A new construction algorithm of the digital economy innovation system

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Abstract. To effectively promote the development of digital economy, we have proposed a new construct algorithm of digital economy innovation system. It mainly researches four indicators: innovation subject, innovation resources, innovation efficiency and innovation environment. The quality synthesis index of digital economy development in recent years is calculated through the entropy method. To further analyse the main factors affecting the development quality, the grey relation analysis method is adopted. Besides, the grey prediction model is established to predict the future development trend of digital economy. Based on the data collected from Jiaxing Statistics Bureau from 2010 to 2018, we find that its overall development is growing year by year, in which the innovation efficiency contributes the most, and it is closely related to the innovation resources and environment, but there is still an uneven development among the indicators. The research is conducive to promoting the development of the digital economy and helping to build a modern industrial system for the digital economy.

1. Introduction

According to the initiative released by the G20, the digital economy refers to a series of economic activities in which digitalized knowledge and information are used as key factors of production, modern information networks are used as important carriers, and the effective use of information and communication technologies is an important driving force for improving efficiency and optimizing economic structure.\cite{1}

Domestic scholars mainly focus on China's digital economic development strategy and comparative research with other countries. For example, in 2012, Sun Hong et al.\cite{2} analysed the development of the digital economy in the United Kingdom and London based on the comparative digital economy development, which provided beneficial inspiration for China's new round of informatization urbanization development. In 2017, Zhong Chunping, Liu Cheng, et al.\cite{3} put forward some countermeasures and suggestions for developing China's digital economy from the perspective of Sino-US comparison. Xu Bicong, et al.\cite{4} summarized the importance of the digital economy to China's economic development and proposed measures to continuously promote the development of China's digital economy in 2018.

From the deep integration of various industries and digital economy, it is very important to measure the impact of the digital economy on the overall economic activities. Some researchers have studied the quality of digital economic development from the perspective of indicators. For example, in 2017,
Chen Xi et al.[5] studied the effective mechanism of data acquisition, information analysis, release and dynamic adjustment based on the mature new economic indicator system of the United States. In 2018, Zhang Xueling et al.[6] established a quality evaluation system of digital economy development in China, based on the quality characteristics, and used entropy method to measure the development quality in the past 10 years. They found that the overall trend was rising. In 2019, Lin Yun et al.[7] proposed the statistical monitoring indicator system of digital economy in Zhejiang Province and the comprehensive evaluation indicator system, and considered further improving its statistical system. Xin Jinguo et al.[8] in 2019, selected relevant indicators from five aspects, including digital network popularization, innovation capability, industrial digital investment, e-commerce and quality efficiency. The weight was computed by entropy method, and the index method was adopted to measure its digital economic development. In addition, they have studied the future development trend of the digital economy.

![Digital Economy Innovation Indicator System](image)

**Figure 1.** Digital economy innovation indicator system.

Previous studies have given the meaning of the digital economy, and proposed the indicator evaluation system and corresponding analysis methods, which has reference significance for subsequent research. However, there are still some deficiencies: (1) Most of research is based on theoretical analysis, and it is difficult to carry out quantitative analysis on the development level of digital economy; (2) Existing studies mostly construct digital economic indicators from the perspective of China or province, but not from the perspective of cities. To develop digital economy from the point to face perspective is conducive to accurate modeling and comprehensive analysis of the development level of digital economy.
2. Algorithm

2.1. Indicators of the algorithm
In the algorithm, we have selected the indicators of digital economy innovation system from four aspects, which are innovation subject, innovation resources, innovation efficiency and innovation environment. The specific indicators are shown in figure 1. Innovation subject includes the number of the students and teachers in universities, scientific and technological institutions, etc. Innovation resource includes the number of R&D staff, expenditure, new products and technology investment, etc. Innovation efficiency includes the number of patents of knowledge, etc. The innovation environment includes the policy of the government, just like the tax reduction, etc.

