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Research on the Innovation Path of Modernisation and Development of Industrial Chain Supply Chain Empowered by Digital Economy

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ABSTRACT

The modernization and development of industrial chain supply chain in the era of digital economy is an important content to cultivate new quality productivity, maintain industrial competitiveness and realize industrial modernization. After the promotion effect of digital economy on the modernization and development of industrial chain supply chain, this paper takes China's digital economy data from 2012 to 2022 as the research object, designs the evaluation index system of the development level of digital economy, and measures the development level of digital economy by using entropy value method and Kernel density estimation method. The overall situation of China's digital economy development level is analyzed, and the dynamic evolution trend of digital economy development level is explored. Then, based on the threshold regression model, the benchmark regression and threshold effect analysis of the relevant influencing factors of the digital economy-enabled industrial chain supply chain modernization and development are carried out. 2012-2022 China's digital economy shows a steady upward trend, and its average annual growth rate reaches 1.8%, and the Kernel Density value decreases from 0.0474 in 2012 to 0.0425 in 2022, with the digital economy of each region level gap decreases. For every 1% increase in the level of digital economy development, the level of industry chain supply chain modernization and development is increased by 1.407%, and there are two threshold effects of economic double cycle and digital technology level for digital economy-enabled industry chain supply chain modernization and development. Enhancing the level of digital technology promotes the enhancement of the level of international and domestic economic double cycle, which in turn improves the level of modernization and development of industrial chain supply chain.

Keywords: Entropy value method, Kernel density estimation method, threshold regression model, digital economy, supply chain

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1. Introduction

In the process of building a modern socialist country, the modernization and development of material technology is the foundation. In the specific development, it is necessary to integrate and develop the strategy of expanding domestic demand and the supply-side structural reform, to continuously improve the quality and development level of domestic and foreign cycles, and to play a positive role in promoting the construction of the modernized economic system [1-5]. At the same time, it is necessary to actively improve the level of productivity, promote the integrated development strategy of urban and rural areas, promote the coordination and healthy development of inter-regional, improve the level of the industrial chain and supply chain, and consolidate the foundation for the development of the economy in terms of quality and quantity [6-9]. In the construction of the modernized economic system, the industrial system is the focus, so it is necessary to focus on the development of the real economy, constantly promote the development of the real economy, and consolidate the industrial foundation.

In the era of digital economy, digital infrastructure provides a solid foundation for the operation of the industrial chain supply chain, accelerates the intelligent transformation of important facilities of the industrial Internet, industrial Internet and Telematics, drives industrial digitalization and digital industrialization transformation, and lays a solid foundation for the modernization of the industrial chain supply chain [10-13]. And the digital economy is developing deeply, and digital technology and data elements are embedded to provide a new engine for the internal system operation of the industrial chain supply chain, which strengthens its ability to resist uncertainty risks, facilitates the main body at the end of the chain to carry out innovative activities with the help of new elements, and gradually improves the modernization level of the industrial chain supply chain [14-15]. Accordingly, under the continuous promotion of the digital China strategy, exploring the deep-level role of the digital economy on the modernization of the industrial chain supply chain has become the key to enhance the modernization level of the industrial chain supply chain with the potential of the development of the digital economy.

Literature [16] used structural path analysis to comparatively analyze the supply-driven and demand-pull industry chain structure. The study shows that the industrial chain structure is an important factor leading to the decoupling of the economy and carbon emissions. The more optimized the industrial chain structure is, the more sectors generate economic benefits under unit CO2 emissions, the higher the economic correlation is, and the lower the carbon emission correlation is. Literature [17], based on a large number of literature reviews, introduces the integration of agricultural economy from the aspects of concept, characteristics, layout and mechanism to achieve the maximization of the interests of farmers and enterprises, cities and rural areas, agriculture and other industries, so as to achieve the sustainable development of the whole region. It improves the efficiency of resource utilization and promotes the modernization and competitiveness of agriculture. Literature [18] analyzes a management model that covers the schedule of harvesting activities and transportation of raw materials to the final transformation in several industrial plants. This theoretical model is applied to derive a solution for an actual Argentine company. We show that the model achieves the target levels for the different objectives, except for the carbon balance, which is negative in all scenarios evaluated. Literature [19] investigates the joint optimization problem of production, inventory, transportation and pricing policies in a multi-product two-stage supply chain. It was shown that the profitability of a centralized supply chain is more stable than a decentralized supply chain when the product dependence changes. Literature [20] aims to focus on the impact of automated transportation affecting the logistics industry and will explain the reasons that have led to the increasing adoption of AGVs, but will also take into account the human desire to retain ultimate control over their creation. Literature [21] proposes a Tree Seed Sub-Algorithm based Feature Selection with Optimal Deep Learning Technique for Supply Chain Management (TSA-ODLSCM). The proposed TSA-odlscm model involves the design of feature subset selection method using Tree Search Algorithm (TSA) algorithm. In order to demonstrate the improved performance of the TSA-ODLSCM approach, a large number of simulations are executed and the results are examined in the following aspects. The experimental validation reports 96.52% improvement in the results of TSA-ODLSCM method over other methods.

Taking the connotation and characteristics of digital economy as the entry point, this paper analyzes the specific performance of the modernization and development of industrial chain supply chain, and studies the promotion effect of digital economy on the modernization and development of industrial chain supply chain. A digital economy development level evaluation index system is established from four dimensions: digital foundation, digital industry, digital application and digital environment. Taking China's digital economy development data from 2012 to 2022 as an example, the entropy method is used to measure the digital economy development level index, and the dynamic evolution trend of the digital economy is analyzed by the Kernel density estimation method. In addition, it also deeply analyzes the relevant direct effect and threshold effect of the digital economy empowering the modernization of industrial chain supply chain, and analyzes the specific impact of the economic double cycle and the level of digital technology on the modernization and development of industrial chain supply chain under the digital economy.

