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Allocation Efficiency Measurement and Spatio-Temporal Differences Analysis of Digital Infrastructure: The Case of China's Shandong Province

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Abstract: After Shandong Province started the construction about digital infrastructure, the construction of digital infrastructure reached social consensus, promoting digital development of the province. However, it inevitably exposed problems such as non-targeted policies and uneven development levels. This study uses the non-expectation super-efficiency SBM model and kernel density estimation method to compare the digital infrastructure allocation efficiency of 16 prefecture-level cities in Shandong Province and analyzes the spatial and temporal differences. Results show that the overall level of digital infrastructure allocation efficiency in Shandong Province shows a steady and policy-stimulated growth, but no high-value aggregation area has been formed and regional synergistic development remains to be strengthened. Recommendations are provided on four aspects: increased government expenditure, policy heterogeneity, attention to low-level construction areas, and promotion of regional synergistic development to improve the construction of digital infrastructure in Shandong and sustain its strong digital thrust.

Keywords: digital infrastructure; allocation efficiency; spatio-temporal differences

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1. Introduction

China's 14th Five-Year Plan forwards the strategic goal of "accelerating digital development and building a digital China". This means an efficient and stable digital infrastructure is considered key to the construction of said digital China. Shandong Province closely followed this national development strategy and pushed for strong provincial construction needs, issued a guiding document on the "digital infrastructure construction in Shandong Province", and created a forward-looking layout for emerging infrastructure.

To properly execute this important strategic goal layout, Shandong Province formulated the 14th Five-Year Development Plan, and forwarded a grand blueprint to "increase the construction of digital infrastructure, strengthen the provincial capital economic circle, enhance the Jiaodong economic circle, revitalize the Lunan economic circle, and promote high-quality economic development, and build a strong digital province". This blueprint indicated the direction and specific goals. The 16 cities in Shandong Province have differences in economic and social development, resource endowment and other aspects, and allocation of digital infrastructure needs which have obvious differences. Hence, it is now important to measure the efficiency of digital infrastructure allocation in Shandong Province, clarify its spatial and temporal differences, and formulate a synergistic linkage mechanism for digital infrastructure allocation, considering the goal of building an efficient and synergistic digital infrastructure system in the province.

Existing studies on digital infrastructure mainly focus on the connotation and extension of digital infrastructure, its driving effects, and the construction models and paths. First, in terms of connotation and extension, the existing studies introduce digital infrastructure systematically and elaborate the beneficial effects of digital infrastructure construction on society and economy on the macro and micro levels [1–3]. Second, the literature on driving effects usually unites digital infrastructure and digital economy to advance the development of the digital economy through digital infrastructure construction, while the digital economy also promotes digital infrastructure construction [4,5].

Simultaneously, the construction of digital infrastructure also promotes industrial development, enhances employment, and produces a multiplier effect on total economic volume [6,7]. Last, digital technology innovation should be promoted according to the characteristics of digital infrastructure, government support should likewise be increased, and timely responses to difficulties such as high costs and lack of talent should be developed to facilitate the rapid formation of digital cities and societies [1,2,8].

However, limited studies explore the allocation efficiency of digital infrastructure, with indicators and methods for measuring allocation efficiency needing further exploration to investigate potential problems and improve the allocation efficiency of digital infrastructure. Hence, this study examines the measurement perspective, method, and index system.

First, it establishes a digital infrastructure allocation efficiency measurement index system key dimension, namely staff and financial inputs, digital infrastructure, society, economy, and technology. Then, using non-expectation super-efficiency Slacks-based measure model (SBM) and kernel density estimation methods, we analyze the digital infrastructure allocation efficiency and spatial and temporal differences. This comprehensively measures the digital infrastructure allocation efficiency of the entire Shandong Province along with its three economic circles and prefecture-level cities, deeply analyzes the problems and shortcomings in the digital infrastructure construction process, and puts forward targeted policy recommendations.

This study analyzes the digital infrastructure allocation efficiency and spatial–temporal differences in Shandong Province under a strong digital province. It also proposes targeted policy recommendations based on the results to aid in realizing a strong digital province in Shandong Province.

The rest of this study is as follows: the second chapter provides a comprehensive literature review on the status of digital infrastructure research. The third chapter introduces the research object and research methodology, including the specific steps and formulas of the methodology. The fourth focuses on the principles of the construction of the digital infrastructure allocation efficiency measurement index system in Shandong Province and the indicators included. The fifth measures the allocation efficiency of digital infrastructure in Shandong province and analyzes the spatial and temporal differences in the allocation efficiency, as well as potential problems and shortcomings. The sixth part proposes corresponding policy recommendations based on the results of the analysis. The last part summarizes the study and outlines its shortcomings for future research directions.

2. Literature Review

Since the concept of digital infrastructure was proposed, various in-depth studies on digital infrastructure from multiple perspectives in multiple fields have been forwarded. Currently, research on the measurement of digital infrastructure construction efficiency mainly focuses on three areas: the connotation and extension of digital infrastructure, the driving effect, and the mode and path of construction.

The first area explores the connotation and extension of digital infrastructure. Digital infrastructure mainly refers to the new infrastructure based on an information network, and it is driven by the integration and innovation of new generation information technology and various fields of economy and society. This provides the digital capability for social production and life, and digitally empowers various industries [9]. In 2021, Hustad argues that at the micro level, digital infrastructure development is an important guarantee for governments, enterprises, and other organizations to enhance digital technologies and organize digital transformation [2].

Digital infrastructure development has been increasingly involved in a variety of areas and industries. At the macro level, new digital infrastructure breaks down data silos, enhances services, helps modernize urban governance systems and governance capabilities, and promotes high-quality economic development [3]. The successful construction of digital infrastructure opens new economies and societies, creates jobs, and improves the quality of life. Countries also receive a variety of benefits from digital infrastructure, such as capacity expansion, time savings, streamlined operations, cost savings, increased efficiency, and enhanced security [1].

Most extant studies likewise explore the driving effect of digital infrastructure construction. In the development process of the digital economy, digital technologies related to artificial intelligence and big data should be introduced and applied scientifically and reasonably in economic development to enhance the development of the digital economy. Here, it is necessary to have a comprehensive understanding of the development of the digital economy from the perspective of digital infrastructure, identify the existing problems, and develop a high-quality development path based on the actual problems. This effectively promotes the development of the digital economy [4,5].

Digital infrastructure construction on the one hand directly drives economic growth through investment. On the other hand, it attracts the inflow of capital through environmental improvement while driving the development of upstream and downstream industries and producing a multiplier effect on the total economic volume [6,10]. Technology diffusion and knowledge spillover from digital infrastructure during research and development (R&D) and construction positively contribute to services employment. Moreover, the positive effect of digital infrastructure on services employment is stronger for countries with the relatively high institutional quality yet relatively low education levels [7].

Last are extant studies' exploration on the patterns and paths of digital infrastructure construction. Currently, the physical infrastructure construction has become saturated, the promotion kinetic energy of the industry has weakened, and digital infrastructure construction has become the new kinetic energy of regional economic growth. It is therefore necessary to further analyze the mode and path of digital infrastructure construction according to the characteristics of digital infrastructure.

To effectively promote the construction of new digital infrastructure, diversified investment entities should be attracted, the leading role of the government should be strengthened, top-level design should be enhanced, and supporting policy and financial support should be increased [8]. While building digital infrastructure, various obstacles and difficulties exist. These include high costs, lack of public investment funds, lack of Information and Communications Technology (ICT) talents, and concerns about the privacy and security of information data. Hence, government and relevant departments should develop timely, comprehensive, and detailed response plans to ensure the smooth construction of digital infrastructure and promote the rapid formation of digital cities and societies [1]. In 2021, Hustad argues that during this process, there is a need to focus on sustainable development by promoting technological advances and innovations that change the way digital infrastructure is involved and used, thereby finding sustainable responses to economic and environmental challenges for both economic growth and global development [2].