2.2. Each indicator’s weight
A classical method named entropy method for calculating indicator weights, which is often used to judge the indicator dispersion degree. The greater the degree of dispersion, the greater the amount of information, and the smaller the entropy. The smaller the amount of information and the greater the entropy. The dispersion of indicators can be judged by the value. The smaller the entropy of the indicator, the greater its weight in the comprehensive evaluation. The specific steps of the model are as follows.

- Construct indicator matrix.
  \[ X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \] (1)

  Where \( x_{ij} (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m; n = 9; m = 26) \) is the value of the \( j \)-th indicator in the \( i \)-th year.

- Indicator normalization.

- Calculate the proportion of the indicator in the \( i \)-th year under the \( j \)-th indicator.
  \[ p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \] (2)

- Calculate the entropy of the \( j \)-th indicator. The equation (3) satisfies \( k = \frac{1}{\ln(n)} > 0; e_j \geq 0 \).
  \[ e_j = -k \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \] (3)

- Calculate the information entropy redundancy.
  \[ d_j = 1 - e_j \] (4)

- Calculate the weight of each indicator.
  \[ w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \] (5)

- Calculate the overall score.
  \[ s_i = \sum_{j=1}^{m} w_j \cdot p_{ij} \] (6)

2.3. Relationship analysis between indicators
The GRA (Grey Relation Analysis) is a multi-factor statistical analysis method, which is used to calculate the correlation degree between the indicators. If the changes in two factors are basically the same, it means that the correlation between them is large; otherwise, the correlation is small. This method reduces the loss caused by information asymmetry to a great extent, and requires less data and less workload.
Based on the time-series characteristics of the data, we have adopted GRA method to calculate the correlation between indicators. This method can be applied to the situation when the amount of time-series data is small and the data information is uncertain.

2.3.1. Collect indicator data.

\[
(X_0, X_1, \ldots, X_n) = [x_0(1) x_1(1) \cdots x_n(1) \\
x_0(2) x_1(2) \cdots x_n(2) \\
\vdots \quad \vdots \\
x_0(m) x_1(m) \cdots x_n(m)]
\]  
(7)

2.3.2. Determine the reference sequence.

\[X_0 = (x_0(1), x_0(2), \ldots, x_0(m))\]  
(8)

2.3.3. Standardization. The data have been standardized by the average method. The specific calculation formula is as equation (9), where \(i = 0, 1, \ldots, n; k = 1, 2, \ldots, m\).

\[x_i' (k) = \frac{x_i(k)}{\frac{1}{m} \sum_{k=1}^{m} x_i(k)}\]  
(9)

After calculation, the standardized data sequence is as shown in equation (10).

\[
(X'_0, X'_1, \ldots, X'_n) = [x'_0(1) x'_1(1) \cdots x'_n(1) \\
x'_0(2) x'_1(2) \cdots x'_n(2) \\
\vdots \quad \vdots \\
x'_0(m) x'_1(m) \cdots x'_n(m)]
\]  
(10)

2.3.4. Calculate the absolute difference. The absolute difference between the comparison sequence and the reference sequence is calculated according to equation (11), where \(n\) is the number of objects evaluated.

\[|x'_0(k) - x'_i(k)|, (k = 1, \ldots, m; i = 1, \ldots, n)\]  
(11)

2.3.5. Calculate some values using the follow functions.

\[\begin{align*}
\min_{i=1}^{n} &\min_{k=1}^{m} |x'_0(k) - x'_i(k)| \\
\max_{i=1}^{n} &\max_{k=1}^{m} |x'_0(k) - x'_i(k)|
\end{align*}\]  
(12)

2.3.6. Calculate the correlation coefficient. Calculate the correlation coefficient of the corresponding indicator of the comparison sequence and reference sequence separately. The calculation formula is as equation (8), where \(k = 1, \ldots, m\), \(\rho\) is the resolution coefficient and \(0 < \rho < 1\). If \(\rho\) is smaller, the difference between the correlation coefficients is greater and the discriminating ability is stronger. Generally, \(\rho\) is 0.5.