With the rapid development of the digital economy, digital technologies represented by big data, artificial intelligence, Internet of Things, cloud computing and so on penetrate into all aspects of the economy and society, promoting economic development to evolve towards the stage of more advanced form, more optimized division of labor and more reasonable structure, and injecting new impetus into the modernized development of the industrial chain supply chain, the construction of the modernized industrial system, and the transformation and upgrading of industries. Accelerate the construction of a modernized digital economic system, focus on improving total factor productivity, and focus on improving the resilience and security level of the industrial chain supply chain. Accelerating the development of the digital economy can promote the deep integration of the digital economy and the real economy.

The digital economy refers to a series of economic activities in which the use of digitized knowledge and information is the key factor of production, the modern information network is the important carrier, and the effective use of information and communication technologies is the important driving force for efficiency enhancement and the optimization of economic structure. Since entering the new century, with the continuous progress of science and technology, science and technology has also become a key link in changing the global innovation map, which has a significant impact on global economic development. The value created by the digital economy runs through all aspects of circulation, and plays an important role in investment, employment, economic structural transformation and the enhancement of consumption capacity. As a new economic form that creates social wealth, the digital economy, such as the industrial Internet, Internet of Things, intelligent manufacturing, e-commerce, online services and other new forms of the digital economy, has become a new power source that empowers the high-quality development of the economy and the modernization of the industrial chain and supply chain.

The essential features of the digital economy are shown in Figure 1, and the key to its difference from other economies is the change in production factors and production methods, i.e., digitalized knowledge and information, i.e., data, have become the key production factors of the digital economy. Modern information networks and information and communication technologies, i.e. digital technologies, have changed the mode of production, and new technologies and new infrastructures have reconfigured the business forms of the digital economy.

Enhancing the modernization level of industrial chain supply chain is the key to high-quality economic development. This paper tends to define the modernization of industrial chain supply chain as the development process of industrial chain supply chain continuously improving its innovation ability, value-added ability and its position in the global value chain, which is oriented to the fundamental need of building a modern industrial system. Its specific performance, as shown in Figure 2, includes five aspects, such as stronger innovation capacity, greener and more intensive, more digitalization, higher economic efficiency and more autonomy and control.

1) Stronger innovation capacity. Innovation capacity is the core of the modernization of the industrial chain supply chain.

2) Greener and more intensive. Deeply implement the sustainable development strategy, improve the coordination mechanism in the field of ecological civilization, build an ecological civilization system, and promote green development.

3) More digitalization. Develop the digital economy, promote digital industrialization and industrial digitization, promote the deep integration of the digital economy and the real economy, and create internationally competitive digital industry clusters.

4) Higher economic efficiency. Economic efficiency mainly refers to the high value-addedness of the industrial chain supply chain, while high value-addedness refers to the high position of the value chain, i.e. a country is in a higher position in the global value chain.

5) More autonomous and controllable. Enhancing the autonomy and controllability of the industrial chain and supply chain will be deployed as a key task, so as to effectively deal with the risk of chain breakage faced by the industrial chain and supply chain.

The mechanism of the digital economy empowering the modernization and development of the industrial chain supply chain is shown in Figure 3. From the perspective of the domestic cycle, the digital economy can smooth the social reproduction of the supply chain, connect and open the breakpoints and blockages in the production, distribution, exchange and consumption processes, improve the efficiency of the capital cycle and turnover of micro-enterprises, realize the dynamic balance between the supply and demand of the total social reproduction of capital at the macro level, and promote the effective synergy of the supply-side structural reform and the demand-side management to empower the supply chain modernization and development. From the perspective of the international cycle, guaranteeing the security of the industrial chain and supply chain, effectively unimpeded the national economic cycle, and promoting the digital transformation of the industrial chain and supply chain are the realistic and feasible paths for connecting the domestic and international markets, integrating into the global system of international division of labor, and realizing the mutual promotion of the domestic and international double cycle.

1) The digital economy promotes the smooth internal circulation of the industrial chain supply chain from production to consumption, enabling enterprises to accelerate the capital cycle and improve the efficiency of capital turnover, and promoting the dynamic balance of supply and demand in the reproduction of total social capital.

2) The digital supply chain extends the domestic supply chain to the international level and connects the domestic and international markets, which is conducive to enhancing the international competitiveness of the domestic supply chain, forcing the domestic supply chain to leapfrog and upgrade, and optimizing the structure of the international division of labor.

At present, the world is facing a great change that has not been seen in a hundred years, the instability and uncertainty of the external environment have increased significantly, the factor cost of the domestic economy and environmental capacity constraints are tightening, and the conversion of the old and new kinetic energy for economic development and the transformation and upgrading of the industrial structure are imperative. Vigorously promoting the modernization of the digital economy and supply chain, accelerating the shortcomings and weaknesses of the industry chain and supply chain, ensuring the smooth flow of the national economic cycle, and promoting the industry chain to the middle and high end of the value chain is the way to realize the high-quality development of the digital economy and modernization of the supply chain under China's new development pattern.

The research data used in this paper span from 2012 to 2022, and are all from statistical yearbooks, provincial statistical yearbooks, and the official websites of the Ministry of Industry and Information Technology and provincial industry and information technology. The selected data sources are authentic and reliable, and the very few missing values are supplemented by linear interpolation.

1) Digital economy development level index. When measuring the index of the level of digital economic development, this paper will comprehensively measure the level of digital economic development from four dimensions: digital foundation, digital industry, digital application and digital environment. The specific steps for measuring the index of digital economic development level are as follows:

Step1 As the indicators of each dimension in the comprehensive development index of the digital economy have different scales, the data are standardized and calculated by the method of extreme deviation:

2) Kernel density estimation method. Overall, China's digital economy shows an overall upward trend during the period of 2010-2022, and the index of digital economic development level grows from 0.1353 in 2012 to 0.1621 in 2022, and except for the negative growth of the digital economic development index in some years, most of the years show a positive growth trend, with an average annual growth rate of 1.8%. Among them, the digital economy development index in 2020 showed a more obvious downward trend, probably because due to the impact of the epidemic, all aspects of China's economic development have been impacted, and the development of the digital economy has encountered certain difficulties. With the continuation of the economic recovery trend, the scale of China's digital economy will reach a new high in 2022.