Despite these previous explorations, it remains difficult to give clear direction and reference on the main bottlenecks, allocation level, and future trends of digital infrastructure construction in Shandong Province. Hence, this study considers the requirements and characteristics of digital infrastructure construction, constructs a suitable measurement index system, focuses on measuring the level of digital infrastructure allocation, and analyzes the development relationship within and among the three major economic circles of Shandong Province, Jiaodong, and Lunan. This allows the study to better forward suggestions that make the balanced and linked development of digital infrastructure allocation in the three major economic circles of Shandong.

3. Research Objectives and Methods

3.1. Research Objectives

This study takes the 16 prefecture-level cities included in the provincial capital, Jiaodong, and Lunan economic circles proposed in the 14th Five-Year Plan of Shandong Province as the research objects, explores the digital infrastructure allocation efficiency and spatial and temporal differences in the province, and proposes responsive policy recommendations following local conditions and study results.

3.2. Research Methods

The non-expectation super-efficiency SBM model was used to calculate the efficiency of digital infrastructure allocation after combining the requirements and objectives of a "strong digital province" with 16 prefecture-level cities in Shandong Province. Subsequently, kernel density estimation was used to analyze the efficiency of digital infrastructure allocation and spatial and temporal differences in the province.

Introduction to the Research Methods and Feasibility Analysis

(1) Non-expectation super-efficiency SBM model

Data envelopment analysis (DEA) is a nonparametric method for calculating the efficiency of multiple decision units. Jointly proposed by Charnes, Cooper, and Rhodes in 1978 [11], the model compares the efficiency among multiple service units providing similar services by explicitly considering the use of multiple inputs and the generation of multiple outputs. This had led to the model's wide use in performance evaluation.

The shortcomings of traditional DEA models, such as radial DEA's overestimation of the efficiency value of decision-making units (DMUs) when it is over-input and/or under-output and angle DEA's ignorance of the variation of inputs or outputs, often lead to the mismatch between calculated results and objective facts. To overcome these problems, Tone created an efficiency measure based on slack variables (the SBM model) in 2001 and continuously improved it by proposing the super-efficient SBM model and the non-expectation SBM model variants [12].

Following Tone's research, Cheng-Gang combined the super-efficient SBM model in 2014 and the non-expectation SBM model and proposed the non-expectation super-efficient SBM model to evaluate the efficiency value of DMUs. This method has been applied to assess the efficiency of the green economy in China [13], assess the energy efficiency of the inter-provincial service industries [14], and assess the eco-efficiency of coal mining areas [15], among other areas.

When measuring the efficiency of digital infrastructure allocation in Shandong Province, some slack variables were selected to make the assessment scope more comprehensive, and the SBM model considered slack variables in the objective function to solve the problem of slackness of input–output variables. The efficiency values of the effective decision units measured by the traditional SBM model were all 1, which made it difficult to distinguish the efficiency differences among the effective decision units and leads to bias in the final decision. The super-efficient SBM model decomposed the effective units with the efficiency value of 1, thereby comparing the effective decision units and improving the accuracy of the comparison results.

Additionally, while building digital infrastructure, it is inevitable to produce undesired output and the most efficient production method as of current must be the green production method, i.e., producing more desired output and less undesired output with less input. Therefore, this study selected the non-expectation super-efficiency SBM model to measure the level of digital infrastructure allocation in each prefecture-level city in Shandong Province.

(2) Kernel density estimation method

The kernel density estimation method, as proposed by Rosenblatt and Parzen, is based on a nonparametric fitting method to achieve an optimal fit of the parametric distribution and construct a model of the data distribution when the prior knowledge based on the data distribution is unknown [16]. It is one of the most studied methods in nonparametric inspection and is commonly used to estimate an unknown probability density function, which is a natural extension of the histogram. This improves the problem of discontinuity that exists in the histogram using higher analytical accuracy.

Since the kernel density estimation method does not utilize a priori knowledge on the data distribution and does not attach any assumptions to it, the method studies the characteristics of data distribution from the data sample itself, and is therefore widely used in contexts such as wind power penetration dynamic economic dispatch [17], analyzing the spatial and temporal changes of arable land use efficiency in the Yangtze River economic zone [18], exploring 6G multi-source information fusion indoor positioning [19], and analyzing the impact of traffic infrastructure on NO_2 concentration levels [20], among others.

In measuring the allocation efficiency of digital infrastructure in Shandong Province, the method was highly adaptable and flexible because it was not limited by the data and did not require the prior assumption of the probability distribution pattern of the data, but dealt with the probability distribution through the characteristics of the data itself. The kernel density estimation was fitted to all sample observations using a smooth peak function to describe the location, shape, and extension of the distribution of digital infrastructure allocation efficiency along with continuous density curves, revealing the time-series dynamic change pattern of digital infrastructure allocation efficiency in each prefecture-level city in Shandong.

The specific formula of the research methodology is shown in Appendix A.

4. The Measurement Index System of Digital Infrastructure Allocation Efficiency

To scientifically measure the efficiency of digital infrastructure allocation, this study considered the characteristics of digital infrastructure, and constructed a digital infrastructure allocation efficiency measurement index system in Shandong based on the principles of scientificity, systematization, and independence and operability, which was combined with the actual situation in Shandong Province, as shown in Table 1.

4.1. Input Indicators

The allocation of digital infrastructure requires both relevant digital infrastructure as the basis and human and financial support. Hence, this study divided the input indicators into two dimensions: personnel and financial input and digital infrastructure input [21,22].

Staff and financial inputs (X_1)—the construction of digital infrastructure requires science and technology innovation. R&D resources are important indicators of the country's science and technology activities and its level of science and technology investment are a reflection of China's independent innovation capabilities in building an innovative country. Hence, this study used the proportion of R&D personnel to employees (X_{11}) and the proportion of R&D expenditure to Gross Domestic Product (GDP) (X_{12}) the number of R&D resources [23–25].

Table 1. Digital infrastructure allocation efficiency measurement index system in Shandong Province.

Target Layer	Guideline Layer	Indicator Layer
Inputs	Staff and financial inputs X_1	R&D personnel as a proportion of employed persons X_{11} R&D expenditure as a percentage of GDP X_{12} Science and education expenditure as a proportion of general public expenditure X_{13} The proportion of fixed asset investment in information and soft technology to the total social fixed asset investment X_{14} Number of college students per 10,000 people X_{15}
	Digital infrastructure inputs X_2	Number of cell phone subscribers per 10,000 households X_{21} Number of Internet broadband access subscribers per 10,000 households X_{22} Number of computers per 100 people X_{23} Number of websites per 100 companies X_{24}
Expected output	Social Y_1	Inclusive Digital Finance Y_{11} The proportion of employed persons in information and software technology Y_{12}
	Economy Y_2	Total Telecommunications Business Y_{21} E-commerce sales Y_{22} Total Factor Productivity Y_{23} The proportion of tertiary industry output value and secondary industry output value Y_{24}
	Technology Y_3	Number of Invention Patents Y_{31}
Non-desired outputs	Social Injustice Z_1	Income gap between urban and rural residents Z_{11} Consumption gap between urban and rural residents Z_{12}

Digital infrastructure construction requires government and social support, along with a good development environment and material security. Thus, the proportion of science and education expenditure to general public expenditure (X_{13}) and the proportion of investment in information and software technology fixed assets to the total social fixed asset investment (X_{14}) were used to reflect the importance of digital infrastructure by local governments and relevant departments [26,27].

