishment of the Big Data Experimental Zone will facilitate the involvement of relevant investment and financing institutions, leading financial institutions to ease loan conditions for enterprise transformation and offer a broader range of financial products. This initiative aims to alleviate financial pressures on manufacturing enterprises and support their digital transformation efforts. This paper posits that the Big Data Experimental Zone will facilitate the digital transformation of manufacturing enterprises via government support.

To this end, the following hypotheses are proposed in this paper:

H2: The establishment of the Big Data Experimental Zone will promote the digital transformation of manufacturing enterprises through the government support effect.

3.3. Human resource effect

Made in China 2025 focuses on a talent-centric strategy to enhance the development of professional and technical skills, business management expertise, and craftsmanship essential for the manufacturing sector, thereby fostering industry growth through a talent-driven approach. Capital investment and talent investment are essential components in the digitalization process of manufacturing enterprises [28]. They are critical for high-level design execution and industrial organization advancement. The creation of the Big Data Experimental Zone seeks to advance the growth of big data industries and to develop and attract the technical talent necessary for the sector. Simultaneously, it will create conducive conditions for the development and enhancement of big data platforms and associated supporting infrastructure, thereby substantially improving the human capital in the pilot region. Furthermore, the swift advancement of the big data industry has led to a growing demand for skilled professionals. It is increasingly essential for highly skilled workers to acquire expertise in professional technology and data processing within the big data domain. The fundamental shift in market demand necessitates that laborers consistently enhance their skill levels [29], thereby elevating the overall human capital of both the region and enterprises. The establishment of the Big Data Experimental Zone creates favorable conditions for enhancing human capital. By leveraging systemic advantages, it addresses the demand for high-level talent among enterprises and accelerates the digitalization of manufacturing operations.

To this end, the following hypotheses are proposed in this paper:

H3: The establishment of the Big Data Experimental Zone promotes the digital transformation of manufacturing enterprises through the human resource effect.

3.4. Infrastructure effects

Infrastructure is the fundamental framework and essential physical entity necessary for the proper running of organizations, enterprises, and society at large, enabling the seamless operation of businesses and ensuring the services rendered by social organizations to citizens. The Big Data Experimental Zone aims to enhance production process intelligence by bolstering regional network infrastructure, expanding 5G installations, and advancing the development of next-generation Internet technologies, including data centers, cloud computing, artificial intelligence, and blockchain technology. These measures significantly elevate the digitalization in the research and development, production, management, and services of manufacturing firms. Varian 30asserts that AI has significantly transformed industrial structure. The Big Data Experimental Zone has established a platform for the circulation of big data resources and facilitated the aggregation of big data industries [31], resulting in a decrease in the number of firms leasing digital equipment. The strategy not only reduces firms' expenditure on sourcing and integrating digital talent, but it also prevents indiscriminate investment in digital resources. The Big Data Experimental Zone has significantly accelerated the transformation of manufacturing firms towards digitalization and enhanced the overall standards of the manufacturing industry.

To this end, the following hypotheses are proposed in this paper:

H4: The establishment of the Big Data Experimental Zone facilitates the digital transformation of manufacturing companies through infrastructure effects.

4. Study design

4.1. Model Construction

This study examines the influence of the Big Data Experimental Zone on the improvement of manufacturing companies' digital levels using the double-difference method, utilizing the following model configurations:

$$digital\_level_{ijt} = \alpha + \beta bigdata_j \times post_t + X_{it} + Z_{jt} + \rho_i + \tau_t + \varepsilon_{ijt}$$

where subscripts i, j, and t denote firm, city, and year, respectively. The explanatory variable $digital\_level_{ijt}$ denotes the level of intelligent development of manufacturing enterprise i in year t. $bigdata_j$ is a dummy variable indicating whether the address j of the listed company belongs to the Big Data Experimental Zone, and a value of 1 means yes and a value of 0 means no; $post_t$ is a dummy variable before and after the implementation of the Big Data Experimental Zone policy, referring to Sun et al. [18]. The year of policy implementation is set as 2016, which is set as 0 before that, and 1 in 2016 and after. β for the core coefficients to be estimated. X_{it} represents a series of firm-level control variables, and Z_{jt} represents city-level control variables that may affect the level of manufacturing digitalization, the ρ_i represents the firm fixed effects, the τ_t is the time fixed effect, and ε_{ijt} is a random disturbance term.

