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Research on the Impact of Digital Economy on Manufacturing Resilience

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Abstract

This paper investigates the influence of the digital economy on manufacturing resilience by utilizing panel data from 30 provinces and regions in China spanning the period 2011-2020. Furthermore, it examines the mediating effect of technological innovation and industrial upgrading in the relationship between the digital economy and manufacturing resilience. The results demonstrate that the digital economy has a significant overall impact on enhancing manufacturing resilience in China. The analysis of regional heterogeneity reveals that the digital economy has a substantial positive influence on manufacturing resilience in both the eastern and central regions. Notably, the largest impact is observed in the eastern region, whereas the western region shows no significant effect. The mechanism analysis indicates that technological innovation and industrial upgrading partially mediate the impact of the digital economy on manufacturing resilience, with technological innovation acting as the primary mechanism. The conclusions remain robust even when employing alternative methodologies such as replacing the GMM methodology, substituting the measures of core explanatory variables, and utilizing the number of landline telephones per 100 people in each province in 1984 as an instrumental variable for 2SLS estimation.

Keywords

Digital Economy; Manufacturing Resilience; Technological Innovation; Industrial Upgrading.

1. Introduction

The manufacturing industry serves as the foundation of China's economy and acts as the primary driving force behind long-term, stable economic and social development. Since the initiation of the reform and opening up policy, China's manufacturing industry has experienced a phase of rapid development, witnessing an average annual growth rate of 8.12% from 1978 to 2021. However, China's manufacturing industry remains characterized by a large scale yet lacking strength, weak risk resistance, limited industrial core competitiveness, weak independent innovation ability, and a dependency on a few developed countries for key industry core technologies. These factors frequently subject the manufacturing industry to constraints, highlighting the need for improvements in its resilience. As geopolitical conflicts, including the Russia-Ukraine conflict, persist in the complex domestic and international environment, the instability of the global industrial and supply chain and the heightened risk of uncertainty pose significant challenges to the resilience and security of China's manufacturing industry. Given the current circumstances, it is imperative for China to address the urgent task of constructing a manufacturing powerhouse by fortifying the resilience of its manufacturing industry.

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Currently, the value of data as a pivotal production factor is becoming increasingly prominent. As the digital economy continues to transform global factor resources, economic structures, competition patterns, and various other aspects, nations worldwide recognize the significance of leveraging the digital economy and integrating it with the real economy to bolster industry resilience and risk mitigation capabilities. Following extensive infrastructure development, China has established a solid foundation and gained certain competitive advantages in the digital economy. The Global Digital Economy White Paper (2022), released by the China Academy of Information and Communications Technology, reveals that in 2021, the United States dominated the global digital economy with a value of 15.3 trillion U.S. dollars, while China ranked second with a value of 7.1 trillion U.S. dollars. From a proportional perspective, the digital economies of Germany, the United Kingdom, and the United States accounted for a substantial share of their respective GDPs, with the U.S. digital economy representing over 65% of its GDP. China's digital economy has experienced remarkable growth, increasing from 11 trillion yuan in 2012 to over 45 trillion yuan in 2021, with the proportion of the digital economy in the gross domestic product rising from 21.6% to 39.8%. Nevertheless, there is still ample room for improvement compared to developed countries. The rapid growth of China's digital economy has elevated data to the status of a crucial production factor, permeating numerous industries. Notably, it has played a vital supporting role in the development of the manufacturing industry. Hence, the question arises: Does the development of China's digital economy contribute to the enhancement of manufacturing industry resilience? Furthermore, what are the mechanisms through which this enhancement is realized? Existing studies have not reached a consistent conclusion. Therefore, this paper aims to address these questions by analyzing comprehensive development-level data on the digital economy and manufacturing resilience across 30 provinces and regions in China from 2011 to 2020. Econometric models will be employed to examine the impact of the digital economy on manufacturing resilience and elucidate the underlying mechanisms. This investigation holds significant importance in achieving high-quality development in China's manufacturing industry.

2. Literature Review

2.1. Section Headings

2.1.1. Sub-section Headings

In recent years, there has been a growing body of literature exploring the impact of the digital economy on the development of the manufacturing industry, coinciding with the resurgence of manufacturing in developed countries and the rapid advancement of digital technologies.

The first aspect pertains to the definition and measurement of the digital economy. The term "digital economy" was originally introduced by Tapscott Donu (1966). Currently, the academic definition of the digital economy is characterized by its broad scope, encompassing digital information (including data elements) as a vital resource. The Internet platform serves as the primary carrier of information, while digital technological innovation acts as a driving force, giving rise to a plethora of new models and business forms that exemplify the essence of the digital economy [1]. In terms of measuring the digital economy, international organizations such as the EU and OECD have proposed various indicators from different perspectives, including the foundation, application, and impact of the digital economy. In contrast, domestic research on digital economy indicators began relatively late. In 2017, the China Academy of Information and Communications Technology introduced the Digital Economy Index (DEI) evaluation system. Subsequently, several institutions, such as the SEDI Consultant, the Shanghai Academy of Social Sciences, Soochow University, and Xinhua San Group, have developed their own evaluation indicators for the digital economy at the national or regional level. These indicators exhibit significant variations. Broadly speaking, they can be classified into two

