National Accounting Review

NAR, 4(4): 329–361.
DOI: 10.3934/NAR.2022019
Received: 29 July 2022
Revised: 25 September 2022
Accepted: 09 October 2022
Published: 17 October 2022

http://www.aimspress.com/journal/NAR

Research article

Measuring China's urban digital economy

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Abstract: Digital economy is the core driver of high-quality economic development. How to evaluate the development of the digital economy reasonably and scientifically has become a top priority. Taking 278 prefecture-level cities in the Chinese Mainland from 2010 to 2020 as the research subject, this paper first constructs the digital economy indicator system of Chinese cities from four dimensions: digital industry, digital users, digital innovation, and digital platforms. Then, this paper adopts the gray-target entropy weight method to calculate the digital economy index and sub-indexes of Chinese cities. Finally, this paper analyzes the development of China's urban digital economy from the statistical characteristics and development trends of the index and sub-indexes. The results show that China's urban digital economy and the four dimensions, have experienced stable development from 2010 to 2020, but there is regional heterogeneity. This is mainly reflected in the differences in the development speed of different cities in these dimensions, making the gap among different cities expanding year by year. Additionally, from the perspective of city types, central cities have unique advantages in the development of digital economy, taking a leading position in all dimensions of the digital economy, while non-central cities have great potential for developing digital economy.

Keywords: urban digital economy; digital industry; digital users; digital innovation; digital platform; grey target entropy weight method

JEL Codes: G20, G10, O16

1. Introduction

With the passage of time, scholars' definitions of the digital economy have become richer and more diverse. The concept of the digital economy was first proposed by Canadian scholar Don Tapscott in 1996, who emphasized it as the new economy (Tapscott, 1996). After studying the digital economy, many scholars believe that it is based on data as the key production factor, with modern information networks as the main carrier, and the integration and application of information and communication technology (ICT) and the digital transformation of all factors as important driving forces to promote inclusive, innovative, efficient and sustainable new economic forms (Crawford, 1996; Zhen et al., 2021; Liu et al., 2022).

Compared with the traditional real economy that relies on physical space, the digital economy has shown broad application prospects and huge growth potential during the COVID-19 period in 2020 due to its unique advantages of the Internet and data elements, and it is expected to become a new engine for global economic recovery. According to the "Digital Economy Report 2021" released by the United Nations Conference on Trade and Development (UNCTAD), the global Internet and data traffic has exploded in recent decades, and with the rapid development of digital technology, the digital economy will maintain rapid growth. Since 2017, the profits of listed companies related to the digital economy have shown an upward trend. In 2017, 7 of the 10 largest listed companies in the world by market capitalization were related to the ICT industry in the digital economy. During the COVID-19 epidemic in 2020, the net profit of large digital platform companies, such as Amazon, Alphabet (including Google), Apple, Facebook, and Microsoft in the United States, saw their net profits rise over the same period, and the profits of Chinese digital companies such as Alibaba, Baidu, and Tencent have also increased significantly (the above data are all from UNCTAD's Digital Economy Report 2021: "Cross-border Data Flows and Development: For Whom the Data Flow").

A new round of scientific and technological revolution has led all countries in the world to enter the era of the digital economy, and the digital economy has become the core force to promote the high-quality economic development of various countries. According to the latest "White Paper on the Development of China's Digital Economy (2021)" released by the China Academy of Information and Communications Technology, the scale of the digital economy in 47 countries has reached US$32.6 trillion in 2020, accounting for 43.7% of the GDP of these countries, among which, the United States and China rank the top two in the world, respectively, in the aspect of scale; and from the perspective of the growth rate of the digital economy, China's digital economy has grown by 9.6% year-on-year in 2020, ranking first in the world. China's model of actively promoting the development of the digital economy has achieved initial results, and it is worthy of learning and reference by all countries.

However, measuring the digital economy is complicated. The definition and connotation of the digital economy vary obviously in different time and space dimensions. The statistical caliber and industrial classification system of the digital economy and the traditional economy have certain overlaps and similarities, making it difficult to scientifically and accurately measure the digital economy and reasonably evaluate the development of the digital economy in various regions. Therefore, how to reasonably measure and evaluate the digital economy has become a key concern of all countries.

Many international organizations, research institutions, and scholars have been studying and analyzing digital economy development. They have put forward many different methods of calculation and evaluation and achieved a series of research results. Currently, the calculation methods of the

digital economy can be divided into the following two categories. The first is to directly measure the total scale of the digital economy. The Bureau of Economic Analysis (BEA) of the U.S. Department of Commerce and the China Academy of Information and Communications Technology (CAICT) pays more attention to the measurement of the total scale of the digital economy. By defining the scope of the digital economy, they identify key indicators, such as output and added value related to the digital economy, and reasonably estimate the scale of the digital economy in various countries (BEA, 2018; CAICT, 2021). The second is to build a comprehensive indicator system based on the connotation of the digital economy to calculate the development index of the digital economy. As early as 2014, the EU released the EU Digital Economy and Society Report and the Digital Economy and Society Index (DESI). The EU constructs a digital economy and social indicator system from five aspects: broadband access, human capital, Internet application, digital technology application, and the degree of digitalization of public services, thus laying a foundation for the development of the digital economy indicator system (European Commission, 2021). The Organization for Economic Cooperation and Development (OECD) selects 38 internationally comparable indicators to build a digital economy indicator system through four dimensions: investment in intelligent infrastructure, empowerment of society, innovation capacity, ICT application, and promotion (OECD, 2014). The Network Readiness Index (NRI) of the World Economic Forum (WEF) and the ICT Development Index (IDI) of the United Nations International Telecommunication Union (ITU) are also developed based on the concept of the digital economy, having a certain reference value for the measurement of digital technology and digital industry (WEF, 2021). International organizations pay more attention to digital infrastructure and digital applications when calculating the digital economy.

China's third-party research institutions mainly use the comprehensive indicator system to calculate the digital economy, but different research institutions vary in the methods and focus of calculating the digital economy. Tencent Research Institute constructs the "Internet Plus" digital economy index from four dimensions: digital foundation, digital industry, digital innovation and entrepreneurship, and digital smart people's livelihood. By building a global digital economy competitiveness indicator system from the four dimensions of digital facilities, digital industry, digital innovation and digital governance, the Shanghai Academy of Social Sciences released the report "Global Digital Economy Competitiveness Index (2017)", which analyzed the digital economy development level of more than 120 countries around the world. The Alibaba Research Institute and KPMG jointly released the report "2018 Global Digital Economy Development Index" in September 2018, covering 150 countries and regions around the world. The report builds a digital economy indicator system based on five dimensions: digital infrastructure, digital consumers, digital industrial ecology, digital public services, and digital scientific research. In 2021, the CAICT and the Digital Economy Research Institute of H3C jointly issued the "Blue Book of China's Urban Digital Economy Index (2021)". Based on various government documents and various new models of digital application, the two institutes build a digital economy index system for 242 Chinese Mainland cities in 2020 from four dimensions: data and information infrastructure, urban services, urban governance, and industrial integration. According to the evolutionary characteristics of digital economy development, the Research Center of Digital Economy Industry of CCID Consulting constructs an urban digital economy indicator system from four dimensions: digital infrastructure, digital economy industry, digital governance, and data value. The research center officially released the "2021 White Paper on the Development of China's Urban Digital Economy" in September 2021. It presented the 2021 ranking of China's top 100 digital economy cities. Therefore, it can be found that the digital economy

indicator systems established by Chinese third-party research institutions have unique characteristics, and they are in sharp contrast with the digital economy indicator systems of international organizations.

Meanwhile, scholars have carried out a series of effect studies on the digital economy, constructing the digital economy indicator system from different dimensions to achieve their research goals more scientifically. Most scholars prefer to use the comprehensive indicator system method to measure and evaluate the development level of the regional digital economy. For example, by referring to scholars' research on the Internet Index and the digital financial inclusion index (Huang et al., 2019; Guo et al., 2020), Zhao et al. (2020) constructed a digital economy indicator system from the two dimensions of Internet development and digital financial inclusion with the principal component analysis method to reduce the dimension of digital economy indicators, thereby obtaining the urban digital economy development index. This idea of constructing the urban digital economy indicator system is simple and easy to understand, and many scholars use different weighting methods to calculate the digital economy index based on this idea (Liu et al., 2022; Wang et al., 2022; Zou and Deng, 2022; Li and Wang, 2022). Bai and Zhang (2021) constructed a digital economy indicator system from four dimensions: digital industry, digital innovation, digital users, and digital platforms after referring to the connotation interpretation of digital economy by the CAICT and the processing of digital economy variables by Zhao Tao et al. (2020). Since then, scholars have gradually enriched the research topics and have successively constructed digital economy indicator systems from the dimensions of digital infrastructure, digital industrialization, industrial digitization, digital innovation, digital technology, and digital application, to measure and evaluate the development of regional digital economy more comprehensively and scientifically (Li and Liu, 2021; Tang et al., 2021; Wang and Shi, 2021; Zhang et al., 2021; Pan et al., 2022; Chen et al., 2022; Xue et al., 2022; Zhang et al., 2022).

It can be seen from the digital economy calculation by international organizations, research institutions and scholars that they generally adopt the comprehensive indicator system method to measure the digital economy. When constructing the digital economy indicator system, the above-mentioned research will calculate the development level of the digital economy according to their respective advantages and research purposes by combining different weighting methods. International organizations and third-party research institutions in China can obtain multi-dimensional data through advanced digital technologies and inter-institutional collaboration, to construct a diversified digital economy indicator system to measure the digital economy in different countries and regions. Scholars, by contrast, are likely to face more restrictions on data collection. They must consider different research methods and build a digital economy indicator system based on the availability of data. Therefore, a complete and unified evaluation indicator system of the digital economy has not yet been formed, and it is difficult for scholars to update the temporal and spatial dimensions of the digital economy index based on the availability and timeliness of data, thus providing sufficient research space for this paper. In addition, 278 cities in China are studied in this paper. China's vast territory and numerous city types can symbolize the different development types of countries in the world. The study of the development of China's urban digital economy is helpful for the governments of all countries to adjust the development strategy of the digital economy according to their national conditions, thereby improving the level of digital economy. At present, the development of China's digital economy shows a steady upward trend overall. However, there are obvious differences in the development of the digital economy among different cities in China. In order to further narrow the gap of digital economy development among different cities, a scientific and reasonable digital economy indicator system is needed to measure the level of digital economy

development of each city for carrying out multi-dimensional analysis and proposing targeted policy suggestions. Based on this, by referring to the existing literature, this paper calculates the urban digital economy index based on the data set of 278 cities in the Chinese Mainland from 2010 to 2020, thereby carrying out a multidimensional evaluation and analysis.

