Research article

Measuring digital economy in China

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Abstract: The COVID-19 pandemic has highlighted the importance of the digital economy in restoring economic and social development, creating more jobs and improving people's well-being. To inform policy makers about changes to digital strategies, measuring the digital economy is a prerequisite. This study aimed to compile an index of digital economy at the provincial (municipalities, autonomous regions, collectively referred to as "provinces") level to present an accurate and in-depth depiction of how it has developed in China. Our sample covers 31 provinces in China, over the period 2010–2020. This paper firstly constructs the digital economy index system from the four dimensions of digital users, digital platforms, digital industries and digital innovation, and then adopts a combination of entropy weighting method and grey target theory to measure the digital economy index. This paper study revealed that China's digital economy has been on an upward trend from 2010 to 2019 and has a decline in 2020, and the digital innovation is an important driving force for the growth of the digital economy index. The convergence of China's digital economy is decreasing, indicating that the gap in digital economy development between provinces is increasing. The proposed index in this study can be used as a screening tool, decision making tool, benchmarking tool and guidance of high-quality digital economy development.

Keywords: digital economy; index compilation; entropy grey target method; sigma convergence; cluster analysis

JEL Codes: G20, G10, O16

1. Introduction

The digital economy is unquestionably one of the most critical developments in high-quality economic development over these years. It promotes the improvement of labor efficiency and the optimal allocation of resources and alleviates information insufficiency and asymmetry to some extent (Li et al., 2017; Li and Ma, 2021). As of 2022, virtually all of the United Nations (UN) member countries have digital economy strategies in various stages of development. The U.S. Agency for International Development (2021), hereinafter referred to as USAID, publishes *digital Strategy 2020–2024* in which there are thirty missions that USAID shall accomplish in 2020–2024. USAID will work toward two mutually reinforcing strategic objectives: Improve measurable development and humanitarian assistance outcomes through the responsible use of digital technology in our programming; Strengthen the openness, inclusiveness, and security of country digital ecosystems. *The United States Innovation and Competition Act of 2021* suggests that the Comptroller General of the United States shall provide an assessment of network connectivity and, support engagement and participation in the relevant activities. The United States must lead in the international bodies that set the governance norms and rules for digitally enable technologies by increasing digital infrastructure and capital for digital media services and digital safety (The 117th Congress, 2021). Government of Australia (2021) sets out how Australia will secure its future as a modern and leading digital economy and society by 2030 in *DIGITAL ECONOMY STRATEGY 2030*. It builds on the Australian Government's existing digital and data initiatives, sets out further actions the Government is taking through the 2021–2022 Budget and defines future pathways to 2030. The strategy is built around three pillars:
1. Building the foundations to grow the digital economy.
2. Building capability in emerging technologies.
3. Setting Digital Growth Priorities to lift their ambition. These facts have prompted academics to attempt to monitor the digital economy development in order to acknowledge top performers, and to adjust corresponding strategy promptly.

How to tackle valuation of the digital economy is arguably the dominant issue in the digital economy and it will continue to be one of the dominating issues for researchers in these fields over the 21st Century. One way of characterizing the valuation problem is Value Added. U.S. Bureau of Economic Analysis (2018), hereinafter referred to as BEA, defines the digital economy primarily in terms of the Internet and related information and communications technologies (ICT) because it argues, while not all ICT goods and services are fully in scope, the ICT sector and the digital economy largely overlap. After the definition, BEA identifies goods and services within the supply-use framework relevant for measuring the digital economy, uses the supply-use framework to identify the industries responsible for producing these goods and services, and estimates the output, value added, employment, compensation and other variables associated with this activity. In this process, the ratio of intermediate consumption associated with the industrial output in the digital economy is assumed to be the same as the ratio of total industrial intermediate consumption of total industry output. Based on the method, Xu and Zhang (2020) calculated the value added and gross output of China's digital economy in 2007–2017, and compare these results with measurement about the scale of the digital economy in the United States and Australia. China Academy of Information and Communications Technology (2021), hereinafter referred to as CAICT, divides the digital economy into digital industrialization and industrial digitalization, where the value added of digital industrialization is the result of Electronic Information Manufacturing industry, the ICT industry and Internet Software and

Services industry, and, the value added of industrial digitalization is the output brought by the integration of digital products and digital services in various industries. Other approaches estimate the scale of digital economy through the Digital Economy Satellite Account (DESA). DESA is a satellite account used to reflect the whole process of the digital economy in all sectors. This has taken many researchers' efforts to compile DESA. Highly publicized examples of DESA come from BEA and OECD. BEA estimated the digital economy firstly in 2018 and updated its estimation in 2022. In the latest report, the estimation covers the Cloud Services and E-commerce industries (BEA, 2022). However, BEA (2018, 2022) measures only the products that are exclusively or primarily digital. It will continue to explore the measurement of the products that are partially digital to lay the foundation for the establishment of DESA in the future. OECD (2014) defines the connotation of digital economy based on the three major features of digital transactions: digitally ordered, platform enabled and digitally delivered. Then it proposes a preliminary framework for a satellite account that recognizes the multi-dimensional aspects of the digital economy and in line with current (2008 SNA and BPM6) accounting requirements. There are some innovations in the framework that go beyond what is currently required from these accounting standards (for example, "free services") and indeed beyond what is typically collected via conventional structural business and household surveys (used to estimate GDP), namely, information on the nature of transactions. Based on the framework, Xiang and Wu (2019) formed a special design of the production of the digital economy and the value added of the major industries of China's digital economy from 2012 to 2017 is estimated. Yet another approach has been to indices of the digital economy. The World Economic Forum (2021) issues *The Network Readiness Index 2021* for two reasons: first, to better capture the reach and impact of digital transformation, and second, to offer a holistic view of how digital technology use can enhance the development and competitiveness of economies. The CCID Consulting (2020) publishes an annual survey that is intended to measure the digital economy of the 31 autonomous regions of China. Each year, its team of researchers collects data on the availability of online services in each region, the digital infrastructure and digital platforms of each region, and various aspects of high technological innovation. The data are then combined into aggregate indices which are further combined into a top level Digital Economy Development Index by using AHP.