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categories: direct measurement methods and indicator system accounting methods. The former directly assesses the level of digital economy development by considering two components: digital industrialization and industrial digitization within a defined scope [2,3]. The latter method constructs a comprehensive evaluation system that captures multiple dimensions of the digital economy's core essence. This approach, which is relatively mature, enables horizontal or vertical comparisons between regions. For instance, Cheng Xiaomin and Zou Yanfen [4] propose a comprehensive evaluation system based on four dimensions: digital infrastructure, digital industry, revenue generation, digital service capacity, and digital innovation capacity, which allows the quantification of the digital economy's development at the provincial level. Similarly, Zhao Tao et al. [5] assess the comprehensive development of the digital economy at the city level, focusing on Internet development and digital financial inclusion.

The second aspect focuses on measuring manufacturing resilience and examining its influencing factors. The term "resilience" originally emerged in physics research to denote an object's capacity to restore its original state following external impacts. As the understanding of resilience evolved, it has been interpreted from three primary perspectives. The first two perspectives operate under the assumption of static equilibrium. However, as the research deepened, the concept of resilience gradually permeated the field of economics. Martin [6] introduced the concept of regional economic resilience from the standpoint of evolutionary economics. Subsequent studies expanded on this foundation to elucidate the notion of economic resilience [7-8]. Economic resilience entails the adaptive adjustment of a system's structure and functioning to navigate external changes and shocks, facilitating a return to the original growth trajectory or shift to a new one. It encompasses four dimensions: resistance, resilience, reorganization, and renewal [9]. Building upon Martin's theory of adaptive resilience, Li Liangang et al. [10] assert that regional economic resilience refers to a system's ability to withstand shocks, avoiding deviation from the development trajectory, and enabling sustained economic growth through adaptive recovery. They further highlight that this resilience is an ongoing evolutionary process. When examining manufacturing resilience, the measurement methods commonly employed include the indicator system method and the core variable method. One method involves a comprehensive assessment of manufacturing resilience, considering three dimensions: resistance, resilience, and reconstruction [11]. Another method entails measuring manufacturing resilience by comparing the actual growth trajectory of manufacturing labor productivity with a counterfactual growth path [12-13]. Enhancing manufacturing resilience is a systematic process influenced by multiple factors. Liu Rui et al. and Li Lanbing et al. investigated the theoretical mechanism through which manufacturing spatial agglomeration affects manufacturing resilience from the perspective of industry-adaptive structural adjustment and inter-industry interaction. Their findings demonstrated that manufacturing spatial agglomeration significantly enhances manufacturing resilience in China. Moreover, scholars have recognized various factors, including news media [14], emerging Industry 4.0 technologies [15], endogenous disruptions in manufacturing processes and systems, as well as extreme changes in demand and supply caused by exogenous supply chain disruptions [16], and digital twin technologies [17], as significant influences on the agility and resilience of manufacturing.

Thirdly, research has been conducted on the impact of the digital economy on the development of the manufacturing industry. As the digital economy has gained prominence, the relationship between the digital economy and industrial development has emerged as a central focus in academic research. Early studies examining the impact of the digital economy on industrial development primarily focused on the Internet and informatization. Han Xianfeng et al. [18] argued that informatization has emerged as a new driving force for fostering technological innovation activities, significantly enhancing the efficiency of technological innovation in

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China's industrial sector. Similarly, Guo Jiatang and Luo Pinliang [19] found that the Internet plays a substantial role in boosting productivity and driving technological progress, leading to an overall increase in total factor productivity in China. Additionally, Huang Qunhui et al. [20] asserted that Internet development positively impacts urban and manufacturing productivity by reducing transaction costs, mitigating resource mismatches, and fostering innovation. As global attention to the digital economy intensifies, and measurement methods steadily improve, scholars have adopted a holistic approach to investigating the impact of the digital economy on the development of the manufacturing industry. They posit that as digital information becomes a standardized medium in the industrial chain's circulation, the manufacturing industry chain will undergo deconstruction and reconstruction, gradually achieving comprehensive digitalization and transformation [21]. Moreover, the development of the digital economy directly fosters structural upgrading and high-quality development in China's manufacturing industry [22-27]. In comparison, limited research has been conducted on the relationship between the digital economy and manufacturing resilience. Hao Aimin and Ren Zhen conducted an empirical investigation into the impact of digitization in circulation on manufacturing resilience and explored its spatial spillover effect mechanism. The findings reveal a synergistic development between digitization in circulation and manufacturing resilience, showcasing a trend transitioning from low to medium levels of coupling and coordination. Moreover, digitization in circulation exerts a positive influence on enhancing manufacturing resilience.