Human capital is also an important support for scientific and technological innovation, a cornerstone of digital infrastructure construction, and a new driving force for a strong digital province. Hence, the number of university students per 10,000 people (X_{15}) was used to characterize human capital [28,29].

Digital infrastructure inputs (X_2)—mobile communication and the Internet assume an important supporting role in many sectors. Therefore, the number of cell phone subscribers per 10,000 households (X_{21}) and the number of Internet broadband access subscribers per 10,000 households (X_{22}) were used to reflect the level of digital infrastructure construction [30,31]. The digitalization and informatization of enterprises effectively contribute to a strong digital province, hence the number of computers used per 100 people (X_{23}) and the number of websites per 100 enterprises (X_{24}) characterize the investment of enterprises in digital construction in each region [32,33].

4.2. Output Indicators

The construction of digital infrastructure has improved economic productivity and people's living standards. However, it has also brought a negative impact in the construction process. Therefore, this study considered expected and unexpected output in the output indicators.

Expected output indicators—digital infrastructure construction promotes strong digitalization and science and technology innovation. Thus, this study divided the expected output into three dimensions: social, economic, and technological.

Society (Y_1): Digital infrastructure construction enhances public daily work efficiency and improves the quality of life. It also creates more employment opportunities, affecting the employment rate. This study used the Digital Inclusion Index (Y_{11}) to reflect the improvement of residents' daily life and work from multiple perspectives, such as depth of use, breadth of coverage, and degree of digitization. The proportion of employed people in information and technology employment (Y_{12}) was used to reflect the change in employment rate and labor income of the population by digital infrastructure development [34,35].

Economy (Y_2): digital infrastructure construction promotes the economic development of related industries; hence the total telecommunication business (Y_{21}) was used to reflect the economic power provided by digital infrastructure [36,37]. E-commerce, as an important driver of economic development in China, helps clear the obstacles to the development of various industries, hence the use of e-commerce sales (Y_{22}) to characterize the role of digitalization in the process of the strong digital province [38–40]. Total factor productivity includes economic policies, the role of government in the economy, work attitudes, positive externalities caused by an educated workforce, technological learning, among others, explaining the use of total factor productivity (Y_{23}) to reflect the extent of effective economic growth in each location [41–43].

During digital infrastructure construction, the realization of economic and social benefits that the positive environmental benefits generated should be considered. The industrial structure, which is associated with issues such as energy consumption and pollution emission, is key to accelerating the transformation of old and new dynamics. Therefore, the proportion of tertiary industry output value and secondary industry output value (Y_{24}) is used to characterize the industrial structure [44,45].

Technology (Y_3): digital infrastructure construction improves independent innovation capacity and breakthrough key technological issues, injecting new vitality into economic development. This explains the study's use of number of invention patents (Y_{31}) to characterize the scientific research output [46,47].

Non-expected output indicators—currently, digital infrastructure construction mainly focuses on urban areas, increasing an already existing urban–rural divide. Therefore, this study considered the social balance in terms of unexpected output, mainly divided into two dimensions: income and consumption. Since digital infrastructure is mainly carried out in cities, the income gap between urban and rural residents (Z_{11}) and the consumption gap between urban and rural residents (Z_{12}) were used to characterize social injustice (Z_1) [48,49].

5. Empirical Analysis

5.1. Measurement of Digital Infrastructure Allocation Efficiency in Shandong Province

Based on the digital infrastructure allocation efficiency measurement index system and index data of Shandong Province, the non-expectation super-efficiency SBM model was used to obtain the digital infrastructure allocation efficiency values of each prefecture-level city in Shandong Province from 2014 to 2020. To better analyze the allocation efficiency of each prefecture-level city in Shandong Province, the cities in Shandong Province were divided based on three abovementioned economic circles. We then took the average value of the allocation efficiency of the cities included in each economic circle and all cities in Shandong Province as the allocation efficiency value of digital infrastructure at the level of each economic circle and Shandong Province as a whole, and subsequently analyzed the potential problems existing in them. The specific allocation efficiency values are shown in Table 2.

Table 2. Efficiency values of digital infrastructure allocation in Shandong Province.

Region	Prefecture Level City	2014	2015	2016	2017	2018	2019	2020
Provincial Capital Economic Circle	Jinan	1.307	1.226	1.194	1.193	1.188	1.182	1.207
	Zibo	1.039	1.012	1.070	1.060	1.017	1.067	1.061
	Dongying	1.145	1.174	1.165	1.150	1.169	1.210	1.529
	Tai'an	1.094	1.076	1.057	1.035	1.046	1.015	1.050
	Dezhou	1.067	1.042	1.066	1.072	1.049	1.037	1.070
	Liaocheng	1.139	1.406	1.192	1.142	1.018	1.111	1.106
	Binzhou	2.178	1.118	1.023	1.016	1.025	1.038	1.025
	Average value	1.281	1.151	1.110	1.095	1.073	1.094	1.150
Jiaodong Economic Circle	Qingdao	1.193	1.217	1.299	1.278	1.269	1.256	1.223
	Yantai	1.068	1.029	1.006	1.009	1.719	1.156	1.142
	Weifang	1.161	1.042	1.010	1.009	1.035	1.151	1.053
	Weihai	1.095	1.051	1.076	1.071	1.062	1.046	1.033
	Rizhao	1.086	1.113	1.137	1.130	1.153	1.058	1.055
	Average value	1.121	1.090	1.106	1.100	1.247	1.134	1.101
Lunan Economic Circle	Zaozhuang	1.078	1.066	1.030	1.090	1.130	1.088	1.141
	Jining	1.064	1.051	1.015	1.000	1.007	1.045	1.012
	Linyi	1.191	1.145	1.181	1.148	1.267	1.128	1.146
	Heze	1.069	1.144	1.080	1.150	1.247	1.284	1.355
	Average value	1.100	1.102	1.077	1.097	1.163	1.136	1.163
Shandong Province	Average value	1.186	1.120	1.100	1.097	1.150	1.117	1.138

The provincial capital economic circle included the seven cities of Jinan, Zibo, Dongying, Tai'an, Dezhou, Liaocheng, and Binzhou. The Jiaodong economic circle included the five cities of Qingdao, Yantai, Weifang, Weihai, and Rizhao. The Lunan economic circle included the four cities of Zaozhuang, Jining, Linyi, and Heze. The data used was obtained from the China City Statistical Yearbook, the Shandong Statistical Yearbook, the bulletin of the Department of Industry, and Information Technology of Shandong Province, and the statistical bulletin and statistical yearbook of the National Economic and Social Development Bureau of each prefecture-level city in Shandong Province.

To better observe the digital infrastructure allocation efficiency values of each economic circle and each prefecture-level city, this study used a line graph for analysis [50]. The details are shown in Figure 1.