Clearly, these methods are effective measurement of the digital economy. However, there still exists difficulties to establish Value Added and DESA. For Value Added, the digital economy has dramatically influenced our lifestyle. It is pervasive across all aspects of social and economic life and therefore, the traditional statistical caliber is no longer applicable. As for DESA, it is an ideal tool of observation of Digital Industrialization and Industrial Digitalization, but at present, the study on DESA is in the early stage of theoretical research. For example, scholars disagree about the appropriate definition of boundaries in consumption and production, the methodology of evaluating the value of "free" products, and asset pricing. Indices are used to summarize a multitude of indicators thereby providing decision makers with an integrated and more informative overview. For example, the Digital Economy Index provides an easy way to track the overall development of the digital economy. By looking at statistical measurement, it is easy to gauge the current state of digital economy and individuals could be longitudinally compared in different dimensions. That can help them to make better digital economy strategies. Further, the importance of indicators could be adjusted when indicators are aggregated. Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM) are often used. In this way, of particular interest to this study is to get the digital economy index of China's autonomous regions by using the entropy grey target theory which is established based on EWM and

grey target method. This not only enriches the digital economy performance evaluation methods, but also provides corresponding reference to improving the digital economy strategies. The remainder of this paper is divided into five sections. Section 2 presents an overview of construction of the digital economy index. Analysis of statistical characters and further analysis of indices are given in Section 3 and Section 4. Finally, conclusions are drawn in Section 5.

2. Indicator System and method

In the first step, a framework should be developed. It aims to clearly present:
- the indicator selection
- the method of aggregation

2.1 Indicator selection

In the second step, indicators of the composite index should be identified. To select the indicators reasonably, we started by reviewing the existing literature on the digital economy index. The framework developed by the CCID Consulting (2020) has five dimensions which are relevant to digital infrastructure, resources, technology, and integration between digital technology and traditional industries. The Ali Research Institute and KPMG (2018) proposes five factors of digital economy which include infrastructure, consumer, ecology of digital industries, digital public service and digital scientific research, so as to depict the development and path of digital economy in 113 countries. CAICT (2017) constructs Digital Economy Index based on the characteristics of the digital economy and indicators which are related to the cyclical fluctuations in the development of digital economy significantly. The index is Prosperity Index, which depicts the trend of digital economy development, reflects the status of digital economy development, and describes the historical change law of the digital economy. The indicators cover the scale of digital users, digital industry revenue and the transaction scale of digital services. The International Telecommunication Union (2017) provides a snapshot of the status of ICT markets in 192 economies, including significant infrastructure developments, and government policy and initiatives, to improve the access and use of ICTs. Each profile is structured around three key areas: mobile services, fixed services, and government policy. The profiles are supported by key factors of penetration rates of infrastructure, prices of ICT services and data on access and use of ICTs by households and individuals. Digital Economy and Society Index (DESI) is a tool to measure the digital economy development in EU member States (European Commission, 2021). The indicator system comprises four dimensions: (a) Connectivity. Under the dimension, both fixed and mobile broadband are analyzed with indicators measuring the supply and the demand side as well as retail prices. (b) Human capital. It accesses both internet user skills of citizen and advanced skills of specialists. (c) Integration of digital technology. The dimension is made up of three sub-dimensions: digital intensity, take-up of selected technologies by enterprises and E-commerce. (d) Digital public services. It describes the demand and supply of e-government as well as open data policies. The purpose of the State New Economy Index is to measure states' economic structure (Atkinson and Foote, 2021). It assembles 25 indicators across 5 categories that best capture what is important above the New Economy. One of the categories is the digital economy, which measures internet and computer use by farmers; the degree to which state governments use information technologies to deliver services; adoption and speed of broadband telecommunications; and use of health information technologies. OECD (2014) selects indicators to

monitor the information society. These indicators could be divided into four categories: (a) Investing in smart infrastructure; (b) Empowering society; (c) Unleashing creativity and innovation; (d) Delivering growth and jobs. Topics ranging from infrastructure availability to openness and participation in the Internet Economy, cyber security and privacy, protection and empowerment of consumers and citizens, and innovation and sustainability are covered.

Common to all the relevant literature is the digital economy index comprises four requisite factors: infrastructure, platforms, industries and innovation. In this way, digital economy can be regarded as an economic form which is infrastructure-based, user-centered, platform-mediated, and innovation-driven. Therefore, in line with previous studies on formative index construction, this paper constructed a digital economy assessment framework with four dimensions of digital users, platforms, industries and innovation (Hajkowicz, 2006; Whitmore, 2012; Baker et al., 2016; Lee and Zhong, 2016; Baboo et al., 2021; Liao et al., 2022).

• Digital User. Digital users are the producers or consumers of digital products. The dimension assesses the adoption of broadband telecommunications, which includes seven aspects. (a) Mobile phone penetration rate. It refers to the number of mobile phones per 100 people. (b) Number of Internet broadband users. It refers to the number of users who access the Chinese Internet through xDSL, WLAN and other ways. (c) Number of mobile Internet users. Mobile Internet refers to the combination of mobile communication and the Internet, so that users can internet and use network services anytime and anywhere. (d) Total volume of telecommunications services. It is the total volume services provided by the telecommunication sector to users, which is presented in the form of money. Besides, the growth of digital infrastructure leads to the increase in internet access, so the above indicators also reflect the employment of digital infrastructure to some extent.

• Digital Platform. Digital platform refers to the digital environment that provides users with interactive services under the support of digital technologies. The dimension has three indicators to assess the vitality of digital platforms. (a) Number of domain names (DMU). It shows the users' traffic, for DMU is the unique identification of computers on the Internet. (b) Number of websites. It reflects the requirements of users, since network services are provided or obtained through the websites. (c) Number of netizens. It refers to the number of users using the Internet, which reflects the agglomeration degree of users.

• Digital Industry. The dimension assesses the vitality of related industries from the perspective of input and output. It comprises software and information technology service industry, Internet and service industry, telecommunications industry, and electronic information manufacturing industry (CAICT, 2021). But the data collection is hard, for the input-output table is compiled every five years. In *Industrial classification for national economic activities (GB/T 4754-2011)*, software and information technology services include telecommunications, radio, television and satellite transmission services, Internet and related services, and software and information technology services, which overlaps the definition of Digital Industry largely. Thus, the related indicators of it are chosen finally.

