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Evaluating the Development Level of Digital Economies Using the Topsis Comprehensive Assessment Approach

-- A Case Study of China's Provincial Regions

Yanlin Liu
SWUFE-UD Institute of Data Science, Southwestern University of Finance and Economics, Chengdu, China
3135997655@qq.com

Abstract. The digital economy, as a pivotal engine of global economic advancement, reached a valuation of 50.2 trillion yuan in China in 2022, making up 41.5% of the GDP. This research established an evaluative framework for digital economy progress featuring 1 primary indicator, 4 secondary indicators, and 17 tertiary indicators. Weights were assigned using the Analytic Hierarchy Process, and the development of the digital economy across China's 31 provincial regions in 2022 was assessed through the Topsis comprehensive assessment method. The findings indicate that Guangdong is at the forefront of digital economy development, whereas Qinghai remains relatively underdeveloped. Drawing on these observations, the paper proposes targeted policy measures aimed at encouraging equitable growth of the digital economy and inclusive regional economic development.

Keywords: Digital Economy; Influencing Factors; Topsis Comprehensive Evaluation Method; Analytic Hierarchy Process.

1. Introduction

As Internet technologies advance, the digital economy—encompassing IoT, big data, and cloud computing—has emerged as a pivotal driver for economic growth and the modernization of traditional industries. It demonstrated resilience during the pandemic by supporting the real economy. In the 20th National Congress report, Xi Jinping emphasizing, "to promote the implementation of the national big data strategy, accelerate the enhancement of digital infrastructure, push forward the integration and open sharing of data resources, ensure data security, and hasten the construction of digital China.". By 2022, China's digital economy accounted for 41.5% of the GDP at 50.2 trillion yuan, with productivity indices suggesting it outperforms the broader economy [1]. Despite notable progress, challenges persist, including uneven distribution of human resources, different levels of policy implementation and support, different levels of economic development, and uneven regional development., with coastal regions generally outperforming inland areas. Notably, northern regions like Beijing, Tianjin, Jiangsu, and Shandong are in the first tier of the digital economy development index (65-100), yet provinces such as Inner Mongolia, Heilongjiang, and Jilin remain relatively backward due to geographical constraints, challenges in the digital transformation of traditional industries, and inadequate policy and strategic focus [2].

In light of these issues, this study proposes a digital economy development level measurement model with 4 secondary and 17 tertiary indicators to enhance national digital economy progress and reduce disparities between the south and north. It applies the Analytic Hierarchy Process for indicator weighting and the Topsis method for evaluating and scoring the digital economy of 23 provinces, 5 autonomous regions, and 4 municipalities in the year of 2022. The analysis aims to identify differences in digital economy development and offer strategic advice to governments.

2. Literature Review

2.1. Factors Influencing Digital Economy Development

The digital economy's growth is influenced by various factors. Studies by Lin et al. [3] emphasize the significant role of policy in Guangdong's port cities, with spatial spillover effects on digital economy development that increase over time. Okpalaoka [4] stresses the importance of collaboration, regional policies, and information dissemination for business, calling for robust frameworks to support digital growth. Reports like the EC's "DESI" [5] and OECD's "Digital Economy Outlook 2020"[6] identify key drivers such as digital skills, 5G deployment, SME digitalization, investment, and gender equality in digital public services.

Research by Ge et al. [7] using the DEA-Malmquist model highlights technological progress as a primary efficiency driver in central provinces' digital economies, suggesting improvements in industrial configuration and resource allocation. Liu et al. [8], through threshold and spatial autoregressive models, recognize economic growth, foreign capital reliance, government intervention, human capital, and wage levels as foundational. They advise on openness and regional welfare for balanced growth. Wang et al. [9] propose region-specific strategies using interpolation and Zipf's law to address varied digital economy stages across China. Yang's [10] assessment of Shenyang's digital economy underscores the importance of infrastructure, industrial growth, and talent development for performance enhancement.