Compared with previous studies, the marginal contribution of this paper is mainly reflected in the following two aspects. First, this paper measures and updates China's urban digital economy index scientifically. By calculating the digital economy index and sub-indices of 278 cities in the Chinese mainland from 2010 to 2020, this paper broadens the time dimension of the urban digital economy index, reflecting the degree of development and equilibrium of the digital economy in Chinese cities. Based on the rationality and availability of data, this paper constructs an indicator system of China's urban digital economy from four dimensions: digital industry, digital users, digital innovation, and digital platforms. Then, the gray target entropy weight method is adopted to calculate the total index and sub-indices of the urban digital economy. Second, this paper analyzes and evaluates the development of the digital economy in Chinese cities reasonably. By evaluating and analyzing the development of China's urban digital economy from multiple dimensions, this paper identifies the bottlenecks and obstacles faced by the development of the urban digital economy, to promote the healthy and sustainable development of the urban digital economy. Further, based on the analysis of the basic characteristics of the overall index and sub-indices of the digital economy, this paper combines the digital economy development models of the cities with the top rankings in each index to provide different development strategies for other cities with the potential for digital economy development, thereby narrowing the gap among cities in the digital economy.

2. Digital economy indicator system and calculation method

2.1. Construction of the urban digital economy indicator system

Based on the above-mentioned academic research on the digital economy indicator system, the connotation of the digital economy is rich, and the measurement methods are diverse, so it is difficult to use a unified and universal index system to generalize. Therefore, the construction of a reasonable urban digital economy indicator system needs to be combined with specific research purposes and research content (Ojanperä et al., 2019; Baboo et al., 2022). The research purpose of this paper is to establish a relatively objective and scientific indicator system of the urban digital economy, which is convenient for discovering the development characteristics of digital economy in different cities during different periods, thus, putting forward a series of research conclusions and suggestions. After summarizing the measurement methods of the digital economy by international organizations, research institutions and scholars, we found that digital industry, digital environment, and digital application are the three core elements of the digital economy, among which, the digital environment is the foundation, the digital industry is the key, and the digital application is an important achievement of the development of the digital economy. By drawing on the research on the connotation and characteristics of the digital economy (Bukht and Heeks, 2017), this paper refers to the digital economy indicator system proposed by Bai and Zhang (2021) to build China's urban digital economy indicator system from four dimensions: digital industry, digital users, digital innovation, and digital platforms. As one of the core elements of the digital economy, the digital industry can reflect the degree of digital industrialization and the status of the digital economy in the overall economy. Digital platforms can well explain the operating

environment of the digital economy, including platform construction, policy support, and Internet infrastructure. Digital users and digital innovation can represent the application scope of the digital economy in users and production innovation activities, reflecting the actual level of digital applications. Therefore, the digital economy indicator system in this paper is reasonable and comprehensive.

The digital industry is a basic, leading and strategic industry for the development of digital economy. It is represented by big data, the internet, artificial intelligence, and cloud computing, which can reflect the main development characteristics of the digital economy. As the core key to driving the transformation and upgrading of the industrial chain, the digital industry can not only accelerate the rapid development of technology-intensive industries but also reshape social production relations and provide strong support for the digital economy development. The scope and definition of the digital industry by the CAICT have been widely recognized by academia. The CAICT put forward that the digital industry includes the software and information technology service industry, the Internet and service industry, the telecommunications industry, and the electronic information manufacturing industry. Based on the development status of China's urban digital industry and academic research results, this paper considers the use of three variables: the urban unit employment in the information transmission, computer service and software industry, the total retail sales of social consumer goods, and the total market value of listed digital economic enterprises to measure the development of urban digital industry. The specific reasons are as follows:

First, this paper selects the employment of urban units in the information transmission, computer services and software industries as one of the secondary indicators of the digital industry. At present, the digital economy still relies mainly on information and communication technology (ICT). This variable can reflect the development scale of digital industries such as information and the Internet through the human resources of the ICT industry in each city. Secondly, the digital industry is a highly permeable industry, which can be penetrated and applied to various industrial sectors through information technology to reshape people's economic life. Based on the strong spillover effect of the digital industry, this paper selects digital consumption as one of the secondary indicators of the digital industry. This indicator can reflect the impact of the spillover and permeability of the digital industry on people's economic and social consumption. In view of the availability of digital consumption data and the correlation between the total retail sales of consumer goods and digital consumption, this paper uses the total retail sales of consumer goods to indirectly measure the scale of digital consumption. Finally, in the digital economy era, enterprises are first affected, so they need to accelerate the digital transformation to meet the needs of the times. From the perspective of digital economy enterprises, combined with the availability of enterprise data, this paper selects the total market value of listed digital economy enterprises in various cities as a secondary indicator of the digital industry. Based on the "Statistical Classification of Digital Economy and Its Core Industries (2021)" issued by the National Bureau of Statistics of China, this paper selects listed companies in related industries to calculate the total market value of listed digital economy enterprises in each city. This indicator can measure the productivity level of a city's digital industry to a certain extent, thus making the measurement of the digital industry more comprehensive.

The variable of digital users can reflect the digitalization level of users and the application scope of digital mobile payment in creating new values for the development of the digital economy. Information and communication infrastructure is the hub connecting the digital economy and users. After referring to related studies (Zhao et al., 2020; Bai and Zhang, 2021), this paper selects three secondary indicators: the mobile phone penetration rate, the Internet penetration rate and the total

amount of telecommunication services to measure the dimension of urban digital users, according to the characteristics of information infrastructure and the availability of urban data. Digital users' access to the digital economy cannot be separated from the effective support of mobile phones and the Internet. Using mobile phones and computers as carriers, digital users can publish and obtain information through the Internet, making the connection between supply and demand of information simpler and more convenient, thereby effectively reducing transaction costs and improving the efficiency of digital economic transactions. The total amount of telecommunication services reflects the needs of individuals for information transmission. With the expansion of the telecommunication business scale, the activity of mobile Internet users will gradually increase accordingly. High user stickiness will create a good audience for the digital economy, thereby promoting the development of the digital economy. For the measurement of the secondary indicators of the digital user's variable, this paper uses the number of mobile phone users to measure the mobile phone penetration rate, and the number of internet broadband users to measure the Internet penetration rate. The more mobile phone users and internet broadband users in a city, the greater the total amount of telecommunications services, which can explain that the digital economy has a broader audience and application range in the city. This not only reflects the level of digital users in the city but also reflects the development level of the digital economy. In addition, this paper uses aggregate indicators to measure digital users, rather than per capita indicators for the following reasons. The per capita indicator does not reflect the overall disparity in the digital user dimension among cities but may incorrectly assess the overall level of the digital user dimension, resulting in a large error in the calculation of the digital economy index. Based on this, this paper adopts the total indicators to measure the three secondary indicators of digital users to avoid the measurement errors mentioned above.

Digital innovation is the internal driving force of the digital economy development. The connotation of digital innovation lies in innovation, and innovation activities need a certain amount of financial support in order to convert ideas into practical results. Therefore, this paper integrates the achievements and funding of digital innovation activities and selects three secondary indicators, namely, the number of patent applications, the number of patent authorizations, and the R&D funding, to measure the development of the dimension of urban digital innovation. Firstly, this paper selects the number of patent applications and patent authorizations as one of the secondary indicators, because patents are the embodiment of technological innovation and can reflect the results of digital innovation to a certain extent. The number of patent applications represents the innovation vitality of a city, reflecting the investment degree of the city's economic development along the path of innovation and transformation. The number of patent authorizations represents a city's innovation achievements., reflecting the effect of the city's economic development along the road of innovation and transformation. Secondly, the R&D funding is the economic basis of digital innovation activities. Based on the availability of urban data and the concept of digital innovation investment, this paper selects science and technology expenditure in local budget expenditure to measure the R&D funding. Science and technology expenditure can reflect the capital investment of a city in digital innovation activities. To summarize, it is feasible and representative to select these three secondary indicators to measure the development level of digital innovation in this paper.

Digital platforms are important carriers for the development of digital economy, which can reflect the operating environment of digital economy and provide a guarantee for the coordinated allocation of resources for the development of digital economy. From the perspective of the operating environment of digital economy, this paper selects three variables: the number of listed digital economy

enterprises, the strength of digital policy support, and the Internet comprehensive development index to measure the development of the dimension of urban digital platforms. This paper selects the number of listed digital economy enterprises as one of the secondary indicators of the digital platform, because it can effectively reflect the overall operating environment of a city's digital economy, reflecting the development level of the city's digital economy. The more listed digital economy enterprises in a city, the higher the digital level of the city, which reflects the construction level of the digital platform. Based on the "Statistical Classification of Digital Economy and Its Core Industries (2021)" issued by the National Bureau of Statistics of China, this paper calculates the number of listed digital economy enterprises in each city. Secondly, the indicator of digital policy support can reflect the government's attention to the development and the operating environment of digital economy. The higher the digital policy support, the more attention the government attaches to the development of the digital economy, which is conducive to the introduction of more advanced digital economy enterprises, thus effectively improving the development level of urban digital economy. Based on the text data of the annual government working reports of 272 cities in China, this paper employs Python software and the text analysis method to construct the digital policy index of Chinese cities, to measure the digital policy support of cities. Specifically, this paper first selects 22 keywords: artificial intelligence, blockchain, big data, cloud computing, mobile payment, digital RMB, digital currency, Internet finance, digital finance, financial technology, inclusive loan, green finance, financial services, artificial intelligence, mobile payment, Internet connection, inclusive finance, 5G news, mobile finance, digital insurance, digital investment, and digital financing. Then, this paper uses Python software to conduct a statistical analysis of the relevant sentences of digital policies in the annual work reports of the governments. Further, this paper calculates the ratio of the total number of words of digital-policy-related sentences to the total number of words of the government work reports, which is used as the urban digital policy support indicator. Finally, referring to the indicators and methods used by scholars to calculate the comprehensive development level of the Internet (Huang et al., 2019), this paper employs the gray target entropy weight method to weigh the four variables: the number of Internet broadband users, the employment of urban units in the information transmission, computer services and software industries, the total amount of telecommunications business, and the number of mobile phone users to construct the urban Internet comprehensive development index. As an important platform for the development of the digital economy, the comprehensive development level of the internet can reflect the development of digital platforms. Based on this, this paper uses the above three secondary indicators to measure the digital platform development.

To sum up, this paper selects 12 secondary indicators to measure these four dimensions of digital industry, digital users, digital innovation, and digital platform, respectively, thus, forming an evaluation indicator system for China's urban digital economy. The specific measurement methods and data sources of each indicator are summarized in Table 1.