• Digital Innovation. It is an activity which aims to create value by using digital technology. The dimension assesses the vitality of digital innovation through the granted patents of 5G, Industrial Internet and E-commerce. (a) 5G is the 5th generation mobile network, which is meant to deliver higher multi-Gbps data speeds, more reliability, massive network capacity and ultra-low latency. (b) The Industrial Internet heavily depends on the adoption of digital technologies in traditional industries, which makes it has the potential to bring profound transformation to

traditional industries (Li, JQ et al). (c) E-commerce is often used to refer to the sale of physical products online, but it can also describe any kind of commercial transaction that is facilitated through the internet.

The four-level structure of DEI is depicted in Table 1. The digital economy index aggregated in this paper differs from the others. Firstly, indicators are selected accordingly based on the four requisite dimensions in digital economy measurement which are in line with previous studies, which ensures the reliability of the framework of the index. Secondly, it is more concrete. Take the digital innovation dimension as an example, the indicators selected in this paper show the innovative potential in digital technology by using the number of 5G industry, Industrial Internet and E-commerce patent granted while others mainly focus on the input and patent granted of R&D.

Table 1. DEI structure.

Target	Dimension	Indicator	Source
Digital Economy Index (DEI)	Digital Industry	Urban employment of Information transmission, Computer services, and software industry	Chinese National Bureau of Statistics
		Software revenues	
		Total Investment in Fixed Assets of Information transmission, Computer services, and software industry	EPS Database
	Digital Innovation	Number of 5G industry patents granted	CBDPS
		Number of Industrial Internet Patent granted	
		Number of E-commerce patent granted	
	Digital User	Mobile phone penetration rate	Chinese National Bureau of Statistics
		Total volume of telecommunication services	
		Number of Internet broadband users	
		Number of mobile Internet users	
	Digital Platform	Number of DMS	
		Number of websites	
		Number of netizens	

2.2 Method

Weighting is a process to measure the importance of indicators. Two major categories of weighting techniques used commonly are AHP and EWM. AHP considers a set of alternative options among which the best decision is to be made and generates a weight for each indicator through the decisions makers' pairwise comparisons according to a set of evaluation criteria. It is an effective tool for decision maker to set priorities and make the optimal decision. However, some inconsistencies may arise when many pairwise comparisons are performed, for when it involves large number of pairwise comparisons, to obtain consensus on experts' opinion is difficult and time consuming. Besides, it requires decision makers' experience and knowledge to weight indicators, which is quite subjective. Entropy is a measure of uncertain information. Entropy is inversely proportional to the amount of information. The smaller the entropy, the greater the amount of information and the weight. The weight can be calculated through the data itself, which could avoid the interference of human factors on the weights of indicators, thus

enhancing the objectivity of the comprehensive evaluation results (Zhu et al., 2020). The grey target method objectively reflects the interaction between the characteristic of each unit (Zhu and Hipel, 2012; Xu et al., 2017). It treats the optimal model of the existing models as the standard model according to the evaluation criteria when the standard model is unknown, takes comparisons of each model and standard model, and calculates values that can reflect the differences between them, in which the higher the value, the closer the model is to the standard mode. It aids to get the degree to which each indicator of models affects the corresponding indicator of standard model. And it evaluates and ranks model's indicator from the perspective of difference and growth between models' indicators and indicators of standard model, in which the value obtained is named by the bullseye coefficient. The bullseye degree is the average of all the bullseye coefficients, which can evaluate and rank each model. However, when the coefficients are aggregated, equal weight is commonly used, which is contradictory to the fact. Hence, to evaluate the digital economy development more effectively, this article employs the combination of the EWM and the grey target method.

To base digital economy index (DEI) on the entropy grey target method needs to work through the following process: (a) Data processing procedure. After retrieving data from samples of indicators, it is usually followed by missing data imputation. In this article, missing data are mostly filled by regression models. Once the complete data of indicators is achieved, an initial data matrix is constructed. (b) Weighting procedure. First, normalize the raw data. Normalization is a process of making data from samples of indicators comparable. Since indicators are typically measured in different units (e.g., kilometres, hectares), it is necessary to transform them into dimensionless units. Min-max normalization is a strategy commonly adopted, which puts all of the measures on the same scale of one to zero. The formula is given below:

$$z_{ij} = \frac{x_{ij} - \min x_{i\cdot}}{\max x_i - \min x_{i\cdot}} \tag{1}$$

where n samples and m indicators are set in the evaluation, and the data from samples of indicators of the jth indicator in the ith sample is recorded as x_{ij}. The standardized value of x_{ij} is denoted as z_{ij}. Second, calculate the information entropy of indicator j. The entropy e_j of the jth indicator is defined as follows:

$$e_j = \frac{-\sum_{i=1}^{n} p_{ij} \cdot ln p_{ij}}{\ln n} \tag{2}$$

where $p_{ij} \cdot ln p_{ij}$ is set as zero if p_{ij} is equal to zero and

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}}, i = 1,2,\cdots,n; j = 1,2,\cdots,m. \tag{3}$$

The range of e_j is $[0,1]$. The larger the e_j is, the greater the differentiation degree of indicator j is, and more information can be derived. Hence, higher weight should be given to the indicator. Third, compute the weight of indicator j. The calculation method of weight w_j is defined as follows:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m}(1 - e_j)}, j = 1,2,\cdots,m. \tag{4}$$

(c) Aggregation procedure. First, establish an influence space. That is to determine the evaluation objects and evaluation indicators. Second, sort the indicator sequence in chronological order. The value of x_{ij} in the kth period is recorded as $x_{ij}(t_k)$. Third, set the standard model. That is to build a series

of the optimum of each indicator, which is denoted as:

$$x_o = \{x_{o1}, x_{o2}, \cdots, x_{om}\} \tag{5}$$

where x_{oj} is the optimum of $x_{ij}(t_k)$ in the evaluation criteria. Fourth, perform grey target conversion. It means that the $x_{ij}(t_k)$ is compared with the X_{oj}, and the pattern sequence after the polarity change is obtained. The transformation is as follows:

$$T\left(x_{ij}(t_k)\right) = \frac{\min\{x_{ij}(t_k), x_{oj}\}}{\max\{x_{ij}(t_k), x_{oj}\}} \tag{6}$$