2.2. Digital Economy Development Insights

Xu Yanting and Li Tinghui [11] charted China's digital economy growth from 2010 to 2019, noting a downturn in 2020 and increasing regional disparities. Shi et al. [12] emphasized the critical role of merging industrialization with digitalization, which has spurred new services and industries, expecting further integration and innovation. Chijindu Iheanacho Okpalaoka [4] identified five key trends driving the digital economy, including scientific innovation, structured growth, regional development, theoretical progress, and fostering creativity and entrepreneurship, all enhancing economic and social welfare. Mohd Javaid et al. [13] explored how the digital economy, using AI and IoT, transforms traditional industries and enhances socio-economic activities.

Wang Jun, Zhu Jie, and Luo Xi [14] used entropy methods to analyze regional variations in China's digital economy, recommending enhancements to digital infrastructure and industry. Wu Xiaoyi and Zhang Yajing [15] applied principal component analysis and efficacy scores to advocate for better digital infrastructure and industrial planning. Chen Changsheng, Xu Wei, and Lan Zongmin [16] reviewed trends during China's "14th Five-Year Plan," noting the digital economy's direct 6.6% GDP contribution in 2019 and urged a faster adoption of the "dual circulation" strategy to improve economic quality.

2.3. Review of Literature

International research primarily explores the socio-economic effects of ICT proliferation, focusing on its role in promoting social equity and narrowing the digital divide. In contrast, domestic studies typically highlight measurable factors like technological progress, policy support, and infrastructure that propel the digital economy, but often overlook cultural, educational, and legal factors. There is also a noted deficiency in discussions about the social issues that the digital economy may introduce, including digital divides and privacy concerns. Although regional developmental disparities have been analyzed, there is a shortage of in-depth studies on internal differences within specific regions. Additionally, the digital economy's rapid changes and complexity present significant challenges regarding data timeliness and relevance.

This study develops a model to evaluate the digital economy's development level, incorporating one primary, four secondary, and seventeen tertiary indicators. It employs the Analytic Hierarchy Process (AHP) to weight these indicators and the Topsis method for a comprehensive evaluation, quantitatively analyzing and comparing the digital economy throughout China's provinces, autonomous regions, and municipalities. The goal is to illuminate the development disparities between northern and southern China, offering policymakers scientific insights and specific recommendations to promote balanced growth in the digital economy and advance in-depth research in this dynamic area.

3. Indicator Weight Construction

3.1. Preliminary Data Selection and Sources

This study developed a comprehensive digital economy evaluation system, which assesses various development aspects as detailed in Table 1 The system includes indicators for infrastructure, technological innovation, industry scale, and digital application prevalence. These indicators not only reflect the scope and quality of ICT foundations but also the region's innovation activity and its economic impact. Moreover, they evaluate how digital technology integrates into business and social spheres, providing a framework to analyze its influence on traditional industries and supporting informed policy-making.

Table 1. Inter-provincial Digital Economic Development Indicator System

Level 1 Indicator	Level 2 Indicator	Level 3 Indicator	Unit
Digital Economic Index	Infrastructure Construction	Broadband Access Rate	%
		Number of Mobile Phone Base Stations	myriad
		Number of Domain Names	myriad
		Number of IPv4 Addresses	myriad
	Technological innovation ability	New product development expenditure	billion ¥
		Number of invention patent applications	pieces
		Number of R&D institutions	companies
		Full-time equivalent of R&D personnel	individuals
		Graduates and Enrolled Master's Students	individuals
	Digital Economy Industry Scale	Number of websites per hundred enterprises	sites
		Total telecommunications business volume	billion ¥
		Number of enterprises in the digital industrialization sector	companies
		Information technology services revenue	billion ¥
	Digital Application Penetration	E-commerce sales	billion ¥
		Total retail sales of consumer goods	billion ¥
		Number of computers per hundred people	computers
		Digital financial inclusion index	——

This study focuses on the 31 provincial regions of Mainland China in 2022, including municipalities and special administrative regions. Data sources include the China Digital Inclusive Finance Index from Peking University's Digital Finance Research Center; data on the increase in the number of people with bachelor's degrees and higher from the Ministry of Education's official website (www.moe.gov.cn); and numbers of digitally-focused listed companies from the "2022 China Listed Companies Digital Economy White Paper." Additional data comes from the CSMAR database (data.csmar.com) and Tonghuashun's iFind database. All data used are from 2022 to ensure timeliness and accuracy of the analysis.