Table 1 provides an intuitive understanding of the urban digital economy indicator system constructed in this paper. Compared with the international organizations and research institutions, this paper has difficulties in collecting more representative data to describe the digital economy level of Chinese cities. Therefore, based on the existing urban data, this paper characterizes the development level of the urban digital economy through four different dimensions. Compared with other scholars' research on China's urban digital economy, this paper focuses on building an indicator system with multi-dimensional, reasonable and time-sensitive indicators to measure the development level of the digital economy in Chinese cities more comprehensively.

Table 1. Evaluation indicator system of the urban digital economy.

Goal	Primary indicator	Secondary indicator	Measurement method	Data sources
The Urban Digital Economy Index	Digital industry	The employment of urban units in the information transmission, computer services and software industries	Employment in the information transmission, computer services, and software industries	Urban statistical yearbooks and statistical yearbooks of various provinces and cities
		Digital consumption	Total retail sales of urban social consumer goods	Urban statistical yearbooks
		The total market value of listed digital economy enterprises	The total market value of listed companies related to the digital economy in a city	The CNRDS database
	Digital users	Mobile phone penetration rate	Number of mobile phone users	The EPS database
		Internet penetration rate	Number of Internet broadband users	The EPS database
		The total amount of telecommunication services	Total amount of telecommunication services in a city	Provincial statistical yearbooks
	Digital innovation	Number of patent applications	Number of a city's patent applications	The CNRDS database
		Number of patent authorization	Number of a city's patent authorization	The CNRDS database
		R&D funding	Public finance expenditure on science and technology	The CSMAR database
	Digital platform	Number of listed digital economy enterprises	The number of businesses related to the digital economy in a city	The CNRDS database
		Digital policy support strength	Text analysis	Government working reports
		The comprehensive Internet development index	Gray target entropy weight method	Urban statistical yearbooks, provincial and municipal statistical yearbooks, and the EPS database

2.2. Comparison, selection and calculation of the weighting method of the urban digital economy index

2.2.1. Comparison and selection of the weighting method

After constructing the urban digital economy indicator system, it is necessary to select a scientific index weighting method to give weights to the indicators at all levels. There are a variety of index

weighting methods for measuring the digital economy, which is mainly divided into two categories: subjective weighting methods and objective weighting methods. The subjective weighting method mainly refers to experts' subjective judgment of the importance of indicators at all levels according to experience, thereby giving corresponding weights to indicators. This kind of method, such as the analytic hierarchy process, has a certain subjectivity and is easily affected by subjective factors. The objective weighting method mainly calculates the weights of indicators at all levels through different calculation methods according to the data characteristics of indicators. According to the existing academic research, most scholars generally adopt objective index weighting methods. Common objective weighting methods include the principal component analysis method, the factor analysis method, the efficiency coefficient method, the variation coefficient method, and the entropy value method. The actual meaning of the principal components extracted by the methods of principal component analysis and factor analysis in the process of dimensionality reduction is not clear, and it is difficult to find the corresponding economic meaning to explain. The entropy method and the variation coefficient method mainly rely on the difference in data to extract relevant information to give weights. These methods are easy to understand and have certain feasibility, but they rely too much on the data and may be affected by extreme values, making the indicator weighting inaccurate. Based on this, after drawing on the research of many scholars, this paper adopts the gray target entropy weight method as the weighting method of China's urban digital economy indicators. The gray target entropy weight method is a method formed by the combination of the gray target decision-making method and the entropy weight method. This method effectively solves the problems encountered in the conventional gray target theory, and the combination of the entropy weight method can avoid the influence of subjective factors as much as possible, making the weighting of indicators more convincing. The entropy weight method is mainly based on the information entropy value of the data to present the information size of the index, and assign corresponding weights to the indicators with different information sizes. The gray target decision-making method is an important method commonly used in the gray systematic theory to solve multiple attribute decision-making problems. It mainly refers to setting a gray target without a standard mode, finding the bullseye in the gray target and then comparing the index value to be evaluated with the standard mode to calculate the bullseye degree as the evaluation result. The modeling idea of this method is concise and clear, and the applicability is strong. However, the conventional gray target decision model has problems such as the single weighting of the bullseye coefficient of the indicators. Therefore, based on the gray target decision-making model, this paper uses the weight determined by the entropy weight method to synthesize the weight of the bullseye coefficient, to calculate the overall index and sub-indices of the digital economy of each city.

2.2.2. Weight calculation of the urban digital economy indicators

In this paper, the weights of the indicators at all levels are calculated through the gray target entropy weight method, thereby forming the urban digital economy index. The specific calculation steps are as follows.

First, the original sequence is established. That is to determine the evaluation objects and evaluation indicators. The evaluation objects in this paper are 278 cities at the prefecture level and above in China, and the evaluation indicators are those listed in Table 1.

Second, the indicator sequence of urban digital economy is created. The data mode established in this step determines the number of elements contained in the indicator sequence and the chronological

order. That is, the data sequence of evaluation objects and evaluation indicators is obtained and arranged in chronological order from 2010 to 2020. For example, the original data of urban digital economy $x_{ij}(t_k)$ can be arranged to form an indicator sequence sorted by 2010–2020.

Third, a standard mode for the indicator sequence of urban digital economy is set. That is to determine the indicator types selected in this paper, such as positive indicators, reverse indicators, and moderate indicators. The indicators selected in this paper to measure the urban digital economy are all positive indicators, and the larger the expectation, the better, so the indicators in this paper have maximum polarity. Therefore, the maximum value of each indicator sequence is selected as the standard sequence, that is, the maximum value of each indicator sequence is used as the bullseye. The details are shown in Equation (1).

$$x_{0j} = max_{1\le i\le m} max_{t_1\le t_k\le t_N}\{x_{ij}(t_k)\} \tag{1}$$

Fourth, the gray target transformation is carried out for the indicator sequences of each city. That is, the indicator sequences in the second step are numerically compared with the standard mode sequence in the third step to obtain the mode sequence after the polarity transformation, as shown in Equation (2).

$$T(x_{ij}(t_k)) = \frac{min\{x_{ij}(t_k), x_{0j}\}}{max\{x_{ij}(t_k), x_{0j}\}} \tag{2}$$

Fifth, the grey relation difference information space is built. That is, calculate the information difference $\Delta_{ij}(t_k)$ between the gray target transformation mode sequence and the standard mode sequence of the corresponding elements, as shown in Equation (3).

$$\Delta_{ij}(t_k) = \left|T(x_{0j}) - T(x_{ij}(t_k))\right| = \left|1 - T(x_{ij}(t_k))\right| \tag{3}$$

Sixth, the bullseye coefficients of each city are calculated. Based on the information difference $\Delta_{ij}(t_k)$ measured in the fifth step and the adjustment correlation coefficient ρ, the bullseye coefficient $\gamma\left(x_{0j}(t_k), x_{ij}(t_k)\right)$ of each city is calculated, as shown in Equation (4). According to the sensitivity analysis of Chang and Lin, it can be seen that, when $\rho = 0.5$, the discrimination effect and stability are relatively good. Therefore, this paper adopts $\rho = 0.5$.

$$\gamma\left(x_{0j}(t_k), x_{ij}(t_k)\right) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{0i}(t_k) + \rho\Delta_{max}} \tag{4}$$

Seventh, the approaching degree of each city is calculated. In the seventh step, the entropy method is used to calculate the weights of indicators at all levels as the weights ω_j of different target coefficients of indicators, to replace the weighting method in the conventional gray target decision-making model. Finally, the approaching degree of each city is finally formed by weighting the bullseye coefficient of each indicator of the city, to measure the development level of the digital economy of the city.

$$\gamma(x_0, x_i)(t_k) = \sum_{j=1}^{n} \omega_j \gamma\left(x_{0j}(t_k), x_{ij}(t_k)\right) \tag{5}$$

In Equations (1) – (5), i represents the city; j is the evaluation indicator in the urban digital economy indicator system, and t_k represents the year. Through the above steps, the weights of indicators at all levels are finally calculated, as shown in Table 2.

Table 2. Weights of indicators at all levels.

Goal	Primary indicator	Weight	Secondary indicator	Weight
Urban digital economy index	Digital industry	0.3263	The employment of urban units in the information transmission, computer services and software industries	0.3124
			Digital consumption	0.1101
			The total market value of listed digital economy enterprises	0.5775
	Digital users	0.1215	Mobile phone penetration rate	0.2423
			Internet penetration rate	0.3810
			The total amount of telecommunication services	0.3767
	Digital innovation	0.3080	Number of patent applications	0.3690
			Number of patent authorization	0.3170
			R&D funding	0.3140
	Digital platform	0.2442	Number of listed digital economy enterprises	0.5735
			Digital policy support strength	0.1651
			The comprehensive Internet Development Index	0.2614

It can be seen from Table 2 that, first, the digital industry has the largest weight among the four first-level indicators, accounting for 0.3263 of the overall index. This shows that the digital industry occupies a dominant position in the development of China's urban digital economy, which is also in line with the research institutions' conclusions on China's urban digital economy. Among the secondary indicators of the digital industry, the market value of listed digital economy enterprises accounts for as high as 0.5775. This reflects that the development of the digital industry is inseparable from the support of digital economy enterprises. The indicator of the total retail sales of social consumer goods, which represents the level of digital consumption, only accounts for 0.1101, which shows from the side that the current level of digital consumption of residents in various cities is still not high enough and needs to be paid more attention. Second, the proportion of digital innovation in the overall digital economy index is 0.3080, second only to the digital industry. This indicates that digital innovation is the core driving force for the development of a city's digital economy. Among the secondary indicators of the sub-index digital innovation, the weights of patent applications, the number of patent authorization, and the R&D funding are not significantly different, indicating that the three can promote the development of digital innovation in a coordinated manner. Third, the sub-index digital platforms accounts for 0.2442 of the overall digital economy index, indicating that there is still a certain development space for digital platforms to provide platform support for the digital economy. Among them, the number of listed digital economy enterprises accounts for 0.5735 of the sub-index digital platforms. The number of listed digital economy companies plays a central role in the development of digital platforms. The digital policy support only accounts for 0.1651 of the sub-index digital platforms. This may be because the breadth and depth of digital policy implementation still cannot meet the digital economic development of most cities, so there is still some room for improvement in digital platform construction. Fourth, digital users have the smallest weight among the four first-level indicators, accounting for only 0.1215 of the digital economy index. This shows that the digital users have little role in promoting the development of the urban digital economy at this stage. In the sub-index digital users, the internet penetration rate and the total amount of

telecommunication services account for a larger proportion, which indicates that the internet and telecommunication services have a significant impact on the development of digital users.

3. The basic characteristics analysis of the urban digital economy index

3.1. Analysis of the overall characteristics of the urban digital economy index

In this paper, the gray target entropy weight method is used to calculate the urban digital economy index and sub-indices, and their data are pre-processed so that the index is more intuitive. In order to better evaluate the development level of the urban digital economy, this paper analyzes the statistical characteristics and development trend of the total index and sub-indices of the urban digital economy.