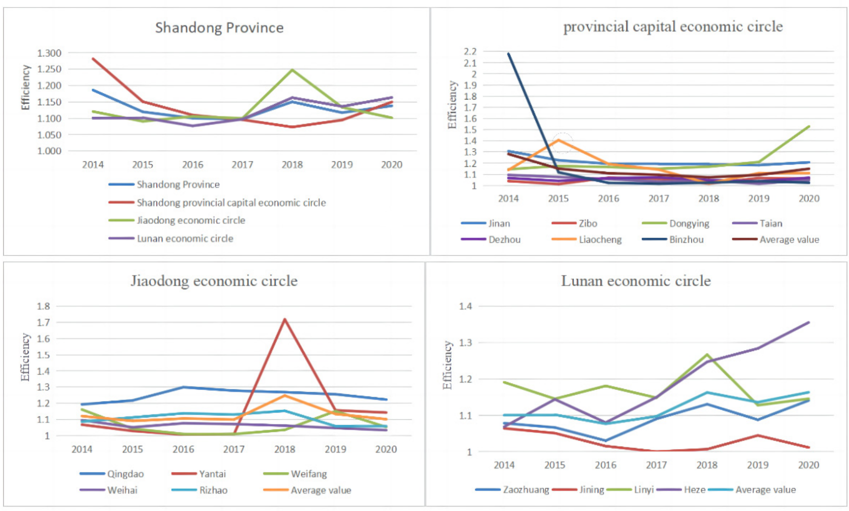

Figure 1. Line graph of digital infrastructure allocation efficiency for Shandong Province as a whole, the three economic circles and prefecture-level cities.

5.1.1. Overall and Inter-Economic Circle Measurement

From the perspective of Shandong Province as a whole, the specific values and dynamic change process of its allocation efficiency values are analyzed in conjunction with Table 2 and Figure 1. During the study period, the overall digital infrastructure allocation efficiency of Shandong Province first decreased and then increased. The average efficiency of Shandong Province decreased from 1.186 in 2014 to 1.097 in 2017. With the promulgation of the Digital Shandong Development Plan in 2018, the average efficiency increased to 1.138 in 2020.

This guiding document forwards the requirements and goals for the construction of digital infrastructure in Shandong Province, which provides a good construction environment for the construction of digital infrastructure and encourages all regions in Shandong to further regard digital infrastructure. This efficiency of digital infrastructure allocation gradually improves and tends to stabilize.

By comparing the three major economic circles, the digital infrastructure allocation efficiency of the provincial capital economic circle has drastically changed during the study period. The Jiaodong and Lunan economic circles were at 1.281 in 2014, and then experienced a yearly decline until they fell to the same level as their 2017 numbers. In 2018, these economic circles were influenced by the policies of Shandong Province, hence the increase in their digital infrastructure allocation efficiency.

In contrast, the allocation efficiency of the provincial capital economic circle continues to decline to 1.073, widening its gap with the Jiaodong and Lunan economic circles. It only started to rebound in 2019 and improved to 1.150 in 2020, which is higher than the average level of the province. The quantified range of digital infrastructure allocation efficiency of the provincial capital economic circle during the study period is 1.073~1.281. The digital infrastructure allocation efficiency of the Jiaodong economic circle performed better during the study period, which was higher than the provincial average during 2016–2019 and increased significantly in 2018 with an allocation efficiency of 1.247, far ahead of the provincial capital and Lunan economic circles.

However, this also led to a yearly decline in the allocation efficiency of the Jiaodong economic circle in the two succeeding years which was lower than the 2020 provincial average. The quantified range of digital infrastructure allocation efficiency in the Jiaodong economic circle during the study period was at 1.090~1.247. The digital infrastructure allocation efficiency in the Lunan economic circle was already steadily increasing during the study period, being lower than the provincial average between 2014 and 2016: equal to the provincial average in 2017 and higher than the provincial average from 2018 onwards. The quantified range of digital infrastructure allocation efficiency for the Lunan economic circle during the study period was from 1.077 to 1.163.

5.1.2. Measurement of Cities within Each Economic Circle

This study measured the level of digital infrastructure allocation efficiency of the cities included in each economic circle to better analyze the digital infrastructure allocation efficiency of 16 prefecture-level cities in Shandong Province.

Provincial capital economic circle—during the study period, Jinan, as the core city of the provincial capital economic circle, had a high value of digital infrastructure allocation efficiency with a stable trend, which is higher than the average level of the provincial capital economic circle and the quantified range of allocation efficiency was 1.182~1.307. Dongying is another city with good performance, which was in an overall rising state during the study period. It was higher than the overall level of the provincial capital economic circle since 2015 and reached 1.529 in 2020, much higher than other cities in the provincial capital economic circle. Its quantified range of allocation efficiency is 1.145~1.529.

Liaocheng also had a large change in allocation efficiency during the study period, with an inverted V changing mode between 2014 and 2017, which later stabilized with an overall level close to the average level of the economic circle. Binzhou had a high start and a low end except for 2014, when it ranked the highest in the province with 2.178. In the following years, however, it was lower than the average of the economic circle, with a quantified range of 1.016 to 2.178. The overall situation of the cities of Zibo, Tai'an, and Dezhou are similar, with the allocation efficiency of Zibo, Tai'an, and Dezhou being the same value as during the study period. The overall situation of efficiency is also similar with efficiency values lower than the average level of the economic circle during the study period, a small changes range, and the quantitative range of allocation efficiency of 1.012~1.076.

Jiaodong economic circle—like Jinan, as the core city of the Jiaodong economic circle, Qingdao had high values and stable trends in digital infrastructure allocation efficiency: higher than the average of the Jiaodong economic circle, with a quantitative range of allocation efficiency of 1.193 to 1.300. Yantai's allocation efficiency declined yearly in the early part of the study period until 2018 when it began to increase significantly to 1.719, but in 2019 it dropped back to 1.156 where it remained stable. Weifang's allocation efficiency showed a wave-like change: first decreasing, then increasing, and then decreasing again, with a quantified range of 1.009 to 1.151. Rizhao's allocation efficiency showed a stable trend during the study period, with a quantified range of 1.055 to 1.523. Last, Weihai's allocation efficiency was low, and its efficiency was lower than the average of the Jiaodong economic circle during the study period.

Lunan economic circle—although Linyi's allocation efficiency varies more, its overall level was above the average level of the Lunan economic circle, with a quantified range of 1.128 to 1.267. Heze's allocation efficiency was generally on the rise during the study period, from 1.069 to 1.355, while Zaozhuang's and Jining's allocative efficiencies were below the average level of the Lunan economic circle. There exists a significant gap between the allocation efficiency of Jining and other cities in the economic circle. The quantified allocation efficiency of Zaozhuang and Jining ranged from 1.030 to 1.141 and 1.000 to 1.064, respectively.

5.2. Time-Series Variance Analysis

The kernel density distribution curves of digital infrastructure allocation efficiency in Shandong Province as a whole, and the three major economic circles from 2014 to 2020, was plotted using Stata16.0 to further study the dynamic characteristics of the time-series distribution of digital infrastructure allocation efficiency values in Shandong Province. The details are shown in Figure 2.

At the provincial level, the main peak of the kernel density curve from 2014 to 2020 shows a yearly trend of decreasing height and extending width. This indicates that the efficiency of digital infrastructure allocation in Shandong Province is gradually improving macroscopically, and there is a certain magnitude of increase in the absolute difference. The regional distribution curve of the province lacks smoothness and there is also a stage of multipolar development.

After the promulgation of relevant policy documents on digital infrastructure construction in Shandong Province in 2018, the main peak of the kernel density curve in 2018 substantially decreased and the change interval shifts significantly to the right, indicating that the government's emphasis on digital infrastructure construction directly affects the efficiency of digital infrastructure allocation in each region and the development of related work. Additionally, 2014, 2018, and 2020 have an obvious right-trailing phenomenon, meaning that the gap between cities with higher digital infrastructure allocation efficiency and the provincial average is gradually widening.