\[\varphi_i (k) = \frac{\min_{i=1}^{n} \min_{k=1}^{m} |x'_0(k) - x'_i(k)| + \rho \max_{i=1}^{n} \max_{k=1}^{m} |x'_0(k) - x'_i(k)|}{|x'_0(k) - x'_i(k)| + \rho \max_{i=1}^{n} \max_{k=1}^{m} |x'_0(k) - x'_i(k)|}\]  
(14)

2.3.7. Calculate the correlation order. For each comparison series, the average value of the correlation coefficient of each indicator is calculated, which reflects the association between each evaluation object and the reference series. This is called the association order, which is recorded as equation (15).

\[y_i = \frac{1}{m} \sum_{k=1}^{m} \varphi_i (k)\]  
(15)
2.4. Prediction algorithm

The grey prediction model is directly used to the generated data sequence, not the original data sequence. Grey model (GM) is its core, which generates approximate exponential distribution by accumulating raw data. We use the grey prediction to predict the indicators according to the historical data. Different problems have different grey prediction models. The GM (1,1) mainly solves that the generated sequence has an exponential change rule, which can only describe the monotonous change process. According to the characteristics of digital economy data, GM(1,1) is adopted to predict the comprehensive indicator value of the digital economy in this paper.

2.4.1. GM(1,1) model. For element sequence data: \( x^{(0)} = (X^{(0)}(1), X^{(0)}(2), ..., X^{(0)}(n)) \), the accumulation sequence can be calculated as equation (16), where \( x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), k = 1,2, ..., n \).

\[
x^{(1)} = (X^{(1)}(1), X^{(1)}(2), ..., X^{(1)}(n))
\]

\( Z^{(1)} \) is the average generation sequence of \( X^{(1)} \), where \( z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5x^{(1)}(k-1) \).

\[ Z^{(1)} = (z^{(1)}(2), z^{(1)}(3), ..., z^{(1)}(n)) \]

Establish the grey differential equation of GM(1,1): \( x^{(0)}(k) + az^{(1)}(k) = b \), where \( a \) is the development coefficient and \( b \) is the grey effect. Let \( \hat{a} \) be the parameter vector to be estimated, i.e. \( \hat{a} = (a, b)^T \). The least square method is used to estimate the grey differential equation’s parameters, which satisfies:

\[
\hat{a} = (B^T B)^{-1}B^T Y_n
\]

where \( B = \begin{bmatrix} -z^{(1)}(2), 1 \\ -z^{(1)}(3), 1 \\ \vdots \\ -z^{(1)}(n), 1 \end{bmatrix}, Y_n = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix} \)

Build the white equation of the grey differential equation (16), and the solution is: \( x^{(1)}(t) = \left( x^{(1)}(0) - \frac{b}{a} \right) e^{-at} + \frac{b}{a} \).

\[
\frac{dx^{(1)}}{dt} + ax^{(1)} = b
\]

The time response sequence of the grey differential equation of GM(1,1) is as follows.

\[
\hat{x}^{(1)}(k+1) = [x^{(1)}(0) - \frac{b}{a}] e^{-at} + \frac{b}{a}
\]

where let \( x^{(1)}(0) = x^{(0)}(1) \), and we can get equation (21).

\[
\hat{x}^{(1)}(k+1) = [x^{(0)}(1) - \frac{b}{a}] e^{-ak} + \frac{b}{a}, k = 1,2, ..., n - 1.
\]

The cumulative reduction can obtain the prediction equation (22), where \( k = 1,2, ..., n - 1 \).

\[
\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) = x^{(0)}(1) - \frac{b}{a} (1 - e^{-ak}) e^{-ak}
\]

2.4.2. Algorithm steps

(1) Data ratio test. To ensure the feasibility of grey prediction, it is necessary to conduct a level comparison test on the original sequence data. For the original data column \( x^{(0)} = (X^{(0)}(1), X^{(0)}(2), ..., X^{(0)}(n)) \), calculate the sequence ratio as equation (23), where \( k = 2,3, ..., n \).
\[ \lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)} \]  

(23)

If all the order ratios \( \lambda(k) \) fall within the tolerable coverage \( \theta = (e^{-2/(n+1)}, e^{2/(n+1)}) \), then grey prediction is possible; otherwise, translation transformation needs to be performed on \( x^{(0)} \), i.e. \( Y^{(0)} = x^{(0)} + c \), so that \( Y^{(0)} \) meets the requirements.