Firstly, this part makes a comparative analysis from three aspects: the mean, the median, and the standard deviation of the urban digital economy index. The basic statistical characteristics of the digital economy index of 278 cities in the Chinese Mainland from 2010 to 2020 are shown in Table 3. In order to facilitate the study of the overall level of urban digital economy development and regional differences, this paper draws Figure 1 to record the median growth rate of the urban digital economy index from 2010 to 2020 and the gap between the median and the mean.

Table 3. Statistical characteristics of the urban digital economy index from 2010 to 2020.

Year	Obs	Mean	Median	Median growth	SD
2010	278	100.4048	100.1348		1.4344
2011	278	100.4427	100.1561	0.0213%	1.4112
2012	278	100.5272	100.1770	0.0209%	1.7202
2013	278	100.6399	100.2232	0.0461%	2.1277
2014	278	100.7662	100.2659	0.0426%	3.0252
2015	278	100.9307	100.2942	0.0282%	4.1766
2016	278	101.0994	100.3240	0.0297%	5.1052
2017	278	101.3018	100.3670	0.0429%	6.6515
2018	278	101.4997	100.4042	0.0371%	7.6821
2019	278	101.6921	100.4256	0.0213%	9.9262
2020	278	101.6960	100.4127	–0.0128%	10.1747

It can be seen from Table 3 that China's urban digital economy has basically achieved steady growth year by year from 2010 to 2020, and there are regional differences. From the perspective of the mean value of the index, China's urban digital economy has achieved steady growth from 2010 to 2020, and there is a relatively obvious growth trend from 2012 to 2019. From the perspective of the median of the index, China's urban digital economy achieved steady growth from 2010 to 2019, and then it declined for the first time in the period 2019–2020. This shows that in recent years, China's urban digital economy has maintained a stable growth trend and may have been negatively affected by the COVID epidemic. From the standard deviation of the index, it can be found that there are significant regional differences in the development of the urban digital economy. Except for the period 2010–2011, the difference in the development of the urban digital economy has been increasing year by year.

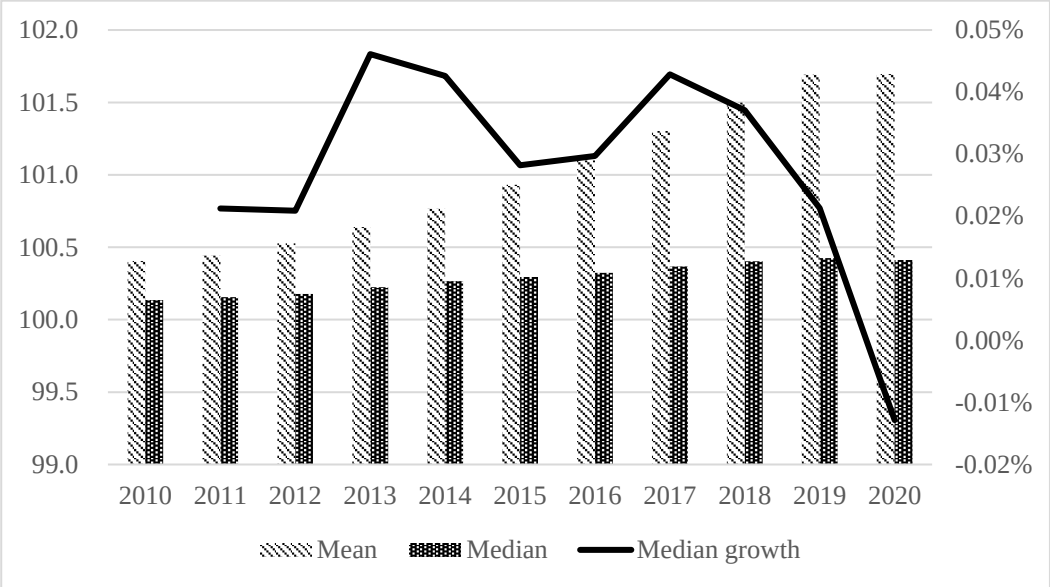

Figure 1. The mean, median and growth rate (%) of the urban digital economy index from 2010 to 2020.

The conclusions drawn from Table 3 can be more directly illustrated in Figure 1. Judging from the median growth rate of the urban digital economy index in Figure 1, the overall urban digital economy shows a steady growth trend. In 2020, due to the serious impact of the COVID-19 epidemic, the urban digital economy experienced negative growth for the first time in 2010–2020. From the difference between the mean and the median of the urban digital economy index in Figure 1, we can see that there are obvious differences in the development of digital economy in different cities, and this difference is expanding year by year.

Secondly, this part analyzes the digital economy gap among cities from the convergence coefficient σ of the urban digital economy index, which further illustrates the heterogeneity of digital economy development among Chinese cities. σ can reflect the different degrees of each city's digital economy deviating from the overall average level and the dynamic change process of this difference. If σ is relatively large, it indicates that the urban digital economy does not have the characteristics of convergence, which means that the difference in the development of the digital economy between cities is getting bigger and bigger. The calculation method of the convergence coefficient σ is shown in Equation (6).

$$\sigma_t = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(lnDEI_{it} - \frac{1}{n}\sum_{i=1}^{n} lnDEI_{it})^2} \quad (6)$$

In Equation (6), i represents the city; n represents the number of cities; t represents the year; $lnDEI_{it}$ represents the logarithm of the digital economy index of city i in year t, and σ_t stands for the logarithm of the convergence coefficient σ of the digital economy index of city i in year t. The changing trend of the convergence coefficient σ of China's urban digital economy index from 2010 to 2020 is shown in Figure 2.

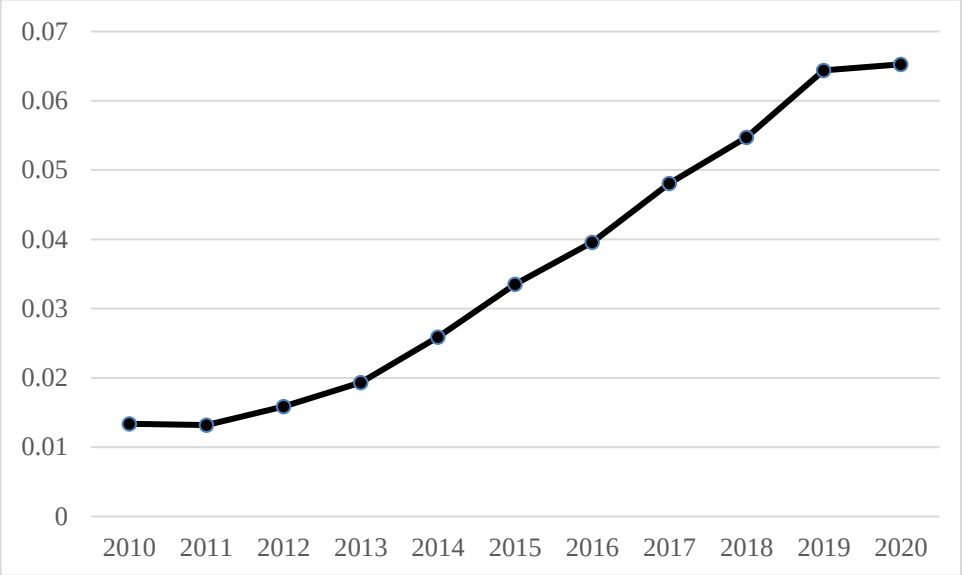

Figure 2. Convergence coefficient σ of urban digital economy index from 2010 to 2020.

In Figure 2, the gap in the digital economy development between different cities is increasing year by year. The convergence coefficient σ continued to rise from 0.0133 in 2010 to 0.0652 in 2020, which indicates that the development gap of digital economy among cities is expanding, effectively confirming the previous conclusion that there is significant heterogeneity in the development of digital economy among different cities. Due to the gaps in digital infrastructure, digital industry development and digital planning among regions, it is easy for the urban digital economy to develop in an unbalanced and uncoordinated way. In addition, there are many reasons for the above situation, which will not be repeated here.

3.2. Analysis of regional development trend of the urban digital economy

Based on the analysis in sub-section 3.1, this paper has found that the urban digital economy shows an upward development trend overall, and the development of the digital economy among cities has certain heterogeneity. Therefore, we further analyze the development trend of the digital economy in different cities in this sub-section. Due to the large number of urban samples in China calculated in this paper, it is difficult to conduct a comprehensive analysis of all cities. Therefore, this paper takes the municipalities directly under the central government, provincial capitals, and cities under separate state planning in Chinese mainland as central cities. By analyzing the digital economy development trends of central cities, this paper further studies the trends of digital economic development in different types of cities from 2010 to 2020. The digital economy development and ranking changes of central cities in Chinese mainland in 2020 are shown in Table 4.

According to Table 4, firstly, from the digital economy index ranking of central cities in 2020, it can be found that the top 20 cities are central cities, which indicates that compared with non-central cities, central cities are in the leading position in the development of the digital economy. Among them, the top four cities, Beijing, Shanghai, Shenzhen and Guangzhou, have a much higher digital economy development index than other cities, indicating that these four cities maintain an absolute leading position in the development of the digital economy. Secondly, from the perspective of the digital

economy ranking change of central cities, the ranking of most central cities does not change much, and some cities have obvious changes in the ranking. For example, Yinchuan dropped 93 places in 2020 compared with that in 2015, while Xining rose 83 places in 2020 compared with that in 2015. The top four cities, Beijing, Shanghai, Shenzhen and Guangzhou, basically remain unchanged. Most of the central cities have a certain rise in ranking compared with the situation in 2010 and in 2015, and only a few cities show a downward trend. Beijing, Shanghai, Shenzhen, and Guangzhou have a prominent leading position in the digital economy, and most of the central cities have experienced rapid digital economy development from 2010 to 2020. The development of the urban digital economy gradually forms the trend with the central cities as the mainstay.

Table 4. The development trend of digital economy in China's central cities from 2010 to 2020.