(1) Explained variable (digital_level): "Digital level". This study assesses the level of digitalization in manufacturing enterprises using six indicators across three dimensions: intelligent manufacturing, intelligent application, and intelligent benefits, as outlined in the evaluation index system proposed by Jianxuan [32]. Advanced technology underpins intelligent manufacturing, and only with strong intelligent technology can essential assistance be offered for intelligent applications and advantages. As a result, two sub-indicators are chosen to measure the amount of intelligent technology: research and development (R&D) intensity, defined as the ratio of enterprise R&D expenditures to primary business revenue, and talent intensity, defined as the ratio of enterprise R&D staff to total employees. Two sub-indicators show that intelligent application is important for improving the intellectual capabilities of manufacturing companies. These are patent application (the ratio of invention patent applications to the number of employees) and software application (the ratio of utility model patent applications to the number of employees). Intelligent benefits show how far manufacturing companies have come intellectually in the market. This is measured by two sub-indicators: return on assets (the ratio of net profit to total assets) and cost-profit ratio (the ratio of net profit to the total of costs and expenses). This study utilizes the entropy weight approach to objectively ascertain the weights of the aforementioned indicators, finally determining the level of digital transformation in industrial businesses.

(2) Core explanatory variables (did=bigdata*post): dummy variables for the pilot policy of the Big Data Experimental Zone. Among them, bigdata represents the dummy variable for pilot and non-pilot areas, with pilot areas assigned a value of 1 and non-pilot areas assigned a value of 0; post is a dummy variable for shocks in the year of implementation of the pilot policy and in each time period afterward, with the year of implementation and afterward assigned a value of 1 and before implementation assigned a value of 0.

(3) Control variables (*X*, *Z*): this paper mainly controls from two aspects: enterprise level and city level. The specific measurement indicators are shown in Table 1.

Table 1: Control variable-specific measurement

variable	Name	measurement
firm_age	Age of business	Current year minus listed year 1, taken logarithmically
firm_asset	business asset	Natural logarithm of total assets at year-end
firm_dual	two jobs in one	Chairman of the Board of Directors and ManagingDirector (1=same person, 0=different person)
roe	net equity margin	Net Profit/Total Assets Closing Balance
audit	Audit opinion	1 for a standard unqualified opinion issued by anaccounting firm, 0 otherwise
capital_intensity	capital intensity	Total assets/operating income
top1	The shareholding ratio of the largest shareholder	The shareholding ratio of the largest shareholder (%)
cash_liquid	cash flows	Cash flow/total assets
firm_bm	Book-to-market ratio	Shareholders equity/company market

		capitalization
leve_ratio	Leverage/gear ratio	Total liabilities/total assets
city_gdp	Per capita GDP	Logarithmic urban GDP per Capita
gdp_2	Secondary industry structure	Share of secondary GDP (%)
gdp_3	Tertiary structure	Share of GDP in the third sector (%)

(4) Mechanism variables. The intensity of fiscal science and technology expenditures was selected to measure the government support effect (expenditure) [33]; using the city's information transmission, computer services and software industry employees/total urban employees to measure the city's digital talent (human) [34]. The total amount of telecommunication services, the number of cell phone subscribers, and the Internet penetration rate are selected, and the entropy method is used to assign weights to the indicators, and the resulting composite score characterizes the level of digital infrastructure construction (infra) [35].

4.2. Data collection and descriptive statistics

This study focuses on Chinese A-share listed manufacturing businesses from 2011 to 2022, employing the following methodologies to analyze the samples: Companies listed as ST and those delisted during the research period are eliminated; samples lacking essential characteristics are omitted; and to mitigate the impact of outliers on the regression results, a 1% winsorization is applied to continuous variables. A total of 23,071 valid samples were ultimately acquired. The financial and patent data for this study are sourced from the Cathay Pacific and Wind databases, while the city-level data is obtained from the National Bureau of Statistics. Table 2 presents the descriptive statistics of the primary variables in this study, revealing a significant disparity in the digital levels among various manufacturing businesses.