Overall, research on the connotations and measurement of the digital economy and the factors influencing manufacturing resilience has been relatively extensive. However, studies investigating the mechanisms through which the digital economy influences the level of manufacturing resilience are limited. Therefore, a clear policy framework for leveraging the advantages of the digital economy to enhance the industry's resilience remains lacking. Building upon this foundation, this paper gathers panel data at the provincial level to examine the impact of the digital economy on the resilience of the manufacturing industry and investigate its underlying mechanisms. Specifically, it investigates the mediating role of technological innovation and industrial upgrading to elucidate the developmental pathway. The research's findings are expected to contribute valuable insights for promoting the high-quality development of China's manufacturing industry.

3. Mechanism Analysis and Research Hypotheses

3.1. Direct Impact of the Digital Economy on Manufacturing Resilience

Drawing upon the established definition of resilience, this research examines the influence of the digital economy on the manufacturing industry across three dimensions: resistance, resilience, and reconstruction. Firstly, the digital economy is significantly impacting the development of China's real economy, with the manufacturing industry serving as its primary battleground. The digital transformation of the manufacturing industry enhances the market competitiveness and value creation capabilities of manufacturing enterprises, resulting in accelerated revenue and profit growth [28]. Consequently, this strengthens the risk resistance capability of manufacturing enterprises and enhances the resilience of the manufacturing industry, establishing a solid economic foundation. Secondly, the digital economy is redefining the structure of the manufacturing industry, with the direction of digital and intelligent transformation becoming increasingly apparent. By addressing bottlenecks in the innovation chain, improving the quality of the manufacturing chain, and optimizing supply chain efficiency, the digital economy continuously strengthens the resilience of the manufacturing industry's supply chain [29]. Furthermore, it accelerates the speed and extent of recovery in times of crisis. Moreover, the digital economy enables the real economy to expand the industrial chain, reconfigure organizational models, and effectively integrate fundamental resources in the real

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economic domain. This fosters the ongoing stimulation of application scenarios and innovation in business models, ultimately facilitating the transformation of the manufacturing industry onto a new developmental trajectory [30]. Furthermore, as the digital economy permeates the manufacturing industry, influencing production modes, organizational structures, and value distribution, the industry undergoes adaptive adjustments that enhance its ability to navigate new developmental paths, thereby bolstering the resilience of the manufacturing industry.

Consequently, this paper posits Hypothesis 1: The digital economy significantly enhances the level of manufacturing resilience.

3.2. Mechanisms of the Digital Economy's Impact on Manufacturing Resilience

First, the effect of technological innovation: The advancement of digitalization enhances the innovation capacity of enterprises. In the digital economy, data resources possess the inherent advantages of shareability, reproducibility, and limitless growth. The development of highly connected and synergistic networks transcends spatial and temporal limitations in the flow of production factors, reduces information transfer costs and transaction costs, and provides enterprises with a convenient way to identify, acquire, integrate, and transform knowledge. This, in turn, accelerates knowledge spillover among enterprises and improves their innovation efficiency [31]. Moreover, the development of digital finance has a "structural" driving effect on enterprise technological innovation [32]. It effectively addresses the challenge of "difficult and expensive financing" for enterprises and promotes technological innovation output by facilitating enterprise deleveraging and stabilizing their financial status. The financial situation stimulates increased technological innovation output. The deepening of the digital economy has disrupted the traditional mode of commodity exchange through Internet technology. It fosters the transformation and development of the manufacturing industry from both the supply and demand sides. The digital economy industry plays a prominent role in driving the growth of the manufacturing industry, while the majority of manufacturing industries heavily rely on the development of digital elements driven by the digital product service industry [33]. The development of the digital economy has injected new impetus into China's manufacturing sector, accelerating its transformation, upgrading, and resilience.

Second, the effect of industrial upgrading: Industrial upgrading facilitates the efficient flow of production factors, optimizes resource allocation, and integrates different segments of the value chain. It stimulates technological innovation, strengthens the resistance and resilience of manufacturing enterprises, fosters self-regulation and creativity, and ultimately enhances the resilience of the manufacturing industry. On the one hand, data has emerged as a critical production factor, and the deep integration of digital economy-related industries with traditional sectors yields a multiplier effect, driving manufacturing enterprises to adopt new business models and pathways. This transformation and upgrading encompass digitization, networking, and intelligence [34]. Similarly, in the production process, digital information technology enables the digitization of the entire value chain, encompassing production, R&D and design, product manufacturing, marketing, management, and services. This digital transformation significantly enhances the information output capacity and value creation efficiency for manufacturers. Consequently, it stimulates the development of new industries, transforms traditional sectors, and continually, reshapes the fundamental structure of the industrial landscape under the new economic paradigm. These changes drive the transformation and upgrading of traditional industries through industrial collaboration, technology diffusion, and other mechanisms [35]. Industrial upgrading facilitates the advancement of the advanced manufacturing industry, facilitates adjustments in the manufacturing industry structure, and plays a positive role in promoting the resilience of the manufacturing sector.

