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EXPLORING FACTORS INFLUENCING THE DIGITAL ECONOMY: UNCOVERING THE RELATIONSHIP STRUCTURE TO IMPROVE SUSTAINABILITY IN CHINA

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Abstract. Digital economy is a great route to promote the efficient utilization of natural resources and promote sustainability due to its high-tech, rapid growth, extensive penetration, deep integration and other characteristics. Existing study on the influencing factors of the digital economy is not deep enough and lacks the analysis on the relationship structure of factors influencing the digital economy, which is not conducive for an overall grasp of the digital economy. To correctly understand how to better develop the digital economy, this paper studies its influencing factors and the relationships between them. Based on the time-series data of China from 2002 to 2018, grey correlation analysis was applied to calculate the correlation between these influencing factors and the digital economy, and determine the major influencing factors of digital economy development in China. The Granger causality test and a review of existing research were used to judge the interrelationship of various factors. The interpretative structure model was utilized to determine the relationship structure of the main factors affecting the development of China's digital economy. The results show that the number of digital talents, state of the technology market, and degree of digitalization are direct influencing factors of the digital economy. The results help to better understand the development of the digital economy and will enable the implementation of policies to improve towards more sustainable cities.

Keywords: digital economy, influence factors, relationship structure, sustainability.

JEL Classification: L63, L86, L96, Q56.

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1. Introduction

Natural resources are important material basis of the survival and development for human beings, and indispensable guarantee for economic and social development and people's livelihood. With the rapid economic and social development, natural resources have been largely consumed and wasted by human beings (Zhu et al., 2017). The unreasonable development and utilization of natural resources have led to resource shortage and environmental problems. The rational development and efficient use of natural resources have become extremely important for the fulfilment of the Sustainable Development Goals (SDGs). The vigorous development of digital economy (DEY) opens up new possibilities for the realization of this goal.

The DEY has turned into a new driver for global economic recovery and prosperity, greatly changing people's productivity and lifestyles through the availability of new products and services and contributing to the development of more sustainable cities (Pouri & Hilty, 2018; Karintseva et al., 2019; Adedoyin et al., 2020). With the fast development of digital technology, the unique advantages of this economic form have emerged. A DEY is characterized by high technology, extensive penetration, rapid growth, and deep integration. It is becoming more important to the country's economic development in the new era (Zhu & Chen, 2022), and governments of various countries have supported it in varying degrees.

China, as the world's second largest economy, its DEY is in good shape with a expanding scale and optimized structure. In 2002, the total value of China's DEY was 1,222 billion yuan, accounting for 10.3% of its gross domestic product (GDP); 614.6 billion yuan (5.2%) was from digital industrialization, and 607.4 billion yuan (5.1%) was from industrial digitalization (China Academy of Information and Communications Technology [CAICT], 2015). In 2021, China's DEY hit 45.5 trillion yuan, with the share of the DEY in national GDP being 39.8% in 2021; 8.35 trillion yuan (7.3%) was from digital industrialization, and 37.18 trillion yuan (32.5%) was from industrial digitalization. In terms of each region, the DEY development level in economically developed provinces is higher. The total volume of the DEY in 16 provinces has all exceeded 1.0 trillion yuan in 2021, such as Guangdong, Jiangsu, Shandong, Zhejiang, Shanghai, Beijing, and Fujian. In this respect, Beijing, Shanghai, and Tianjin accounted for more than 50% of the GDP ratio in the same year. Additionally, Guizhou and Chongqing led the country in 2021 with more than 20% growth rate in DEY (CAICT, 2022a).

However, there is still a significant gap in China's development in the DEY compared to advanced economies. From a global perspective, China, the United States, and the European Union have formed a three-pole pattern for the development of the world's DEY: In 2021, in terms of scale, the US DEY still ranked first in the world, with a scale of $15.3 trillion, while China ranked second with a scale of $7.1 trillion, with a difference of $8.2 trillion between the two; In terms of proportion, the DEY in Germany, the United Kingdom, and the United States all account for over 65% of GDP, much higher than China (CAICT, 2022b). Against the backdrop of carbon emissions reduction, China's DEY urgently needs to achieve better development, which is a Chinese issue and also a global concern. Therefore, China is selected as the research case to examine the theme of this article.

The growth of China's DEY has driven productivity growth with a disparate influence on employment across economic sectors (Zhang & Chen, 2019). Moreover, Tian et al. (2022) have empirically found that the penetration of the DEY into green finance reduces the unbalance of regional economic development in Chinese provinces. And Dai et al. (2022) have shown how to accelerate the development of regional green innovation. For all these reasons, it is vital to know the factors that favor the DEY development, since in this way the appropriate measures could be implemented to maximize the benefits of digitalization, while minimizing the risks that could be associated with it, such as the misusing natural resources, environmental pollution, violation of privacy, emerging oligopolies or financial risks. Verhoef et al. (2021) also expressed the need to better understand the elements that promote digital economic development in their study on digital transformation and business model innovation.

Therefore, scholars have carried out study on the influencing factors (IFS) of the DEY. For example, Forenbacher et al. (2019) established a binary logit model to study the determinants of mobile phone ownership in Nigeria, and the results showed that the most important factors seem to be education level, informal work, social participation, type of electricity supply, and employment status. The research of Peña et al. (2020), based on the principal component analysis method, indicates that the technological capability of a region clearly depends on the formal education level of its residents, while their use of technology (such as information and communication technology) depends on the social openness level and cultural level of citizens. However, the present study on the IFS of the DEY is not deep enough, and the lack of analysis on the relationship structure of the factors affecting its development is not conducive for an overall grasp of the DEY. While correctly understanding the relationship structure of the factors is the basis of predicting the DEY development and its effects, which can refer to the approach of Nie and Duan (2023). To this end, this article takes the IFS and relationship structure of the DEY as the study theme. Through the complementary advantages of multiple methods, the analysis of this problem in this article is more scientific and the results are better presented.