At the level of the three major economic circles in Shandong Province, first, the nuclear density curve of the provincial capital economic circle increases the main peak height yearly during 2014–2018, and the change interval shows a left-shifting trend, before leading to a turn from 2019, when the center of the nuclear density curve and its change interval had an obvious right-shifting trend, and the main peak height starts to decline significantly with an increasingly extended width. Simultaneously, in 2014 and 2020, there was an obvious right-trailing phenomenon, indicating that the efficiency of digital infrastructure allocation in the provincial capital economic circle shows a changing trend that was decreasing and then increasing.

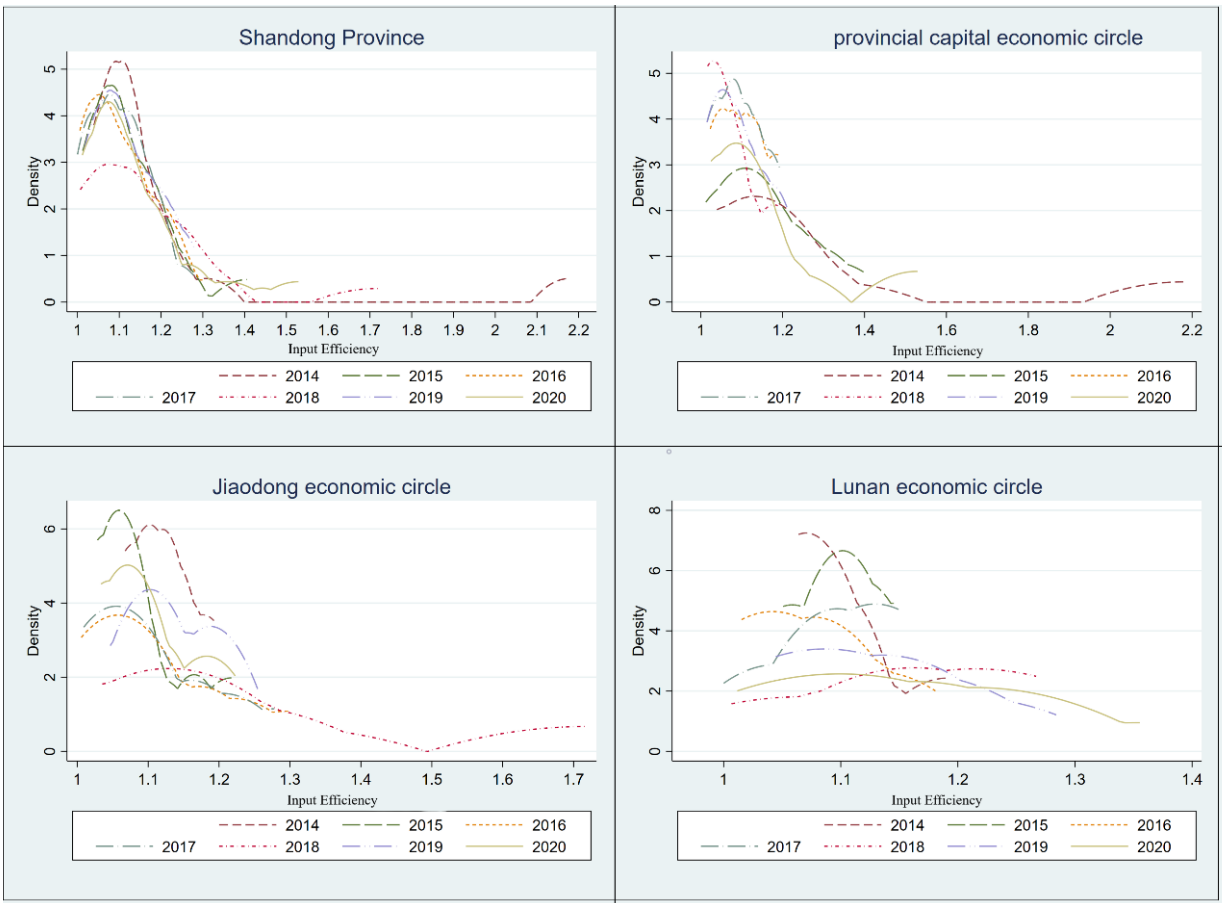

Figure 2. Kernel density distribution curve of Shandong Province as a whole and the three major economic circles.

Second, the nucleus density curve of the Jiaodong economic circle declined in height year by year during 2014–2018 with a gradual rightward shift in the change interval, followed by a rebound in 2019 and a stabilization thereafter, coinciding with the overall level changes in the province. Due to the incentive effect of digital infrastructure policies, the nuclear density curve of the Jiaodong economic circle decreased significantly in the main peak height in 2018 and the width appears significantly extended, meaning that the allocation efficiency gap among cities in the Jiaodong economic circle is large and polarization occurred in 2018. This is also the reason for the rebound phenomenon of the curve in 2019.

Furthermore, the curve shows a bimodal phenomenon in 2019 and 2020, indicating the trend of polarization within the Jiaodong economic circle. Last, the main peak of the nuclear density curve of the Lunan economic circle shows a yearly decrease in height and an increasing extension in width, indicating a gradual macroscopic increase in the allocation efficiency of digital infrastructure in the Lunan economic circle and a certain magnitude of increase in absolute differences.

5.3. Spatial Variation Analysis

To reflect the spatial agglomeration and dynamic evolution of digital infrastructure allocation efficiency values in Shandong Province, this study classified the digital infrastructure allocation efficiency values of 16 prefecture-level cities in Shandong Province into five categories: “very high level”, “high level”, “medium level”, “low level”, and “very low level" using natural breakpoint method. The natural breakpoint method grades and classifies according to the law of statistical distribution of values, which maximizes the difference between classes. The breakpoint itself is a good boundary for grading and the use of the natural breakpoint method helps to analyze the level of digital infrastructure allocation efficiency and its structural distribution, thereby reflecting the spatial differences of regional subjects [51,52]. Here, the measured digital infrastructure allocation efficiency values of 16 prefecture-level cities in Shandong Province in 2014, 2017, 2018 and 2020 was followed to analyze the spatial divergence phenomenon of each prefecture-level city in Shandong Province in terms of digital infrastructure construction. The detailed situation is shown in Figure 3: blue represents "very high level", green represents "high level", pale yellow represents "medium level", orange color represents "low level", and red represents "very low level" [52].

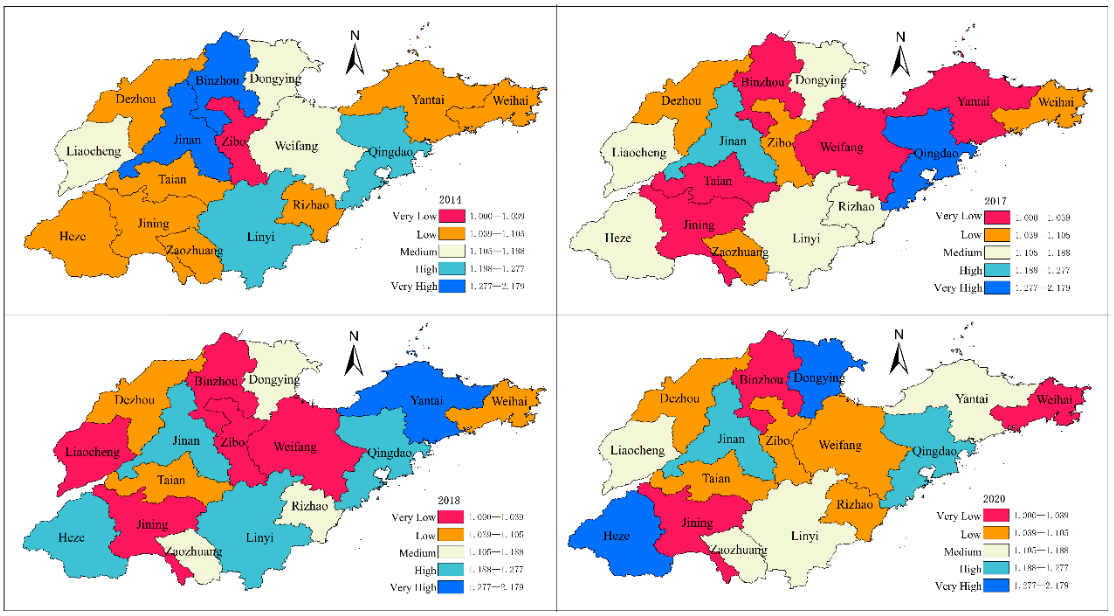

Figure 3. Digital infrastructure allocation efficiency values in Shandong Province.