3.2. Analytic Hierarchy Process Framework

The Analytic Hierarchy Process (AHP) is an evaluative method that structures decision-making elements into a hierarchical model, facilitating the conversion of subjective judgments into relative importance assessments among factors. This method is widely utilized in models requiring comprehensive evaluations.

3.2.1. Hierarchical Structure Development

The indicator system in this study comprises one primary, four secondary, and seventeen tertiary indicators. The secondary indicators encompass infrastructure development, technological innovation capabilities, digital economy industry scale, and digital applications penetration. Details on the tertiary indicators are illustrated in Figure 1, providing a granular view of each category's components.

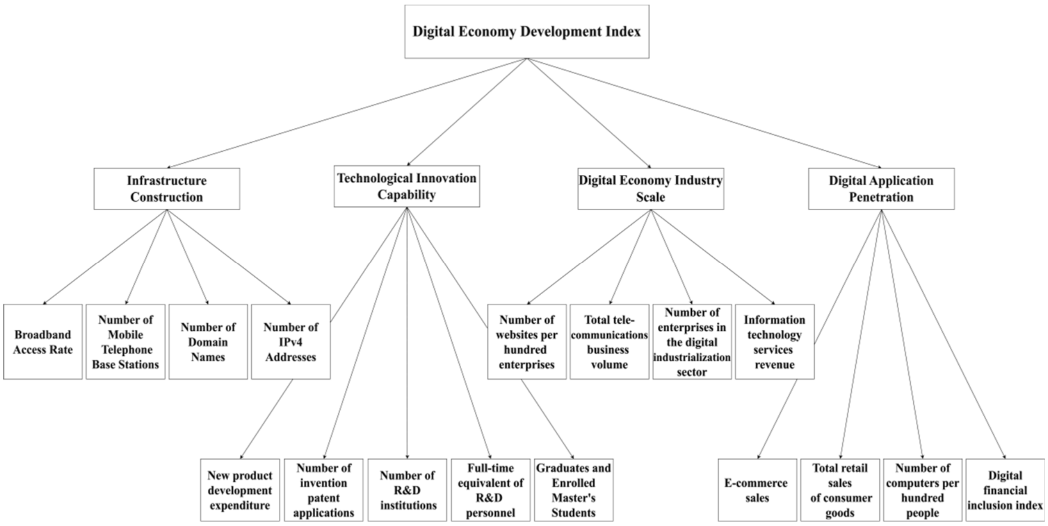

Figure 1. Framework of the Hierarchical Structure Analysis Model

3.2.2. Construction of the Judgment Matrix

In the Analytic Hierarchy Process, the judgment matrix is central, with elements reflecting decision-makers' subjective evaluations of relative importance, significantly influencing decision quality. A 1 to 9 scale and their reciprocals quantify these evaluations, converting expert opinions into analytical data.

Table 2. Scale for Constructing the Judgment Matrix

Scale	Meaning
1	Equal importance
3	Slightly more important
5	Clearly more important
7	Strongly more important
9	Extremely more important
2,4,6,8	Intermediate values between the above judgments
Reciprocal	If element a_{ij} is an assessment of factor i compared to j, then $a_{ji} = 1/a_{ij}$

3.2.3. Single-Level Sorting and Consistency Check

Single-level sorting in AHP involves ranking elements based on their importance relative to a previous level. This is achieved by calculating the eigenvector of matrix A through solving $AW=\lambda_{max}W$, yielding a vector W. After normalization, this provides the relative importance weights. The Consistency Ratio (CR) is then calculated to check the randomness in the matrix's consistency, ensuring the reliability of the rankings.