This study makes three major novel contributions to the literature as follows: first, the relationship structure of factors influencing the DEY, a field that has received little attention, was explored. Second, a modified interpretative structure model (ISM), namely LGG-ISM, was built by combining the literature research method, grey relational analysis, Granger causality test, and ISM. This model absorbs the advantages of these four methods, and is feasible and more scientific. Third, the LGG-ISM was used to quantitatively study the relationship structure of factors affecting the DEY of China, and these factors' relationship structure was directly presented in the form of diagram and numbers. This enables policy makers to examine China's DEY development from a new perspective, providing a reference for the country to better advance sustainable development of its DEY.

This article is structured as follows: Section 2 summarizes and analyzes the existing research. On this basis, the possible IFS of DEY development and their corresponding measurement indicators are screened at first in Section 3. Then this section also presents the grey relational analysis method utilized to quantitatively explore the main factors affecting the development of China's DEY. Section 4 explores the relationship between the IFS through a Granger causality test, and the ISM is used to study their relationship structure. Finally, the research results are summarized and discussed, and policy implications and future research fields are set forth.

2. Literature review

Study on the DEY has grown in the late years as scholars across the world began to pay more attention to it. The existing literature covers many aspects, such as the concept, connotation, measurement (Xiao et al., 2023), IFS, development path, effects, and government regulation of the DEY. However, people's understanding of DEY is limited because it is still an emerging economic form. Therefore, it is necessary to understand the factors affecting its development to formulate precise and efficient policies and measures to better promote it. A good start has already been made in this area, with scholars having conducted qualitative studies on it (Alam, 2012; Sturgeon, 2019; Sukhodolov et al., 2019), and others having examined it quantitatively (Zhao et al., 2015; Domazet & Lazić, 2017; Ali et al., 2018; Lechman & Popowska, 2022). The IFS of the DEY can be summarized as internal and external factors.

According to existing research, the external factors that affect the DEY development can be mainly divided into regional factors, sociodemographic factors, institutional factors, and policy factors. Among them, regional factors incorporate city level, economic development status, industrial structure level, degree of opening up, science and technology level, and so on. They often play a positive role in the DEY development. Beilock and Dimitrova (2003) used a Tobit model and regression analysis to analyze the difference in Internet usage in 105 countries. The study showed that social openness is an important factor causing differences in Internet usage. Li (2013) used Partial Least Square method to empirically analyze the factors affecting Internet diffusion in China, which showed that economic level, scientific and technological level, and urbanization level are the major factors affecting Internet diffusion in China. Cai et al. (2022) analyzed the IFS of China's DEY development based on the panel data of 30 provinces in China from 2013 to 2019. The results indicated that economic growth, foreign capital dependence, industrial structure optimization, and urbanization have a positive promoting effect on the DEY development level.

There are differences in research conclusions regarding the impact of sociodemographic factors on the DEY development. However, more studies have shown that sociodemographic factors can also affect the DEY development. Based on panel data on the development of the Internet in 161 countries from 1999 to 2001, Chinn and Fairlie (2007) used a regression analysis to study the IFS of computers and the Internet popularization. The results showed that per capita income, education level, and population structure impact the use of computers and the Internet. Vicente and López (2008) used the linear random utility model to study the Internet development in nine Eastern European countries. Their research showed that income level, education level, and age are the main factors affecting Internet use. The empirical research based on panel data model by Billon et al. (2017) indicates that education inequality affects Internet use. The study of Quiban (2021), based on the Bass diffusion model, shows that compared to low-income countries, high-income ones have higher internet diffusion rates. Gazzola et al. (2021) investigated the main characteristics of the DEY in Italy through a questionnaire analysis and revealed the potential behavioral factors of its participants. The results showed that the age of consumers affected participation in the DEY, while gender and annual income were not important determinants.

The influence of institutional and policy factors on the development of the DEY cannot be ignored. Zhao et al. (2007) based on a panel data of 39 countries from 1995 to 2003, used the Pooled ordinary least squares (OLS) regression model and weighted least square procedure to test the relationship between social institutional factors and Internet diffusion. They found that the rule of law and educational systems have a significant impact on Internet diffusion, while economic systems have not had a significant impact. Yu et al. (2021) used a Pooled OLS regression model and a fixed effect model to explore the influence of industrial policies such as government subsidies, credit loans, tax incentives, and industry access systems on technological innovation in the DEY industries. The results have shown that government subsidies and industry access systems greatly affect the number of patent applications and inventions in the DEY industries, while the role of credit loans and tax incentives is relatively less prominent. Based on data from 2010 to 2017, Sansa (2019) adopted a simple regression model to analyze the influence of China's industrial policy on the DEY. China's industrial policy was expressed as economic openness and taken as an independent variable, while macroeconomic variables i.e. Information Technology (IT) GDP, IT employment, and population using the Internet were taken as dependent variables. The research results showed that, other than the population using the Internet (IT GDP, IT employment), the relationship between economic openness and macroeconomic variables is positive and significant. Jha and Saha (2020) found that the national telecom policy have a positive impact on mobile broadband services.