Table 2: Descriptive statistics of the main variable

Variable	Obs	Mean	Std.dev.	Min	Max.
digital_level	23,071	18.67	8.501	8.592	50.92
did	23,071	0.265	0.441	0	1
top1	23,071	33.49	14.05	8.900	71.62
roe	23,071	6.362	12.40	-61.69	34.22
firm_age	23,071	1.903	0.954	0	3.332
firm_asset	23,071	22.01	1.160	19.96	25.58
capital_intensity	23,071	983.8	822.5	164.0	5550
audit	23,071	0.976	0.152	0	1
firm_dual	23,071	0.335	0.472	0	1
cash_liquid	23,071	59.44	16.77	19.33	92.39
firm_bm	23,071	35.34	16.64	0	78.60

leve_ratio	23,071	38.46	19.12	5.317	85.40
city_gdp	23,071	11.22	0.453	10.17	12.14
gdp_2	23,071	40.59	7.801	15.97	52.93
gdp_3	23,071	52.76	9.825	36.61	83.73

5. Empirical analysis

5.1. Benchmark regression

This study employs the fixed effect model for analysis, as indicated by Model 1. Table 3 presents the model's estimation results for assessing the influence of the Big Data Experimental Zone establishment on the digital development level of manufacturing enterprises. Column (1) includes only enterprise and year-fixed effects. Column (2) adds enterprise-level control variables, while column (3) incorporates city-level control variables in addition to those in column (2). The analysis reveals that the inclusion of various control variables and fixed effects results in a significantly positive effect at the 1% level, indicating that the establishment of the Big Data Experimental Zone substantially enhances the digitalization level of manufacturing enterprises.

Table 3: Benchmarking Results

	(1)	(2)	(3)
	digital_level	digital_level	digital_level
did	1.27698***	1.29460***	1.28280***
	(0.00002)	(0.00002)	(0.00002)
Firm-level control variables	No	Yes	Yes
City-level control variables	No	No	Yes
firm fixed effect	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
_cons	18.26247***	-2.15086	-29.99434***
	(0.00000)	(0.59331)	(0.00906)
observed value	23071	23071	23071
Adjustment R2	0.7971	0.8012	0.8015

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses represent robust standard errors clustered at the company level. The subsequent tables are identical.

5.2. Robustness tests

In order to ensure that the results of the previous analysis are robust, the following robustness tests are performed.

5.2.1. Parallel trend test

A crucial prerequisite for employing the double-difference method is that the test and control groups exhibit identical trends prior to the policy shock 36. Consequently, this paper utilizes the event study method to perform the parallel trend test and analyze the dynamic effects surrounding the policy implementation.

Based on the sample interval, a window of 11 years is established, encompassing the initial 4 years (pre_4-pre_1) and the subsequent 6 years (post_1-post_6) of the Big Data Experimental Zone policy, with the 4th period prior to implementation (pre_4) as the reference period. If none of the coefficient estimates β for the periods preceding the establishment of the Big Data Experimental Zone are significant, this indicates that the manufacturing firms in both the control group and the pilot group do not exhibit significant differences prior to the establishment of the Big Data Experimental Zone, thereby satisfying the parallel trend test. The regression results are presented in Figure 1 (95% confidence interval). According to the parallel trend test, the coefficients from pre_1 to pre_3 are not significant, indicating no substantial difference between the pilot and non-pilot areas before and after policy implementation. Beginning in 2016, the coefficient demonstrates a notable upward trend, suggesting that the Big Data Experimental Zone positively influences the digital transformation of manufacturing enterprises.