Central City	Digital Economy Index in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Beijing	256.6555	1	0	0
Shanghai	150.6323	2	0	0
Shenzhen	141.1754	3	0	0
Guangzhou	111.4482	4	0	0
Hangzhou	108.6409	5	3	1
Chongqing	107.9724	6	–1	3
Chengdu	106.9479	8	–2	–1
Nanjing	106.1838	9	2	1
Wuhan	105.4260	10	2	4
Tianjin	104.6926	11	–1	–6
Hefei	104.0732	12	9	18
Xian	103.7025	13	1	0
Ningbo	103.3047	14	1	–3
Zhengzhou	103.1154	16	8	12
Changsha	103.0603	17	3	0
Qingdao	102.9403	18	–5	2
Jinan	102.8987	19	0	5
Fuzhou	102.7422	20	2	–8
Xiamen	101.8873	25	3	0
Changchun	101.8015	26	6	6
Shenyang	101.7560	28	–5	–7
Guiyang	101.7454	29	–20	21
Harbin	101.6390	31	–6	–13
Shijiazhuang	101.5396	34	0	2
Nanchang	101.5144	35	13	5
Kunming	101.5063	36	0	–9
Dalian	101.4761	37	–10	–15
Nanning	101.2657	43	1	9
Taiyuan	101.2478	44	3	0

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Central City	Digital Economy Index in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Urumqi	100.8816	55	3	1
Lanzhou	100.8016	59	23	15
Xining	100.7103	68	83	61
Hohhot	100.6817	70	8	2
Haikou	100.5638	93	7	–36
Yinchuan	100.3458	173	–93	24

In order to further illustrate that the urban digital economy index in this paper is of reference value, this paper will explain from the following two aspects. Firstly, after comparing the rankings of the urban digital economy index calculated by well-known research institutions in China, this paper finds that the ranking of the urban digital economy index in this paper is similar to the research results of these research institutions, which shows that the urban digital economy index calculated in this paper is have a certain robustness. Secondly, according to the measurement methods commonly used in the existing research on urban digital economy and the availability of data, this paper selects information transmission and computer services from the perspective of the comprehensive development level of the Internet and digital inclusive finance (Zhao et al., 2020). The city's digital economy index is calculated based on five indicators, including the number of software employees, the number of mobile phone users, the number of Internet users, the total number of telecommunications services, and the Peking University Digital Financial Inclusion Index. By comparing the ranking of the city digital economy index under the two different measurement methods, there is no significant difference in the ranking results of the city digital economy index measured by the two different methods, and the top 20 cities are basically the same. The urban digital economy index in this paper is robust. This paper analyzes the development characteristics of cities with the leading digital economy development from multiple perspectives by combining the data of various dimensions of the top ten cities in the digital economy ranking in 2020. Specific information is shown in Table 5.

Table 5. Comparison of the advantages of the top cities in the digital economy ranking in 2020.

City	Digital economy index	Digital economy ranking	Digital industry	Digital users	Digital innovation	Digital platform
Beijing	256.6555	1	293.3361	162.8842	228.0620	243.1740
Shanghai	150.6323	2	163.6894	239.3595	153.2255	162.2428
Shenzhen	141.1754	3	163.8839	133.2455	149.9396	201.5224
Guangzhou	111.4482	4	116.5516	146.9284	125.7555	115.8785
Hangzhou	108.6409	5	114.7965	118.5630	122.0813	118.4414
Chongqing	107.9724	6	112.9215	153.2438	109.3628	109.2686
Suzhou	107.1795	7	108.6292	119.8593	121.1905	113.2076
Chengdu	106.9479	8	112.1735	132.3605	113.4210	111.3888
Nanjing	106.1838	9	112.7717	113.4432	117.3636	110.2175
Wuhan	105.4260	10	107.5723	115.0863	117.7363	107.4562

As can be seen from Table 5, the top 10 cities in the digital economy ranking in 2020 have different development characteristics. Firstly, Beijing, Shanghai and Shenzhen have absolute advantages in digital industry, digital innovation and digital platforms, which is in line with the economic development characteristics of the three cities. They have strong strength in digital industry scale, digital technology application and digital platform construction, presenting a balanced and advanced development in the digital economy. Secondly, Shanghai, Beijing, Chongqing, Guangzhou, Shenzhen, and Chengdu have a leading position in the development of digital users. This is thanks to the construction of digital infrastructure in these cities, which enables residents to better enjoy the digital dividends brought by the development of the digital economy, resulting in a win-win situation. Finally, Hangzhou, Suzhou, Nanjing and Wuhan are more comprehensive in the process of digital economy development, having certain advantages in digital innovation. This shows that these cities attach great importance to the rational allocation of R&D and innovation and digital technologies, thereby effectively promoting the rapid development of the digital economy.

4. Characteristic analysis of the sub-indices of the sub-index urban digital economy

4.1. Characteristic analysis of the sub-index *urban digital industry*

4.1.1. Descriptive statistics and convergence analysis

Firstly, this part analyzes the mean, median and standard deviation of the sub-index urban digital industry. The mean, median, median growth rate and standard deviation of the sub-index digital industry of 278 cities in Chinese mainland from 2010 to 2020 are shown in Table 6. In order to facilitate the study of the overall level of the urban digital industry development and regional differences, this paper draws Figure 3 to record the median growth rate of the urban digital industry and the gap between the median and the mean from 2010 to 2020.

Table 6. Statistical characteristics of the sub-index urban digital industry from 2010 to 2020.

Year	Obs	Mean	Median	Median growth	SD
2010	278	100.6302	100.1977		3.1564
2011	278	100.6731	100.2307	0.0329%	3.2018
2012	278	100.7745	100.2608	0.0300%	3.5648
2013	278	100.9968	100.3051	0.0442%	4.1025
2014	278	101.2581	100.3365	0.0313%	6.7584
2015	278	101.5682	100.3734	0.0368%	8.9611
2016	278	101.5314	100.4032	0.0297%	7.5390
2017	278	101.8394	100.4294	0.0261%	10.4911
2018	278	101.6935	100.4287	–0.0007%	8.4943
2019	278	102.1486	100.4797	0.0508%	11.9500
2020	278	102.2706	100.4536	–0.0260%	12.8521

As can be seen from Table 6, the sub-index urban digital industry in China generally shows a gradual growth trend from 2010 to 2020, and heterogeneity exists among different cities. In terms of the mean value of the sub-index, China's urban digital industry has achieved stable growth from

2010 to 2020. Except for the downward trend in 2017–2018, it has maintained positive growth in the rest of the years. From the perspective of the median of the sub-index, the conclusions are basically the same, but the median has a downward trend in 2019–2020, which shows that the development of the digital industry in some cities has been affected by the COVID epidemic. The standard deviation of the sub-index presents an expanding trend from 2010 to 2020. This indicates that there are significant regional differences in the development of the urban digital industry, and the gap has widened further in 2019–2020.

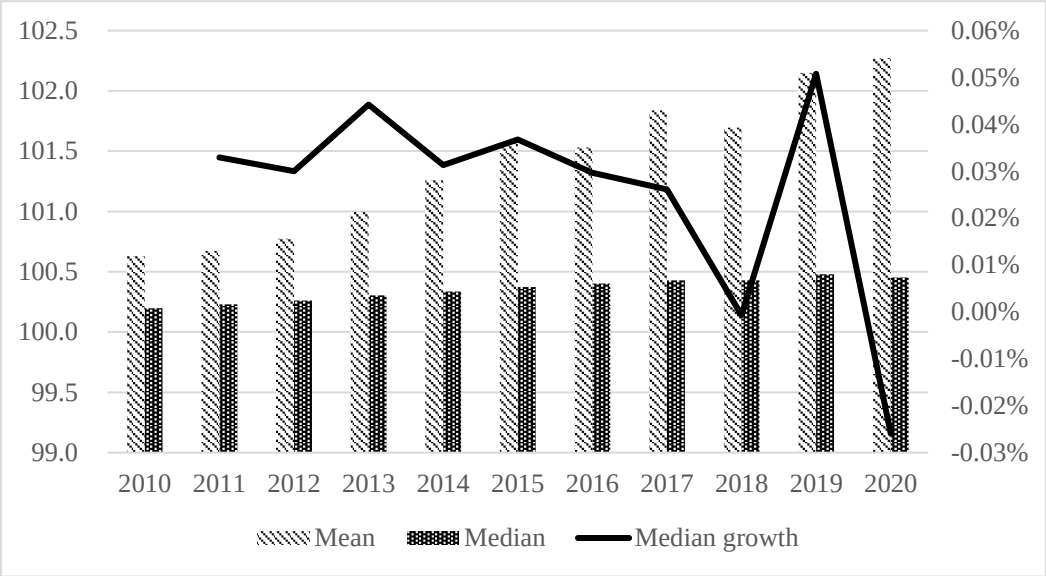

Figure 3. The mean, median and growth rate (%) of the sub-index urban digital industry from 2010 to 2020.

Figure 3 reflects the development trend and regional gap in the urban digital industry. Judging from the median growth rate of the sub-index urban digital industry in Figure 3, the urban digital industry has shown a steady growth trend overall, with negative growth only in 2018 and 2020. The difference between the mean and the median shown in Figure 3 presents an increasing trend year by year. This indicates that there are obvious differences in the digital industry development among different cities, and this difference has been expanding.

Secondly, this part illustrates the convergence of the urban digital industry by measuring the convergence coefficient σ of the sub-index urban digital industry from 2010 to 2020, which is shown in Figure 4.

It can be seen from Figure 4 that the convergence coefficient σ of the sub-index urban digital industry shows a trend of increasing fluctuations from 2010 to 2020. Specifically, σ rose from 0.0260 in 2010 to 0.0783 in 2020 but rebounded in 2016 and 2018. This indicates that the digital industry development has significant regional heterogeneity, and the gap among cities is widening further. Except for the period 2015–2016 and 2017–2018, the convergence characteristics of the sub-index digital industry are consistent with the convergence characteristics of the overall digital economy index.

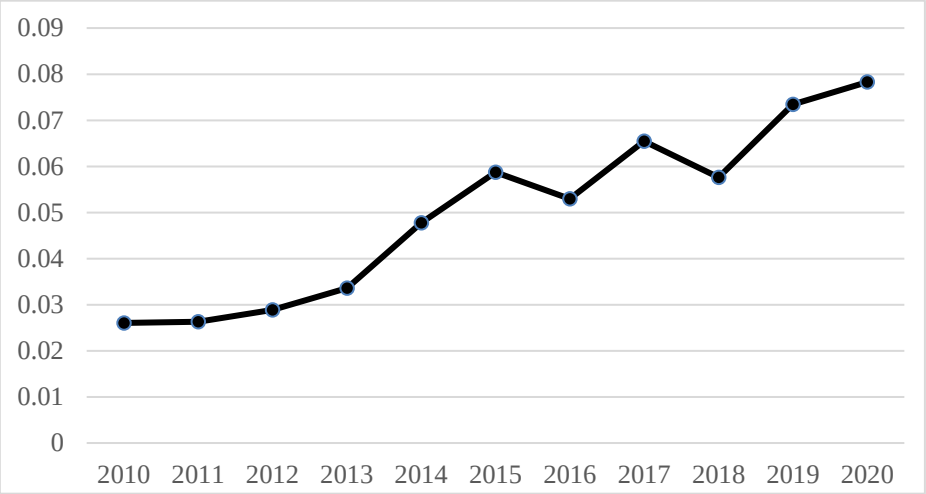

Figure 4. Convergence coefficient σ of the sub-index urban digital industry from 2010 to 2020.