The internal factors that impact the DEY development mainly include the digital infrastructure level, digital talent status, and the innovation, popularization, and application of digital technology. Among them, the construction of digital infrastructure is the foundation of the DEY development. The better the digital infrastructure, the more conducive it is to the DEY development. Oyeyinka and Lal (2005) studied Internet diffusion in sub-Saharan African countries based on data from 1995 to 2000, and found that telecommunications infrastructure plays an important role in it. Zhang et al. (2022) explored the spatio-temporal evolution characteristics and driving factors of the fusion of China's DEY and real economy from 2013 to 2019 using methods such as entropy method, coordination degree model, and spatial econometric model. The results indicated that digital infrastructure is beneficial for advancing the integrated development of the DEY and real economy.

The key to the DEY development lies in digital talent, which determines the speed, scale, and quality of the DEY development. Wang (2021) pointed out that it is necessary to strengthen the cultivation of digital technology talents and consolidate the talent guarantee for the DEY development. He et al. (2015), based on the annual data of 29 provinces in China from 2003 to 2011, used the panel data model to study the determinants of China's Internet industry. The study found that the number of human resources in this industry is one of the major factors. Yoon (2018) studied the policy implications of servicization with skill premium in a constantly developing DEY through an endogenous growth model. It was found that the exogenous growth of a highly skilled labor force can accelerate economic growth brought by DEY development.

The innovation, popularization, and application of digital technology are important driving forces for the DEY development. Szeles and Simionescu (2020) studied the main driving forces of regional DEY in 27 countries in the European Union through a dynamic panel regression model. Their empirical results showed that stimulating patent development is one of the most effective ways for improving the development of DEY. Cui et al. (2021) explored the IFS of the DEY development using different models based on text mining. The results showed that technological and regulatory innovations are the new driving forces for the future development of the DEY. Chen et al. (2021) based on the Technology-Organization-Environment framework, with Fuzzy-set Qualitative Comparative Analysis explores the factors driving development in China's provincial DEY. He finds four pathways to drive high levels of digital economic development, with the digital competence of enterprises being a very important factor. When enterprises have high levels of digital competence and technological innovation capability, digital infrastructure, government policy support and digital consumption readiness can be used as substitutes to improve the DEY. In addition, the cost of digital access will also impact the DEY development. Kiiski and Pohjola (2002) used the Gompertz technology diffusion model to study the factors that determine the spread of the Internet among member countries of the Organisation for Economic Cooperation and Development, based on their data of per capita Internet hosts from 1995 to 2000. The results showed that Internet access cost is one of the factors that best explain the growth in the number of computer hosts per capita.

In summary, scholars have examined the IFS of the DEY from different perspectives based on various methods. However, due to the difficulty of data acquisition, there is limited empirical study on the factors influencing the DEY. The existing research in this area mainly adopts regression analysis, panel data model, spatial econometrics model, vector autoregression model for empirical analysis. These methods are only used to analyze which factors affect the DEY, without considering the interrelationships between these factors and the hierarchical structure of their relationship with the DEY. This makes the understanding of the IFS of the DEY one-sided, which is not conducive to better promoting the DEY development. Therefore, it is essential to further study the relationship structure of the factors affecting the DEY.

3. Grey relational analysis of factors affecting the development of China's DEY

3.1. Variable selection and data description

The DEY development is influenced by many factors. The literature on this issue was screened, sorted, and analyzed by searching through the Chinese journal full-text database using combinations of keywords such as "DEY", "influencing factor", "digital factor", and "cause", among others. A total of 14 IFS were extracted after literature research: digital talent quantity (x_1), education level (x_2), digital infrastructure level (x_3), digital product number (x_4), economic level (x_5), income level (x_6), research and development (R&D) investment (x_7), scientific and technological achievements (x_8), technical market situation (x_9), urbanization level (x_{10}), industrial structure level (x_{11}), degree of government intervention (x_{12}), opening-up level (x_{13}), and degree of digitalization (x_{14}).

These IFS can be classified into four categories: digital factors, scientific and technological factors, economic factors, and social factors (Table 1).

Factors x_1 to x_{14} were used as independent variables to explore their influence on the DEY development (dependent variable y_0). Table 2 shows the indicators used to construct each of these variables.

This study selected China's DEY as the research object. The research period is from 2002 to 2018. The research data were collected from the China Statistical Yearbook (National Bureau of Statistics of China, 2003–2019), Report or White Paper on China's Digital Economy issued by CAICT (2015–2019), and the website of the National Bureau of Statistics of China (https://data.stats.gov.cn/easyquery.htm?cn=C01). Corresponding data were obtained through collection and collation. To more accurately measure the development of China's DEY and its IFS,

Table 1. Factors influencing the DEY (source: authors' visualization)

Digital	Digital talent quantity (x_1) Digital infrastructure level (x_3) Digital product number (x_4) Degree of digitization (x_{14})
Scientific and technological	R&D investment (x_7) Scientific and technological achievements (x_8) Technical market situation (x_9) Degree of government intervention (x_{12})
Economic	Economic level (x_5) Income level (x_6) Industrial structure level (x_{11}) Opening-up level (x_{13})
Social	Education level (x_2) Urbanization level (x_{10})

Table 2. Definition and indicator of variables (source: authors' visualization)

Variable	Corresponding indicators
Development of the DEY (y_0)	Per capita digital economic added value
Digital talent quantity (x_1)	Employee number of information transmission, software, and IT services in urban units per 10,000 people
Education level (x_2)	Per capita education years
Digital infrastructure level (x_3)	Mobile phone exchange capacity per 10,000 persons
Digital product number (x_4)	Number of mobile phones owned by urban households per 100 households
Economic level (x_5)	GDP per capita
Income level (x_6)	Per capita disposable income of urban residents
R&D investment (x_7)	R&D spending as a share of GDP
Scientific and technological achievements (x_8)	Number of invention patents authorized per 10,000 people
Technical market situation (x_9)	Ratio of technical market turnover to GDP
Urbanization level (x_{10})	Proportion of urban population
Industrial structure level (x_{11})	Added value of secondary and tertiary industries as a proportion of the GDP
Degree of government intervention (x_{12})	Per capita fiscal expenditure for science and technology
Opening-up level (x_{13})	Proportion of imports and exports of high-tech products in the import and export of goods
Degree of digitalization (x_{14})	Internet penetration rate

the value data utilized in the research were all based on the first year (2002) of the research period, and the influence of price factors (i.e., per capita GDP, per capita disposable income of urban residents, per capita scientific and technological fiscal expenditure, per capita digital economic added value, etc.) was excluded.