(2) Calculate the sequence of the predicted values.

(3) Relative residual test. Calculate \( \varepsilon(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)} \), \( k = 2, 3, ... , n \), if \( \varepsilon(k) < 0.2 \), it is considered to meet the general requirements; if \( \varepsilon(k) < 0.1 \), it is considered to meet the higher requirements.

(4) Predict growth sequence. Generally, the model only needs four data, not a large amount of data. It can solve the problems of low historical data, low sequence integrity and low reliability. It can use differential equations to full use of the essence of the system. Besides, it can generate irregular original data to get a strong regularity generation sequence, which is easy to operate and does not consider the distribution rule and change trend.

3. Experimental results and analysis

In this paper, we use the digital economy data of Jiaxing Statistics Bureau from 2010 to 2018.

3.1. Indicator analysis

![Figure 2. Development trend of the digital economy innovation system in Jiaxing from 2010 to 2018, where cv, i-sub, i-res, i-eff, i-env respectively represent comprehensive indicator value, innovation subject, innovation resources, innovation efficiency, and innovation environment.](image)

The comprehensive indicator value of the digital economy in Jiaxing has shown an upward trend, indicating its digital economy has developed rapidly from 2010 to 2018, as can be seen from figure 2. The average annual growth rate reached 31.9%. The fastest growth rate was in 2011, with 60.69%. The year-on-year growth rate in 2017 was 16.62%, which was slightly slower than the previous year. The average annual growth rates of the four indicators were 43.87%, 36.16%, 78.3%, and 18.59%, respectively, showing different degrees of upward trend. Among them, the growth rate of innovation efficiency was the fastest, with an average annual growth of 78.3%.

The improvement of innovation efficiency is the result of the digital economic development, which indirectly reflects the promotion of innovation resources. The average annual growth rate of the innovation environment is 18.59%. Constantly strengthening the construction of innovation
environment and creating the best innovation environment will help to stimulate the innovation vitality and entrepreneurship of market participants, which will provide a fundamental guarantee for the innovation and development of Jiaxing digital economy. High-quality innovation environment is conducive to promote the effective use of innovation resources, improve innovation efficiency and accelerate the better development of Jiaxing digital economy.

Figure 3. The correlation between innovation indicators.

3.2. Correlation analysis
As shown in figure 3, the correlation values of the four indicators are between 0.58 and 0.79. Among them, the correlation between innovation subject, innovation resource and innovation environment is not high, which is 0.66 and 0.61. However, its average annual growth rate is higher than that of innovation resources and innovation environment, which fails to play a leading role well. At the same time, it also shows that the innovation subject needs to closely rely on innovation resources and environment to develop the digital economy. Innovation resources are highly correlated with innovation efficiency and innovation environment, which are 0.79 and 0.75 respectively. It means that innovation resources are reasonable in a high-quality innovation environment, which making full use of it can accelerate the improvement of innovation efficiency.

The correlation between innovation efficiency and innovation environment is 0.68, and its development speed is higher than the other three indicators, indicating that existing enterprises should rely on the large environment to develop the digital economy. Continuously stimulating the innovation vitality of market participants, can inject more high-quality products into enterprises, and improve enterprise efficiency.
Further analysis of the correlation between various elements, as shown in figure 4, shows that the correlation between each element is distributed between 0.49 and 0.96. Among them, the correlation between each element and the use of funds for science and technology activities of government departments is relatively weak, in which correlation value is generally around 0.5. Each element is not strongly correlated with the expenditure on technology introduction, digestion and absorption, and the expenditure on domestic technology purchase, in which correlation value is distributed between 0.49 and 0.73.

With the deep integration of the Internet and the real economy, core technologies are occupying an increasingly important position among Internet companies. The lack of domestic technology funding support, government funding and less attention to science and technology activities in Jiaxing, have hindered the development process of digital economy.