4.1.2. Analysis of the development trend of the urban digital industry

By analyzing the development trend of the digital industry in central cities, this paper further studies the digital industry in different types of cities from 2010 to 2020. Table 7 shows the development and ranking changes of the sub-index digital industry in central cities in Chinese Mainland in 2020.

Table 7. Ranking and changes of the sub-index digital industry of central cities.

Central City	Sub-index digital industry in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Beijing	293.336	1	0	0
Shenzhen	163.884	2	1	1
Shanghai	163.689	3	–1	–1
Guangzhou	116.552	4	0	0
Hangzhou	114.797	5	0	0
Chongqing	112.922	6	0	2
Nanjing	112.772	7	1	–1
Chengdu	112.174	8	–1	5
Xian	107.679	10	0	–3
Wuhan	107.572	11	2	–1
Fuzhou	106.923	12	–3	–3
Jinan	105.862	14	0	6
Hefei	105.671	15	8	13
Zhengzhou	105.439	16	8	8
Qingdao	105.021	17	1	2
Changsha	104.757	18	–3	–6
Ningbo	104.552	19	–2	–4

Continued on next page

Central City	Sub-index digital industry in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Tianjin	104.492	20	–8	–9
Dalian	102.878	26	–10	–5
Xiamen	102.861	27	10	11
Harbin	102.687	28	–8	–12
Shenyang	102.637	29	–10	–12
Shijiazhuang	102.633	30	–3	–3
Kunming	102.593	31	2	–6
Nanchang	102.231	36	–1	7
Guiyang	102.216	37	15	17
Nanning	101.851	42	5	4
Changchun	101.773	44	–19	–22
Urumqi	101.741	45	–14	–9
Taiyuan	101.389	50	–9	–16
Haikou	101.305	54	30	42
Lanzhou	101.295	55	11	15
Hohhot	100.824	81	–24	–30
Xining	100.463	135	3	–15
Yinchuan	100.436	143	–51	10

According to Table 7, first, it can be found that the top 20 cities are central cities, which shows that compared with non-central cities, the development of the digital industry in central cities is still in the leading position. Among them, the top three cities, Beijing, Shenzhen and Shanghai, have obvious advantages in the digital industry compared with other cities. Second, from the perspective of the changes in the digital industry ranking of central cities, the top five cities, Beijing, Shenzhen, Shanghai, Guangzhou and Hangzhou, have remained unchanged, and the ranking of most central cities has changed to a certain extent compared with that in 2010 and 2015. For example, Yinchuan's ranking in 2020 decreased by 51 compared with that in 2015, while Haikou's ranking in 2020 increased by 42 compared with that in 2010. Beijing, Shanghai, Shenzhen, and Guangzhou have a prominent leading positions in the digital industry, and the digital industry in other central cities is developing rapidly. Non-central cities need to pay more attention to the development of the digital industry and learn from the experience of the central cities to actively promote the development of the digital economy.

4.2. Statistical characteristics analysis on the sub-index urban digital users

4.2.1. Descriptive statistics and convergence analysis

Firstly, this part analyzes the statistical characteristics of the sub-index urban digital users. The mean, median, median growth rate, and standard deviation of the sub-index of 278 cities in Chinese mainland from 2010 to 2020 are shown in Table 8. In order to facilitate the study of the overall level of the urban digital user development and regional differences, this paper draws Figure 5 to record the median growth rate and the gap between the median and the mean from 2010 to 2020.

Table 8. Statistical characteristics of the sub-index urban digital users from 2010 to 2020.

Year	Obs	Mean	Median	Median growth	SD
2010	278	102.7051	101.3062		5.9305
2011	278	102.6618	101.5164	0.2075%	4.2952
2012	278	103.0295	101.6721	0.1534%	5.1333
2013	278	103.3832	101.8832	0.2076%	6.1490
2014	278	103.6964	102.0244	0.1386%	7.3801
2015	278	103.7499	102.0742	0.0488%	7.4085
2016	278	104.1145	102.2316	0.1542%	9.1164
2017	278	104.2114	102.4422	0.2060%	7.5950
2018	278	104.7306	102.6570	0.2097%	9.2747
2019	278	104.8982	102.7142	0.0557%	9.5334
2020	278	105.1723	102.8230	0.1059%	10.5403

As can be seen from Table 8, China's urban digital users have achieved rapid growth year by year from 2010 to 2020. In terms of the index mean and median, China's urban digital users have achieved positive growth from 2010 to 2020. Compared with the digital economy index and other sub-indices, the mean and the median of the sub-index urban digital users are relatively high, which indicates that China's urban digital users are more active in general. From the standard deviation, it can be found that there are certain differences in the growth of digital users in different cities, and this difference is especially obvious in the past five years.

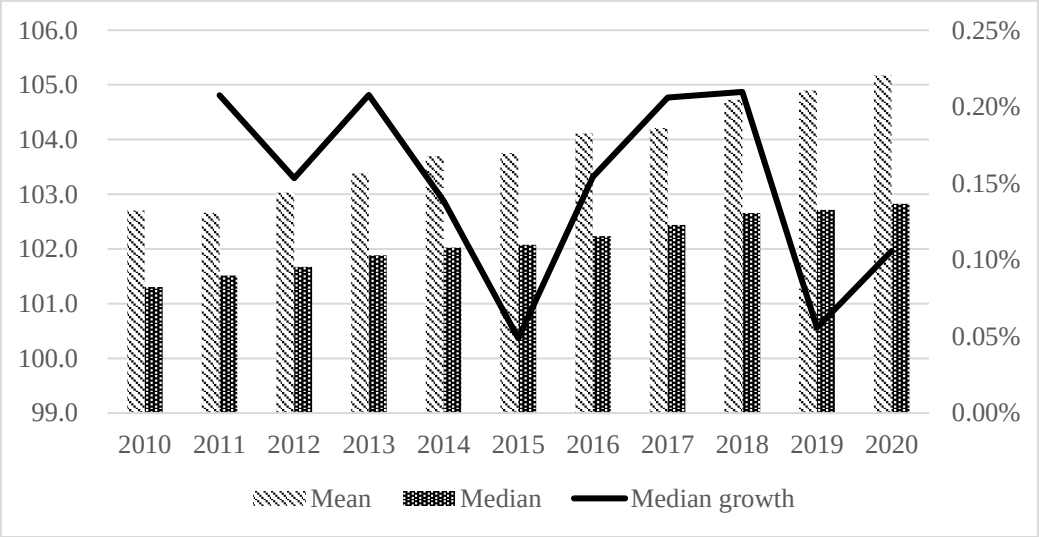

Figure 5. The mean, median and growth rate (%) of the sub-index urban digital users from 2010 to 2020.

Figure 5 reflects the development trend and regional gap of the sub-index urban digital users. According to the median growth rate in Figure 5, urban digital users show a trend of rapid growth; although, with a trend of fluctuation and change, it still maintains a fast growth rate in 2019–2020. The difference between the mean and the median shows an increasing trend year by year, indicating that the gap of digital users among different cities is increasing year by year.

Secondly, the convergence of urban digital users is illustrated by calculating the convergence coefficient σ of the sub-index urban digital users. The trend change of σ from 2010 to 2020 is shown in Figure. 6.

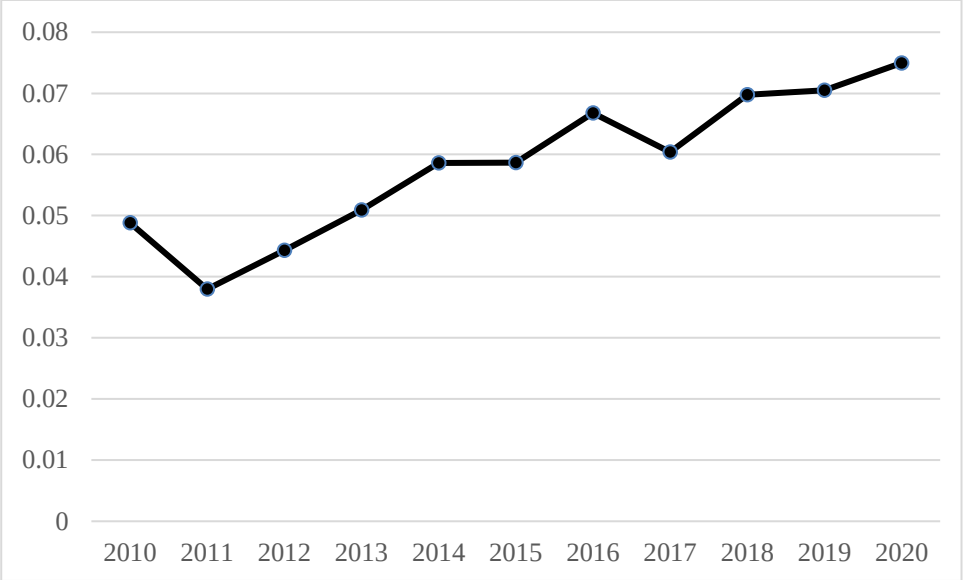

Figure 6. Convergence coefficient σ of the sub-index urban digital users from 2010 to 2020.

It can be seen from Figure 6 that the convergence coefficient σ shows a trend of increasing fluctuations from 2010 to 2020, with a downward trend only in 2010–2011 and 2016–2017. Specifically, σ rose from 0.0488 in 2010 to 0.0750 in 2020 but rebounded in 2011 and 2017. This shows that regional heterogeneity exists in the development of digital users and the gap among different cities is further widening.

4.2.2. Analysis of the development trend of the sub-index urban digital users

Based on the analysis of the development trend of digital users in central cities, this part further studies the development trend of digital users in different types of cities from 2010 to 2020. The development of digital users and their ranking changes in central cities in Chinese Mainland in 2020 are shown in Table 9.

As can be seen from Table 9, first, the top 20 cities in the ranking of digital users are central cities, which shows that compared with non-central cities, the development of digital users in central cities is in a leading position. Secondly, from the perspective of changes in the ranking of digital users in central cities, the top seven cities, Shanghai, Beijing, Chongqing, Guangzhou, Shenzhen, Chengdu and Tianjin, remain unchanged. Compared with those in 2010 and 2015, the rankings of most central cities have risen to a certain extent, and the rise of provincial capital cities, such as Xining and Hohhot, is particularly obvious. Central cities have a considerable digital user base, and their leading position is obvious.

Table 9. Ranking and changes of the sub-index digital users of central cities.

