ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

A Study on Evaluation of Digital Economic Development Level Based on Fuzzy Comprehensive Evaluation

— — Taking the Yangtze River Delta as an example

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Abstract. In recent years, with the increasing improvement of digital technology, the rapid development of digital economy has become a force that cannot be ignored in the development of global economy. The Yangtze River Delta region has a good economic foundation and favorable conditions for the development of digital economy, which plays a driving role in the development of digital economy in China. In this paper, by constructing a model, we firstly use analytic hierarchy process to assign weight to each index, then use fuzzy comprehensive evaluation to give a comprehensive score for the digital economic development level of Shanghai , Jiangsu , Zhejiang and Anhui in the Yangtze River Delta, and make analysis and decision-making according to the score.

Keywords: digital economy ; Yangtze River Delta region ; analytic hierarchy process ; fuzzy comprehensive evaluation ; analytic decision-making

1. Introduction

Since the 18th National Congress of the Communist Party of China, the CPC Central Committee has attached great importance to the digital economy and upgraded it to an international strategy. The 14th Five-Year Plan Digital Economic Development Plan states that digital economy will move towards prosperity and maturity in 2035 and strive to form a unified, fair, competitive, mature and complete modern market system for digital economy, and the basic development level of digital economy and industrial system ranks among the highest in the world.

In this context, how to measure the level of digital economic development in each region has became a realistic question that needs to be answered urgently in the process of studying and developing digital economy. At present, there have been many results on the measure of digital economic development level in domestic related research, but there are few studies on the comparison between regions in the same city cluster. As the strongest city cluster in China, the Yangtze River Delta meets with the "Belt and Road" and the Yangtze River Economic Belt, and is an important platform for China to participate in international competition and an important engine for economic and social development[1] . It has strong representativeness and selection significance.

Based on this, this paper analyzes the development level of digital economy in different regions of the Yangtze River Delta by constructing a hierarchical model of digital economic development, and constructs a total of four secondary indicators: digital infrastructure , digital industrialization , industrial digitization and economic development basis, which also contains fourteen tertiary indicators such as Internet broadband access users, GDP per capita , and total telecommunications business . Combined with the data of 2020 corresponding to each tertiary indicator, this paper firstly uses analytic hierarchy process to assign weights to each indicator, and then uses fuzzy comprehensive evaluation method to score each evaluation indicator of digital economy, and finally ranks them according to the scores so as to provide a quantitative basis for decision-making, and based on this, makes a comparative analysis on the digital development level of each region of the Yangtze River Delta, so as to realize and summarize the measurement of the digital economic development level of each city in the Yangtze River Delta region.

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2. Literature Review

According to the theme of focus, this paper conducts a literature review from the following two aspects: first, is a measure of digital economic development; second, is a regional difference analysis of digital economy .

2.1 Measures of Digital Economic Development Level

Chinese and foreign scholars have studied the measures of digital economic development. Foreign scholars Chinoracky R and Corejova T[2] measured digital economic scale using three indicators: economy, labor and technology. Domestic scholars Zheng Ganwen and Ye Azhong[3] measured the digital economic development level using principal component analysis based on panel data from 241 prefecture-level cities across the country from 2011 to 2018; Liao Xinlin and Yang Zhengyuan[4] measured manufacturing upgrading level and digital economic development level in sample cities with a entropy value method, using panel data from 41 prefecture-level cities within the Yangtze River Delta from 2015 to 2019.