Specifically, the digital foundation index, digital industry index, digital application index and digital environment index also mostly show a fluctuating upward trend. The digital foundation index has been changing more smoothly on the whole, with a closer score each year, and the development trend began to slow down after reaching the highest value of 0.0365 in 2019. The digital industry index shows a trend of slower growth in the early period and faster growth in the later period, with a growth rate of 6.2% from 2017 to 2019, but that growth trend is interrupted in 2020. The change trend of the digital application index is relatively smooth, with fluctuations in individual years in the early stage, and basically maintains an annual growth rate of about 1.5% from 2018 onwards. The digital environment index has the most obvious growth trend, rising from 0.0306 in 2012 to 0.0436 in 2020, an increase of 42.48%, and maintaining growth in 2020, when the indexes are generally declining.

From the distribution position, the main peak position of the kernel density curve keeps moving to the right, indicating that the level of China's digital economy development is constantly improving, and its kernel density value decreases from 0.0474 in 2012 to 0.0425 in 2022, and the gap between the level of the digital economy in various regions is further narrowed. From the distribution pattern, the height of the main peak in 2017 compared with 2012 has a decreasing trend, and the width of the peak shows a gradually expanding trend, indicating that the absolute difference has expanded during this period. 2022 shows an increasing trend in the height of the main peak compared with 2017, and the width of the peak is gradually narrowing, so that the absolute difference decreases. From the perspective of distribution ductility, the kernel density curve shows a right trailing phenomenon, implying that regional differences in the level of China's digital economy development are gradually expanding.

In the age of digital economy, the new data elements are driving the change of the division of labor and status of the industrial chain. In the field of industrial development, the digital technology is embedded in the whole link production link of various industries, giving new development momentum to all walks of life, leading all walks of life to complete the transformation and modernization of the chain supply chain. This chapter mainly USES the relevant panel data collected in the previous article to make an empirical analysis, and explore the innovative path of the modernization of the digital economy.

1) The direct impact of the digital economy on the modernization and development of the industrial chain supply chain. Take the digital economy as the fundamental basis, play the advantageous role of the core enterprises of the digital economy, bring together the core technology and strength for the original type of innovation and development, and focus on the breakthrough of the core technology and the technology of the core project. In-depth implementation of the industrial foundation reengineering project, improve the top-level design, clarify the focus of the project, categorize the organization and implementation, take the digital economy as the basis, promote the deep integration of big data and the real economy, and provide policy guidance for the construction of the industrial foundation system. As a result, this paper puts forward the following hypotheses:

H1: The digital economy promotes the modernization and development level of the industrial chain supply chain.

2) Threshold effect of digital economy on the development of industrial chain supply chain modernization. As discussed in the previous section, the digital economy plays a specific role in promoting the double cycle of the international and domestic economy, and the development of the double cycle of the economy helps to increase the modernization and development level of the industrial chain of the industrial chain. This paper puts forward the following hypothesis:

H2: After controlling other conditions, the enabling role of the digital economy on the modernization and development of the industrial chain supply chain has the threshold effect of the economic double cycle.

The wide application and development of the consumer Internet strongly proves that digital technology can effectively enhance the ability of enterprises to adapt to market demand. At the same time, upstream suppliers can also clearly utilize this information with their own spare parts supply data in a timely manner for on-time supply of parts. If there is no digital technology-based digital ecological intelligence system, enterprises can not communicate and interact with customers in a timely and effective manner, flexible and intelligent production can not be realized, and the competitiveness of the industry chain supply chain can not be reflected. Therefore, this paper proposes the following hypothesis:

H3: After controlling other conditions, there is a threshold effect of digital technology level in the enabling role of digital economy on the modernization and development of industrial chain supply chain.

1) Principle of threshold regression model. Most of the mathematical models for analyzing the relationship between variables are linear models, while the non-linear relationship between variables often better reflects the real changes between variables. According to the data availability and data characteristics, on the basis of the panel threshold model, drawing on the research method of the threshold effect of environmental regulation on economic growth, we further analyze the threshold effect of the digital economy on the development of industrial chain supply chain modernization.

The basic form of the threshold regression model can be expressed as:

The above equation can be abbreviated as:

After obtaining the parameter estimates, it is necessary to test whether the threshold effect is statistically significant and the authenticity of the threshold estimates.

2) Threshold effect significance test

3) Dynamic panel modeling

In order to study the role of digital economy in promoting the modernization and development level of industrial chain supply chain, this paper takes the modernization and development level of industrial chain supply chain (MSCDL) as an explanatory variable and the development level of digital economy (DIG) as an explanatory variable, and establishes the dynamic panel model as follows:

4) Panel threshold model setting. The threshold value and the number of thresholds of the threshold panel model will not be disturbed by the human subjective setting, which mainly depends on the endogeneity of the sample data. In this paper, economic double cycle (CDI) and digital technology level

(DTL) are selected as the threshold variables, and a single threshold panel model and a double threshold panel model are set respectively, so as to study the nonlinear characteristics of the modernization and development level of the supply chain modernization of the digital economy-enabled industrial chain. The specific model settings are as follows:

The results show that the impact coefficient of digital economy on the modernization and development of industrial chain supply chain is significantly positive, indicating that there are persistent and cumulative characteristics of the effect of digital economy. From the estimation results of model (5), it can be seen that the impact coefficient of digital economy is significantly positive, indicating that the rapid iteration of digital economy can accelerate the process of industrial chain supply chain modernization, and its regression coefficient is 1.407, which reflects that for every 1 percentage point increase in the level of development of digital economy, the level of modernization of industrial chain supply chain development is increased by 1.407 percentage points, and at this time, H1 can be verified. The development of digital economy provides a new opportunity for the main bodies of the industrial chain supply chain to reconstruct the production process, organizational structure and product circulation with the help of new technology and data elements, and strengthens the ability of innovation and resistance to external risks. Gradually forging a stronger industry chain supply chain resilience system is conducive to accelerating the process of industry chain supply chain modernization and development.