From 2014, the overall level of digital infrastructure allocation efficiency in Shandong Province was commendable—only one city, Zibo, belonged to the "very low level". Jinan, Binzhou, Qingdao, and Linyi were at "high" or "very high levels", and most other cities were at a "low level". In 2017, the efficiency of digital infrastructure allocation in Shandong Province declined, with "very high level" and "high level" only being Qingdao and Jinan, respectively. Meanwhile, the two core cities in Shandong Province with "very low level" had five cities.

Along with the promulgation of policy documents related to digital infrastructure in Shandong Province, the efficiency of digital infrastructure allocation in Shandong Province increased significantly in 2018. Yantai, Jinan, Qingdao, Linyi, and Heze all improved to become "high level" or "very high level" cities. However, as of 2017, cities at the "very low level" still included five cities, which means that the digital infrastructure construction in Shandong Province has a polarizing trend. After the development from 2018 to 2020, the allocation efficiency of digital infrastructure in Shandong Province in 2020 was relatively evenly distributed among the five categories, and the gap between different cities in the allocation efficiency was gradually widened with a certain gradient effect. Additionally, it can be seen from Figure 3 that the spatial distribution of digital infrastructure allocation efficiency values in Shandong Province does not form an obvious high-value cluster in either year, but is distributed in the form of high and low values in between.

The comparative analysis between the selected years reveals five key points: (1) Jinan and Qingdao are two core cities in Shandong Province. During the study period, the allocation efficiency of digital infrastructure was at or above the "high level", but the allocation efficiency of their surrounding cities was low, especially in Jinan, where the allocation efficiency of the surrounding cities was basically at or below the "low level". This means that Jinan and Qingdao, the two core cities, need to further develop their ability to promote regional common development. (2) The digital infrastructure allocation efficiency of Zibo, Dezhou, Tai'an, Weifang, Weihai, and Jining during the study period was basically below the "medium level", indicating that the above six cities need to strengthen their own digital infrastructure allocation efficiency. (3) Zaozhuang, Dongying, and Heze have steadily improved their digital infrastructure allocation efficiency during the study period, especially Heze, which has developed from "low level" in 2014 to "very high level" in 2020. (4) Yantai made full use of the government's support to achieve a "very high level" of digital infrastructure configuration efficiency in 2018. (5) In 2014, Binzhou's digital infrastructure configuration efficiency value was at a "very high level", which was also the city with the highest configuration efficiency value during the same year. However, in the following years, Binzhou's configuration efficiency value showed a downward trend and remained at a "very low level". Therefore, there is a need to fully summarize the shortcomings in the construction process and learn from the advanced experience of the leading regions.

5.4. Comprehensive Analysis of Digital Infrastructure Allocation Efficiency in Shandong Province

The analysis of digital infrastructure allocation efficiency and spatial and temporal differences in Shandong Province shows that its overall digital infrastructure allocation efficiency has been steadily increasing, but varies widely among cities while showing a multipolar development. There is no high-value agglomeration area in the province. There is instead a form of distribution between high- and low-value. This section further summarizes the analysis above and the allocation efficiency values of digital infrastructure in each city as reflected in each chart. The specific analyses are as follows:

(1) As shown in Table 2 and Figure 1, Jinan and Qingdao, the two core cities in Shandong Province, have achieved good results in digital infrastructure construction, the digital infrastructure allocation efficiency values are both at "high" or "very high level", and the growth rate is relatively stable. However, Figure 3 shows that the digital infrastructure configuration level of the cities around Jinan and Qingdao is relatively poor. For example, the configuration efficiency values of Zibo, Tai'an, Binzhou, and Weifang are relatively low. This shows that Jinan and Qingdao need to further play their role as radiation drivers, promote regional coordinated development, form high-value clusters, and promote the common progress of digital infrastructure construction in the province.

(2) Figures 2 and 3 show that after Shandong Province issued relevant policies on digital infrastructure construction in 2018, all cities positively responded and achieved good construction results. For example, the overall digital infrastructure configuration efficiency of the Jiaodong Economic Circle and the Southern Shandong Economic Circle was improved in 2018, especially in Yantai, where the configuration efficiency value rose from "low level" in 2017 to a "high level" in 2018. Simultaneously, the value of digital infrastructure allocation efficiency in some regions show a downward trend. In 2018, the average allocation efficiency of the provincial capital economic circle showed a reverse growth, and the allocation efficiency of Liaocheng, previously in the "medium level", dropped to a "low level". Therefore, relevant local governments need to further clarify the importance and necessity of digital infrastructure construction, fully consider the heterogeneity of regional economic and social development and resource endowment, and formulate scientific and reasonable digital infrastructure allocation goals and construction paths.

(3) From Figures 1 and 3, it is evident that during the study period, the digital infrastructure allocation efficiency of Zibo, Dezhou, Tai'an, and Binzhou is lower than the

average level of the provincial capital economic circle from 2015 to 2020. Weifang and Weihai are lower than the average level of the Jiaodong economic circle from 2015 to 2018 and in 2020. Jining and Zaozhuang are lower than the average level of the Lunan economic circle. Also, the digital infrastructure allocation efficiency values of these cities are basically at the "lower level" or "very low level". This shows the obvious gap and imbalance between many low-level areas in Shandong Province in terms of digital infrastructure construction. Therefore, Shandong should further increase the support for low-level areas and improve the level of digital infrastructure therein.

6. Recommendations

The study measures the efficiency of digital infrastructure allocation in Shandong Province and analyzes its spatial and temporal differences and potential problems. To address the potential problems, it proposes suggestions for improvement on four specific aspects: government attention, policy heterogeneity, focus on the development of low-level areas, and promotion of regional synergistic development. In addition, this study expands each recommendation to an international context, providing a basis for decision-making in more countries and regions.

6.1. Promote Synergistic Development and Common Progress

During digital infrastructure construction, we should promote institutional coordination to improve the overall common development of Shandong Province. However, the current level of digital infrastructure configuration in Shandong Province remains to form a high-value cluster, thereby needing the strengthened policy guidance of regional coordinated development. Therefore, this study puts forward targeted suggestions from three specific aspects: upgrading industrial digitalization, cultivating human capital, and strengthening digital rural construction to promote the construction of digital infrastructure in Shandong Province and achieve coordinated regional development.

(1) Enhancement of industrial digitization

During digital infrastructure construction, the focus should be on the digital transformation of traditional industries. Relevant departments and enterprises must use digital technology as support to transform traditional industries and carry out technological innovation, thereby promoting industrial transformation with technology and helping achieve high-quality regional development. Along with promoting the digital transformation of traditional industries, relevant departments and enterprises also need to continuously increase the intensity of investment in research and development, strengthen the research and development of key core technologies for digital infrastructure, and improve the efficiency of iterative updating of digital-related technologies.