2.2 Regional Difference Analysis of Digital Economy

For the regional difference analysis of digital economy, Guo Bingnan[5] used Dagum GINI index and kernel density estimation to analyze the regional differences and distribution dynamics of the top ten city clusters; Liu Chuanhui and Yang Zhipeng[6] measured the digital economic indicators of the six city clusters including the Yangtze River Delta and visualized the digital economic development level and spatiotemporal characteristics of city clusters ; Yang Dong[7] carried out the configuration analysis of 27 central cities of Yangtze River Delta integration in process with the help of fuzzy set qualitative comparative analysis method . Cheng Guangbin[8] used entropy weight TOPSIS method to comprehensively calculate the digital economic input and output levels of each province in China in 2018 . In summary, the current scholars on digital economy research has achieved a lot of results, but most of the research content focused on the measurement methods of digital economy development level and the promotion of digital economy for regional economic development, and most of the research objects focused on the comparison between provinces and cities or city cluster, and there are few studies on the digital economy development level between various regions in city cluster. Based on the data of digital economy in Zhejiang, Shanghai and Anhui provinces in 2020, this paper uses analytic hierarchy process and fuzzy comprehensive evaluation method to obtain the comprehensive score of digital economy development level in the four regions and analyzes the decision-making accordingly.

3. Analytical Hierarchy Process

AHP refers to a decision-making method in which the elements always associated with decision-making are divided into targets, criteria, indicators and other levels, based on which the ranking calculation is performed by establishing a judgment matrix combining qualitative and quantitative decision-making methods, and the steps for determining weights by AHP are as follows:

3.1 The Establishment of Hierarchical Analysis Model

In order to explore the level of digital economic development in various regions, a total of 4 secondary indicators and 14 tertiary indicators are set in this paper. The digital financial inclusion index of China in the data comes from The Peking University Digital Financial Inclusion Index of China (2011-2020) , and other data comes from the 2021 China Statistical Yearbook. The evaluation indicators at each level are shown in Table 1.

ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

Table 1: Digital economic development evaluation indicators

Target Layer	Criteria Layer	Indicator layer	Explanation	units
Level of digital economic development	Digital Infrastructure (A)	Internet Broadband Access User (A1)	Reflects Internet popularity	Account
		Fixed asset investment in information transmission, software and information technology services increased over the previous year (A2)	Reflects the extent to which information transmission, software and information technology services contribute to digital economic growth	%
		Number of Domain Names and Web Pages (A3)	Reflects the extent of development and popularity of Internet networks in various regions	Per
		Information transfer, software and information technology services sector practitioners (A4)	Reflects the capacity and potential of regions to use talent to develop digital economies	10,000 people
	Digital Industrialization (B)	Software Business Revenue (B1)	Reflects the ability of each region to use software business to develop digital economy	Billion RMB
		Total Telecommunication Services (B2)	Reflects the overall achievements of telecommunication business development in each region over a given period	Billion RMB
		Total Salary of Employment Personnel in Information Transmission, Software and Information Technology Services (B3)	Reflects how digital industrialization is promoted by information transmission, software and information technology services in various regions	Billion RMB
		Authorization amount for domestic invention patent application (B4)	Reflects digital economic innovation capacity in various regions	Piece
	Industry Digitization (C)	Number of websites owned by each 100 enterprises (C1)	Reflects the ability of enterprises in various regions to apply digital economy	Per
		Percentage of enterprises with e-commerce transactions (C2)	Reflecting the popularity of e-commerce in various regions	%
		Digital financial inclusion index of China (C3)	Reflects the extent to which digital economies contribute to inclusive finance	Point
	Basis for Economic Development (D)	GDP per capita (D1)	Refers to the per capita gross domestic product of each region, reflecting the economic development status of each region	10,000 RMB
		Third industry as a share of GDP (D2)	Reflects the stage of economic development in each region	%
		Engel's Coefficient (D3)	Reflecting the living standards of residents in various regions	%

ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

3.2 Construction of Judgment Matrix

Denote target as A, and factor as u_i、u_j (i，j = 1, 2, … , n). u_{ij} represents the relative importance value of u_i to u_j and also directly impacts the effect of decision-making. The A-U judgment matrix P consists of u_{ij} :

$$P = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ u_{n1} & u_{n2} & \cdots & u_{nm} \end{bmatrix} \quad (1)$$