Consistency Index:

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

In order to measure the size of CI, a random consistency index is introduced:

Table 3. Random Consistency Index

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Consistency Ratio:

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - n}{RI \cdot (n - 1)} \quad (2)$$

A Consistency Ratio (CR) below 0.1 signifies acceptable consistency in the judgment matrix A, allowing it to pass the consistency test and enabling the use of its normalized eigenvector as the weight vector. If the CR exceeds this threshold, the matrix requires reconstruction and adjustment of its elements to enhance consistency.

3.2.4. Global Hierarchical Ranking and Consistency Verification

Global hierarchical ranking involves calculating the relative weights of elements against the highest level (overall objective), conducted top-down to ensure comprehensive consideration of weights at each level. The composite consistency ratio (CR) for the p-th level relative to the top level is given by formula:

$$CR^{(p)} = CR^{(p-1)} + \frac{CI^{(p)}}{RI^{(p)}}, \quad p = 3, 4, \ldots, s \quad (3)$$

In this study, a calculated CR of 0.0277, which is less than 0.1, indicates satisfactory consistency within the analytic hierarchy model.

3.3. Indicator Weight Table

Table 4. Inter-provincial Digital Economic Development Indicator System in China

Level 1 Indicator	Level 2 Indicator	Level 3 Indicator	Weight
Digital Economic Development Index	Infrastructure Construction	Broadband Access Rate	0.0251
		Number of Mobile Phone Base Stations	0.0435
		Number of Domain Names	0.0134
		Number of IPv4 Addresses	0.0134
	Technological Innovation Capability	New product development expenditure	0.0554
		Number of invention patent applications	0.0375
		Number of R&D institutions	0.0993
		Full-time equivalent of R&D personnel	0.0214
		Graduates and Enrolled Master's Students	0.0636
	Digital Economy Industry Scale	Number of websites per hundred enterprises	0.0722
		Total telecommunications business volume	0.2374
		Number of enterprises in the digital industrialization sector	0.0433
		Information technology services revenue	0.1144
	Digital Application Penetration	E-commerce sales	0.0421
		Total retail sales of consumer goods	0.0729
		Number of computers per hundred people	0.0226
		Digital financial inclusion index	0.0226

Finally, we obtained the weight of each three-level indicator relative to the overall goal of the digital economy development index, as shown in Table 4.

4. Topsis Method for Composite Evaluation

Topsis is a decision analysis tool that ranks options by measuring their distances to an ideal and a negative ideal solution. It assesses options based on their closeness to these benchmarks, considering the importance of each attribute.

4.1. Construction of the Decision Matrix

The initial decision matrix X is formed by gathering data for each option across various criteria. In this matrix, x_{ij} indicates the performance of the ith option on the j-th criterion. To neutralize differences in scale and magnitude among criteria, the matrix is normalized by following Formula (4) in this study.

$$r_{ij} = \frac{x_{ij} - \min(x_{\cdot j})}{\max(x_{\cdot j}) - \min(x_{\cdot j})} \tag{4}$$

where $\min(x_{\cdot j})$ and $\max(x_{\cdot j})$ are the minimum and maximum values of the j-th indicator respectively.

4.2. Weight Assignment

Weights are allocated to normalized indicators based on their importance using the AHP. Each weighted matrix V's element, v_{ij}, is calculated by:

$$v_{ij} = w_j \times r_{ij} \tag{5}$$

4.3. Ideal and Negative Ideal Solutions

Determine the positive ideal solution S_j^+ and the negative ideal solution S_j^-:

$$S_j^+ = \begin{cases} \max\{r_{ij}\}, & j = 1, \ldots, m;\ \text{larger-the-better criteria} \\ \min\{r_{ij}\}, & j = 1, \ldots, m;\ \text{smaller-the-better criteria} \end{cases} \tag{6}$$

$$S_j^- = \begin{cases} \min\{r_{ij}\}, & j = 1, \ldots, m;\ \text{larger-the-better criteria} \\ \max\{r_{ij}\}, & j = 1, \ldots, m;\ \text{smaller-the-better criteria} \end{cases} \tag{7}$$

For benefit criteria, the ideal solution is the maximum value and the negative ideal is the minimum; for cost criteria, it's the opposite. This approach effectively captures the deviations of each option from the ideal state.