Central City	Sub-index digital users in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Shanghai	239.3595	1	0	0
Beijing	162.8842	2	0	0
Chongqing	153.2438	3	2	4
Guangzhou	146.9284	4	–1	0
Shenzhen	133.2455	5	–1	–2
Chengdu	132.3605	6	0	0
Tianjin	128.2630	7	0	–2
Hangzhou	118.5630	9	–1	5
Zhengzhou	115.4389	10	3	13
Wuhan	115.0863	11	–2	2
Nanjing	113.4432	13	6	6
Xian	113.0668	14	–4	–4
Changchun	112.5107	15	12	25
Changsha	112.3223	16	5	12
Ningbo	112.0718	17	–2	–6
Shijiazhuang	111.6726	18	4	12
Qingdao	111.5807	19	–3	–1
Jinan	110.8220	22	1	4
Shenyang	110.2959	23	–6	–2
Hefei	109.8906	25	6	32
Fuzhou	109.8503	26	–1	–11
Nanning	109.4664	28	7	19
Harbin	109.4602	29	–9	–9
Kunming	109.3617	30	–4	–8
Xining	108.2883	35	109	73
Xiamen	107.3926	39	–5	–12
Dalian	107.2885	40	1	–11
Taiyuan	107.0554	43	1	3
Hohhot	106.8884	45	56	19
Guiyang	106.4819	49	–9	5
Nanchang	106.4410	50	–1	2
Urumqi	105.5476	62	3	3
Lanzhou	104.9834	71	7	12
Haikou	103.2199	120	1	–75
Yinchuan	102.7819	145	–52	62

4.3. Statistical characteristics analysis of the sub-index urban digital innovation.

4.3.1. Descriptive statistics and convergence analysis

Firstly, this part analyzes the statistical characteristics of the sub-index urban digital innovation. The mean, median, median growth rate, and standard deviation of 278 cities in Chinese mainland from 2010 to 2020 are shown in Table 10. In order to facilitate the study of the overall level and regional differences of urban digital innovation development, this paper draws Figure 7 to record the median growth rate and the gap between the median and the mean of the sub-index from 2010 to 2020.

Table 10. Statistical Characteristics of the sub-index Urban Digital Innovation 2010–2020.

Year	Obs	Mean	Median	Median growth	SD
2010	278	100.4394	100.0730		1.7513
2011	278	100.5816	100.1000	0.0270%	2.1350
2012	278	100.7818	100.1387	0.0387%	2.7218
2013	278	100.9683	100.1845	0.0457%	3.3026
2014	278	101.1100	100.2127	0.0281%	3.8294
2015	278	101.4359	100.2536	0.0408%	4.9622
2016	278	101.8671	100.3232	0.0694%	6.7644
2017	278	102.1898	100.3558	0.0325%	7.9418
2018	278	102.6629	100.4328	0.0767%	10.8531
2019	278	102.6232	100.4268	–0.0060%	11.1349
2020	278	102.3118	100.4238	–0.0030%	9.3004

As can be seen from Table 10, digital innovation in Chinese cities maintained a certain growth trend from 2010 to 2018, while there was a slight downward trend in 2019 and 2020. The overall development of digital innovation in Chinese cities is rapid, but due to the impact of the COVID epidemic, the development has stagnated. The standard deviation of the sub-index maintained an increasing trend from 2010 to 2019, rising from 1.7513 in 2010 to 11.1349 in 2019, and only decreased to a certain extent in 2020. This indicates that there are significant differences in the development of digital innovation among different cities.

Figure 7 reflects the development trend and the regional gap of urban digital innovation. According to the median growth rate in Figure 7, urban digital innovation has shown a rapid growth trend overall, with negative growth only in 2019 and 2020. From the difference between the mean and the median in Figure 7, it can be found that the digital innovation development gap among different cities is small from 2010 to 2014 and gradually widens from 2015 to 2020. This shows that there are certain differences in the development of the digital innovation in different cities.

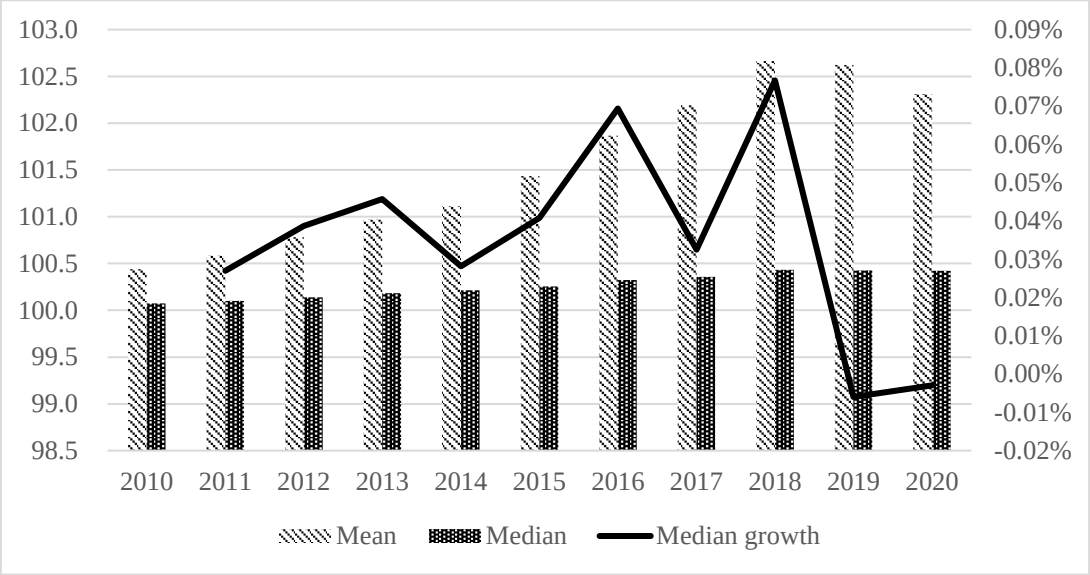

Figure 7. Mean, median and growth rate (%) of the sub-index urban digital innovation from 2010 to 2020.

Secondly, the convergence coefficient σ of the sub-index illustrates the convergence of urban digital innovation in 2010–2020. The trend changes of the convergence coefficient σ is shown in Figure 8.

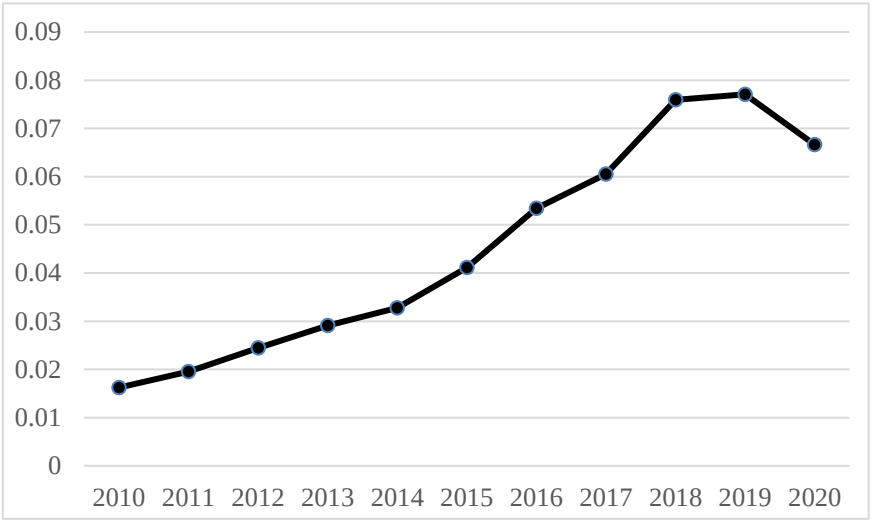

Figure 8. Convergence coefficient σ of the sub-index urban digital innovation from 2010 to 2020.

Figure 8 shows that the convergence coefficient σ of the sub-index urban digital innovation has a trend of increasing year by year from 2010 to 2019, but it decreased from 2019 to 2020. Specifically, σ increased from 0.0162 in 2010 to 0.0666 in 2020 but rebounded in 2019–2020. This indicates that the digital innovation development gap among different cities has been expanding from 2010 to 2019, but there is a certain degree of narrowing trend in 2020. The development of urban digital innovation has regional heterogeneity.

4.3.2. Analysis of the development trend of the urban digital innovation

This paper further studies the trend of digital innovation development in different types of cities from 2010 to 2020 by analyzing that in central cities. Table 11 shows the digital innovation development and ranking changes of central cities in Chinese mainland in 2020.

Table 11. Ranking and changes of the sub-index digital innovation of central cities.

Central City	Sub-index digital innovation in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Beijing	228.062	1	0	0
Shanghai	153.2255	2	0	0
Shenzhen	149.9396	3	0	0
Guangzhou	125.7555	4	3	3
Hangzhou	122.0813	5	5	1
Wuhan	117.7363	7	6	6
Nanjing	117.3636	8	–2	0
Hefei	114.005	9	7	11
Chengdu	113.421	10	1	1
Tianjin	109.7096	11	–6	–6
Xian	109.3852	12	3	2
Ningbo	109.3713	13	1	2
Chongqing	109.3628	14	–6	–2
Qingdao	108.1263	16	–7	7
Changsha	107.4772	17	3	–1
Zhengzhou	106.5199	19	8	7
Jinan	106.3928	20	–3	1
Fuzhou	104.375	25	9	8
Xiamen	103.9367	28	5	0
Harbin	103.1926	33	–11	–14
Shenyang	103.1892	34	–10	–17
Nanchang	103.1835	35	27	19
Changchun	103.135	36	8	–6
Taiyuan	102.9422	38	11	0
Dalian	102.8129	39	–10	–29
Kunming	102.2748	45	–3	–8
Guiyang	102.2087	48	8	3
Shijiazhuang	101.962	52	8	–2
Nanning	101.6285	56	–25	7
Lanzhou	101.1569	65	5	–9
Urumqi	100.7496	97	–23	–25
Yinchuan	100.6392	109	–19	20
Hohhot	100.5292	123	–4	–44

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Central City	Sub-index digital innovation in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Haikou	100.5154	127	–2	–40
Xining	100.3387	157	–27	17

As can be seen from Table 11, first, the top 20 cities are basically central cities in 2020, which shows that compared with non-central cities, central cities are still leading the way in digital innovation than non-central cities. Second, from the perspective of the ranking changes of the central cities, the top three cities, Beijing, Shanghai, and Shenzhen have remained unchanged, and the rankings of most central cities have dropped to a certain extent compared with those in 2010 and 2015. Central cities such as Beijing, Shanghai, and Shenzhen have a prominent leading position in digital innovation, while non-central cities have gradually caught up with some central cities in terms of digital innovation, and the development trend is good.

4.4. Statistical characteristics analysis of the sub-index urban digital platform

4.4.1. Descriptive statistics and convergence analysis

Firstly, this part analyzes the statistical characteristics of the sub-index urban digital platform. The mean, median, median growth rate and standard deviation of 278 cities in Chinese Mainland from 2010 to 2020 are shown in Table 12. In order to facilitate the study of the overall development level of urban digital platforms and regional differences, this paper draws Figure 9 to record the median growth rate from 2010 to 2020 and the gap between the median and the mean.