Fifth, build grey relational difference information space. That is to measure the information difference after the grey target conversion between the elements of indicator sequence and corresponding indicator of standard series. The space is denoted as:

$$\Delta = \{\Delta_{ij}(t_k)|, i = 1,2, \cdots, m; j = 1,2, \cdots, n; k = 1,2, \cdots, N\} \tag{7}$$

where

$$\Delta_{ij}(t_k) = \left|T(x_{oj}) - T\left(x_{ij}(t_k)\right)\right| \tag{8}$$

Sixth, calculate the bullseye coefficient. The calculation method of the bullseye coefficient is as follows:

$$\gamma(x_{oj}(t_k), x_{ij}(t_k)) = \frac{\Delta_{min} + \rho \cdot \Delta_{max}}{\Delta_{ij}(t_k) + \rho \cdot \Delta_{max}} \tag{9}$$

where Δ_{min} and Δ_{max} are the minimum and maximum of the Δ, and $\rho = 0.5$ is generally set. Finally, compute the bullseye degree. The function is written as:

$$\gamma(x_o, x_i)(t_k) = \sum_{j=1}^{m} w_j * \gamma(x_{oj}(t_k), x_{ij}(t_k)) \tag{10}$$

The whole process of constructing DEI is shown in Figure 1.

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┌─────────────────────────────┐
│      Select indicators      │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│       Preprocess data       │
└─────────────────────────────┘
       │              │
       ▼              ▼
┌──────────────┐  ┌──────────────────────┐
│Normalize raw │  │  Set the standard     │
│    data      │  │      model            │
└──────────────┘  └──────────────────────┘
       │              │
       ▼              ▼
┌──────────────┐  ┌──────────────────────┐
│calculate the │  │ Perform grey target   │
│entropy of    │  │    conversion         │
│indicators    │  │                       │
└──────────────┘  └──────────────────────┘
       │              │
       ▼              ▼
┌──────────────┐  ┌──────────────────────┐
│  Weighting   │  │Build grey relational  │
│  indicators  │  │difference information │
│              │  │      space            │
└──────────────┘  └──────────────────────┘
       │              │
       │              ▼
       │          ┌──────────────────────┐
       │          │Calculate the bullseye │
       │          │    coefficient        │
       │          └──────────────────────┘
       │              │
       └──────┬───────┘
              ▼
┌─────────────────────────────┐
│  Compute the bullseye degree│
└─────────────────────────────┘
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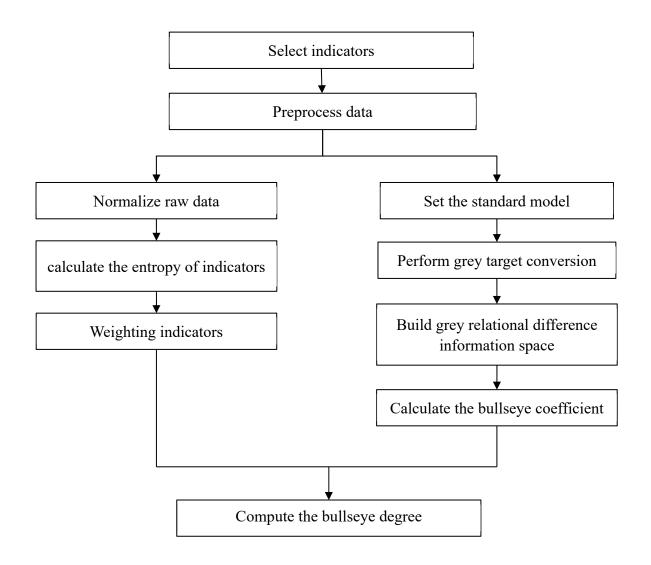
Figure 1. Flowchart of constructing (DEI).

In this article, the evaluation objects are 31 provinces (municipalities, autonomous regions, collectively referred to as "provinces") in China and the time span studied is from 2010 to 2020. The sample size is 330, in which the proportion of missing data is 14.25%. Adjacent-value imputation, the regression approach and the proportion imputation are applied for handling missing data. Adjacent-value imputation is a method in which missing items are replaced with the adjacent values. In regression method, the missing value for a targeted variable is estimated using the regression of the target variable on all other variables or a subset of all other variables. In proportion approach, the proportion is multiplied by the total amount of the target variable to impute the missing data when the total amount in the current period and proportion in adjacent period are known under the assumption that the proportion is constant. After the data processing procedure, the weights of the selected indicators based on the EWM are calculated, which are shown in Table 2.

Table 2. Weights attributed to the DEI dimensions and indicators.

Target	Level	Calculation method	Weight	
Digital Economy	Digital Industry	Urban employment of Information transmission, Computer services, and software industry	0.73	0.23
		Software revenues	0.16	
		Total Investment in Fixed Assets of Information transmission, Computer services, and software industry	0.11	
	Digital Innovation	Number of 5G industry patents granted	0.10	0.43
		Number of Industrial Internet Patent granted	0.19	
		Number of E-commerce patent granted	0.72	
	Digital User	Mobile phone penetration rate	0.41	0.15
		Business Total of Telecommunications Service	0.24	
		Number of Internet broadband access users	0.12	
		Number of mobile Internet users	0.23	
	Digital Platform	Number of DMS	0.60	0.19
		Number of websites	0.15	
		Number of netizens	0.24	

The conclusions are easily drawn based on Table 2. In the weighted result of the EWM, the weight of Digital Innovation is as high as 0.43, far more than any other dimensions. The other elements followed by Digital Innovation are Digital Industry, Digital Platform and Digital User.

3. Analysis

Using the entropy grey target method discussed above, the digital economy index for Chinese provinces is obtained. In addition to the overall index, subindexes for digital innovation, digital platforms and digital users are also compiled, which are attached in Appendix. This section features province profiles highlighting the digital economy developments in 31 provinces in China. Each profile includes an overview of overall index and subindexes, as well as the cluster analysis. The profiles seek to highlight the achievements by each index and help in identifying good practices as well as future improvements specific to each index.