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Accordingly, this paper proposes hypothesis 2: The digital economy enhances the manufacturing resilience through the effects of technological innovation and industrial upgrading.

Table 1. Three Scheme comparing

Numble	Scheme 1	Scheme 2	Scheme 3
1	456	456	123
2	789	213	644
3	213	654	649

4. Econometric Methodology

4.1. Model Specification

This research utilizes panel data from 30 provinces in China spanning the period from 2011 to 2020. The econometric model is employed to empirically design and test the hypotheses regarding the impact of the digital economy on manufacturing resilience, as discussed in the previous section. Firstly, the following econometric model is constructed to investigate the direct impact of the digital economy on manufacturing resilience:

$$MR_{it} = \alpha_0 + \alpha_1 Dig_{it} + \alpha_j X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{1}$$

In Equation (1), i,t denote region and year, respectively, Dig denotes the digital economy, MR represents the level of manufacturing resilience, X is the ensemble of control variables, u,v are individual fixed effects and time fixed effects respectively, and ε is the random error term. If the regression coefficient is significantly positive, it proves that the digital economy can enhance manufacturing resilience.

In order to investigate the underlying mechanism through which the digital economy impacts manufacturing resilience, the research incorporates the mediating effect methodology introduced by Wen Zhonglin and Ye Baojuan [36]. The specific model expands upon the previously mentioned Equation (1) and is presented as follows:

$$M_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_j X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{2}$$

$$MR_{it} = \gamma_0 + \gamma_1 Dig_{it} + \gamma_2 M_{it} + \gamma_j X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{3}$$

In Equation (2) and (3), The mediating variable M includes both technological innovation and industrial upgrading. In equation (1), the significance of coefficient α_1 is initially examined. Subsequently, in regressions (2) and (3), if any of the coefficients β_1 and γ_2 are found to be insignificant, the Bootstrap method is utilized to test the significance of the coefficient product. The presence of significantly positive coefficients in the regression confirms the assumption that the mediating variables play a role in enhancing the resilience of the manufacturing industry through the digital economy.

4.2. Selection of Evaluation Index System

In this paper, the explanatory variable selected is manufacturing resilience (*MR*), with the digital economy (*Dig*) serving as the core explanatory variable. Additionally, the control variables include the openness level (*open*), the degree of government intervention (*gov*), transportation infrastructure (*lntransport*), and market size (*lnrkmd*). Furthermore, the

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intermediary variables considered are technological innovation (*lninv*) and industrial upgrading (*upg*).

The explained variable, manufacturing resilience (*MR*), is measured using a comprehensive evaluation index system based on the approach proposed by Hao Aimin and Ren Zhen [11]. The entropy value method is utilized to assess the overall development level of manufacturing resilience on an annual basis. To capture the multidimensional aspects of manufacturing industry toughness, 14 secondary indicators are employed, categorized into three levels: resistance, resilience, and reconstruction. Table 2 provides a detailed overview of these indicators.

Table 2. Manufacturing resilience system evaluation index system

Total indicators	Level 1 indicators	Level 2 indicators
Manufacturing Resilience	Resistance	Manufacturing revenue/100 million CNY
		Total manufacturing assets/100 million CNY
		Total manufacturing profit/100 million CNY
		Manufacturing tax revenue /ten thousand CNY
	Resilience	Number of employed persons in manufacturing urban units/person
		Average number of employees in high-tech industries (manufacturing) / person
		Number of enterprises in high-tech industries (manufacturing)
		Number of enterprise-run R&D organizations in high-tech industries (manufacturing)
	Regenerative Power	Fixed Asset Investment in Manufacturing Industry /100 million CNY
		Number of new product development projects/item
		Number of R&D Personnel in High-tech Industries (Manufacturing) / People
		High-tech industries (manufacturing) R&D expenditure / million CNY
		Number of patent applications in high-tech industries (manufacturing) / piece
		Expenditure on technological transformation of high-tech industries (manufacturing industry) / ten thousand CNY

Core explanatory variables: digital economy (Dig). Referring to the research idea of Zhao Tao et al., this paper takes Internet development as the core of measurement and adds the index system of digital transactions, selects five specific indicators to construct the index system, and measures the comprehensive development index of the digital economy of 30 provinces and regions in China from 2011 to 2020 by using entropy method to reflect the level of development of digital economy in each region. Table 3 provides a detailed overview of these indicators.

Table 3. Digital economy development evaluation indicator system

Total indicators	Level 1 indicators	Level 2 indicators	Calculation notes
Digital economy	Internet development	Internet penetration rate	Number of Internet users per 100 people
		Number of Internet employees	Number of computer services and software employees
		Internet output	Total telecommunication services per capita
		Number of mobile Internet users	Number of cell phone users per 100 people
	Digital Financial Inclusion	Digital Financial Inclusion Development Level	Digital Financial Inclusion Index

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Control variables: In order to mitigate the estimation bias resulting from omitted variables, several control variables are included in the model. These variables are: the level of openness, which is measured as the proportion of total imports and exports to GDP. The degree of government intervention, which is measured by the ratio of fiscal expenditure to GDP, indicates the extent of government involvement. Transportation infrastructure, measured by the logarithm of road transportation route length. Market size, measured by the logarithm of city population density.