1) Threshold effect test. Based on the threshold regression model established in this paper, the threshold effect test of digital economy empowering industrial chain supply chain modernization development is carried out, and the test results are shown in Table 4.

When the economic double cycle is the threshold variable, its P-value of single threshold at 1% significance level is 0.000, passing the single threshold test. However, the test values of double threshold and triple threshold are 0.312 and 0.956, respectively, which fail the significance test, indicating that only a single threshold exists when the economic double cycle is the threshold variable. When the level of digital technology is the threshold variable, its p-value of single threshold at 1% significance level is 0.003, which passes the single threshold test. The test values for double and triple thresholds are 0.295 and 0.891 respectively, both of which also fail the significance test, and there is also only a single threshold when digital technology level is the threshold variable. In addition, in order to test whether the threshold estimates are true, this paper uses the least squares likelihood ratio statistic LR to test the truthfulness of the threshold values. From the feedback results, it is easy to see that the LR statistic of the two threshold variables are located below the dotted line, which is smaller than the critical value under the corresponding significant level, indicating that the threshold estimation and the real value are consistent, and the estimation is real and reliable.

The threshold effect of the threshold is fully explained, and the threshold model proposed in this paper is reasonable. The two indexes of economic double circulation and number of word technology have the impact of the development level of the industrial chain supply, which is worth the return of the threshold.

2) Threshold effect model estimation results. On the basis of determining the number of thresholds and threshold values, this paper estimates the impact relationship of digital economy empowering industrial chain supply chain modernization development in different intervals through the threshold model. For more intuitive analysis, Table 5 shows the results of the threshold regression analysis of digital economy development on the modernization and development of industrial chain supply chain.

Under the single threshold model, the digital economy has a threshold only at the economic double cycle level of 0.458, which means that when the economic double cycle level is lower than 0.458, the role of the digital economy on the development of industrial chain supply chain modernization is -0.035, i.e., for every unit increase in the index of the level of the digital economy development, the development of the industrial chain supply chain modernization will be shrunk by 0.035 units. Above the threshold this facilitating effect becomes stronger, and the coefficient of effect is 0.283. This indicates that the level of economic double-cycle presents a nonlinear enhancing effect in the process of digital economy development to improve the development of industrial chain supply chain modernization, and at this time H2 can be verified. Also under the single threshold model, the digital economy has a threshold only at the digital technology level of 9.243. This means that when the digital technology level is lower than 9.243, the role of the digital economy on the modernization and development of the industrial chain supply chain is -0.085, i.e., for every unit increase in the digital economy index, the modernization and development of the industrial chain supply chain will shrink by 0.085 units. The promotion effect is enhanced after higher than the threshold value, and the coefficient of effect is 0.324. This indicates that the level of digital technology presents a non-linear enhancement in the process of digital economy empowering industrial chain supply chain modernization development, and at this time, H3 can be verified. In the process of digital economy development, innovative digital technology inputs can make the effective distribution of factor resources, and the crowding out effect is conducive to the rationalization and efficient allocation of all kinds of industrial chain supply chain factor resources, so the enabling effect of the digital economy on the modernization and development of industrial chain supply chain is obviously strengthened.

Based on analyzing the relevance of digital economy empowering the development of industrial chain supply chain modernization, this paper carries out a comprehensive measurement of the development level of digital economy with China's digital economy data from 2012-2022, and analyzes the impact of digital economy empowering the development of industrial chain supply chain modernization in combination with the panel threshold regression model.

1) China's digital economy shows a slow upward trend between 2010 and 2022, with the index value growing from 0.1353 in 2012 to 0.1621 in 2022, with an average annual growth rate of 1.8%. This reflects that the current development momentum of China's digital economy is more obvious, relying on the high-quality development of digital technology, which provides a technical guarantee for the development of the digital economy, and the industry is more clustered and at the same time, it is more in line with the development of the times.

2) The main peak position of the digital economy kernel density curve keeps moving to the right, and its kernel density value decreases from 0.0474 in 2012 to 0.0425 in 2022, reflecting that the level of China's digital economy development continues to improve, and the gap in the level of digital economy development between regions gradually decreases.

3) The high-speed iteration of the digital economy can promote the industrial chain supply chain modernization and development process to accelerate, the benchmark regression coefficient of the two is 1.407, which is manifested in the fact that for every 1% increase in the level of development of the digital economy, the level of modernization and development of the industrial chain supply chain is increased by 1.407%.

4) There is a single threshold effect of the economic double cycle of digital economy and the level of digital technology on the modernization development of industrial chain supply chain, with the threshold value of 0.458 and 9.243 respectively, and when the value of the threshold variable exceeds the threshold limit, the economic double cycle and the level of digital technology have a significant enhancement on the modernization development of industrial chain supply chain.