3.1 Analysis of Digital Economy Index

This section provides an overview of some basic features of the Digital Economy Index (DEI) of Chinese autonomous regions in 2010–2020, to determine the dynamics of changes in index values. To measure the relative gap in DEI in a more scientific manner, the Sigma coefficient approach is used, which refers to the variation of the index between regions. A decrease in variation over time provides empirical evidences that Sigma convergence takes place. Specifically, the Sigma coefficient of the index in the t th period can be defined as follows:

$$\sigma_t = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}(\ln index_{it} - \frac{1}{n}\sum\nolimits_{i=1}^{n}\ln index_{it})^2} \tag{11}$$

where n provinces are set in this formula, and the logarithm value of the index of i th province in t th period is recorded as $\ln index_{it}$. If $\sigma_t < \sigma_{t-1}$, the index in the t th period is more convergent than it in $(t-1)$ th period.

Table 3. Statistical characters of DEI

Year	Max	Min	Mean	Median	Growth rate of median	Sigma convergence
2010	146.10	100.01	114.65	111.33		0.09
2011	148.14	100.00	115.27	111.12	−0.19	0.10
2012	156.35	100.50	118.08	114.33	2.69	0.11
2013	167.30	100.53	120.87	116.71	4.83	0.12
2014	174.40	100.84	122.99	118.23	6.20	0.13
2015	186.37	101.46	126.38	119.90	7.70	0.14
2016	194.96	101.04	128.73	120.16	7.93	0.16
2017	210.82	101.70	131.50	124.85	12.14	0.17
2018	238.80	104.11	136.40	126.05	13.22	0.18
2019	267.61	103.32	140.84	129.88	16.66	0.20
2020	233.84	103.81	137.79	129.35	16.19	0.18

The digital economy is steadily expanding throughout China, yet the regional imbalance in the digital economy level in China is increasing over time. As shown in Table 3, DEI in China shows a steady development from 2010 to 2020. The median of the provincial DEI was 111.33 in 2010, grew to 119.90 in 2015 and further rose to 129.35 in 2020. The median of the provincial DEI in 2020 was 1.16 times that of 2010, representing an average annual growth of 8.74%. In 2020, the growth rate of the median has a slight downward trend compared with 2019, which is mainly due to the new crown epidemic. From the above, the steady development trend of the digital economy in Chinese provinces can be observed. From the perspective of growth rate, it has an upsurge in 2017. It is mentioned before the entropy grey target method could identify the degree to which each factor of index affects, through which we can know the digital platforms and digital industries have a positive impact on this increase. It can be explained by three factors: a large and young Chinese market enabling the massive digitization of business models; a rich digital ecosystem expanding beyond a few giants; and the government allowing space for digital platforms to make investors and consumers participate in as much as possible (Woetzel et al, 2017). Firstly, in mobile payments, penetration among China's internet users has grown rapidly and the value of China's mobile payments related to consumption by individuals was 203 trillion yuan in 2017, up 28.8 percent, according to the People's Bank of China, which offers China powerful scale advantages to drive rapid commercialization of digital business models and the advantage of extremely enthusiastic digital natives who are eager to embrace digital in all its forms. Secondly, the rich ecosystem that was initially centered on the BAT companies, but that is now spreading and deepening. Well-capitalized BAT players are building multifaceted and multi-industry digital ecosystem that touches every aspect of consumers' lives, such as digitalization of traditional manufacturing industries, e-commerce, Yu'e Bao which offers higher interest rates to depositors and Didi Chuxing which offers a full range of app-based transportation and life services. Thirdly, government regulators provide support for China's burgeoning digital sector by facilitating investment in, and adoption of the latest technologies. Besides, the average DEI is always higher than

its median, which means DEI is in a right skewed distribution, namely average is affected by large outliers. The overall trend of the Sigma coefficients shows an upward trend from 2010 to 2019, indicating the digital economy disparity between regions has increased.

As mentioned above, digitalization is not happening equally, because imbalance exists. To specify which digital economy development level is each province in, K-Means Cluster Analysis could be used in classifying regions in terms of similarity of DEI values. Among the 31 regions in China, four clusters are distinguished. Results in Table 4 demonstrate the dynamic change of the clustering center of DEI. By ranking the DEI in each province from 2010 to 2020, it is found that the ranking almost remained the same, thus we decide to count the number of times of each region occurs in each category and use the maximal number to determine the category that provinces are in instead of showing the clustering results of each province annually. The results are summarized in Table 5.

Table 4. The clustering center of DEI in China's provinces.

Year	I	II	III	IV
2010	145.32	126.73	113.25	104.97
2011	147.29	129.52	113.14	104.66
2012	155.96	134.79	116.93	107.45
2013	164.29	141.59	117.52	106.78
2014	173.72	143.28	119.45	107.70
2015	184.08	147.92	126.04	112.24
2016	194.43	151.12	126.98	112.59
2017	203.87	155.98	129.42	113.90
2018	238.80	205.48	150.08	120.18
2019	267.61	213.40	156.51	122.09
2020	233.84	193.07	148.93	121.63

The clustering center of DEI maintains the upward trend in 2010-2019 and has a decline in 2020. Apparently, the higher the value, the higher the level of DEI. As shown in Table 4, the center values of all the groups show an increase in 2010–2019. The growth rate of the clustering center of group IV is lower than that of other groups. Center values of all the groups have a reduction in 2020 with the rate of decline in group I and group II is higher than that of group III and group IV. It is probably because the disease caused adverse consequences for the demand and supply chains of products and finance, which induced the greater negative effects on the regions with high digital economy development level given that resources tend to be agglomerated in these regions in large scale.

The spatial differentiation of Chinese digital economic development is obvious. The development level of the digital economy is decreasing from east to west at the provincial level. The regions of the first echelon, second echelon are eastern regions. All of them are high-income regions characterized by significant investment in emerging digital technologies and successful adoption of information and communications technologies by governments, businesses and individuals (Wang et al., 2018). However, some regions differ. Take Tianjin for example, which belongs to the eastern regions with quite rich resources. Its manufacturing industry has been ahead for years, but the digital transformation of it is insufficient still. It needs to take measures to support the digital technological innovation and promote the deep integration of digital technology and the industry.

Table 5. The clustering results of DEI in Chinese autonomous regions.

I	II	III	IV
Guangdong, Beijing	Shanghai, Jiangsu, Zhejiang, Shandong	Fujian, Sichuan, Henan, Hubei, Anhui, Hunan, Hebei, Liaoning, Shaanxi, Chongqing, Heilongjiang, Guangxi	Jiangxi, Yunnan, Tianjin, Shanxi, Jilin, Guizhou, Nei Mongol, Xinjiang Uygur, Gansu, Hainan, Ningxia Hui, Qinghai, Xizang

3.2 Analysis of Digital Platform Index

The numbers shown in Table 6 are the statistical characters of the Digital Platform Index (DP) of Chinese autonomous regions in 2010–2020. Table 7 and Table 8 are summarized by the clustering results of DP of Chinese autonomous regions in 2010–2020.