Mediating variables: To examine the impact of the digital economy on the resilience of the manufacturing industry and better understand the underlying mechanisms, this research introduces two mediating variables: technological innovation and industrial upgrading. Technological innovation is measured by the logarithm of the number of patent applications related to the digital economy in the region, a commonly used measure in the existing literature. Industrial upgrading is measured by the proportion of high-tech industries' main business income to the total industrial output value.

4.3. Measurement of Core Variables

To ensure a rigorous and objective approach, the evaluation index system construction method proposed by Hao Aimin and Ren Zhen [11] is adopted in this research to measure both the comprehensive development level of manufacturing resilience and the digital economy. The entropy method is employed for measurement. Prior to analysis, the data were standardized using the forward standardization method, which accounts for both the polarity and magnitude of each indicator, effectively eliminating their influence on the results. The specific Equation is as follows:

$$\mathrm{S_{ijt}}=(\mathrm{X_{ijt}}-\mathrm{X_{min}})/(\mathrm{X_{max}}-\mathrm{X_{min}})\times 0.99+0.1 \tag{4}$$

In equation (4): *i, j, t* are region, indicator, and year, respectively. X_{ijt} and S_{ijt} are the original data and standardized data, respectively. X_{max} and X_{min} are the maximum and minimum values of the j-term indicator during the sample period, respectively.

Next, the information entropy redundancy and indicator weights are measured. The calculation Equation is as follows:

$$W_{ijt}=S_{ijt}/\sum_{t=1}^{k} S_{ijt} \tag{5}$$

$$d_{jt}=1+(\ln m)^{-1}\sum_{i=1}^{m} W_{ijt}\times\ln W_{ijt} \tag{6}$$

$$d_{jt}=1+(\ln m)^{-1}\sum_{i=1}^{m} W_{ijt}\times\ln W_{ijt} \tag{7}$$

In equations (5)-(7): *k, m*, and *n* are the time range of the sample, the total number of regions, and the total number of indicators, respectively. $\mathrm{d_{jt}}$ is the information entropy redundancy. w_{jt} is the final weight of each indicator.

Finally, the comprehensive evaluation of manufacturing resilience (MR_{it}) and digital economy (Dig_{it}) in each year is obtained using the linear weighting method. The calculation Equation is as follows:

$$MR_{it}=\sum_{j=1}^{n}(w_{jt}\times S_{ijt}) \tag{8}$$

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$$Dig_{it}=\sum_{j=1}^{n}(w'_{jt}\times S'_{jt}) \tag{9}$$

The measurement process of the above variables and the related statistical descriptions are shown in Table 4.

Table 4. Results of basic descriptive statistics

Variable symbols	N	mean	sd	min	max
MR	300	0.127	0.135	0.0142	0.758
Dig	300	0.292	0.165	0.0277	0.859
open	300	0.274	0.290	0.0076	1.464
gov	300	0.264	0.114	0.120	0.758
lntransport	300	11.68	0.848	9.400	12.89
lnrkmd	300	7.890	0.407	6.639	8.669
ivgh	240	8.920	0.713	7.327	10.96
lninv	300	7.992	1.739	2.639	11.57
upg	300	0.923	0.071	0.002	0.338

5. Findings and Discussions

5.1. Benchmark Regression Results

The estimation results of the benchmark regression are presented in Table 5. Firstly, the regression equation includes only the explanatory and explained variables, and the estimation results are presented in column (1) of Table 5. The coefficient of MR is significantly positive at a 5% level, suggesting that the digital economy has a significant impact on enhancing the manufacturing resilience level of the provinces. Secondly, the regression model incorporates all control variables, and the results are displayed in column (2) of Table 5. It provides further evidence that the digital economy positively influences the manufacturing resilience level of the provinces at a significant level of 1%. The estimation results from column (1) to column (2) of Table 5 reveal that the core explanatory variables demonstrate stronger robustness. This indicates that the advancement of the digital economy contributes to an increase in the level of manufacturing resilience, supporting hypothesis 1.

Table 5. Benchmark regression test results

	(1)	(2)
	MR	MR
Dig	0.6236**	0.5808***
	(2.5976)	(4.1345)
open		-0.0581
		(-0.4879)
gov		0.1424
		(1.1364)
lntransport		-0.0185
		(-0.2923)
lnrkmd		0.0299
		(1.2060)
_cons	0.0291	-0.0027
	(0.9640)	(-0.0034)
Year	Yes	Yes
N	300	300
Adj. R2	0.3875	0.4134

Note: Values in parentheses indicate t-values of variables; ***, ** and * indicate 1%, 5%, and 10% significance levels, respectively.