2. Relevance of the digital economy to the modernization and development of the supply chain

2.1. Connotation and Characteristics of the Digital Economy

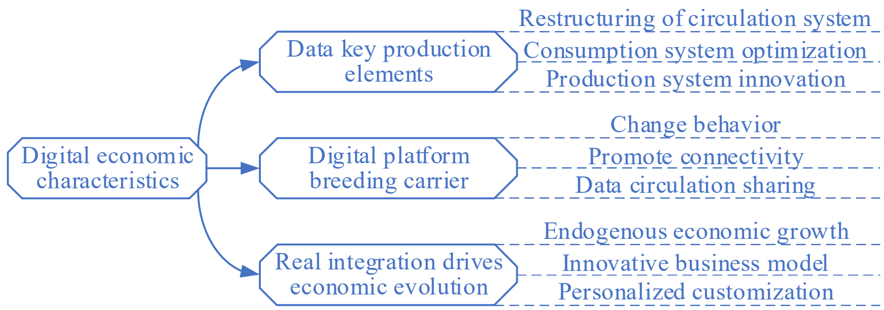

Fig. 1. The nature of the digital economy

2.2. Modernization of the industrial chain supply chain

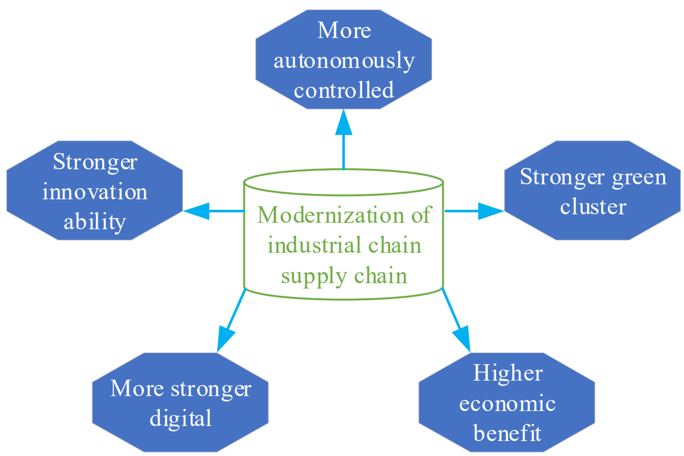

Fig. 2. Modernization of industrial chain supply chain

2.3. The role of the digital economy in the supply chain

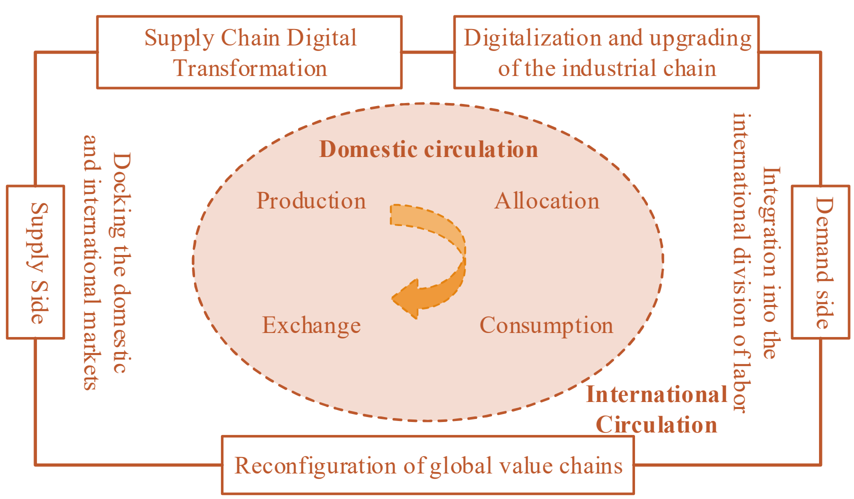

Fig. 3. The role of digital economy to supply chain

3. Measurement and evaluation of the level of development of the digital economy

3.1. Evaluation system for the level of development of the digital economy

3.1.1. Indicator system for the level of development of the digital economy. If you want to study the innovation-driven role of the digital economy on the modernization and development of the industrial chain supply chain, it is necessary to have an overall grasp of the level of digital economic development. Internationally, the EU measures the level of digital economy development by constructing a system of indicators for broadband access, human capital, Internet applications, digital technology applications, and the degree of digitization of public services. The OECD, on the other hand, measures through a four-indicator system of investing in smart infrastructure, empowering society, innovation capacity, and ICT for economic growth and job creation. The World Economic Forum measures the level of digital economy development by four indicators, including environment, readiness, application and impact. Synthesizing the research of domestic and foreign research institutions and academics, it can be found that the measurement of the development of the digital economy is mainly carried out from the three major modules of digital infrastructure, the convergence application of the digital economy, and the digital industry. Therefore, the evaluation system for the level of digital economy development established in this paper is shown in Table 1, which is mainly composed of four first-level indicators of digital infrastructure, digital industry, digital application and digital environment, as well as 17 second-level indicators.

Table 1. Digital economic development level index system

Level 1 index	Level 2 index	Code	Attribute
Digital base	The length of the cable per square kilometer	DB1	Forward
	Number of Internet broadband access terminals per square kilometer	DB2	Forward
	Every 100 people have a domain name	DB3	Forward
	Every 100 people have web pages	DB4	Forward
Digital industry	The main business income of electronic information manufacturing is the proportion of GDP	DE1	Forward
	The total amount of telecommunications is a proportion of GDP	DE2	Forward
	Internet and related service income	DE3	Forward
	E-commerce transactions account for the proportion of GDP	DE4	Forward
Digital application	Mobile phone penetration	DA1	Forward
	Internet broadband access	DA2	Forward
	Digital TV user penetration	DA3	Forward
	Industrial enterprises use computer Numbers per 100 people	DA4	Forward
	The proportion of enterprises with e-commerce trading activities	DA5	Forward
Digital environment	Telecom fixed asset investment total club will invest in fixed assets investment ratio	DE1	Forward
	The technology market is the proportion of GDP	DE2	Forward
	The number of people in the manufacturing industry of electronic and communication equipment	DE3	Forward
	Information transfer, software and information technology service industry	DE4	Forward

3.1.2. Digital economy development index measurement methodology

$$Y_{ij}=\frac{X_{ij}-\min\left(X_{ij}\right)}{\max\left(X_{ij}\right)-\min\left(X_{ij}\right)}+0.01 \tag{1}$$

Where i denotes the province, j denotes the measurement index, X_{ij} and Yij denote the initial data and the standardized index respectively, and $\max\left(X_{ij}\right),\min\left(X_{ij}\right)$ denotes the maximum and minimum values of X_{ij} respectively.