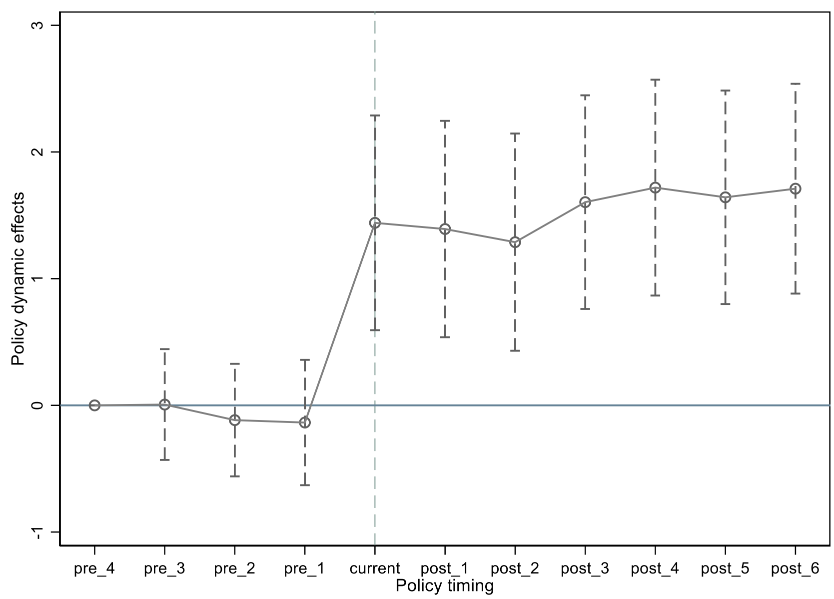

Figure 1: Parallel trend test

5.2.2. Placebo test

Even after accounting for many aspects that could affect manufacturing firms' digital transformation, it is still ineffective to definitively determine whether any significant explanatory variables have been excluded in the benchmark model. This work performs a placebo test to alleviate the influence of unobservable omitted factors on the benchmark regression findings. A random selection of cities in the treatment group, matched by treatment time, was generated based on the establishment of the Big Data Experimental Zone in 2016. Based on this, a randomly generated "pseudo" variable is created by cross-multiplying the two dummy variables, resulting in an estimate of the coefficient for the implementation of the city placebo related to the pilot policy of the Big Data Experimental Zone on the digital transformation of manufacturing enterprises. Executing the aforementioned steps 500 times will produce coefficient estimates for 500 "pseudo" Big Data Experimental Zones.

Figure 2 illustrates the density distribution of p-values for the regression coefficients pertaining to the "pseudo" big experimental zone in relation to the digital level of manufacturing enterprises. The black vertical line in the figure represents the actual regression coefficient (1.282801) found in column (3) of Table 3. The figure illustrates that the coefficient values of the randomly generated "pseudo" Big Data Experimental Zone. cluster around zero and are consistently lower than the benchmark regression results. The majority of p-values are significantly distant from zero, with only a minority falling within the 5% significance level (indicated by the horizontal black dotted line). This suggests that the observed results are not due to random chance but are indeed a consequence of the establishment of the Big Data Experimental Zone.

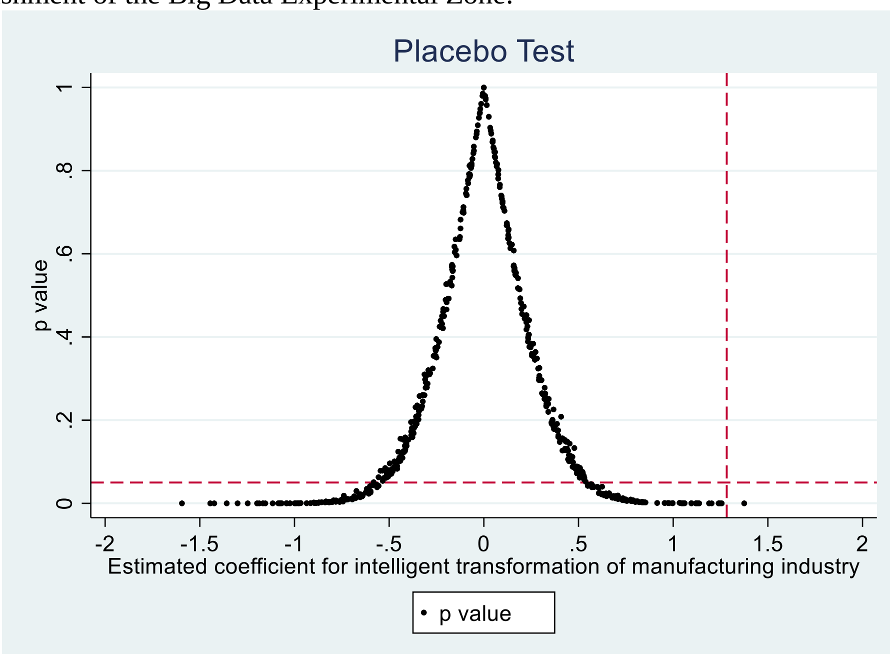

Figure 2: Placebo test

5.2.3. Other robustness tests

(1) Replacement of explanatory variables. This paper references the conceptual framework of digital transformation within the context of strategic change [37], defining digital transformation as a process that encompasses enterprise resources, capabilities, and the overall system. This assessment evaluates manufacturing enterprises through two dimensions: "strategic change" (intention) and "intelligent innovation" (behavior). The results in Table 4's column (1) show a significantly positive did coefficient. This means that changing the variable that is being explained does not change the results of the regression, which proves that the estimation results are reliable.