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5.2. Robustness Tests

5.2.1. Altering the Measurement of Core Explanatory Variables

In order to mitigate the impact of measurement errors in key variables on the credibility of the regression results, this section replaces the measurement method of the digital economy and performs robustness tests. The principal component analysis method is used to replace the measurement method of the digital economy. The robustness test results, obtained by substituting the measurement method of the core explanatory variables, are presented in Table 6. Irrespective of the measurement method used, the impact of digital economy development on the resilience of the manufacturing industry remains relatively stable, as observed across various measurement methods of the core explanatory variables.

Table 6. Robustness test results for alternative measures of core explanatory variables

	(1)	(2)
	MR	MR
Dig_alt	0.0926**	0.0847***
	(2.5599)	(3.7335)
open		-0.0704
		(-0.5666)
gov		0.1285
		(0.9724)
lntransport		-0.0415
		(-0.6143)
lnrkmd		0.0277
		(1.0901)
_cons	0.2010***	0.4467
	(5.4933)	(0.5447)
Year	Yes	Yes
N	300	300
Adj. R^2	0.3544	0.3884
F	5.5084	6.9594

Note: Values in parentheses indicate t-values of variables; ***, ** and * indicate 1%, 5%, and 10% significance levels, respectively.

5.2.2. System GMM and Difference GMM Methods

The benchmark regression results presented above demonstrate a significant improvement in the level of manufacturing resilience due to the digital economy. In order to ensure the robustness of the empirical findings, this paper employs the GMM method to retest the model and validate the results. The specific results are presented in Table 7, where column (1) corresponds to the Difference GMM model, and column (2) corresponds to the System GMM model. The dynamic panel regression, as indicated by the P-value of AR (2) and the Sargan test, shows values greater than 0.1, suggesting the absence of autocorrelation in the residual term. The dynamic panel regression results reveal that the estimated coefficients of MR maintain their sign and significance, thereby confirming the robustness of the aforementioned empirical findings.

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Table 7. Robustness test results

	(1)	(2)
	MR	MR
L.MR	0.7660***	0.9484***
	(3.7926)	(4.8688)
Dig	-0.0135	-0.0114
	(-0.1007)	(-0.0694)
L.Dig	0.0492	0.0138
	(0.3556)	(0.0668)
open	0.0091	0.0582
	(0.3015)	(0.7800)
gov	0.0312	-0.0941
	(0.2399)	(-0.7673)
lntransport	-0.0240	0.0184
	(-0.1191)	(0.3597)
lnrkmd	0.0021	0.0008
	(0.0569)	(0.0280)
_cons	0.2794	-0.1997
	(0.1081)	(-0.2491)
N	240	270

Note: Values in parentheses indicate t-values of variables; ***, ** and * indicate 1%, 5%, and 10% significance levels, respectively.

5.3. Endogeneity Test

The above regression results confirm the impact of the digital economy on the level of manufacturing resilience. However, potential endogeneity issues arise as the level of digital economy development may exhibit reverse causality with manufacturing resilience, and unobserved factors may be omitted, leading to biased empirical results. Therefore, this paper adopts the indicator selection method proposed by Huang Qunhui et al. and Zhao Tao et al. and employs the number of fixed-line telephones per 100 people in each province in 1984 as an instrumental variable for two-stage least squares (2SLS) estimation. On the one hand, the public's exposure to the Internet initially relied on dial-up access through telephone lines, gradually evolving into the current fiber optic broadband access technology. Internet technology development can be traced back to the widespread adoption of fixed-line telephones. As the digital economy is reliant on modern information technology, there exists a strong correlation between the number of fixed-line telephones in history and the level of digital economy development. On the other hand, the number of fixed-line telephones in 1984 does not directly influence the current level of manufacturing resilience, satisfying the requirement of the instrumental variable "homogeneity". Furthermore, since this paper utilizes panel data, the aforementioned indicators represent cross-sectional data from a single year and cannot be matched with one another. Building upon the approach proposed by Peiwen and Yun Zhang [37], panel instrumental variables are created by incorporating time-varying variables. As such, an interaction term is constructed for each region between the national technical service income [38] and the number of fixed-line telephones per 100 people in 1984 from the previous year. These variables serve as instrumental variables for the digital economy index. The results presented in Table 7 indicate that the first column represents the first stage of 2SLS estimation. The estimated coefficient of the instrumental variable ivgh is significantly positive, suggesting a correlation with the instrumental variable. Additionally, the F-value exceeds 10, eliminating the concerns of a weak instrumental variable. The Kleibergen-Paap rk LM statistic

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demonstrates significance, rejecting the original hypothesis of inadequate instrumental variable identification. Moreover, the Cragg-Donald Wald F statistic is 1062.732, surpassing the critical value of 16.38, thereby rejecting the original hypothesis of weak instrumental variables. The second column in Table 8 represents the second stage of the analysis, which takes into account the issue of endogeneity. It is observed that the coefficients of the variables, both positive and negative, remain consistent with the previous benchmark regression results. This indicates that the impact of the digital economy on the level of manufacturing resilience remains positive and significant at a significance level of 10%. These findings further reinforce the reliability of the benchmark regression results, providing additional evidence that the development of the digital economy in the provinces contributes to the improvement of manufacturing resilience.