Step2 Measure the information entropy S_{ij} of indicator Y_{ij} in the comprehensive development level system of digital economy as:

$$S_j=-\ln\frac{1}{n}\sum_{i=1}^{n}\left[\left(Y_{ij}:\sum_{i=1}^{n}Y_{ij}\right)\right]\times\ln\left(Y_{ij}/\sum_{i=1}^{n}Y_{ij}\right) \tag{2}$$

Step3 Calculate the weight w_j for each indicator, i.e:

$$W_j=\left(1-S_j\right)/\sum_{j=1}^{mm}\left(1-S_j\right) \tag{3}$$

Step4 Construct the weighting matrix of the integrated digital economy development level system R_{ij} for:

$$R_{ij}=W_{ij}\times Y_{ij} \tag{4}$$

Step5 Multiply each of the standardized indicators with the weights and then sum them up to arrive at an index of the overall level of development of the digital economy for each year D_i, viz:

$$D_i = \sum_{i=1}^{n} R_{ij} \tag{5}$$

In order to more clearly and intuitively show the absolute difference and dynamic evolution of China's digital economy development level, this paper adopts the Kernel density estimation method to analyze the distribution position, posture, ductility and other characteristics of the kernel density curve of the digital economy development level, and tries to summarize the distribution law of digital economy development. Assuming that $f(x)$ is the density function of China's digital economy development level x, its specific form can be expressed as:

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{X_i - x}{h}\right) \tag{6}$$

Where N is the number of observations, X_i is the observation value, x is the mean value of the observation value, $K(\cdot)$ represents the kernel density function, h is the bandwidth, the smaller the bandwidth, the higher the estimation accuracy. In this paper, the Gaussian kernel function is used to estimate the dynamics of the distribution of digital economic development, then:

$$K(x) = \frac{1}{\sqrt{2}}\exp\left(-\frac{x^2}{2}\right) \tag{7}$$

3.2. Comprehensive evaluation of the level of development of the digital economy

3.2.1. Overall assessment of the level of development of the digital economy. Based on the above index system and calculation formula, this paper calculates the total index of China's digital economy development between 2012 and 2022. Then, based on the content of the indicators included in each sub-index, the scores of the dimensions of digital foundation, digital industry, digital application and digital environment are calculated, and the specific measurement results are shown in Table 2.

Table 2. The economic development level of 2012-2022

Year	Digital base	Digital industry	Digital application	Digital environment	Level index
2012	0.0291	0.0381	0.0375	0.0306	0.1353
2013	0.0324	0.0372	0.0369	0.0299	0.1364
2014	0.0318	0.0413	0.0405	0.0341	0.1477
2015	0.0332	0.0389	0.0411	0.0365	0.1497
2016	0.0301	0.0394	0.0402	0.0326	0.1423
2017	0.0319	0.0403	0.0392	0.0321	0.1435
2018	0.0353	0.0395	0.0376	0.0358	0.1482
2019	0.0365	0.0428	0.0382	0.0372	0.1547
2020	0.0324	0.0401	0.0394	0.0389	0.1508
2021	0.0306	0.0378	0.0406	0.0427	0.1517
2022	0.0342	0.0426	0.0417	0.0436	0.1621

3.2.2. Dynamic evolution of the level of development of the digital economy.With the help of the kernel density estimation method, taking 2012, 2017 and 2022 as the representative years, we analyze the distribution position, development trend and extensibility of the kernel density curve to explore the distribution characteristics and evolution trend of China's digital economy development. Figure 4 shows the distribution dynamics of China's digital economy development level.

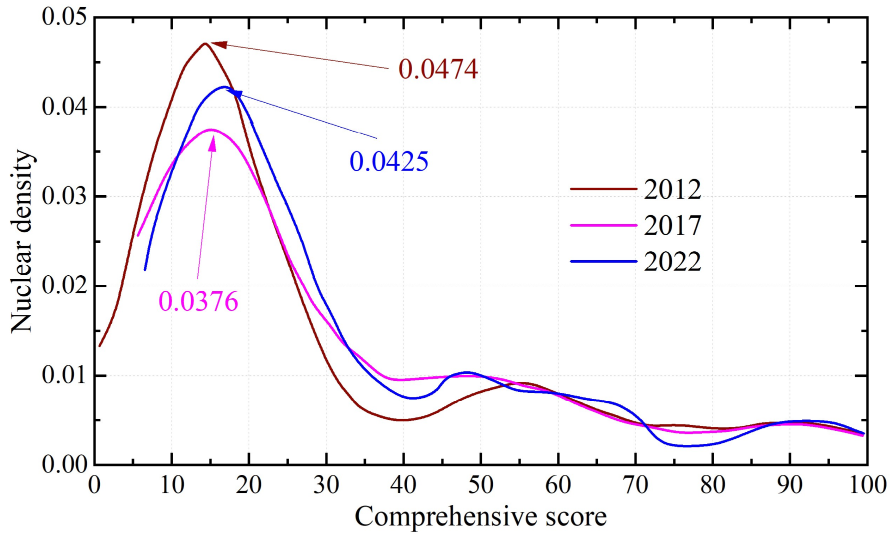

Fig. 4. The distribution of China's digital economic development level

4. Impact of digital economy-enabled supply chain modernization

4.1. Research Assumptions and Modeling

4.1.1. Research hypotheses for the digital economy:

1) The direct impact of the digital economy on the modernization and development of the industrial chain supply chain

Take the digital economy as the fundamental basis, play the advantageous role of the core enterprises of the digital economy, bring together the core technology and strength for the original type of innovation and development, and focus on the breakthrough of the core technology and the technology of the core project. In-depth implementation of the industrial foundation reengineering project, improve the top-level design, clarify the focus of the project, categorize the organization and implementation, take the digital economy as the basis, promote the deep integration of big data and the real economy, and provide policy guidance for the construction of the industrial foundation system. As a result, this paper puts forward the following hypotheses:

H1: The digital economy promotes the modernization and development level of the industrial chain supply chain.

2) Threshold effect of digital economy on the development of industrial chain supply chain modernization

As discussed in the previous section, the digital economy plays a specific role in promoting the double cycle of the international and domestic economy, and the development of the double cycle of the economy helps to increase the modernization and development level of the industrial chain of the industrial chain. This paper puts forward the following hypothesis:

H2: After controlling other conditions, the enabling role of the digital economy on the modernization and development of the industrial chain supply chain has the threshold effect of the economic double cycle.

The wide application and development of the consumer Internet strongly proves that digital technology can effectively enhance the ability of enterprises to adapt to market demand. At the same time, upstream suppliers can also clearly utilize this information with their own spare parts supply data in a timely manner for on-time supply of parts. If there is no digital technology-based digital ecological intelligence system, enterprises can not communicate and interact with customers in a timely and effective manner, flexible and intelligent production can not be realized, and the competitiveness of the industry chain supply chain can not be reflected. Therefore, this paper proposes the following hypothesis:

H3: After controlling other conditions, there is a threshold effect of digital technology level in the enabling role of digital economy on the modernization and development of industrial chain supply chain.