As a mediating variable between digital infrastructure and high-quality development, digital capacity is pivotal to high-quality development, hence the need to focus on regional digital capacity. Simultaneously, relevant departments must strongly support the development of digitalization-related enterprises, for example, by giving certain financial subsidies and tax incentives.

(2) Cultivating human capital

Digital infrastructure construction needs digital industry talents, and digital talents are one of today's important influencing factors of high-quality development. This underlines the need to establish a perfect talent training system to support and encourage relevant enterprises and universities to cultivate digital talents with broad industry application prospects. This in turn strengthens the support for innovative talents to lay high-quality development for the region's solid digital foundation.

Additionally, governments at all levels should break institutional barriers to allow the cross-regional flow of digital talents, promote the cultivation and introduction of talents by providing a good material foundation and environment, play to the strengths of each region, provide more incentivizing policies and full autonomy to capable talents in relevant fields, stimulate their innovative initiatives and enthusiasm, promote the concentration of human capital, and ultimately accelerate the construction of regional digital infrastructure and high-quality development.

(3) Strengthen the construction of digital countryside

Shandong Province is a large agricultural province, hence rural areas and populations account for a relatively large proportion. Therefore, to achieve a comprehensive high-quality development and realize a "strong digital province", we should coordinate and promote the construction of the countryside and collaborate to promote the integrated digital development of both urban and rural areas. These include policies to accelerate the extension of digital infrastructure to the countryside, improve the supply of information services in rural areas, promote the free flow of urban and rural elements in both directions, and reasonably allocate public resources to form a digital urban–rural integration development pattern with urban and rural areas and common construction and sharing.

Digital infrastructure is the foundation of digital countryside construction, and its popularity and performance equipment determine the breadth and depth of digital economy development, which has a strong positive spillover. Therefore, when promoting the construction of rural digital infrastructure, it should be executed in an orderly fashion; giving priority to areas with large population densities but weak digital infrastructure allocation. The government should include rural digital infrastructure projects into the project pool and arrange funding budgets to provide a good environment for the use of digital technology to be carried out and applied in rural areas.

Governments should also promote the comprehensive application of new-generation information technology in agricultural and rural economic development by strengthening the digital integration of urban and rural areas, enhancing the level of rural digitalization and informatization, and accelerating the digital transformation and restructuring of the original information infrastructure.

(4) Policy Extension

The unbalanced development of the world's regions is a basic economic law, and the development gap between regions has always existed, and how to narrow this gap is one of the major challenges facing all countries and regions at present. Governments need and take more effective measures to control regional disparities and prevent social unrest that may result from widening disparities. In addition, it is necessary for the international community to cooperate in promoting coordinated regional development and controllable regional disparities, jointly coping with the world's increasingly serious social contradictions, and at the same time opening up new ways and fields for the world's future economic development.

6.2. Further Regard to the Role of the Government and Give Full Play to Its Advantages

The government plays an extremely important role in the process of digital infrastructure construction. However, in the context of the National 14th Five-Year Plan, which explicitly proposes to accelerate the construction of digital infrastructure, local governments in the provincial capital economic circle do not pay enough attention to the construction of digital infrastructure. Therefore, this study proposes recommendations to these units on three contextual aspects: digital infrastructure construction environment, government financial support, and promotion of enterprise digitalization process.

(1) Digital infrastructure construction environment

The prerequisite for local cities to improve the level of digital infrastructure construction and accelerate the process of urban digitization is to provide a suitable policy environment for the construction of digital infrastructure. First, the Shandong provincial government should insist on optimizing the digital infrastructure construction environment, continuously improve the top-level design, establish and improve the coordination and promotion mechanism, and accelerate the cultivation and growth of digital infrastructure public service platforms. Next, local municipal governments should follow the construction requirements and development goals of digital infrastructure and develop strategically oriented short-term and long-term digital infrastructure construction programs according to their own construction situation, therein forming a systematic construction in multiple fields and at multiple levels.

(2) Government financial support

Local governments should also strengthen policy support for digital infrastructure construction in their regions, reasonably allocate and utilize national subsidy funds, financial funds at this level, government bond funds, etc. They should also fully utilize government macro-regulation and market competition mechanisms, implement more policy tilts, tax preferences and financial subsidies, and widely absorb social capital to participate in digital infrastructure construction. These undertaking must also be fulfilled while guiding local industrial development investment funds to invest in digital infrastructure construction.

(3) Promote the digitalization process of enterprises

When formulating policies on digital infrastructure, the government should consider the characteristics of different enterprises as far as possible. Enterprises with a high degree of informatization, relatively smooth digital transformation, and relatively intensive digital technology can realize enterprise upgrading more effectively by building an open, secure, and good digital ecosystem and using network externalities to adjust their business models in a timely and appropriate manner.

Enterprises with poor informatization, high difficulty in digital transformation, and less digital technology, should be supported by the government through development and application scenarios that integrate new-generation information technology with enterprise transformation and upgrading. Moreover, the government can select key enterprises with better digital foundations and greater influence to carry out pilot work, tap the leading experience, promote the process of enterprise digitalization, and help enterprises integrate innovation and efficient operation, in order to drive the construction of digital infrastructure.

(4) Policy Extension

Experience from all over the world shows that although the main body of digital infrastructure and industrial digitalization construction is enterprises or other auxiliary organizations, the government has a wide range of roles in the construction process, and in many cases even plays a central role. When the government formulates support policies for digital industries and industrial digitalization, it should reduce information asymmetry and establish a cooperation platform between enterprises and between enterprises and between enterprises and governments, so as to improve the efficiency of resource input and resource use. In addition, when formulating policies, governments of various countries and regions should fully consider the negative effects of policies on the market, so when formulating relevant policies, local governments need to make it clear that the policies are based on improving social livelihood, so that the positive effects of policies are significantly greater than their negative effects.

6.3. Focus on Regional, Inter-Policy Heterogeneity

Accelerating the construction of digital infrastructure is a national policy and social consensus, and Shandong Province actively responds to the national policy by promulgating the Digital Shandong Development Plan to promote the construction of digital infrastructure in the province. Local governments in Shandong Province should formulate policies appropriate to the construction of local digital infrastructure based on this document.

(1) Due to the certain heterogeneity of resource endowment and economic development level of each city, there are certain differences in the construction content, construction

mode, and construction stage of each city in the process of building digital infrastructure. The construction direction and construction path must be determined by combining the characteristics of the population, background, and informatization foundation of the region. Therefore, government departments at all levels should consider the heterogeneous characteristics of economic and social development in different regions when formulating digital infrastructure construction plans, based on the actual situation, to carefully sort out the needs, formulate digital infrastructure construction plans that meet the actual local situation, and essentially optimize the overall planning of digital infrastructure construction according to local conditions.

(2) Government departments at all levels should also strengthen the convergence of national strategies and local policies, enhance synergy and linkage, and establish different cycles of construction plans to avoid piling up development plans and duplication of construction.

(3) Based on regional differences, the contents and ways of digital infrastructure construction differ from place to place. Thus, different standards should be used to measure the level of digital infrastructure construction, and the quality of local digital infrastructure construction should also be guaranteed by extending the construction cycle in less developed areas.

(4) Policy Extension

Due to the existence of the global digital divide, the content, construction methods and stages of digital construction in different countries and regions are different, so when formulating relevant policies, local governments should base themselves on the actual situation, carefully sort out the construction needs, establish an institutional framework that is in line with the local and the times, and fully consider the heterogeneity between regions and policies.