(2) Controlling for other policy shocks. Simultaneously with the establishment of the Big Data Experimental Zone, the execution of other pertinent policies will influence the digital level of manufacturing enterprises. Therefore, this paper aims to accurately determine the overall impact of the Big Data Experimental Zone on the digital transformation of manufacturing enterprises, while also minimizing the influence of other

policies during the research period. An analysis of the policies reveals an overlap between the location-specific initiatives of the Chinese government, such as the "Broadband China" policy pilot initiated in 2014, the national pilot for information accessibility in 2014, the national demonstration zone for Made in China 2025 established in 2017, and the AI innovation and development pilot zone launched in 2019. Additionally, the Big Data Experimental Zone is the only zone-oriented initiative implemented by the government. Geographically focused policies were implemented by the Chinese government. Consequently, to mitigate the impact of these policies on the regression outcomes, this paper incorporates the aforementioned policy shocks as control variables within the model. The regression findings in column (2) of Table 4 indicate that the coefficient of did remains significantly positive.

(3) PSM-DID. This research uses the propensity score matching-double difference method to reconstitute the control group for analysis, thus mitigating the potential issue of selection bias. Column (3) of Table 4 presents the regression results, indicating that the coefficients of the did analysis remain largely consistent with the baseline findings following the matching of experimental and control groups, thereby reinforcing the conclusion that the Big Data Experimental Zone positively influences the digital transformation of enterprises.

(4) Adjust the sample of treatment group. This paper excludes samples of firms registered in the municipalities of Beijing, Shanghai, Chongqing, and Tianjin due to their stronger political and economic scale and more advantageous resource elements. The results following the regression test are presented in column (4) of Table 4. The results remain significantly positive, suggesting that the analysis is more robust.

Table 4: Robustness test results

	(1)	(2)	(3)	(4)
	Substitution of explanatory variables	Policy shock	PSM-DID	Excluding municipalities
did	0.29699** (0.03989)	0.59542** (0.03000)	1.11647*** (0.00200)	0.01025*** (0.00169)
Information for the people		1.90289*** (0.00009)		
Broadband China		-0.56040 (0.22276)		
Made in China 2025		0.99543*** (0.00048)		
Artificial Intelligence Innovation and Development		0.60084*** (0.00232)		
control variable	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observed value	23071	23071	11569	19814
Adjustment R2	0.8432	0.8029	0.7956	0.7934

5.3. Heterogeneity tests

5.3.1. Enterprise heterogeneity

(1) Differences in ownership. Chinese enterprises' digital transformation process reveals differences in systems and resources between manufacturing enterprises, specifically state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs). Consequently, the sample is categorized based on the nature of property rights, and regression analyses are conducted concurrently. Table 5, columns (1) and (2), present the regression results for both analyses. In the regression analysis of state-owned enterprises, the did coefficient is positive yet not statistically significant; conversely, in the regression analysis of non-state-owned enterprises, the did coefficient is significantly favorable. The establishment of the Big Data Experimental Zone has positively impacted the digital transformation of non-state-owned enterprises, whereas its influence on state-owned enterprises remains limited. The disparity may arise due to the more intricate equity relationships and greater constraints faced by state-owned manufacturing enterprises compared to their non-state-owned counterparts, potentially leading to challenges during the digital transformation process.

(2) Firm size. Wang et al. (2019) measure firm size by asset size and categorize firms into large-scale and small-scale based on the median asset size. The findings presented in columns (3) and (4) of Table 5 indicate that the did coefficient is positive yet insignificant for large-scale firms, whereas it is significantly positive in the regression analysis of small-scale firms. The Big Data Experimental Zone significantly promotes the digital transformation of small-scale manufacturing enterprises, likely because these enterprises require external support to overcome technical and financial barriers associated with manufacturing transformation due to resource constraints.

Table 5: Enterprise Heterogeneity

	(1) Nationalized business	(2) Non-state enterprise	(3) broad scale	(4) limited scale
did	0.48530	1.76618***	0.45963	1.78052***
	(0.34668)	(0.00000)	(0.21935)	(0.00056)
Control variable	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observed value	6087	16952	11871	10886
Adjustment R2	0.7733	0.8153	0.8429	0.8116

5.3.2. Urban heterogeneity

(1) Regional Heterogeneity. The sample is categorized into eastern, central, and western cities according to geographic location, receiving values of 2, 1, and 0, respectively. The regression results are presented in columns (1) to (3) of Table 6. The results indicate that the did coefficient is significantly positive in the regression analysis for the eastern region,

while it is insignificant in the regression results for the central and western regions. The establishment of the Big Data Experimental Zone in the eastern region has been shown to significantly enhance the digital transformation of local manufacturing enterprises. Conversely, in the central and western regions, the development of the Big Data Experimental Zone has not yet substantially contributed to advancing the intelligence levels of enterprises in those areas. The disparity may be attributed to the eastern region's superior resources, infrastructure, and economic development compared to the central and western regions. Additionally, the policy support provided by the Big Data Experimental Zone can more effectively facilitate the digital transformation of manufacturing enterprises in the eastern region.

