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Analysis of Coupling Coordination Degree of Digital Economy Industry Synergistic Development—Empirical Evidence Based on Urban Agglomerations in the Northern Region of China

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ABSTRACT

With the rise of the national strategic position of Beijing-Tianjin-Hebei city cluster, Central Plains city cluster and Shandong Peninsula city cluster, inter-city cluster collaboration has become particularly important, and scientific evaluation of the level of digital economy industry synergistic development of major northern city clusters is conducive to cracking the dilemma of industrial synergy of major northern city clusters, and forming the pattern of high-quality integrated development. The data related to digital infrastructure, digital industrialization and industrial digitization of the Beijing-Tianjin-Hebei city cluster, the Central Plains city cluster and the Shandong Peninsula city cluster from 2013 to 2021 are selected, and the coupled synergy model is applied to evaluate the level of collaborative development of digital economy industries in major northern city clusters based on the analysis of digital economy industry development in major northern city clusters. The study found that: the coupling and coordination degree of digital economy industry of the three major northern city clusters from 2013 to 2021 has been improving, and the digital economy industry of the Beijing-Tianjin-Hebei city cluster will reach the intermediate level of coordination in 2021; in terms of the spatial synergy of the digital economy industry of the three city clusters, the synergy of the digital economy industry among the three clusters has reached the level of just barely dislocation, but the degree of industrial digitization synergy among the three clusters has obviously lags behind the level of digital infrastructure synergy and industrial digitalization synergy. Based on this, it puts forward countermeasures and suggestions to accelerate the top-level design of digital economy industry synergistic development in the major northern city clusters and to establish institutional mechanisms to support the synergistic development of digital economy industry in the cities.

KEYWORDS

Major northern urban agglomerations; Digital economy; industrial synergy; Development level evaluation

1. INTRODUCTION

Since the 18th National Congress of the Communist Party of China (CPC), the CPC Central Committee has attached great importance to the development of the digital economy and elevated the development of the digital economy to a national strategy. "The Fourteenth Five-Year Plan and the Government's work report for 2022 have made the digital economy an important engine for economic development. City clusters are an important carrier for the development of digital economy, which will have a profound impact on the inner economic links, industrial layout, spatial structure, technological advancement and factor concentration level of city clusters, etc. On February 26, 2014, Xi Jinping, General Secretary of the CPC Central Committee, listened to the report on the coordinated development of Beijing-Tianjin-Hebei, and since then the integration of Beijing-Tianjin-Hebei has

been brought up to the level of a national strategy; and the "Outline Plan for Ecological Protection and High-Quality Development of the Yellow River Basin" of 2021 will be adopted as a national strategy. The Outline of the Plan for Ecological Protection and High-Quality Development of the Yellow River Basin in 2021 elevated the city clusters of the Central Plains and the Shandong Peninsula, which are located in the Yellow River Basin, to the same status as the Beijing-Tianjin-Hebei city clusters as a national strategy. In addition, since the concept of city clusters has entered the policy vision of China's regional economic development, rational industrial division of labor, innovation and collaboration, and integrated development have been regarded as the basic guideline for the construction of city clusters, and industrial synergy is a prerequisite for the integration and synergistic development of city clusters. Industrial synergy of city cluster refers to the dynamic process of utilizing resources within the city cluster to establish industrial links, form industrial chain and value chain, and promote healthy competition and coordinated regional development of city cluster industries. In the context of China's major city clusters in the north - Beijing-Tianjin-Hebei City Cluster, Central Plains City Cluster and Shandong Peninsula City Cluster - the three major city clusters are in the context of the national strategy for the development of the three major city clusters, at present, the level of integration of the major city clusters in the north is not yet high, and there still exist problems such as obvious homogenization of industries, unsound collaboration mechanism, and high barriers between the city clusters. The key to promoting the integration of major northern city clusters to break through lies in industrial synergy. At the same time, in the era of digital economy, digital economy is a new engine to drive the accelerated development of major northern city clusters, and the synergistic development of digital economy industry injects new kinetic energy into the integration of major northern city clusters. The northern major city cluster must seize the time window of digital economy change to promote the high-quality integrated development of the northern major city cluster with digital economy industry synergy. Therefore, this paper will evaluate the level of collaborative development of digital economy industry in major northern city clusters, which will help clarify the current situation of collaborative development of digital economy industry in major northern city clusters, and provide precise policy basis for further promoting the collaborative development of digital economy industry in major northern city clusters. On the basis of combing relevant literature, this paper calculates the digital infrastructure development index, digital industrialization development index, industrial digitalization development index and digital economy industry comprehensive development index by constructing an evaluation system and using relevant data, and analyzes the synergistic development within and among the three major city clusters by applying the coupling coordination degree model, and then summarizes the main conclusions of this paper and gives the corresponding policy recommendations. Finally, the main conclusions of this paper are summarized and corresponding policy recommendations are given.