3.2. The empirical process of grey correlation analysis

Many scholars use grey correlation analysis method to determine the IFS and the influence degree of related factors (Duan & Pang, 2021). The grey correlation analysis has no strict requirements on the number of samples and whether the sample data have some rules. It has a small computation and high recognition degree. This method shows the dynamic meaning of data well, makes the result more scientific and accurate, and can reflect the general law through the comprehensive results of a partial analysis. Therefore, this method was applied to quantitatively explore the main IFS of the development of the DEY in China.

The steps in Grey Relation Analysis includes: determine reference and comparison sequences; data dimensionless processing; calculate the difference sequence and calculate correlation coefficient for normalized data and correlation degree.

(1) Determine reference and comparison sequences

First, the reference sequence representing the behavior characteristics of the system, and the comparison sequence leading to the change in the behavior of the system should be defined according to the research purpose. The reference sequence represented by the dependent variable is the parent sequence y_0. Here, the per capita digital economic added index data were selected as the parent sequence, and the corresponding index data of other variables constituted each sub-sequence x_j (j = 1,2,...,14).

(2) Data dimensionless processing

To eliminate the deviation caused by the dimension, order of magnitude, and other attributes of the index as much as possible, the data collected were standardized. Min-max normalization is adopted, which puts all of the measures on the same scale of one to zero. According to the properties of the selected indicators (forward), the following formula was utilized to normalize them:

$$r_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}, \quad (1)$$

where x_{ij} is the original value of the j-th index of the i-th evaluation target, i = 1,2,...,17 (i is the year, which means the i-th year), corresponding to 2002, 2003,... 2018. j = 1,2,...,14 correspond to the indices of the independent variable x_1, x_2,..., x_{14}; j = 0 corresponds to the dependent variable y_0. min(x_{ij}) and max(x_{ij}) are the minimum and maximum values of the j-th index in each evaluation target, respectively. r_{ij} is the standardized value of the j-th index of the i-th evaluation target. Based on the obtained standardized data of each indicator, the grey correlation analysis method was applied to study the effect of the above variables on the development of the DEY.

(3) Calculate the difference sequence

After data standardization, the absolute value of the difference between the reference sequence and the corresponding element of each comparison sequence needs to be obtained one by one, namely:

$$\Delta(ij) = | r_{io} - r_{ij} |. \quad (2)$$

Then, the largest and smallest differences must be identified:

$$\Delta(\min) = \min\min | r_{io} - r_{ij} |; \quad (3)$$

$$\Delta(\max) = \max\max | r_{io} - r_{ij} |, \quad (4)$$

where, i = 1,2,...,17; j = 1,2,...,14. Based on the calculation, the smallest difference for Δ(min) = 0, and the biggest difference for Δ(max) = 0.7862.

(4) Calculate correlation coefficient and correlation degree

For the i-th year, the correlation coefficient between the parent sequence $\{r_{i0}\}$ and subsequence $\{r_{ij}\}$ is:

$$\theta_{ij} = [\Delta(\min) + \rho\Delta(\max)] / [\Delta(ij) + \rho\Delta(\max)], \quad (5)$$

where ρ is the resolution coefficient, and ρ = 0.5. According to the correlation coefficient value obtained from the calculation, the mean value of the correlation coefficient between each indicator and the corresponding element of the parent sequence was computed. This is used to reflect the correlation between the respective variable and dependent variable, which is called the degree of correlation. The closer the correlation is to 1, the greater the influence. The formula for computing the degree of association is as follows:

$$R_j = \sum_{i=1}^{17} \theta_{ij} / 17. \quad (6)$$

Finally, the calculated correlations were arranged in descending order, and the grey correlations of the respective variables were compared to judge their influence on the development of the dependent variable DEY. According to the above steps, the grey correlation degree and ranking between the development of China's DEY and various IFS were calculated (see Table 3). The results show that the grey correlation degrees calculated from the corresponding indicators of the 14 independent variables are all greater than 0.5. This declares that these factors have a greater influence on the development of China's DEY.

Table 3. Grey correlation degree of the IFS of China's DEY (source: authors' calculations)

Independent variable	Grey correlation
Digital talent quantity	0.9065
Education level	0.7219
Digital infrastructure level	0.7579
Digital product number	0.6121
Economic level	0.8059

End of Table 3

Independent variable	Grey correlation
Income level	0.8107
R&D investment	0.6790
Scientific and technological achievements	0.8974
Technical market situation	0.8990
Urbanization level	0.7244
Industrial structure level	0.6929
Degree of government intervention	0.8590
Opening-up level	0.5839
Degree of digitalization	0.7789

4. Analysis of the relationship structure of the main factors affecting the development of China's DEY

The ISM is a method for analyzing related issues of complicated social and economic systems. Its basic principle is to utilize various creative techniques to extract the components of the problem, and ultimately transform the system into a multi-level hierarchical model with directed graph and matrix, revealing the system's internal structure and the dependency relationship between factors (Shen et al., 2014). This article applies the ISM to explore the relationship structure among the above-mentioned main factors affecting the development of China's DEY. The ISM analysis will show how these factors are interrelated in a structured and easy-to-understand format. Based on these interrelationships, appropriate actions can be developed to foster the DEY. One can define the ISM technique as a process that transforms unclear and poorly articulated mental models of systems into visible and well-defined models (Attri et al., 2013). A Granger causality test was applied to quantitatively determine the logical relationship between each factor. To reduce the influence of variable heteroscedasticity, the data of each variable x_j (j = 1,2,...,14) were taken logarithmically, and the variables were renamed to X_j (j = 1,2,...,14), respectively.