As shown in Table 6, overall speaking, the performance of DP shows steady progress. The median of DP has been growing. The median of the provincial DP was 132.54 in 2010, grew to 152.9 in 2015, and further rose to 169.62 in 2020. The median of the provincial DP in 2020 was 1.28 times that of 2010, representing an average annual growth of 2.53%. The maximum and minimum decreased in 2018 because of the "1618" domain-name fraud and the strengthened regulations which aim to reduce the risk of fraud and enhance the network security. Table 7 and Table 8 extends this analysis of DP development based on the clustering analysis. Table 7 presents the fluctuations of the clustering center of DP. The decline was recorded in 2011, 2014, 2016 and 2020. A primary driver of the DP is the domain name. Take 2011, 2014 for examples. The biggest domain name bug occurred in 2011. More than half of domain names in China were in a risky state to be attacked, which caused the losses far exceeding the registrations of domain names. As the rapid development of the Internet is accompanied by a number of mislead websites, which has a negative impact on the sustainable development of industry of domain names, the government authorities carry out some regulations to reduce the offensive websites in 2014. Besides, there has been a slight reduction in the Sigma convergence, which indicating the gap of DP has narrowed slightly. The regional gap of digital platforms in China has existed constantly due to the disequilibrium in economic and education resources. In recent years, China has been promoting the implementation of strategies of Internet penetration. With the implementation of the related policy, internet lower transaction costs and equal internet access to products seemingly increase the internet penetration rates. Digital platforms of some provinces with low base increase substantially in which the phenomenon is recognized as "low base effects", which reduces regional inequality. Table 8 indicates that the provinces with high DP value are mainly concentrated in the eastern and central regions. The regions of first echelon are eastern regions. Two eastern regions and five central regions are included in the second echelon of DP. The third echelon includes seven western regions. For example, Fujian is in the first echelon since, its per capita domain names has high ranking in China.

Table 6. Basic features of DP.

Year	Max	Min	Mean	Median	Growth rate of median	σ Convergence
2010	188.43	100	137.78	132.54		0.15
2011	187.64	100.69	137.52	132.37	−0.13	0.15
2012	205.86	100.78	142.38	136	2.74	0.17
2013	213.94	100.42	145.83	138.86	2.11	0.18
2014	217.77	100.96	150.68	147.87	6.49	0.17
2015	225.18	106.3	158.29	152.9	3.4	0.18
2016	230.41	102.73	162.03	155.07	1.42	0.19
2017	234.74	105.59	161.09	153.96	−0.71	0.19
2018	227.37	103.83	164.32	163.94	6.48	0.18
2019	237.68	106.87	172.15	171.37	4.53	0.18
2020	234.11	105.9	170.24	169.62	−1.02	0.18

Table 7. The clustering center of DP in China's provinces.

Year	I	II	III	IV
2010	178.83	153.21	128.46	107.18
2011	177.76	152.81	128.35	107.30
2012	204.05	162.49	136.79	115.95
2013	212.09	166.00	140.64	114.23
2014	204.96	166.21	141.13	110.89
2015	220.33	181.30	146.85	112.70
2016	218.62	179.47	146.38	112.44
2017	225.06	180.67	151.17	121.25
2018	222.55	180.84	151.45	117.03
2019	227.62	188.15	157.80	114.89
2020	209.37	179.75	152.07	115.15

Table 8. The clustering results of Digital Platform Index in China's provinces.

I	II	III	IV
Guangdong, Beijing, Fujian	Hebei, Shanghai, Jiangsu, Zhejiang, Shandong, Henan, Hubei, Hunan, Sichuan	Tianjin, Shanxi, Nei Mongol, Liaoning, Jilin, Heilongjiang, Anhui, Jiangxi, Guangxi, Hainan, Chongqing, Guizhou, Yunnan, Shaanxi, Xinjiang Uygur	Gansu, Ningxia Hui, Qinghai, Xizang

3.3 Analysis of Digital User Index

Table 9 presents the statistic characters of Digital User (DU), and, Table 10 and Table 11 are summarized by the cluster analysis of DU.

Table 9. The basic features of DU.

Year	Max	Min	Mean	Median	Growth rate of median	σ Convergence
2010	161.91	100.06	128.19	125.03		0.1
2011	157.1	100	126.41	123.67	−1.09	0.1
2012	165.63	103	129.87	125.94	0.73	0.1
2013	174.02	104.5	131.87	128.44	2.73	0.11
2014	196.23	106.67	134.7	129.59	3.65	0.12
2015	191.8	107.52	136.1	131.84	5.45	0.12
2016	186.89	104.73	135.99	132.33	5.84	0.12
2017	186.59	105.72	141.19	137.21	9.74	0.11
2018	200.91	110.3	149.33	145.13	16.08	0.12
2019	204.47	113.72	153.61	150.34	20.24	0.12
2020	197.53	114.33	155.63	153.96	23.14	0.11

Table 10. The clustering center of DU in China's provinces

Year	I	II	III	IV
2010	151.05	134.32	122.59	105.66
2011	151.88	135.25	121.39	105.87
2012	160.41	137.83	123.51	109.36
2013	171.05	147.99	127.62	108.64
2014	196.23	168.91	142.59	125.04
2015	191.80	160.35	132.51	112.73
2016	179.33	147.70	129.92	112.22
2017	178.15	149.53	133.71	111.83
2018	197.64	164.17	144.10	127.02
2019	200.83	170.68	147.11	123.44
2020	185.76	155.02	136.18	114.33

Table 11. The clustering results of DU in China's provinces.