3.3 Hierarchical Single Ranking and Consistency Test

Hierarchical single ranking refers to the importance order of each factor in this layer to a certain factor in the upper layer, which is represented by the feature vector of the judgment matrix. According to the judgment matrix, find out the eigenvector w corresponding to its maximum characteristic root $\lambda_{\max}$. The eigenvector w is the ranking weight value of the relative importance of the corresponding factor at the same level for a factor at the previous level after normalization. The equation is as follows:

$$P_w = \lambda_{\max} \bullet w \quad (2)$$

Consistency test is to ensure the credibility of hierarchical single ranking, and it is necessary to calculate the consistent ratio, which is formulated as follows:

$$CR = \frac{CI}{RI} \quad (3)$$

Where CR is the random consistent ratio of the judgment matrix; CI is the consistency index of the judgment matrix; RI is the average random consistency index of the judgment matrix , and the specific value can be known according to the order of the judgment matrix. CI is calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (4)$$

The results of hierarchical singular ordering are considered satisfactory only if CR < 0.1; otherwise adjustments to judgment matrix elements are required until satisfactory.

3.4 Hierarchical Total Ranking and Consistency Test

Hierarchical total ranking is the process of calculating the ranking weight value of all factors of the same level for the relative importance of the uppermost level, which is carried out layer by layer from the highest level to the lowest level. CR is calculated as follows:

$$CR = \frac{wi_1 CI_1 + wi_2 CI_2 + \Lambda + wi_m CI_m}{wi_1 RI_1 + wi_2 RI_2 + \Lambda + wi_m RI_m} \quad (5)$$

The results of the total ranking of levels are considered satisfactory only if CR < 0.1; otherwise adjustments to judgment matrix elements are required until satisfactory.

The weights occupied by each indicator were obtained by analytic hierarchy process as shown in Table 2:

ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

Table 2: Analytical Hierarchy Process Decision Weighting Table

Target Layer	Criteria Layer	Weight	Indicator layer	Weight
Level of digital economic development	Digital Infrastructure (A)	0.1481	Internet Broadband Access User (A1)	0.0107
			Fixed asset investment in information transmission, software and information technology services increased over the previous year (A2)	0.0814
			Number of Domain Names and Web Pages (A3)	0.0239
			Information transfer, software and information technology services sector practitioners (A4)	0.047
	Digital Industrialization (B)	0.3736	Software Business Revenue (B1)	0.1154
			Total Telecommunication Services (B2)	0.1632
			Total Salary of Employment Personnel in Information Transmission, Software and Information Technology Services (B3)	0.0385
			Authorization amount for domestic invention patent application (B4)	0.0544
	Industry Digitization (C)	0.3736	Number of websites owned by each 100 enterprises (C1)	0.0389
			Percentage of enterprises with e-commerce transactions (C2)	0.0959
			Digital financial inclusion index of China (C3)	0.2366
	Basis for Economic Development (D)	0.1047	GDP per capita (D1)	0.0297
			Third industry as a share of GDP (D2)	0.0562
			Engel's Coefficient (D3)	0.0082

It can be seen from Table 3 that digital industrialization and industrial digitization have the highest weight of 0.3736; digital-related business has become increasingly prominent in the industrial structure thanks to the rapid development of digital technology, the position occupied by the industrial form with digital technology as the core has become more and more important, and digital technology has become more and more significant in the transformation and contribution of traditional industries, and digital integration promotes the increasing industrial added value of relevant industries[9]. Occupying the main part of the digital economic system is digital industrialization and industrial digitization, and the sustainable, stable and healthy development of digital economy is inseparably from the mutual promotion of the two[10], so digital industrialization and industrial digitization become the two criterion layer indicators with the highest weight; the weight of digital infrastructure is 0.1481; the economic development foundation has the least impact on the development of digital economy, accounting for a weight of 0.1047.

ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

4. Fuzzy comprehensive evaluation method

4.1 The Domains of Evaluation Factors and Their Weight Coefficients

Evaluation factors are limited sets of evaluation indicators. The weight coefficient of each indicator can be obtained by using AHP to reflect the importance of each factor, which can be expressed by the weight matrix $W=\{w_1,w_2,\cdots,w_m\}$.