4.4. Distance to Ideal Solutions

The Euclidean distances of each alternative from both the positive ideal solution and the negative ideal solution:

$$S_{d_i}^+ = \sqrt{\sum_{j=1}^{m} \left(S_j^+ - r_{ij}\right)^2} \quad i = 1, \ldots, n \tag{8}$$

$$S_{d_i}^- = \sqrt{\sum_{j=1}^{m} \left(S_j^- - r_{ij}\right)^2} \quad i = 1, \ldots, n \tag{9}$$

The Euclidean distance quantifies proximity to the ideal digital economy state, providing deviations for each region.

4.5. Relative Closeness Calculation

Relative closeness, η_i, is computed as:

$$\eta_i = \frac{S_{d_i}^-}{S_{d_i}^+ + S_{d_i}^-} \tag{10}$$

η_i range from 0 to 1, with higher values indicating closer alignment with the ideal state, aiding in the assessment and comparison of regional digital economy levels for policy-making and resource allocation.

4.6. Topsis Method Empirical Analysis

Using Python 3.9.12 and the specified formulas, this study calculated comparative evaluation scores for China's 23 provinces, 5 autonomous regions, and 4 municipalities, detailed in Table 5.

Table 5. Digital Economy Development Scores by Province

Province(City)	Score
Guangdong	0.8681
Jiangsu	0.6240
Zhejiang	0.5156
Shandong	0.4747
Beijing	0.4411
Sichuan	0.3993
Henan	0.3906
Shanghai	0.3577
Hunan	0.3409
Hubei	0.3153
Hebei	0.3099
Anhui	0.2931
Fujian	0.2527
Shaanxi	0.2396
Chongqing	0.2204
Jiangxi	0.2146
Liaoning	0.2013
Yunnan	0.1982
Guangxi	0.1975
Guizhou	0.1739
Gansu	0.1487
Shanxi	0.1410
Xinjiang	0.1313
Tianjin	0.1311
Heilongjiang	0.1281
Tibet	0.1266
Ningxia	0.1253
Jilin	0.1220
Inner Mongolia	0.1196
Hainan	0.1144
Qinghai	0.1086

5. Conclusion

(1) Guangdong and Jiangsu are at the forefront of China's digital economy, with scores of 0.8681 and 0.6240 respectively.

Guangdong's strategic "one core, two poles" approach, outlined in the "Guangdong Province Plan (2021-2035)," leverages the Pearl River Delta to create a sustainable "smart port" through digital innovation [3]. The "Digital China Development Report (2022)" positions Guangdong as a national leader in digital advancement and 5G utilization [17]. Similarly, Jiangsu is emerging as a digital powerhouse, particularly in big data, blockchain, and AI. It has established a national AI innovation application pilot zone and made significant strides in blockchain, with its digital economy reaching a substantial 5.1 trillion yuan, or 11.8% of China's total, as reported in the "Digital Jiangsu Development Report (2022)" [18]. Guangdong's dominance in "total telecom business volume" further highlights the provinces' digital economic prowess, reflecting their advanced and mature digital transformation.

(2) Zhejiang, Shandong, Beijing, Sichuan, Henan, Shanghai, Hunan, Hubei, and Hebei have robust digital economies, scoring from 0.3099 to 0.5156.

Zhejiang is a leader in e-commerce but has regional disparities [19]. Shandong's industrial base supports digital growth but needs innovation. Beijing, a tech innovation center, excels in digital tech but could better support SMEs. Sichuan's cultural and tourism sectors bolster its digital services, yet infrastructure is lacking. Henan's large consumer market drives digital economy but requires high-tech development. Shanghai is competitive in fintech and e-commerce despite market challenges. Hunan and Hubei are advancing digital economy through media and innovation; Hunan needs to enhance tech and talent, while Hubei is recovering from the 2020 pandemic. Hebei is leveraging regional integration but must diversify its industries. Each region faces unique challenges and requires strategic policies for balanced, sustainable digital growth [2].