4.1. Judging the relationship between factors

(1) Stationarity test

First, the augmented Dickey-Fuller (ADF) unit root test was applied to test the stationarity of the time-series data of each variable. The test results are shown in Table 4. Among them, the ADF test P value of the original series X_1, X_2, X_7, X_8, X_9, X_{12}, X_{14} is greater than 5%, indicating that the time-series is not stable and there is a unit root. After the first-order difference processing, X_1, X_2, X_7, X_8, X_9, X_{12} become a stationary time-series. X_{14} becomes a stationary time-series only after the second-order difference processing. The results indicate that the original series becomes a stable time-series after the second-order difference processing.

(2) Granger causality test

Because of differences in the stationarity of the variables, the Johansen cointegration test was used to the combination of two variables that at least one is unstable to investigate whether there is a long-term equilibrium relationship between them. If two variables pass the cointegration test at the 5% significance level, there is a long-term equilibrium relationship between them. At this time, the Granger causality[1] test can be further carried out on these variables to determine whether there is a situation in which one party affects the other or each other. Granger causality tests were performed on different sets of variables in $X_1 - X_{14}$ that have long-term equilibrium relationships. According to the test results, combined with existing research, the logical relationship between the variables that pass the Granger causality test at the 10% significance level is determined.

Table 4. ADF inspection results (source: authors' calculations)

Variable	Level		First-order difference		Second-order difference	
	P value	Stationarity	P value	Stationarity	P value	Stationarity
X_1	0.4517	unstable	0.0030	stable	0.0000	stable
X_2	0.1988	unstable	0.0007	stable	0.0000	stable
X_3	0.0158	stable	0.1888	unstable	0.0044	stable
X_4	0.0000	stable	0.0035	stable	0.0017	stable
X_5	0.0029	stable	0.0794	unstable	0.0002	stable
X_6	0.0179	stable	0.0071	stable	0.0009	stable
X_7	0.1644	unstable	0.0317	stable	0.0007	stable
X_8	0.1498	unstable	0.0029	stable	0.0013	stable
X_9	0.9629	unstable	0.0476	stable	0.0004	stable
X_{10}	0.0002	stable	0.0343	stable	0.0016	stable
X_{11}	0.0341	stable	0.0014	stable	0.0001	stable
X_{12}	0.0770	unstable	0.0084	stable	0.0001	stable
X_{13}	0.0056	stable	0.0227	stable	0.0008	stable
X_{14}	0.5195	unstable	0.0883	unstable	0.0460	stable

(3) Determine the adjacency matrix

According to the determined logical relationship between the variables, the adjacency matrix R of each factor can be obtained, and R is a 14th-order square matrix. The elements in the square matrix are defined as follows:

$$r_{st} = \begin{cases} 1, & X_s \text{ directly affects } X_t \\ 0, & X_s \text{ not directly affects } X_t \end{cases}, \quad (s,\ t = 1, 2, \ldots, 14), \tag{7}$$

where r_{st} is the element in the s-th row and t-th column of the R square matrix. If X_s is the

[1] Granger causality is a popular framework for inferring potential causal mechanisms between different time series (Yin & Barucca, 2022).

Granger cause of X_t , then r_{st} = 1; otherwise r_{st} = 0. Therefore, the adjacency matrix can be obtained as follows:

$$R=\begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&0&0&0\\ 1&0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0&0&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1\\ 0&0&1&0&0&1&0&0&0&1&0&1&0&0\\ 0&1&0&1&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix}. \tag{8}$$

4.2. Determining the inter-level relationship among the various factors

(1) Compute reachability matrix

The adjacency matrix is a Boolean matrix. According to the Boolean matrix arithmetic rules, there must be a positive integer n to satisfy:

$$M=(R+I)^{n+1}=(R+I)^{n}\neq(R+I)^{n-1}\neq(R+I)^{n-2}\neq\ldots\neq(R+I), \tag{9}$$

where I is the identity matrix of the same order as R, then M = $(R + I)^n$ is the reachable matrix of the adjacency matrix R. According to the above operation rules, the reachable matrix M was calculated using the Matlab R2018b software:

$$M=(R+I)^{4}=\begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&0&0\\ 1&1&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&1&1&0&0&0&0&0&0&0&0&0&1\\ 0&0&0&1&0&0&0&0&0&0&0&0&0&1\\ 1&1&1&1&1&1&0&1&1&1&0&1&0&1\\ 1&1&0&1&0&1&0&0&0&0&0&0&0&1\\ 0&0&0&0&0&0&1&1&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&0&0&0&0\\ 1&1&0&0&0&0&0&0&0&1&0&0&0&0\\ 1&1&1&1&1&1&0&1&1&1&1&1&0&1\\ 0&0&0&0&0&0&0&1&1&0&0&1&0&0\\ 1&1&1&1&1&1&0&1&1&1&1&1&1&1\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix}. \tag{10}$$

(2) Level division

According to the reachable matrix, each influencing factor was classified into different levels. The set of factors affected by the factor X_i is called the reachable set $R(X_i)$, and the set of factors affecting the factor X_i is called the antecedent set $A(X_i)$. If $C(X_i) = R(X_i) \cap A(X_i)$, then $C(X_i)$ is called the common set. If $R(X_i) = C(X_i)$, then X_i is the level factor to be identified. The factors satisfying this condition are at the same level. The first-level reachable set, antecedent set, and common set for the main factors influencing the DEY development are shown in Table A.1 in Appendix.