Table 8. Endogeneity results

	(1)	(2)
	Dig	MR
ivgh	0.2800***	
	(28.2423)	
Dig		1.7299*
		(1.8361)
open	-0.0662**	-0.0158
	(-2.7564)	(-0.1189)
gov	-0.2190**	0.4522
	(-2.1149)	(1.4760)
lntransport	-0.0280	0.0315
	(-0.7255)	(0.3503)
lnrkmd	0.0053	0.0122
	(0.3407)	(0.4149)
_cons	-1.7696***	-0.7940
	(-4.4228)	(-0.6347)
Year fixed effect	Yes	Yes
Individual fixed effect	Yes	Yes
N	240	240
Adj. R^2	0.9789	
F	427.4127	
Kleibergen-Paap rk LM statistic	73.608***	
Cragg-Donald Wald F statistic	1062.732	

Note: Values in parentheses indicate t-values of variables; ***, ** and * indicate 1%, 5%, and 10% significance levels, respectively.

5.4. Heterogeneity Analysis

This research categorizes the sample of 30 provinces in mainland China into three regions: the eastern region (including Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan), the central region (including Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, and Chongqing), and the western region (including Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Guangxi). The regional heterogeneity regression results are presented in columns (1), (2), and (3) of Table 9. The analysis reveals that the digital economy has a positive impact on the level of manufacturing resilience across all regions. Specifically, the digital economy significantly influences the level of manufacturing resilience in the eastern and central regions, while its

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impact on the western region is not significant. These findings indicate that the digital economy facilitates the development of manufacturing resilience in the eastern and central regions, ultimately enhancing the level of manufacturing resilience within these regions. A comparison of coefficients shows that the digital economy has the greatest effect on manufacturing resilience in the eastern region, followed by the central region, whereas its impact on the western region is not statistically significant. This discrepancy may be attributed to the higher level of digital economy development and application in the eastern and central regions, which have led to rapid advancements in the manufacturing industry. In contrast, the western region lags in digital economy development and has yet to fully reap the benefits of the digital economy.

Table 9. Results of heterogeneity test

	(1)	(2)	(3)
	eastern region	central region	western region
Dig	0.8293***	0.5562***	0.2358
	(3.2353)	(3.3655)	(1.2572)
open	-0.0561	0.1828**	0.1166**
	(-0.3267)	(2.2799)	(2.4174)
gov	0.4336	0.1098	-0.0017
	(1.3934)	(0.7350)	(-0.0280)
lntransport	-0.0334	0.0819	-0.0221
	(-0.2534)	(1.4646)	(-0.5709)
lnrkmd	0.1613	-0.0082	-0.0060*
	(1.1563)	(-0.3660)	(-1.8604)
_cons	-0.8834	-0.9376	0.3207
	(-0.4377)	(-1.3595)	(0.6825)
Year	Yes	Yes	Yes
N	110	100	90
Adj. R^2	0.4521	0.7392	0.5670

Note: Values in parentheses indicate t-values of variables; ***, ** and * indicate 1%, 5%, and 10% significance levels, respectively.

6. Mechanism Analysis

In this research, a new mediation effect model (Wen Zhonglin and Ye Baojuan, 2014) is employed to examine whether the digital economy enhances manufacturing resilience through the pathways of technological innovation and industrial upgrading. The results of the mechanism test, presented in Table 10, illustrate the impact of the digital economy on manufacturing resilience. Following the mediation effect process proposed by Wen Zhonglin and Ye Baojuan (2014), a stepwise regression is conducted as the first step. Although the stepwise coefficient test method ensures low Type I error, the test's strength must be considered. If any coefficient appears to be insignificant in the second step of the test, the Bootstrap method can be utilized to examine the significance of the coefficient product. However, the estimated coefficients in columns (1) and (2) of Table 10 do not pass the significance test. This outcome may be attributed to potential lags in innovation output, the time required to measure the level of technological innovation in the region, and the relatively short sample period in this research. Consequently, in the third step of the Bootstrap method, the Z statistic value is 3.50, surpassing the critical value of 2.58 at the 1% level. This indicates that technological innovation plays a mediating effect in the relationship between the digital economy and the resilience of the manufacturing industry. Furthermore, the test coefficient is

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significant, with an estimated coefficient of 0.5808 in column (2), suggesting that technological innovation partially mediates the impact of the digital economy on the resilience of the manufacturing industry. The mediation effect accounts for 0.8327 of the total effect. As shown in Table 10, columns (3) and (4) demonstrate that industrial upgrading, as the mediating variable, yields a Z statistic value of 1.96, which is significant at the 5% level of statistical significance. Additionally, the estimated coefficient of 0.4936 passes the 1% significance level, indicating that industrial upgrading partially mediates the impact of the digital economy on the resilience of the manufacturing industry. The ratio of the mediating effect to the total effect is 0.0859. The regression results in Table 10 confirm that the digital economy enhances manufacturing resilience through the effects of technological innovation and industrial upgrading. Technological innovation serves as the primary mechanism, thus supporting Hypothesis 2.