4.2 The Domains of Evaluator Sets

The evaluator set is a collection of evaluators' evaluation results that may be made for the evaluated object, and is shown in $V=\{v_1,v_2,\cdots,v_n\}$. v_i represents the i th evaluation result, n represents the total evaluation result.

4.3 Single-Factor Fuzzy Evaluation and the Establishment of Fuzzy Relationship Matrix R

Single-factor fuzzy evaluation refers to the process of evaluating from a single factor to determine the membership degree of evaluation object to evaluation set V . Determining the degree of membership of the evaluated object to each grade fuzzy subset from a single factor can obtain a fuzzy relationship matrix R , where matrix coefficient $r_{ij}(i=1,2,\cdots,m;j=1,2,\cdots,n)$ indicates the degree of membership of a certain evaluated object to v_j grade fuzzy subset from a factor u_i , which can be obtained by using absolute value subtraction according to the scoring results .

In this paper, normalized processing is used to map the collected data of digital economic development level indicator to 0 ~ 1, so as to make data processing more convenient and rapid. For positive impact indicators the formula is as in (6) and for negative impact indicators the formula is as in (7):

$$x^*=\frac{x}{x_{\max}} \quad (6)$$

$$x^*=\frac{x_{\min}}{x} \quad (7)$$

The results of indicator layer normalization processing data in this paper are shown in Table3 :

Table 3 : Normalized Processing Results

Region / Indicators	Shanghai	Jiangsu	Zhejiang	Anhui
Internet Broadband Access User	0.2446	1 .0000	0.7823	0.5571
Fixed asset investment in information transmission, software and information technology services increased over the previous year	-0.0223	0.5469	0.1172	1 .0000
Number of domain names and pages	0.6045	0.3824	1 .0000	0.0745
Information transmission, software and information technology services sector practitioners	1 .0000	0.7321	0.6317	0.2165
Software Business Revenue	0.6074	1 .0000	0.6505	0.0725
Total Telecommunication Services	0.2423	0.4491	1 .0000	0.1387
Total Salary of Employment Personnel in Information Transmission, Software and Information Technology Services	1 .0000	0.4393	0.5551	0.0809
Amount of domestic invention patent application granted	0.3112	1 .0000	0.7847	0.2398
Number of websites per 100 enterprises	1 .0000	0.9649	0.8421	1 .0000
Percentage of enterprises with e-commerce	0.8421	0.7820	0.9173	1 .0000

ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

transactions				
Digital inclusive financial index	1 .0000	0.8835	0.9420	0.8107
GDP per capita	1 .0000	0.7783	0.6460	0.4072
Third industry as a share of GDP	1 .0000	0.7182	0.7633	0.7018
Engel 's coefficient	1.0000	0.9534	0.9256	0.7932

4.4 Multi-Factor Fuzzy Evaluation

Multi-factor fuzzy evaluation is the process of synthesizing W and fuzzy relationship matrix R to obtain the fuzzy comprehensive evaluation result vector B of each evaluated object by using appropriate synthesis operators. The fuzzy comprehensive evaluation model is:

$$B = W \bullet R = \{w_1, w_2, \cdots, w_m\} \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = (b_1, b_2, \cdots, b_n) \quad (8)$$

Where $b_j (j = 1,2,\cdots,n)$ is obtained by the jth column operation of W versus R and represents u_i the degree to which the rated object is globally affiliated to a v_j graded fuzzy subset.