2. LITERATURE REVIEW

The literature on the development of the digital economy industry in city clusters focuses on the exploration of the intrinsic mechanism, which is divided into three main categories.

First, research on the development of digital economy industry in city clusters. The current academic research on digital economy industry of city cluster focuses on the impact of digital economy on the development of city cluster and the evaluation of digital economy industry development of city cluster. In terms of the impact of digital economy on the development of city cluster, foreign scholars generally believe that the digital economy has significant positive investment effects, spillover effects and network externalities on city cluster (Kenneth, 2000; Ellison et al., 2010); domestic scholars have found that the digital economy strengthens the spatial economic linkages of city cluster, promotes the development of industry in the city cluster and the spatial layout of industry, improve the economic efficiency of city clusters, and have positive spillover effects on regional economic growth (Liu Shenglong et al., 2010). In the evaluation of digital economy and industrial development of city clusters, due to the complexity of the digital economy system, there is not yet a unified or common

standard in the academic world about the evaluation standard of the level of digital economy development. Liu Chuanhui et al. (2010) assessed the level of digital economy development and the level of digital economy development of the six city clusters of the Yangtze River Delta, Beijing-Tianjin-Hebei, Pearl River Delta, Central Plains, Chengdu-Chongqing, and Guanzhong Plains through the construction of the digital economy index system. city clusters' digital economy development level and spatio-temporal characteristics; Guo Bingnan et al. (2022) examined the digital economy development level, regional differences, distribution dynamics and convergence of China's top ten city clusters by using entropy method, Dagum's Gini coefficient and kernel density estimation and coefficient of variation.

Second, research on the synergistic development of digital economy industries in city clusters. Academic research on the synergistic development of digital economy industries in city clusters is still in its infancy. Chen Yuefei et al. (2021) studied the synergistic problem of the internal structure of China's digital economy, measured the degree of synergistic development of the internal structure of China's digital economy through the construction of the coupled coordination degree model of digital industrialization, industrial digitization and digital governance, and found that the overall structure of the internal structure of China's digital economy has reached the degree of high-quality coordination, but the green level of China's digital industrialization, the level of innovation in the digitalization of industry and green level are yet to be further improved, and the benefits of digital governance are not yet obvious. Liu Vanadium et al. (2021) studied the internal mechanism of the coupling development between digital industrialization and industrial digitization, and measured and assessed the level of digital industrialization and the degree of coupling and coordination between industrial digitization of 11 provinces (municipalities) in the Yangtze River Economic Belt from 2013 to 2018. Huihui Deng et al. (2022) empirically examined the impact of digital economy development on the synergistic development of the three major city clusters of Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta from the perspective of the relationship between the digital economy and the synergistic development of city clusters by using a spatial Durbin model of global nighttime light data and a panel instrumental variable model, and found that the digital economy is conducive to promoting the formation of synergistic innovation networks in city clusters, and is beneficial to the agglomeration of neighboring cities' production elements and increase the spatial concentration of cities.

In addition, there is also some literature on industrial synergy in Beijing-Tianjin-Hebei city cluster, Central Plains city cluster and Shandong Peninsula city cluster, and the research on industrial synergy in major northern city clusters focuses on industrial synergy problems, influencing factors and practical paths. Yang Daoling (2022) and others found that for industrial synergy in the Beijing-Tianjin-Hebei city cluster, the government's willingness, especially the central government's willingness, is strong, and the people's willingness is high, but the market demand needs to be further stimulated, and there are differences in the basic security and the supporting measures need to be improved. Sun Ning (2023) argues that the way to promote the development of the Shandong Peninsula city cluster is to improve the specialization of urban industry clusters, enhance the integrity of each metropolitan area, and promote the synergistic development of each metropolitan area. Zhai Muyang (2023), based on the basis of cooperation foundation, cooperation mechanism, cooperation field and cooperation framework, suggests that rebuilding the image of a strong agricultural province, strengthening exchanges and cooperation with neighboring urban agglomerations, and reinforcing infrastructure construction can help the future development of Central Plains Urban Agglomeration.