I	II	III	IV
Guangdong, Beijing	Fujian, Zhejiang, Shandong, Jiangsu, Shanghai, Henan, Sichuan, Hebei	Hubei, Hunan, Anhui, Liaoning, Jiangxi, Guangxi, Shaanxi, Heilongjiang, Shanxi, Chongqing, Yunnan, Tianjin, Jilin, Guizhou, Hainan, Nei Mongol, Gansu, Xinjiang Uygur	Ningxia Hui, Qinghai, Xizang

Table 9 shows an upward trend in the performance of DU despite the fluctuations. The median has been increasing in general. The median of the provincial DU was 125.03 in 2010, grew to 131.84 in 2015, and further rose to 153.96 in 2020. The median of the provincial DU in 2020 was 1.23 times that of 2010, representing an average annual growth of 8.65%. It can be observed that the growth rate of median increased from 9.74% in 2017 to 16.08% in 2018. It is largely driven by the mobile phone penetration rate and total volume of telecommunication services. 4G network covered all the cities and villages nearly, which promotes the expansion of mobile phone users. Meanwhile, the

communications industry has implemented the policy of reducing fees actively. The comprehensive price index fell by 56.7% and the average mobile traffic charges are less than ten yuan per GB. Table 10 shows the decline of the clustering center of DU in 2015 and 2020. The possible reason for decline in 2015 could be the reduction of the volume of traditional telecommunication services, since the network environment is getting better and better, which has prompted many users to use 4G. The drop in 2020 can be explained by the following reasons probably. First, China's mobile phone penetration rate has reached a high level, which means the incremental space is limited. In 2020, the penetration rate of mobile phone users in China reached 113.9 households per 100 people, much higher than the global average mobile phone penetration rate of 102.94 households per 100 people. Second, the causes of decreasing probably lie in the boost of internet speed and fee reduction, which accelerates the coverage of 5G. At present, the number of 5G users in China has reached 450 million, according to the Ministry of Industry and Information Technology. The unit-price of 5G traffic has dropped to 4.4 yuan per GB, which meets the needs of many users. So many dual-SIM users become single-SIM users. Table 11 indicates the decreasing trend from east to west in China. The regions of first echelon are eastern regions. Six eastern regions and one central region are included in the second echelon of DP. The third echelon includes eight western regions and five central regions.

3.4 Analysis of Digital Innovation Index

Table 12 shows the statistic characters of the Digital Innovation Index (DINV), and, Table 13 and Table 14 are summarized based on the cluster analysis of DINV.

Table 12. The basic features of DINV.

Year	Max	Min	Mean	Median	Growth rate of median	Sigma Convergence
2010	170.7	100	117.37	112.69		0.14
2011	177.28	100	120.61	113.51	0.73	0.16
2012	184.2	100.41	126.9	117.73	4.47	0.17
2013	189.89	100.66	129.87	120.27	6.73	0.17
2014	198	100.41	132.21	124.18	10.20	0.18
2015	213.38	100	138.68	127.83	13.44	0.19
2016	233.91	101.13	142.77	131.31	16.52	0.22
2017	263.54	103.32	149	136.54	21.16	0.23
2018	283.06	108.83	157.98	147.22	30.64	0.23
2019	299.82	107.45	160.27	145.88	29.45	0.25
2020	262.3	110.25	150.78	136.66	21.27	0.22

Table 12 shows an upward trend in the performance of DINV in 2010–2019. The median of the provincial DINV was 112.69 in 2010, grew to 127.83 in 2015, and further rose to 136.66 in 2020. The median of the provincial DINV in 2020 was 1.21 times that of 2010, representing an average annual growth of 10.86%. It can be observed that the growth rate of median increased from 21.16% in 2017 to 30.64% in 2018, which was up by 9.48%. It was mainly because of the implementation of the innovation-driven development strategy. It based on the present situations and looking forward, strengthened the deployments in key fields of emerging industries, which provides quite great support

for innovation and accelerates the innovation. The China Innovation Index compiled by the Chinese National Bureau of Statistics exceeded 200 for the first time in 2018, reaching an increase of 8.6% over the previous year which is the highest value since the calculation. In terms of Global Innovation Index released jointly by WIPO, Cornell University (2018) and other organizations to help global decision makers better understand how to stimulate the innovative activity, China broke into the world's top 20 most-innovative economies with the number 17 ranking in 2018. As shown in Table 13, the clustering center decreased in 2014 except the first echelon. The possible reason may be the plunge of real estate price, which leads to the depreciated wealth, bad debts and the growth of financial risks, but the regions in the first echelon are economically developed regions, tend to be more capable of guarding against financial risks than other regions (Selahattin et al., 2021). Center values of all the groups have a reduction in 2020 with the rate of decline in group I and group II are higher than that of group III and group IV. Table 14 indicates the positive correlation between digital innovation and economic development. The regions of first echelon are eastern regions, partially due to the sheer scale of China' internet user base and rich resources which encourages continuous digital experimentation, facilitates rapid adoption of digital technique and promotes the digital innovation (Abrell et al., 2016). Three eastern regions and one central region are included in the second echelon of DINV. Western regions mainly concentrated in the third echelon and the fourth echelon. Take Anhui for an example, it belongs to the second echelon. At present, important progress has been made in the construction of the digital innovation in Anhui. The Hefei Digital Economy Innovation and Development Pilot Zone (hereinafter referred to as "Pilot Zone") which strives to make the Pilot Zone a national one and build a high-standard Big Data Center has accelerated the institutional innovation and technological innovation.

Table 13. The clustering center of DINV in China's provinces.

Year	I	II	III	IV
2010	168.79	143.70	121.21	108.40
2011	171.99	151.05	115.20	105.18
2012	179.48	157.98	129.29	109.88
2013	184.79	167.40	131.39	112.77
2014	185.54	156.18	123.50	107.49
2015	200.34	164.92	131.73	112.78
2016	212.26	173.61	144.96	116.76
2017	263.54	194.89	148.05	117.45
2018	283.06	211.80	159.18	128.88
2019	299.82	221.02	172.56	130.86
2020	246.78	190.52	147.15	124.02

Table 14. The clustering results of DINV in China's provinces.

I	II	III	IV
Guangdong, Beijing, Shanghai	Zhejiang, Shandong, Jiangsu, Anhui	Fujian, Henan, Sichuan, Hubei, Hunan, Guangxi, Shaanxi, Chongqing, Guizhou	Hebei, Liaoning, Jiangxi, Heilongjiang, Shanxi, Yunnan, Tianjin, Jilin, Hainan, Nei Mongol, Gansu, Xinjiang Uygur, Ningxia Hui, Qinghai, Xizang

3.5 Analysis of Digital Industry Index

Table 15 shows the statistic characters of the Digital Industry Index (DIND), and, Table 16 and Table 17 are summarized based on the cluster analysis of DIND.