6.4. Increase Support to Enhance the Development of Low-Level Areas

Due to certain differences in the development degree between different cities, Zibo, Dezhou, Weifang, Zaozhuang, Jining, and other regions are basically at a "low level" or "very low level" in terms of digital infrastructure construction and allocation efficiency. To comprehensively promote digital infrastructure construction in Shandong Province, recommendations for cities with low efficiency are proposed herein.

(1) In view of the backwardness of digital infrastructure allocation efficiency in the above cities, local governments should explore the potential problems of backwardness, accelerate digital infrastructure construction according to local conditions, comprehensively reshape production relations, release digital productivity, and ensure the sustainable growth of digital infrastructure allocation efficiency. This forces them to focus on the construction quality and investment efficiency of digital infrastructure construction.

Digital infrastructure construction is mainly concentrated in the tertiary industry and is the first to integrate with the tertiary industry before penetrating primary and secondary industries. For some regions with poorly developed secondary industries, they can cross the short board of secondary industries, give full play to their own advantages, and build digital infrastructure by developing the tertiary industries with small investment, light volume, good efficiency, and large employment capacity to achieve high-quality development.

(2) For cities with poorly developed digital infrastructure, it is relatively easy to expand the scale and application of digital technology, allowing them to fully learn from the advanced technology and construction system of better-developed cities, maintain effective communication and close exchange with better-developed cities, promote the technology transfer of digital technology from high-level areas to low-level areas, and improve the digital infrastructure construction of poorer cities.

(3) To prevent the continuous expansion of the Matthew effect (a phenomenon that the strong are stronger and the weak are weaker.), the provincial governments should shift policy resources towards cities that need to be further improved for digital infrastructure configuration efficiency, and make full use of the demonstration and signaling effects to enhance the financial capital, human capital, and physical capital of less-developed regions. This improves the solid foundation guarantee for the digital infrastructure construction of these cities.

(4) Policy Extension

The global digital divide refers to the trend of further polarization of the information gap and the gap between rich and poor due to different levels of ICT ownership and application in the global digitalization process. This trend has intensified the polarization between the two levels of the world, resulting in a serious shortage and shortage of digital literacy and digital technology in underdeveloped countries and regions, and seriously inhibiting the space for the future development and growth of the digital economy in backward regions. For countries and regions with developed digital levels, they should take the initiative to assume the core role of governing the global digital divide and supporting the digital construction of backward regions, and bridge the digital divide and improve the digital level of backward countries and regions by increasing financial support and technical assistance, and vigorously promoting digital infrastructure construction and digital talent training. In addition, the key to whether backward regions can continuously narrow the digital divide lies in the support of the country and region for digital construction, so backward regions should take the initiative to summarize the shortcomings of local digital construction and learn from the advanced experience of leading regions.

7. Conclusions

Digital infrastructure is an important strategic deployment to adapt to the development of the new era, which adds new momentum to the construction of a digital-driven regional innovation system, the overall improvement of the effectiveness of the national innovation system, and thus accelerate the construction of digital China and a strong network country. Shandong Province actively responds to the national policy, puts forward the development goal of "digital infrastructure in the forefront", and is committed to building up a digital infrastructure system with ubiquitous connectivity, efficient coordination, full domain awareness, intelligent integration, security and trustworthiness, creation of a national information infrastructure pioneer area and convergence infrastructure demonstration area, and improving the digital infrastructure construction to promote the realization of high quality.

In the process, it is inevitable that there are problems such as uncoordinated regional development, and lack of targeted policies. A problem therefore is finding ways to solve these problems and promote Shandong Province to achieve the strategic goal of a "strong digital province".

This study takes 16 prefecture-level cities in Shandong Province and constructs a digital infrastructure allocation efficiency measurement index system based on the principles of scientificity, systematization, independence, and operability, takes into account the actual situation in Shandong Province, adopts the methods of non-expectation super-efficiency SBM model and kernel density estimation, measures and analyzes the spatial and temporal differences of digital infrastructure allocation efficiency in 16 prefecture-level cities in Shandong Province, and forwards policy recommendations for problems of uncoordinated regional development, insufficient government attention, lack of policy targeting, and more low-level areas.

This research has three contributions: First, it fully considers the path of digital infrastructure construction and its impact on society and economy, and identifies the inputs of two aspects of staff and financial, digital infrastructure, as well as the outputs of four aspects of social, economic, technological and social injustice, which provides important insights for promoting digital infrastructure construction. Secondly, the selected method can reflect the changes in the level of digital infrastructure construction and allocation efficiency in various regions in recent years, and help identify problems such as shortage of resource allocation, uncoordinated regional development, and gaps between policies and their implementation. Finally, intuitive data and graphs and detailed analysis results can provide guidance and solid basis for decision-makers in various regions to formulate digital infrastructure-related policies and resource allocation, so as to connect theory and practice.

The research ideas, research methods, and countermeasure suggestions of this study also provide references for the construction of digital infrastructure and subsequent related studies. However, because digital infrastructure is in the construction and development stage, the amount of data on indicators related to digital infrastructure is relatively small. Hence, subsequent research can further improve the measurement index system, optimize the measurement system of digital infrastructure allocation efficiency, and enhance the allocation efficiency of digital infrastructure.

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Appendix A

Research method specifics.

The non-expectation super-efficiency SBM model with the help of kernel density estimation was used, to measure the efficiency of digital infrastructure allocation in prefecture-level cities in Shandong Province and analyze their spatial and temporal differences, which are expressed as follows:

(1) Non-expectation super-efficiency SBM model

$$\min\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{\overline{x}}{x_{ik}}\right)}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\frac{\overline{y^d}}{y_{sk}^d}+\sum_{q=1}^{r_2}\frac{\overline{y^u}}{y_{qk}^u}\right)} \quad \text{(A1)}$$

Which also satisfies:

$\overline{x} \geq \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j$; $\overline{y^d} \leq \sum_{j=1,j\neq k}^{n} y_{sj}^d\lambda_j$; $\overline{y^d} \geq \sum_{j=1,j\neq k}^{n} y_{qj}^d\lambda_j$; $\overline{x} \geq x_k$; $\overline{y^d} \leq y_k^d$; $\overline{y^u} \geq y_k^u\lambda_j \geq 0$; $i = 1,2,\cdots,m$; $j = 1,2,\cdots,n$; $s = 1,2,\cdots,r_1$; $q = 1,2,\cdots,r_2$.

Where, ρ is the digital infrastructure allocation efficiency. n is the number of cities. m is the number of inputs. r_1 and r_2 represent the desired and undesired outputs, respectively. x, y^d, y^u are the elements in the corresponding input matrix, desired output matrix and undesired output matrix, respectively.

(2) Kernel density estimation method

Kernel density estimation generates a smooth surface reflecting continuous changes in the density of point data in a plane space. In a two-dimensional space, various cases of calculation methods exist for kernel density estimation. The calculation formula chosen in this study is as follows:

$$\hat{f}(x,y) = \frac{1}{nh^2}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}, \frac{y - y_i}{h}\right) \quad \text{(A2)}$$

where $\hat{f}(x,y)$ is the kernel density estimate of point (*x*,*y*). *n* is the total amount of sample data in the study area. *h* is the bandwidth. *K* is the kernel function. (x_i, y_i) is the coordinate of the i^{th} sample.

To ensure the reasonability of the kernel density estimation, the kernel function must satisfy the following three conditions, as shown in Table A1.

Table A1. Kernel function conditions.

Conditions	Formula
Symmetry	$K(x) = K(-x); (x \in R)$
Homogeneity	$\int_{-\infty}^{+\infty} K(x)dx = 1$
Non-negativity	$K(x) > 0; (x \in R)$

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