3.3. Prediction analysis

In this paper, the indicator data collected from Jiaxing Statistics Bureau from 2010 to 2018, which is used as the original data, and an accumulation sequence \( x^{(1)} \) is generated. Besides, the grey differential equation of GM(1,1) is established. The model based on the least squares method to estimate the parameter series, can be obtained \( B \) and \( Y_n \).

\[
B = \begin{bmatrix}
-0.1711, & 1 \\
-0.3517, & 1 \\
-0.5963, & 1 \\
-0.9138, & 1 \\
-1.32825, & 1 \\
-1.85545, & 1 \\
-2.48375, & 1 \\
-3.2418, & 1 
\end{bmatrix},
Y_n = \begin{bmatrix}
0.1524 \\
0.2088 \\
0.2804 \\
0.3546 \\
0.4743 \\
0.5801 \\
0.6765 \\
0.8396 
\end{bmatrix}
\]

According to \( \hat{a} = (B^T B)^{-1} B^T Y_n \), we can get \( \hat{a} = \begin{bmatrix}
-0.2204 \\
0.1444 
\end{bmatrix}, \frac{b}{a} = -0.6552 \). Bring them into the equations: \( \hat{x}^{(1)}(k+1) = x^{(0)}(1) - \frac{b}{a} e^{-a k} + \frac{b}{a} \), so we can get the time response sequence equation: \( \hat{x}^{(1)}(k+1) = 0.7501 \cdot e^{0.2204 k} - 0.652 \).
Table 1. Predicted results of comprehensive indicator values for the digital economy innovation system.

| Years | True value | Predicted value | Residual | Relative error | Relative residual |
|-------|------------|----------------|----------|----------------|------------------|
| 2010  | 0.0949     | 0.0949         | 0        | 0              | 0                |
| 2011  | 0.1524     | 0.185          | -0.0326  | 0.2139         | 0.1762           |
| 2012  | 0.2088     | 0.2306         | -0.0218  | 0.1044         | 0.0945           |
| 2013  | 0.2804     | 0.2874         | -0.007   | 0.025          | 0.0244           |
| 2014  | 0.3546     | 0.3583         | -0.0037  | 0.0104         | 0.0103           |
| 2015  | 0.4743     | 0.4466         | 0.0277   | 0.0584         | 0.062            |
| 2016  | 0.5801     | 0.5567         | 0.0234   | 0.0403         | 0.042            |
| 2017  | 0.6765     | 0.694          | -0.0175  | 0.0259         | 0.0252           |
| 2018  | 0.8396     | 0.865          | -0.0254  | 0.0303         | 0.0294           |

Table 1 lists the predicted performance errors and residuals of the model. We can see that the relative residual test values of the model are all less than 0.2, indicating that the GM meets the general requirements, i.e., the fitting effect is well.

Figure 5. A comparison chart of the predicted and true values of the GM.

The effect of the GM adopted in this paper on predicting the Jiaxing digital economy development is shown in figure 5. We can see that the predicted value of the GM is consistent with the changing trend of the comprehensive value, indicating that the model's prediction performance is better, and the fitting effect is better. In general, the model adopted in this paper is suitable for forecasting the development trend of the digital economy.

4. Conclusions and suggestions
Generally, the development of the digital economy is increasing year by year, but there are still some problems of uncoordinated development. There is a phenomenon of uneven development in digital economic indicators. The development of the innovation environment is relatively slow, but the
innovation environment occupies a very important position in the digital economy. It is necessary to accelerate the construction of resources and environments, optimize the digital development environment, and create a good industrial ecological environment. Innovation efficiency is the main indicator to promote digital economic development. A new round of scientific and technological revolution has brought more fierce competition. From the traditional factor-driven to innovation-driven development has a great driving force. Digital technology is the innovation result of the science and technological revolution, and realizes innovation in different ways. By optimizing the supply of public products in terms of platforms, systems, policies, and services, we can create a free and relaxed entrepreneurial atmosphere, a solid industrial foundation, and a perfect public platform. An optimized innovation environment is conducive to build an ecosystem for the healthy development of the digital economy in the future.

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