1) According to the data in Table A.1, the first-level element $L_1 = \{X_1, X_9, X_{14}\}$ of the major IFS of the development of the DEY can be obtained.
2) Cross out rows 1, 9, and 14 and columns 1, 9, and 14 in the reachable matrix M to find the second-level elements. According to the data in Table A.2, the second-level element $L_2 = \{X_2, X_4, X_8\}$, which is the main influencing factor of the DEY, can be obtained.
3) Cross out the second, fourth, and eighth rows and the second, fourth, and eighth columns of the reachable matrix M to find the third-level elements. According to Table A.3, the third-level element $L_3 = \{X_3, X_6, X_7, X_{10}, X_{12}\}$, the main IFS of the DEY, can be obtained.
4) Continue to cross out rows 3, 6, 7, 10, and 12 and columns 3, 6, 7, 10, and 12 of the reachable matrix M, and look for the fourth-level elements. According to Table A.4, the fourth-level element $L_4 = \{X_5\}$ can be obtained.

In the same way, from the data in Tables A.5 and A.6, we can get the fifth- and sixth-level factors of the major IFS of the DEY: $L_5 = \{X_{11}\}$, $L_6 = \{X_{13}\}$.

Based on the above analysis, a modified ISM (referred to as LGG-ISM method) of the major IFS of the DEY that reflects the degree of relevance is constructed, as shown in Figure 1. The value in brackets represents the degree of relevance (Grey correlation degree) of each element to the DEY.

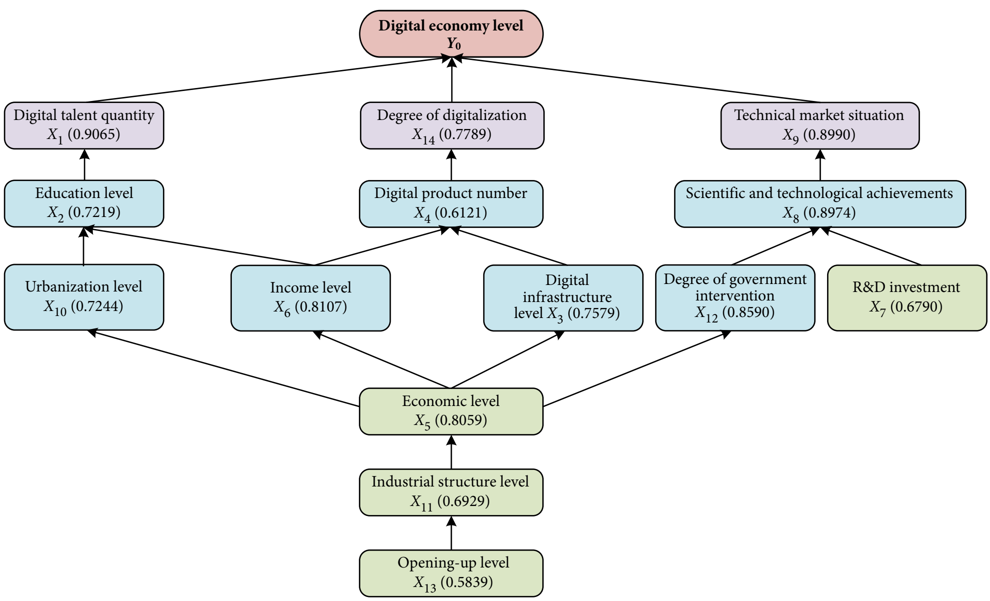

Figure 1. Interpretative structure model of the major IFS of the DEY (source: authors' visualization)

4.3. Analyzing the relationship among the various factors

According to Figure 1, the DEY is a complex system with a multi-level hierarchical structure. The first-level elements include digital talent quantity (x_1), technical market situation (x_9), and the degree of digitization (x_{14}); the second-level elements are education level (x_2), digital product number (x_4), and scientific and technological achievements (x_8); the third-level elements are digital infrastructure level (x_3), income level (x_6), R&D investment (x_7), urbanization level (x_{10}), and degree of government intervention (x_{12}); the fourth-level factor is the economic level (x_5); the fifth-level factor is the industrial structure level (x_{11}); and the sixth-level factor is the degree of digitalization (x_{13}).

(1) Relationship between the factors in levels 1 and 0 (DEY level)

The number of digital talents (x_1), technology market conditions (x_9), and degree of digitalization (x_{14}) have a direct impact on the DEY level. The key to the DEY development lies in digital talents, which determine the speed, scale, and quality of development. The state of the technology market reflects the trading situation of technological achievements. The more developed the technology market, the more conducive it is to industrial digitalization and digital industrialization. The degree of digitalization is not only a direct reflection of the current level of DEY development but also indicates its development potential. Therefore, the first-level factors are the superficial and direct IFS of DEY development.

(2) Relationship between the factors in levels 2 and 1

The three elements in the second level have a direct impact on the corresponding elements in the first level; that is, the improvement in education level (x_2) can advance the increase in the number of digital talents (x_1); whether people have digital products and how much (x_4) affects the development of the DEY through the influence on the degree of digitization (x_{14}); the quantity and quality of scientific and technological achievements (x_8) determine the prosperity of the technology market (x_9), affecting the popularization and application of technology, and then the development of the DEY. The second-level factors influence the DEY through the first-level factors, so they are the middle-level indirect influencing factor of DEY development.