4.1.2. Modeling the digital economy

$$y_{it}\begin{cases} u_i+\beta_1 x_{it}+\sum\Phi\cdot z_{it}+e_{it}q_{it}\le\gamma \\ u_i+\beta_2 x_{it}+\sum\Phi\cdot z_{it}+e_{it}q_{it}>\gamma \end{cases} \tag{8}$$

$$y_{it}=u_i+\beta_1 x_{it}\cdot I\left(q_{it}\le\gamma\right)+\beta_2 x_{it}\cdot I\left(q_{it}>\gamma\right)+\sum\Phi\cdot z_{it}+e_{it} \tag{9}$$

where i denotes the region, t denotes the year, y_{it}, x_{it} are the explanatory and interpretative variables, respectively, z is a set of control variables, here Φ is the corresponding parameter vector, q_{it} is the threshold variable, γ is the threshold to be estimated, $I(\cdot)$ is the schematic function, u_i is used to control for unobservable individual characteristics of the different regions, and e_{it} denotes the random perturbation term.

If $\beta_1{}'\ne\beta_2{}'$ in the single threshold model of equation (9) holds, it suggests that the differences in the effects of the explanatory variables x_{it} on the explained variables y_{it} in the sample intervals with lower $\left(q_{it}\le\gamma\right)$ thresholds and in the intervals with higher $\left(q_{it}>\gamma\right)$ thresholds are characterized by nonlinearity. To estimate Eq. (9), within-group de-meanings of the sample observations of each variable to eliminate the effects of Eq. (9) fixed effects u_i are obtained:

$$\tilde{y}_{it}=\beta_1\tilde{x}_{it}\cdot I\left(q_{it}\le\gamma\right)+\beta_2\tilde{x}_{it}\cdot I\left(q_{it}>\gamma\right)+\sum\Phi\cdot\tilde{z}_{it}+\tilde{e}_{it} \tag{10}$$

where $\tilde{y}_{it}=y_{it}-\frac{1}{J}\sum_{i=1}^{J}y_{it},\tilde{z}_{it}=z_{it}-\frac{1}{J}\sum_{i=1}^{J}z_{it},\tilde{e}_{it}=e_{it}-\frac{1}{J}\sum_{i=1}^{J}e_{it}$, is iterated continuously over all observations, and the transformed model takes the form of a matrix, denoted:

$$y^*=z^*(\gamma)\cdot\beta+e^* \tag{11}$$

Least squares (OLS) estimation for a given threshold γ yields an estimate of parameter β:

$$\hat{\beta}(\gamma)=\left(z^*(\gamma)'z^*(\gamma)\right)^{-1}z^*(\gamma)'y^* \tag{12}$$

The corresponding residual sum of squares is denoted as $S_1(\gamma)$, i.e:

$$S_1(\gamma)=\hat{e}^*(\gamma)'\hat{e}^*(\gamma) \tag{13}$$

where $\hat{e}^*(\gamma)=y^*-z^*(\gamma)\hat{\beta}(\gamma)$, is the residual vector.

Since the residual sum of squares $S_1(\gamma)$ is a function of the threshold γ, the value of γ corresponding to the smallest hour of $S_1(\gamma)$ can be obtained endogenously by searching, i.e:

$$\hat{\gamma}(\gamma)=\arg\min_{\gamma}S_1(\gamma) \tag{14}$$

This in turn leads to $\hat{\beta}=\hat{\beta}(\hat{\gamma})$, the residual vector $\hat{\varepsilon}^*=\hat{\varepsilon}^*(\hat{\gamma})$, and the residual sum of squares $\hat{\sigma}^2=\hat{\sigma}^2(\hat{\gamma})$.

Although it is assumed that there is a threshold effect in the model setting process, whether it is statistically significant needs to be further tested. The original hypothesis for the significance test of threshold effect is $H_0:\beta_1=\beta_2$, the corresponding alternative hypothesis is $H_1:\beta_1\ne\beta_2$, and its test statistic is:

$$F = \frac{S_0 - S_1(\gamma)}{\hat{\sigma}^2} \tag{15}$$

Where, S_0 is the residual sum of squares obtained under the original hypothesis H_0. $S_1(\gamma), \hat{\sigma}^2$ is the residual sum of squares and residual variance obtained under alternative hypothesis H_1, respectively. If the original hypothesis is valid, the threshold value γ cannot be recognized and the distribution of the F-statistic is non-standard.Bruce E. Hansen proposes to use the self-sampling method to obtain the asymptotic distribution, which in turn leads to the corresponding probability P-value, also known as the self-sampling method P-value.

$$MSCDL_{i,t} = \beta_0 + \beta_1 DIG_{i,t} + \beta_2 HUM_{i,t} + \beta_3 FIN_{i,t} + \beta_4 INF_{i,t} + \beta_5 URB_{i,t} + \mu_{i,t} \tag{16}$$

The control variable HUM, FIN, INF, URB represents human capital, financial development, infrastructure development and urbanization level, respectively. i represents different provinces and cities, t represents different years, $\mu_{i,t}$ is a random disturbance term, and $\beta_0 \sim \beta_5$ is the coefficient of each variable.

$$\begin{aligned} MSCDL_{i,t} = {} & \alpha_0 + \alpha_1 DIG_{i,t} \times I(CDI_{i,t} \le \gamma_1) + \alpha_2 DIG_{i,t} \times I(CDI_{i,t} > \gamma_1) \\ & + \alpha_3 Control_{i,t} + \mu_{i,t} \end{aligned} \tag{17}$$

$$\begin{aligned} MSCDL_{i,t} = {} & \beta_0 + \beta_1 DIG_{i,t} \times I(DTL_{i,t} \le \gamma_1) + \beta_2 DIG_{i,t} \times I(\gamma_1 < DTL_{i,t} \le \gamma_2) \\ & + \beta_3 DIG_{i,t} \times I(DTL_{i,t} > \gamma_2) + \beta_4 Control_{i,t} + \mu_{i,t} \end{aligned} \tag{18}$$