Taking Jiangsu as an example, the relevant calculation process is:

B=W • R=(0.0107*1.0000) +(0.0657*0.5469) +(0.0226*0.3824) +(0.0491*0.7321) +(0.1161*1.0000) +(0.1641*0.4491) +(0.0387*0.4393) +(0.0547*1.0000) +(0.0376*0.9649) +(0.0843*0.7820) +(0.2517*0.8835) +(0.0254*0.7783) +(0.0701*0.7182) +(0.0092*0.9534) =0.7562

The final evaluation result was B = (0.6949, 0.7562, 0.7982, 0.5242) as shown in Table 4:

Place Name	Shanghai	Jiangsu	Zhejiang	Anhui
Score	0.6949	0.7562	0.7982	0.5242

Table 4 : Combined local scores

4.5 Analysis of the Results of Fuzzy Comprehensive Evaluation

From the above results, it can be seen that the two regions with the highest scores are Zhejiang and Jiangsu, with scores of 0.7982 and 0.7562 respectively; Shanghai comes second with a score of 0.6949; and Anhui has the lowest score of 0.5242.

The highest-scoring Zhejiang province has strong digital economic strength. As the first place of digital economy, Zhejiang Province launched the construction of "digital Zhejiang" as early as 2003, and began to grasp digital economy as the "No. 1 Project" in 2017. At present, digital economy has become the" gold business card "of Zhejiang Province. So far, the digital economy in Zhejiang Province has been expanding and improving in scale and industrial competitiveness; the depth of digital technology integration has been deepening; and the development of characteristic industries and modernization governance have been rapidly developed with the help of digital economy[11]. At the same time, in recent years, Zhejiang Province has seized the opportunities of emerging industries related to digital economy, actively increased effective investment and innovation investment, and fostered high-quality projects to develop new kinetic energy to cope with the impact of the epidemic[12] .

The digital economic development of Jiangsu Province, which scored the second, has received multiple support: the "14th Five-Year Plan" for digital economic development proposes to establish and improve credit based digital economic market supervision and escort the digital economy[13] ; carry out technological innovation with Jiangsu characteristics such as "chief data officer" and

ISSN:2790-1661 DOI: 10.56028/aemr.3.1.141

"digital currency application"[14] ; and the document report of the China Digital Economic Development Index (DEDL) shows that the digital economic competitiveness index of Jiangsu Province is as high as 81.83 in 2020, ranking among the forefront in China.

Shanghai, which scored third, is also doing well in the development of digital economy. In Shanghai, the industries of ITC, manufacturing, retail, medical treatment and finance have a good digital talent base and a relatively uniform distribution of talents[15] . In terms of policies, the Opinions on Comprehensively Promoting the Digitization Transformation of Shanghai Cities issued at the beginning of the opening of the 14th Five-Year Plan proposed that digital industrialization and industrial digitization should be accelerated to amplify the radiation-driving effect of the digital economy[16] . Yan Wei, deputy to the Shanghai Municipal People 's Congress, mentioned in an interview with the special report of the Shanghai two sessions in 2022 that the pilot of the new area of Lingang in Shanghai created many favorable conditions and provided empirical practices for the development of the digital economy in Shanghai[17] .

The economic development level of Jiangsu, Zhejiang and Shanghai is at the forefront of the country, and all of them have relatively perfect policies and rich talent reserves to support the development of digital economy. However, due to the smaller geographical scope of Shanghai compared to Jiangsu and Zhejiang, its data are smaller than those corresponding to Jiangsu and Zhejiang provinces in the statistics of indicators such as Internet access users, and its total scale of digital economy is smaller than that of Jiangsu and Zhejiang provinces, so Shanghai has a smaller score than Jiangsu and Zhejiang provinces in the comprehensive evaluation.

The comprehensive score of Anhui province is obviously smaller than that of Jiangsu, Zhejiang and Shanghai, and its digital economy development level also has a significant gap compared to that of other three regions. According to the Research Report on the Development of Digital Economy in Anhui Province in 2018, there are problems in the development of digital economy in Anhui Province: the integration of real economy and information technology is insufficient; information management mode does not adapt to the new requirements of development; and industrialization of learning technology needs to be accelerated. In the future, Anhui Province can promote the development of digital economy by accelerating the integration of digital economy and real economy, innovating management mode according to the development requirements, and increasing the training and introduction of digital talents, so as to narrow the gap with the development level of digital economy in other regions.

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