(3) Relationship between the factors in levels 3 and 2

The factors that have a direct impact on education level (x_2) are income level (x_6) and urbanization level (x_{10}). The increase in urbanization level can enable people to have higher-quality educational resources and a better learning environment, and the increase in income can make people afford high-quality education. The two factors synergistically advance the improvement of education level. The level of digital infrastructure (x_3) and income level (x_6) affects the abundance of digital products in terms of digital experience and digital consumption capacity (x_4). In addition, R&D investment (x_7) and government intervention (x_{12}) respectively reflect the investment and support of society and government for scientific and technological progress. They jointly advance the formation of scientific and technological achievements. Among the third-level elements, R&D investment (x_7) is the deep fundamental influencing factor of the DEY, while other elements are the middle-level indirect IFS of the DEY.

(4) Relationship between the factors in levels 4 and 3

Level 4 has only one element, economic level (x_5), which has a direct influence on the level of digital infrastructure (x_3), income level (x_6), urbanization level (x_{10}), and government intervention (x_{12}) in level 3. The more developed the economy is, the more it can promote the construction of digital infrastructure, income growth, and urbanization, and improve government intervention ability. Therefore, the economic level (x_5) is the fundamental influencing factor of the DEY.

(5) Relationship between the factors in levels 5 and 4

The industrial structure level (x_{11}) is the only element in the fifth level. It has a direct influence on the economic level (x_5), which in turn affects the DEY development. The rationalization and advancement of the industrial structure promotes the effective allocation and efficient use of social resources, and continuously promotes rapid economic growth and higher-quality development. This promotes the development of the DEY. It can be observed that the level of industrial structure (x_{11}) is also a fundamental influencing factor of the DEY.

(6) Relationship between the factors in levels 6 and 5

The level of openness (x_{13}) is the only element in the sixth level. With the increase in the breadth and depth of opening to the outside world, the transformation and upgrading of the industrial structure can be promoted (x_{11}), and the economic level can be continuously improved, thereby affecting the development of the DEY. Therefore, the level of opening to the outside world (x_{13}) is a deep and fundamental influencing factor of the DEY, and this impact is far-reaching.

As seen in Figure 1, the order of relevance to the DEY from high to low is the number of digital talents (x_1), technology market conditions (x_9), technological achievements (x_8), government intervention (x_{12}), income level (x_6), economic level (x_5), digitization level (x_{14}), digital infrastructure level (x_3), urbanization level (x_{10}), education level (x_2), industrial structure level (x_{11}), R&D investment (x_7), number of digital products (x_4), and opening-up level (x_{13}). Among the direct IFS at the surface level, the number of digital talents (x_1), technology market conditions (x_9), and the degree of correlation with the DEY are the top two among the 14 factors, reaching 0.9065 and 0.8990, respectively; for the middle-level indirect IFS, scientific and technological achievements (x_8), government intervention (x_{12}) and the DEY are highly correlated, reaching 0.8974 and 0.8590, respectively; in the underlying fundamental IFS, economic level (x_5) is more closely related to the DEY, reaching 0.8059.

5. Discussion and conclusion

The adjacency matrix of the traditional ISM is obtained based on expert opinions, which cannot overcome the subjectivity problem brought by this way, and it is difficult to guarantee the quality of the evaluation results. Therefore, a modified ISM (LGG-ISM) method that can solve this problem is used in this article to reflect the main IFS of the DEY. The LGG-ISM is constructed by combining the literature research method, grey relational analysis, Granger causality test, and ISM.

The LGG-ISM incorporates the advantages of these methods. This method can provide theoretical basis and guidance for corresponding research through literature research, which helps to clarify research directions, preliminarily select possible IFS and promote research efficiency. On this basis, it uses the grey correlation analysis method to conduct empirical analysis on these factors, so as to determine the actual IFS and their correlations through quantitatively test. Then, it adopts the Granger causality test to further examine the inter-relationship of the IFS from a quantitative perspective. Simultaneously, combining this with literature research can better determine whether there is a relationship, direction of action, and degree of different IFS. Finally, this method intuitively presents the relationship structure of different IFS in the form of diagram and numbers through ISM. To sum up, the LGG-ISM not only considers the role of subjective factors but also respects objective reality; it is easy to not only learn the relationship structure of various factors but also understand the degree of relevance between them and the DEY. Therefore, it is an effective tool that explores the relationship structure of the major factors affecting the development of the DEY.

The research results indicate that the number of digital talents, state of the technology market, and degree of digitization are the superficial and direct IFS of the DEY. The number of digital talents and the status of technology market have a particularly significant influence on the DEY. Education level, digital product quantity, scientific and technological achievements, digital infrastructure level, income level, urbanization level, and government intervention are middle-level indirect factors, among which scientific and technological achievements and government intervention have a significant influence on the DEY; R&D investment, economic level, industrial structure level, and opening-up level are the underlying fundamental IFS, among which economic level has a significant influence on the DEY. This manifests that factors such as the number of digital talents, technology market conditions, technological achievements, government intervention, and economic level played a prominent role in the DEY development during the study period. The development of DEY involves the interaction between the government and market, and a reasonable government-market relationship can better advance the DEY development by adjusting the above factors. In summary, the government and market are two important entities for the DEY development, and the relationship between them should be properly handled: respecting market laws and effectively leveraging the role of the government.

The research conclusions of this article are consistent with most existing studies. There are many factors that affect the DEY development, such as social aspects, demographic factors, economic development, and related policies. Numerous studies have shown the exceptional importance of economic development in the development of the DEY. Compared with current research, our study does not solely analyze the specific IFS of the DEY, but also examines their relationship structure, and visually displays their relationships using diagram and numbers. This can provide a more systematic and accurate understanding of the complex mechanism underlying the DEY development, and better assist policy makers in promoting its development.