Where $I(\cdot)$ is a schematic function, and the result is denoted as 1 when the inequality in parentheses holds, and vice versa. $CDI_{i,t}$ and $DTL_{i,t}$ are the two threshold variables in this paper, γ_1, γ_2 is the threshold to be estimated, $DIG_{i,t}$ is the core explanatory variable, and $\mu_{i,t}$ is the error term. α_1, α_2 is the to-be-estimated impact coefficient of digital economic development on urban-rural integration development under different levels of economic development. $\beta_1, \beta_2, \beta_3$ represents the to-be-estimated impact coefficient of digital economic development on the development of industrial chain supply chain modernization under different levels of digital technology. The samples are divided into different groups by the above two models, so as to further analyze the nonlinear impact of digital economic development on the development of industrial chain supply chain modernization under different levels of economic double-cycle and digital technology.

4.2. Enabling effects of the digital economy

4.2.1. Analysis of baseline regression results.For the dynamic panel model set in this paper, the asynchronous system GMM method is used to estimate its specific parameters, and the stepwise addition of control variables is used to estimate the benchmark regression. The results of the benchmark regression are obtained as shown in Table 3, where ***,**,* are significant at the 1%, 5%, and 10% levels, respectively, and the explanatory variables bracketed data are Z-statistic values.

Table 3. Benchmark estimate

	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)
DIG	1.416*** (9.125)	1.516*** (5.715)	1.689*** (5.523)	1.485*** (4.658)	1.407*** (4.715)
HUM	-	0.163*** (2.164)	0.171*** (2.012)	0.465*** (4.219)	0.385*** (4.015)
FIN	-	-	0.575*** (8.157)	0.627*** (7.859)	0.516*** (6.547)
INF	-	-	-	0.664***	0.689***

				(3.157)	(3.568)
URB	-	-	-	-	0.323*** (1.282)
AR (2)	-0.367 (0.518)	-0.061 (0.872)	0.065 (0.793)	0.514 (0.508)	0.481 (0.554)
Hansen	28.165 (1.024)	26.514 (0.847)	25.639 (0.751)	22.417 (0.723)	25.208 (0.642)
(Con_)	0.072* (1.769)	0.163*** (1.896)	0.241* (1.519)	0.276 (1.424)	0.251 (1.206)

4.2.2. Threshold effects of the digital economy.In the regression analysis of digital economy, structural mutation occurs from time to time, and the existence of the threshold effect model is to better explain and deal with such problems, and more accurately explore the change rule of the independent variable under the action of the dependent variable under different threshold values. In order to further explore the role of digital economy development in the modernization of industrial chain supply chain, this paper takes the economic double cycle and the level of digital technology as the threshold variable to carry out the threshold effect regression on the modernization of industrial chain supply chain, and explores the influence of digital economy on the modernization of industrial chain supply chain under the different levels of economic double cycle and digital technology.

Table 4. Threshold effect test results

Variable	Threshold	Threshold estimate	P	F	95% confidence interval		
					1%	5%	10%
CDI	Single	0.458	0.000	68.45	63.473	40.514	31.928
	Double	0.372	0.312	18.79	68.277	42.506	36.415
	Triple	0.269	0.956	5.62	50.246	33.572	27.833
DTL	Single	9.243	0.003	72.37	66.518	44.475	36.297
	Double	8.516	0.295	23.76	56.265	37.868	33.176
	Triple	10.184	0.891	8.58	98.626	66.597	54.329

Table 5. Threshold effect model estimates

Variable	Replace the explained variable	
	CDI (1)	DTL (2)
HUM	0.302***(3.573)	0.344***(3.816)
FIN	0.498***(2.469)	0.468***(2.547)
INF	0.515***(1.782)	0.523***(1.853)
URB	0.308***(1.054)	0.316***(1.018)
CDI	-	0.002(0.007)
DTL	0.018***(0.005)	-
DIG (CDI⩽0.458)	-0.035***(0.008)	-
DIG (CDI>0.458)	0.283***(0.051)	-
DIG (DTL⩽9.243)	-	-0.085***(0.005)
DIG (DTL>9.243)	-	0.324***(0.038)
(Con_)	0.157***(0.092)	0.105***(0.034)
R2	0.8671	0.8592

5. Conclusion

Based on analyzing the relevance of digital economy empowering the development of industrial chain supply chain modernization, this paper carries out a comprehensive measurement of the development level of digital economy with China's digital economy data from 2012-2022, and analyzes the impact of digital economy empowering the development of industrial chain supply chain modernization in combination with the panel threshold regression model.

1) China's digital economy shows a slow upward trend between 2010 and 2022, with the index value growing from 0.1353 in 2012 to 0.1621 in 2022, with an average annual growth rate of 1.8%. This reflects that the current development momentum of China's digital economy is more obvious, relying on the high-quality development of digital technology, which provides a technical guarantee for the development of the digital economy, and the industry is more clustered and at the same time, it is more in line with the development of the times.

2) The main peak position of the digital economy kernel density curve keeps moving to the right, and its kernel density value decreases from 0.0474 in 2012 to 0.0425 in 2022, reflecting that the level of China's digital economy development continues to improve, and the gap in the level of digital economy development between regions gradually decreases.

3) The high-speed iteration of the digital economy can promote the industrial chain supply chain modernization and development process to accelerate, the benchmark regression coefficient of the two is 1.407, which is manifested in the fact that for every 1% increase in the level of development of the digital economy, the level of modernization and development of the industrial chain supply chain is increased by 1.407%.

4) There is a single threshold effect of the economic double cycle of digital economy and the level of digital technology on the modernization development of industrial chain supply chain, with the threshold value of 0.458 and 9.243 respectively, and when the value of the threshold variable exceeds the threshold limit, the economic double cycle and the level of digital technology have a significant enhancement on the modernization development of industrial chain supply chain.

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