(2) City size heterogeneity. This study categorizes the data into three groups according to population size: small and medium-sized cities (less than 1 million), large cities (between 1 million and less than 5 million), and megacities (population size of 5 million or more). The detailed results are presented in columns (4) to (6) of Table 6. The creation of the Big Data Experimental Zone does not significantly impact the transformation of manufacturing industries in large and small to medium-sized cities; however, it does have a notably positive effect on the digital transformation of manufacturing enterprises in megacities. Megacities' economic aggregation effect and talent concentration advantage enable effective use of big data for urban resource allocation. This process accelerates the integration of big data with local industries, promotes industrial optimization and upgrading, and enhances the digitization level of manufacturing enterprises.

Table 6: Analysis of Urban Heterogeneity

	(1)	(2)	(3)	(4)	(5)	(6)
	the east	central section	western part	megacity	large cities	small or medium size city
did	1.23481***	1.07013	0.17596	1.25814***	0.39508	-0.99667
	(0.00064)	(0.19632)	(0.77232)	(0.00178)	(0.37132)	(0.22570)
control variable	Yes	Yes	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
observed value	16397	3833	2835	14001	7583	1477
Adjustment R2	0.8065	0.8002	0.7623	0.8125	0.7704	0.7300

5.4. Testing the influence mechanism

The prior theoretical analysis indicates that the establishment of the Big Data Experimental Zone may influence the digital transformation of manufacturing enterprises via three mechanisms: government support, infrastructure enhancement, and human capital development.

5.4.1. Government support effect

Analysis of the results regarding the government support mechanism indicates that the promotion effect of the Big Data Experimental Zone on the intensity of fiscal S&T expenditures is significantly positive at the 1% level, as shown in column (1) of Table 7. This finding suggests that the establishment of the Big Data Experimental Zone encourages local governments to enhance their investment in S&T innovation. Column (2) indicates that fiscal S&T expenditure positively influences the digital transformation of manufacturing enterprises. According to the results presented in column (4), both factors have a positive and significant impact on enterprises' digital transformation following the inclusion of the pilot policy in the model. Furthermore, compared to column (3), the did coefficient has decreased, indicating that the Big Data Experimental Zone policy enhances the technological innovation capacity of manufacturing enterprises. This is achieved by increasing the fiscal science and technology investment intensity, mitigating financing constraints encountered during the transformation phase, and ultimately facilitating a seamless digital transformation of manufacturing enterprises.

Table 7: Government support effects

	(1) expenditure	(2) digital_level	(3) digital_level	(4) digital_level
did	0.42460***		1.28280***	1.18171***
	(0.00000)		(0.00002)	(0.00013)
expenditure		0.31886***		0.23808**
		(0.00144)		(0.02019)
Control variable	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observed value	23071	23071	23071	23071
Adjustment R2	0.9005	0.8009	0.8015	0.8017

5.4.2. Human resource effects

At the 1% level, the results presented in Table 8 indicate that the Big Data Experimental Zone has a significantly positive impact on human capital in column (1). The Big Data Experimental Zone has positively influenced the advancement of big data-related industries and the development of talent within the big data sector. Column (3) incorporates the pilot policy and the level of human capital into the model, indicating a decrease in talent compared to Column (2). This means that the Big Data Experimental Zone can help solve the problem of not having enough talent for digital transformation by raising the level of human capital. This will provide a lot of talent to help manufacturing companies go digitalization and raise the level of digital transformation overall.