Table 15. The basic features of DIND.

Year	Max	Min	Mean	Median	Growth rate of median	Sigma Convergence
2010	212.28	100.81	138	137.5		0.16
2011	221.04	100	140.47	139.74	1.63	0.17
2012	227.55	101.35	142.54	139.68	1.59	0.17
2013	235.06	100.29	150.99	146.18	6.31	0.19
2014	238.32	101.1	152.98	149.98	9.08	0.2
2015	247.71	101.92	155.57	151.37	10.09	0.2
2016	248.6	102.7	157.26	152.14	10.65	0.2
2017	259.86	102.44	159.53	155.62	13.18	0.21
2018	267.48	102.68	161.21	154.85	12.62	0.22
2019	270.3	102.99	163.35	156.1	13.53	0.22
2020	277.96	104.31	165.15	157.78	14.75	0.23

Table 15 shows a steady development in the performance of DIND in 2010–2020. The median of the provincial DIND was 137.5 in 2010, grew to 151.37 in 2015, and further rose to 157.78 in 2020. The median of the provincial DIND in 2020 was 1.15 times that of 2010, representing an average annual growth of 9.34%. Meanwhile, the provincial imbalance of the digital industries in China is increasing over time. Digital inequalities have been existing for a long time because not all are equal in terms of access to network or connected devices, or when it comes to the skills to navigate computerized space optimally. The digital plays a leading role in the fight against coronavirus and accelerates the digital industrialization and industrial digitalization (Golinelli et al., 2020). However, not every individual can be able to grasp chances to develop digital technologies which broaden the gap of digital industries (Beaunoyer et al., 2020). Table 16 shows a reduction in the clustering center of DIND in 2016. The stock market collapse in 2015 and the overvaluation of the internet industries may lead to the decline. Table 17 shows a decreasing trend from the east to the west in China. The regions of first echelon are eastern regions and four eastern regions in the second echelon. Liaoning, which is in the northeast China and not the traditional economically developed regions, belongs to the second echelon. Driven by a series of digital strategies, significant progress has been made in digital industrialization and industrial digitalization. Liaoning, Beijing and Shanghai constitute the three key areas of Integrated Device Electronics (IDE) in China. Liaoning accounted for 4.6% of the national total volume of IDE in 2020. The income of the software and information technology services has reached 185.7 billion yuan, with an average annual growth rate of more than 10% during the 13th Five-Year Plan period. The digital penetration rate in the above-scale enterprises up to 75% and the CNC rate of key processes has reached 51.8%. 48 projects were selected as a national pilot demonstration in the field of industrialization and information technology.

Table 16. The clustering center of DIND in China's provinces.

Year	I	II	III	IV
2010	212.28	162.41	136.78	109.12
2011	221.04	164.41	138.93	112.19
2012	227.55	167.64	140.96	112.71
2013	216.86	175.62	143.48	106.50
2014	219.85	179.02	148.12	116.84
2015	247.71	194.40	153.37	123.11
2016	237.93	178.94	144.04	112.33
2017	247.93	195.70	159.01	127.63
2018	257.99	197.58	158.84	127.00
2019	262.52	200.56	161.02	128.17
2020	270.74	205.00	161.74	128.89

Table 17. The clustering results of DIND in China's provinces.

I	II	III	IV
Guangdong, Beijing	Zhejiang, Shandong, Jiangsu, Shanghai, Sichuan, Liaoning	Shaanxi, Hubei, Fujian, Henan, Hunan, Hebei, Anhui, Heilongjiang, Jilin, Tianjin, Chongqing, Jiangxi, Guangxi, Yunnan, Nei Mongol, Shanxi	Guizhou, Hainan, Gansu, Xinjiang Uygur, Ningxia Hui, Qinghai, Xizang

4. Conclusions

The objective of this paper is to measure the digital economy for 31 provinces in mainland China, over the period 2010 to 2020. First, to compile this index, we have referred to the existing literature on the digital economy. After the theoretical foundation, we compiled the digital economy index from the four dimensions of digital users, digital platforms, digital industries and digital innovation. Then, we compared the aggregation methods and selected the entropy grey target theory which is established based on EWM and grey target method. Use the dynamic evaluation method based on grey target to evaluate the level of each indicator, and use the entropy weight method to measure the weight of each dimension. Finally, we analyze the overall and clustering characteristics of urban digital finance. The main conclusions drawn from this analysis are as follows.

First, the digital economy is steadily expanding throughout China with increasing disparity. The development level is decreasing from east to west in China, for eastern regions tend to adopt advanced digital technologies effectively. There is a drop in 2020 which possibly caused by the COVID-19. The rate of decline in some economically developed regions which resources tend to be agglomerated in is higher than economically backward regions, because the epidemic has severely disrupted the demand and supply chains of products and finance.

Second, overall speaking, the performance of digital platforms shows steady progress. The Domain Name is the important contributor of fluctuations in DP. The decrease of DP in 2018 may be caused by the "1618" domain-name fraud and the strengthened regulations which aim to reduce the

risk of fraud and enhance the network security. There also exists a regional imbalance. Regions with high DP are mainly concentrated in the eastern and central regions. Besides, the gap of DP has narrowed slightly.

Third, the upward trend is shown in the performance of DU despite the fluctuations. It is largely driven by the mobile phone penetration rate and total volume of telecommunication services. The network environment is getting better and better, internet lower transaction costs and equal internet access to products, which seemingly increases the internet penetration rates. And it also indicates the decreasing trend from east to west in China.

Fourth, DINV shows an upward trend in 2010–2019. The geographical distribution of digital innovation appears to be influenced by the socioeconomic landscape, with more developed regions usually generating relatively more innovations. However, China is taking steps to channel more digital resources from its developed regions to its less developed regions, which gives them the potential to nurture the development of digital techniques and improve the overall innovative capacity.

Fifth, a steady development of DIND is shown in 2010–2020. It shows a decreasing trend from the east to the west in China and the provincial imbalance of the digital industries in China is increasing over time. Despite of this, some less developed regions perform well in digital industries with the help of supportive policies. For example, significant progress of digital industrialization and industrial digitalization in Liaoning has been made.

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Conflict of interest

The authors declare no conflict of interest.

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