Table 10. Results of intermediary effect test

	(1)	(2)	(3)	(4)
	lninv	MR	upg	MR
Dig	0.0160	0.5808***	0.2009*	0.4936***
	(0.0149)	(4.1322)	(1.7455)	(3.3164)
lninv		-0.0007		
		(-0.1253)		
upg				0.4344
				(1.1935)
open	0.0541	-0.0581	0.0176	-0.0658
	(0.1956)	(-0.4863)	(0.4786)	(-0.5442)
gov	-1.6717	0.1412	-0.1045	0.1878
	(-1.5729)	(1.1267)	(-1.3249)	(1.3246)
lntransport	0.3476	-0.0182	0.1011*	-0.0624
	(0.8640)	(-0.2896)	(1.9300)	(-0.9326)
lnrkmd	-0.1390	0.0298	-0.0111	0.0347
	(-1.2374)	(1.1985)	(-0.7957)	(1.3393)
_cons	4.2470	0.0002	-1.0097*	0.4359
	(0.8688)	(0.0003)	(-1.7211)	(0.5566)
Year	Yes	Yes	Yes	Yes
N	300	300	300	300
Adj. R^2	0.8441	0.4113	0.3780	0.4498
F	108.1531	9.5769	8.0577	4.3027
Bootstrap test	Z=3.50>2.58, The mediation effect is significant		Z=1.96≥1.96, The mediation effect is significant	
proportion of mediation effect	Mediation/total effect=0.8327		Mediation/total effect=0.0859	

Note: Values in parentheses indicate t-values of variables; ***, ** and * indicate 1%, 5%, and 10% significance levels, respectively.

7. Conclusion and Recommendations

7.1. Research Conclusion

This research has constructed a comprehensive evaluation index system for the development level of the digital economy and manufacturing resilience at the provincial level. By collecting manufacturing data from 30 provinces in mainland China from 2011 to 2020, the impact of the

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digital economy on manufacturing resilience and its internal mechanisms has been empirically examined using panel fixed-effects model, instrumental variable two-stage least squares, and mediation effect models in a multidimensional empirical test. The following conclusions are drawn: Firstly, the development of the digital economy significantly enhances the level of manufacturing resilience and serves as a crucial driving force for the high-quality development of the manufacturing industry. This conclusion is consistent even after conducting robustness tests such as GMM. Secondly, the eastern and central regions experience greater dividends from the digital economy compared to the western region. Moreover, the digital economy has a more pronounced effect on improving the level of manufacturing resilience in the eastern and central regions compared to the western region. Thirdly, technological innovation and industrial upgrading play a partial mediating role in the positive impact of the digital economy on manufacturing resilience, with technological innovation being the primary mechanism of action.

7.2. Policy Recommendations

First, it is recommended to vigorously develop the digital economy and promote its deep integration with the manufacturing industry. Government departments should prioritize the construction of digital infrastructure, accelerate the implementation of artificial intelligence, cloud computing, 5G, and other emerging technologies, and facilitate the application of modern information and digital technology in the manufacturing sector. This will provide technical support and create the necessary conditions for the digital transformation of the manufacturing industry, consolidating the advantage of the digital economy in enhancing manufacturing resilience and gradually realizing the goal of becoming a strong manufacturing nation.

Second, it is important to leverage the strengths of each region and promote the synergistic development of the digital economy across all regions. For the eastern and central regions, building upon their existing advantages in digital economic development, increased investment in digital technology research and development is recommended. This will support the high-quality development of the manufacturing industry, improve data and information infrastructure, and actively explore new ways to integrate the digital economy with the manufacturing industry. Such measures will strengthen the positive impact of the digital economy on the resilience of the manufacturing industry. For the western region, considering the level of economic development and the regional development structure, the first step should be to enhance digital infrastructure construction and improve Internet communication network services. This will provide a solid foundation for the development of the digital economy in the region. Additionally, efforts should be made to enhance the mobility of spatial elements, tapping into the spatial spillover effect of the digital economy, and promoting the synergistic development of the digital economy in the eastern, central, and western regions.

Third, the significance of technological innovation and industrial upgrading in harnessing the positive role of the digital economy on the resilience of the manufacturing industry should be acknowledged, particularly the role of the technological innovation mechanism. The digital economy should be leveraged as a catalyst to drive technological innovation and industrial upgrading. This entails increased investment and support for innovation and research and development related to the digital economy. Manufacturing enterprises should be encouraged to widely adopt digital technology, capitalizing on the technological innovation effect of the digital economy to enhance the resilience of the manufacturing industry. Relevant government departments should promote and support technological innovation activities in the digital economy field, expedite the establishment of an appropriate digital economy governance system, strengthen intellectual property rights protection, and improve the supervision system for data element security. These measures will create a favorable policy environment that drives technological innovation and enhances the level of manufacturing resilience.

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