Table 8: Human resource effects

	(1) human	(2) digital_level	(3) digital_level
did	0.29891***	1.28280***	0.93280***
	(0.00000)	(0.00002)	(0.00375)
human			1.17093***
			(0.00009)
control variable	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observed value	23071	23071	23071
Adjustment R2	0.9709	0.8015	0.8020

5.4.3. Infrastructural effects

This paper further analyzes the baseline model by incorporating interaction terms between the Big Data Experimental Zone policy dummy variable and the Internet penetration rate, the number of mobile Internet subscribers, and the total amount of telecommunication services per capita. The results are presented in Table 9. The coefficients of the interaction terms are significantly positive, suggesting that the establishment of the Big Data Experimental Zone enhances the digital transformation of manufacturing enterprises in cities characterized by higher Internet penetration, a greater number of mobile Internet users, and a larger total volume of telecommunication business.

Table 9: Infrastructure effect

	(1) digital_level	(2) digital_level	(3) digital_level
did	-2.38406	-11.66231**	1.14649***
	(0.14326)	(0.02077)	(0.00011)
internet	-2.18486***		
	(0.00074)		
did*internet	0.92928*		
	(0.05064)		
mobile		-2.52973***	
		(0.00058)	
did*mobile		2.62081**	
		(0.01156)	
tele			0.00005
			(0.31064)
did*tele			0.00003*
			(0.09062)
control variable	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observed value	23071	23071	23071
Adjustment R2	0.8022	0.8022	0.8016

6. Conclusions and recommendations

This study examines China's A-share manufacturing companies listed on the stock market from 2011 to 2022, utilizing the double difference model to systematically analyze the impact of the national-level big data comprehensive pilot zone policy on the digital transformation of these enterprises. The study concludes that the establishment of a big data pilot zone significantly promotes digital transformation in manufacturing enterprises. This conclusion remains robust across various testing methods, including parallel trend tests, placebo tests, PSM-DID, and variable substitution. Heterogeneity analysis reveals variations in the impact of big data experimental areas on enterprises' digital transformation. At the enterprise level, the Big Data Experimental Zone significantly contributes to the digital transformation of non-state-owned manufacturing enterprises, whereas its impact on state-owned enterprises remains minimal. The policy demonstrates a more pronounced impact on facilitating digital transformation in smaller manufacturing enterprises relative to larger ones. The establishment of big data pilot zones in the eastern region has had a positive impact on manufacturing enterprises' digital transformation. However, in the central and western regions, the development of these pilot zones has not significantly advanced the digital transformation and upgrading of local enterprises. The establishment of big data pilot zones in large and small to medium-sized cities has a negligible impact on the manufacturing industry's transformation. However, the digital transformation of manufacturing enterprises in megacities has a notably positive effect. The creation of big data pilot zones has a significant impact on the intelligent development of manufacturing enterprises, particularly in first-tier cities. Additionally, these zones have a more pronounced positive impact on the transformation of manufacturing enterprises in non-resource cities compared to resource cities. 3 Mechanism analysis indicates that big data pilot zones can significantly enhance the digital transformation of manufacturing enterprises via government subsidies, human resources, and infrastructure.

The study's findings yield the following recommendations: Regions must actively promote big data development and leverage its positive impact on technological advancement and enterprise growth. Furthermore, it is critical to improve the policy-enabling effects of pilot big data zones on intelligent enterprise transformation. Second, big data pilot zones should develop strategies that reflect the specific circumstances of each region and the needs of businesses. Regions should integrate their unique characteristics, including economic development levels and resource endowments, to investigate a synergistic and innovative development model for the digital and traditional industries that is appropriate for the region. This approach will enhance the understanding of digital transformation and facilitate the digital transformation process within enterprises. The government should enhance its support for the digital transformation of non-state-owned and small to medium-sized manufacturing enterprises. Preferential policies, including finance and taxation, should allocate additional resources and financial support to improve the intelligence and innovation capabilities of non-state-owned enterprises and small to medium-sized enterprises, thereby facilitating their transformation and upgrading. Simultaneously, there should be an increased focus on talent development. Specialized training programs must be established to cultivate skills in pertinent technologies and management, addressing the requirements of non-state-owned manufacturing enterprises and small to medium-sized manufacturing firms. Practical opportunities and training resources enhance individuals' professionalism and application capabilities, thereby providing essential talent support for digital transformation. Infrastructure construction is essential for the digital transformation of manufacturing enterprises. To effectively promote digital transformation, localities must enhance the development of networks, cloud computing, the Internet of Things, and other infrastructures. This enhancement will provide robust support for big data collection, storage, processing, and analysis, thereby establishing a solid foundation for the advancement of the manufacturing industry and facilitating economic transformation and upgrading.

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