Findings of this research have several main implications for China's DEY development, resulting in the following recommendations. First, China should fully leverage major factors' role and expand their existing advantages, while attaching great importance to the role of other IFS, which can make up for shortcomings and better unleash the potential of DEY development. Second, continue to expand opening up to the outside world in scope and depth, strengthen international exchanges and cooperation in the field of DEY, continuously enhance international competitiveness in this area, and provide strong impetus and vitality for the development of the DEY. Third, the country should strive to promote digital industrialization and industrial digitization, upgrade its industrial structure, advance sustainable economic development, and in turn drive the development and virtuous cycle of DEY. To this end, the government should consolidate the foundation for the development of the DEY, promote the construction of digital infrastructure, and improve the allocation of factors that promote DEY by allocating a larger amount of corresponding resources. Fourth, the government should increase investment in digital technology and its innovation, promote the formation and transformation of scientific and technological achievements, advance the prosperity of the technology market, and create a good technological development environment for the DEY. Fifth, establish a digital talent training system and intensify the cultivation of digital talents, so as to provide continuous digital talent support for DEY development.

Although this research discusses the elements of the digital economic system and their interrelationships, it does not examine them from different national or provincial levels, or establish a model to simulate the development of the DEY and its effects. For example, it is essential to predict the DEY development and its carbon emission effects. What needs to be further improved in the future is that we should make a profound investigation of the relationship structure of factors affecting the DEY based on panel data from different countries or provinces; predict the development trend of DEY according to historical data and government policies, find out the weaknesses in the development process of DEY in time, and explore the countermeasures to improve the development level of DEY; Meanwhile, analyze the development advantages of the DEY itself, the opportunities and challenges it brings, and probe into the economic, social, political, cultural, environmental and other effects brought by the DEY. For example, the ways and paths that DEY affects the utilization of natural resources and sustainability should be deeply explored, so as to provide references for promoting the efficient utilization of natural resources and environmental protection.

Availability of data and materials

The datasets used or analyzed during the current study are available from the yearbooks or the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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Conceptualization, Writing – original draft, Software J.W.; Formal analysis, Data curation, Methodology, J.Z.; Investigation, Supervision S.C.; Project administration, Visualization, Resources J.C.; Validation, Writing – review & editing, Funding acquisition X.Z.

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APPENDIX

Level division

Table A1. The main factors affecting the development of the DEY: Level 1 reachable set, antecedent set, and common set (source: authors' calculations)

Index	$R(X_i)$	$A(X_i)$	$C(X_i)$
X_1	1	1,2,5,6,10,11,13	1
X_2	1,2	2,5,6,10,11,13	2
X_3	3,4,14	3,5,11,13	3
X_4	4,14	3,4,5,6,11,13	4
X_5	1,2,3,4,5,6,8,9,10,12,14	5,11,13	5
X_6	1,2,4,6,14	5,6,11,13	6
X_7	7,8,9	7	7
X_8	8,9	5,7,8,11,12,13	8
X_9	9	5,7,8,9,11,12,13	9
X_{10}	1,2,10	5,10,11,13	10
X_{11}	1,2,3,4,5,6,8,9,10,11,12,14	11,13	11
X_{12}	8,9,12	5,11,12,13	12
X_{13}	1,2,3,4,5,6,8,9,10,11,12,13,14	13	13
X_{14}	14	3,4,5,6,11,13,14	14

Table A2. The main factors affecting the development of the DEY: Level 2 reachable set, antecedent set, and common set (source: authors' calculations)

Index	$R(X_i)$	$A(X_i)$	$C(X_i)$
X_2	2	2,5,6,10,11,13	2
X_3	3,4	3,5,11,13	3
X_4	4	3,4,5,6,11,13	4
X_5	2,3,4,5,6,8,10,12	5,11,13	5
X_6	2,4,6	5,6,11,13	6
X_7	7,8	7	7
X_8	8	5,7,8,11,12,13	8
X_{10}	2,10	5,10,11,13	10
X_{11}	2,3,4,5,6,8,10,11,12	11,13	11
X_{12}	8,12	5,11,12,13	12
X_{13}	2,3,4,5,6,8,10,11,12,13	13	13

Table A3. The main factors affecting the development of the DEY: Level 3 reachable set, antecedent set, and common set (source: authors' calculations)

Index	$R(X_i)$	$A(X_i)$	$C(X_i)$
X_3	3	3,5,11,13	3
X_5	3,5,6,10,12	5,11,13	5
X_6	6	5,6,11,13	6
X_7	7	7	7
X_{10}	10	5,10,11,13	10
X_{11}	3,5,6,10,11,12	11,13	11
X_{12}	12	5,11,12,13	12
X_{13}	3,5,6,10,11,12,13	13	13

Table A4. The main factors affecting the development of the DEY: Level 4 reachable set, antecedent set, and common set (source: authors' calculations)

Index	$R(X_i)$	$A(X_i)$	$C(X_i)$
X_5	5	5,11,13	5
X_{11}	5,11	11,13	11
X_{13}	5,11,13	13	13

Table A5. The main factors affecting the development of the DEY: Level 5 reachable set, antecedent set, and common set (source: authors' calculations)

Index	$R(X_i)$	$A(X_i)$	$C(X_i)$
X_{11}	11	11,13	11
X_{13}	11,13	13	13

Table A6. The main factors affecting the development of the DEY: Level 6 reachable set, antecedent set, and common set (source: authors' calculations)

Index	$R(X_i)$	$A(X_i)$	$C(X_i)$
X_{13}	13	13	13