(3) Anhui, Fujian, Shaanxi, Chongqing, Jiangxi, Liaoning, Yunnan, Guangxi, and Guizhou score from 0.1739 to 0.2931.

Anhui excels in smart manufacturing but faces a weak information industry and talent scarcity[20][21]. Fujian has strengths in digital governance and e-commerce, yet requires advancements in AI and cloud computing [22]. Shaanxi is building digital infrastructure but needs policy refinements for a mature digital economy. Chongqing, with its national data channel, must enhance digital technology integration and innovation. Jiangxi's reliance on traditional manufacturing for digital economy indicates a need for deeper digital-tech integration. Liaoning confronts innovation and scale challenges, along with talent and enterprise brain drain [23] Yunnan's digital economy, boosted by tourism and culture, is hindered by outdated information infrastructure. Guangxi and Guizhou, despite growth, must strengthen their digital economy's depth and breadth, particularly in big data and cloud services [2].

(4) Gansu, Shanxi, Xinjiang, Tianjin, Heilongjiang, Tibet, Ningxia, Jilin, Inner Mongolia, Hainan, and Qinghai exhibit lower digital economy development score from 0.1086 to 0.1487.

Gansu's digital economy is nascent with small industry scale and weak support systems [24]. Despite a growing number of enterprises, its data centers are dispersed and underutilized, indicating suboptimal resource planning. Shanxi, with a legacy in coal, is integrating 5G and smart industries into its digital economy but faces structural transformation challenges [25]. Tianjin shows lower "total telecom business volume," suggesting a smaller digital economy scale. Peripheral regions including Xinjiang, Heilongjiang, Tibet, Ningxia, Jilin, Inner Mongolia, Hainan, and Qinghai are constrained by economic and geographical factors, leading to funding shortages, talent outflows, and information seclusion, which impede digital economy expansion. These provinces score below the median in 13 of 17 tertiary indicators, highlighting the need for strategic interventions to foster equitable digital development.

6. Suggestions

6.1. Coastal Innovation Leadership, Accelerated Technology Integration

Coastal provinces like Guangdong and Jiangsu must continue to utilize their advanced infrastructure and technological prowess to deepen the fusion of digital industrialization and industrial digitization. Strengthening digital technology innovation, particularly in 5G and AI, and enhancing support for SMEs are crucial for driving industrial upgrades and competitiveness.

6.2. Inland Distinctiveness Emerges, Enhanced Policy and Funding Support

Inland areas such as Gansu and Shanxi necessitate robust policy and financial backing to fortify their digital economy foundations. A strategic focus on infrastructure enhancement and technological innovation, leveraging local resources to tap into the digital potential of sectors like cultural tourism and modern agriculture, is advised. Upskilling traditional industry workers in digital capabilities is also essential.

6.3. Digital Blueprints Established, Regional Synergies Fostered

The synergy of regional collaborative development is vital for harnessing the full potential of the digital economy. It is imperative to reinforce strategic alignment and coordination among regions, exemplified by the integration efforts of the Beijing-Tianjin-Hebei and the Yangtze River Economic Belt. Establishing cross-regional cooperation platforms to promote the interflow of information and aligned industrial initiatives, with an emphasis on bolstering network and data processing capabilities in the central and western regions, is recommended.

6.4. Talent Hubs Converge, R&D as the Future's Pillar

The inflow of skilled talent and investment in research and development are foundational to the digital economy's advancement. It is suggested to implement proactive talent acquisition strategies, cultivate an enticing environment for living and working, and ramp up investments in pivotal technologies and innovative ventures. Innovative policy measures should be employed to invigorate R&D efforts, ensuring the digital economy's sustained innovative drive.

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