Table 12. Statistical characteristics of the sub-index urban digital platform from 2010 to 2020.

Year	Obs	Mean	Median	Median growth	SD
2010	278	100.8300	100.1547		3.0123
2011	278	100.9873	100.2276	0.0728%	3.6088
2012	278	101.1101	100.2503	0.0226%	4.1567
2013	278	101.3501	100.4225	0.1718%	4.8392
2014	278	101.5710	100.5598	0.1367%	5.4349
2015	278	101.8503	100.6795	0.1190%	6.3695
2016	278	102.2045	100.7567	0.0767%	8.1795
2017	278	102.4787	100.8938	0.1361%	9.1413
2018	278	102.6774	101.0996	0.2040%	9.8414
2019	278	102.7913	101.1800	0.0795%	10.2086
2020	278	102.8032	101.0830	–0.0959%	11.1810

It can be seen from Table 12 that, overall, the sub-index urban digital platform maintained a steady growth trend from 2010 to 2019, but there was a downward trend in 2020. China's urban digital platforms have been developing at a high speed in recent years, but after being affected by events such as the COVID-19 epidemic in 2020, there has been negative growth. The standard deviation maintained a steady growth trend from 2010 to 2020, rising from 3.0123 in 2010 to 11.1810 in 2020.

There are significant differences in the development of digital platforms among different cities, and this development difference is increasing year by year.

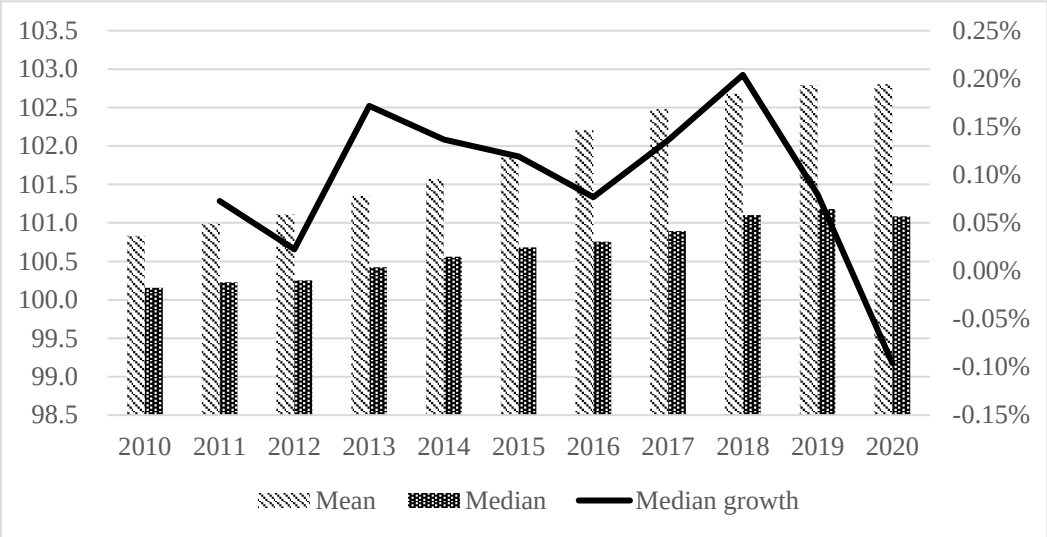

Figure 9. The mean, median and growth rate (%) of the sub-index urban digital platform from 2010 to 2020.

Figure 9 reflects the development trends and regional gaps of urban digital platforms. Judging from the median growth rate in Figure 9, the urban digital platform has shown a steady growth trend in general, but it has experienced a large degree of negative growth for the first time in 2019–2020. This shows that China's urban digital platforms have been developing rapidly in recent years, but after the impact of the COVID epidemic in 2020, there has been a certain downward trend. The difference between the mean and the median is constantly expanding. This indicates that the gap in the development of digital platforms among cities is constantly widening, that is, there is heterogeneity in the development of urban digital platforms.

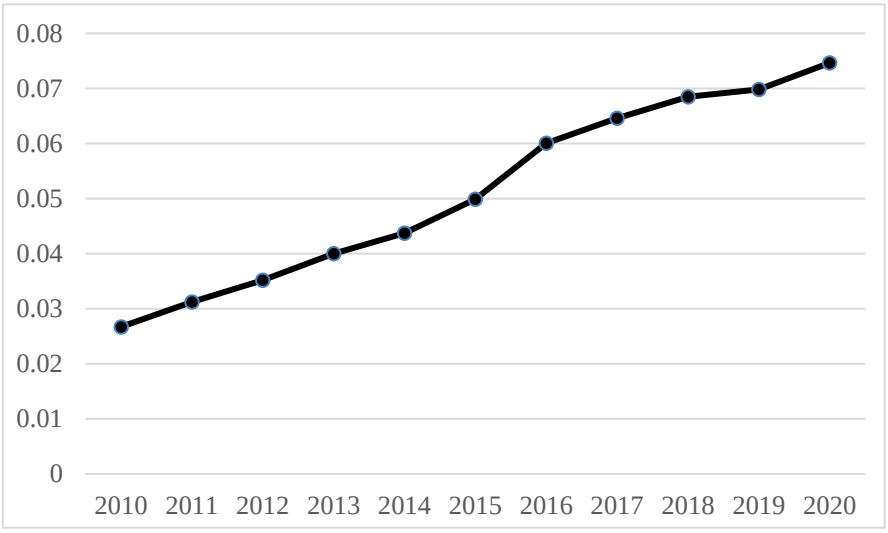

Figure 10. Convergence coefficient σ of the sub-index urban digital platform from 2010 to 2020.

According to Figure 10, the convergence coefficient σ has been increasing year by year from 2010 to 2020. Specifically, σ increased from 0.0267 in 2010 to 0.0746 in 2020. This indicates that regional heterogeneity exists in the development of urban digital platforms and the gap among cities is increasing year by year.

4.4.2. Analysis of the development trend of the urban digital platforms

By analyzing the development of digital platforms in central cities, this part further studies the development trend of digital platforms in different types of cities from 2010 to 2020. Table 13 shows the development and ranking changes of digital platforms in central cities in Chinese Mainland in 2020.

Table 13. Ranking and changes of the sub-index digital platform in central cities.

Central City	Sub-index digital platforms in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Beijing	243.174	1	0	0
Shenzhen	201.522	2	0	0
Shanghai	162.243	3	0	0
Hangzhou	118.441	4	2	0
Guangzhou	115.879	5	0	0
Chengdu	111.389	7	0	1
Nanjing	110.218	8	1	2
Chongqing	109.269	9	1	5
Tianjin	107.539	10	2	–3
Wuhan	107.456	11	0	2
Guiyang	106.952	12	–8	35
Fuzhou	106.495	13	2	–7
Hefei	105.985	15	9	6
Changsha	105.858	16	7	1
Ningbo	105.728	17	–4	–6
Jinan	105.688	18	8	2
Xian	105.588	19	–1	–3
Zhengzhou	105.219	20	25	19
Xiamen	104.894	21	0	–6
Qingdao	104.116	25	2	–2
Nanchang	103.746	27	40	0
Changchun	103.437	29	5	4
Shenyang	103.383	30	1	1
Kunming	102.949	36	11	–7
Dalian	102.835	38	–5	–8
Harbin	102.769	39	–4	–20
Shijiazhuang	102.332	48	–7	11

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Central City	Sub-index digital platforms in 2020	Ranking in 2020	Change in ranking compared with that in 2015	Change in ranking compared with that in 2010
Nanning	102.327	49	28	20
Urumqi	102.305	50	21	6
Taiyuan	102.201	53	26	5
Lanzhou	101.796	78	101	5
Haikou	101.442	98	–15	–26
Xining	101.059	148	–6	0
Hohhot	100.978	156	–102	–36
Yinchuan	100.401	254	–192	–42

From Table 13, first, it can be found that the top 20 cities are central cities, which are in the leading position in the digital platform development compared with non-central cities. Second, the top five cities, Beijing, Shenzhen, Shanghai, Hangzhou and Guangzhou, have remained unchanged in ranking, and the rankings of most central cities have risen to a certain extent compared with those in 2010 and 2015. For example, Lanzhou's ranking in 2020 has risen by 101 places compared to that in 2015. Central cities such as Beijing, Shenzhen and Shanghai have a prominent leading position in digital platforms, and other non-central cities are also continuing to promote the construction of digital platforms.

5. Conclusions

Based on the data of Chinese cities from 2010 to 2020, this paper constructs the urban digital economy indicator system from four dimensions: digital industry, digital users, digital innovation, and digital platforms. On this basis, we evaluate the development trend of China's urban digital economy from multiple perspectives. The conclusions are as follows.

First, China's urban digital economy has achieved steady growth from 2010 to 2020, and the four dimensions: urban digital industry, digital users, digital innovation and digital platforms also have experienced steady growth during the same period. Affected by events such as the COVID-19 epidemic in 2020, China's urban digital economy, digital industry, digital innovation, and digital platforms all suffered negative growth for the first time in 2020.

Second, there is significant regional heterogeneity in the development of the urban digital economy in China, and the gap among different cities is widening year by year overall. The development of the urban digital industry, digital users, digital innovation and digital platforms also presents obvious regional heterogeneity, which is specifically reflected in the differences in the development speed of different cities in these four dimensions. The gap among different cities in these four dimensions is widening year by year, which may lead to the emergence of regional imbalances in the development of the urban digital economy.

Third, compared with non-central cities, central cities have advanced and unique characteristics in digital economy development. The development of digital industry, digital users, digital innovation and digital platforms in central cities maintains a leading position. The development of the urban digital economy has gradually formed a development trend, with central cities as the mainstay and non-central cities holding significant potential for major development of their digital economy.

Based on the above research conclusions, this paper proposes the following policy implications. First, the development level of China's urban digital economy must be further improved. From 2010 to 2020, all dimensions of the urban digital economy have developed well, but in the face of extreme events such as the COVID-19 epidemic, the development of the urban digital economy has fluctuated to a certain extent. Therefore, local governments should comprehensively promote the urban digital economy and improve the stability of digital economy development, to provide new momentum for the development of the real economy. Second, the gap among cities in the development of the digital economy must be narrowed. At present, the development of the digital economy in various cities is unbalanced and uncoordinated. The central government should face up to the development differences and formulate digital economy development policies suitable for different regions, so as to coordinate the speed of digital economy development among cities and narrow the digital divide. Third, the development of the digital economy in different types of cities should be reasonably planed. When formulating the digital economy development plans for central and non-central cities, the government should fully consider the regional resource endowment and local unique conditions. In addition, the government should pay attention to not only the promotion of the advanced experience of central cities but also the special development problems encountered by non-central cities and put forward timely solutions.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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