In summary, the existing literature has carried out useful explorations in the development of digital economy industry in urban agglomerations and industrial synergy in major northern urban agglomerations, but in the field of digital economy research, the attention paid to the regional scope of major northern urban agglomerations is obviously insufficient, and few researches have included the major northern urban agglomerations, the digital economy, and industrial synergy into the overall analytical framework, and carried out a systematic research on the synergistic development of digital

economy industries in the major northern urban agglomerations. In particular, there is a lack of scientific assessment of the level of digital economy industrial synergy in major northern city clusters using empirical methods.

3. EVALUATION INDICATORS AND MODELING

3.1. Evaluation indicators and methodology

To scientifically assess the level of synergistic development of the digital economy industry in major northern city clusters, it is necessary to comprehensively map out the basic situation of the development of the digital economy industry in major northern city clusters. In accordance with the connotation of digital economy, drawing on the "2021 Report on the Development of Digital Economy in Chinese Cities" published by China Academy of Information and Communication Research, "2020 China Digital Economy Development Index (DEDI)" published by Saidi Research Institute, etc., and combining with the research results of other scholars (Kang Tiexiang, 2008; Xu Xianchun, et al. 2020; Liu Xinzhi, et al. 2021), this paper selects three first-level indicators to evaluate the development of the digital economy industry in major northern cities, namely, digital infrastructure, digital industrialization and industrial digitization. , digital industrialization, and industrial digitization as three first-level indicators to evaluate the level of digital economy industry development in major northern urban agglomerations. In order to eliminate the large size of some evaluation indicators due to the large land area or population base of some regions, which causes the index to be high when measuring, this paper adopts the ratio indicator for each level 2 indicator.

Digital infrastructure is the basis for ensuring the operation and development of the digital economy industry, which mainly includes the length of long-distance optical cable lines per square kilometer, the capacity of mobile telephone exchanges per square kilometer, the penetration rate of mobile telephones, Internet broadband access ports per 100 people and Internet broadband access users per 100 people. Digital industrialization and industrial digitization are the "double direction" of digital economy, in which digital industrialization is mainly reflected by the per capita software business income, per capita technology market turnover and the number of employees in information transmission, software and information technology service industry; industrial digitization is mainly reflected by the number of computers used by enterprises per 100 people, the number of websites owned by enterprises per 100 people, and the proportion of enterprises in e-commerce trading activities. The digitalization of industry is mainly reflected by the number of computers used by enterprises per 100 people, the number of websites per 100 enterprises, the proportion of enterprises with e-commerce trading activities, the ratio of e-commerce sales to GDP, the ratio of e-commerce purchases to GDP, the full-time equivalents of R&D personnel of industrial enterprises above the large-scale enterprises per 100 people and the ratio of R&D expenditures of industrial enterprises above the large-scale enterprises to GDP, and the construction of the indicators is shown in Table 1.

Table 1. Indicator construction and data sources

Level 1 indicators	Secondary indicators	Data sources
digital infrastructure	Length of long-distance fiber-optic cable lines per square kilometer	China Statistical Yearbook
	Mobile telephone exchange capacity per square kilometer	China Statistical Yearbook

	Cell phone penetration rate	China Statistical Yearbook
	Internet broadband access ports per 100 population	China Statistical Yearbook
	Internet broadband access users per 100 population	China Statistical Yearbook
digital industrialization	Software business income per capita	China Statistical Yearbook
	Technology market turnover per capita	China Statistical Yearbook
	Information transmission, software and information technology	
Number of persons employed in services" Industrial Digitization	China Statistical Yearbook	
	Computers per 100 persons in enterprises	China Statistical Yearbook
	Websites per 100 businesses	China Statistical Yearbook
	Share of enterprises in e-commerce trading activities	China Statistical Yearbook
	E-commerce sales to GDP ratio	China Statistical Yearbook
	Ratio of e-commerce purchases to GDP	China Statistical Yearbook
	Full-time equivalent of R&D personnel per 100 persons of industrial enterprises above designated size	China Science and Technology Statistical Yearbook

The northern city clusters selected for this paper are the three relatively large ones: the Beijing-Tianjin-Hebei City Cluster, the Central Plains City Cluster and the Shandong Peninsula City Cluster, and this paper will examine the degree of synergy of their digital economy industries. Since the Beijing-Tianjin-Hebei City Cluster, the Central Plains City Cluster and the Shandong Peninsula City Cluster cover most of the cities in Beijing, Tianjin, Hebei, Henan and Shandong, the Beijing Municipality, Tianjin Municipality, Hebei Province and Shandong Province have been selected in view of the availability of data, Given the availability of data, data related to digital infrastructure construction, digital industrialization and industrial digitization in Beijing, Tianjin, Hebei Province, Henan Province and Shandong Province are selected for analysis, and the time span of the study is 2013-2021, and the data for the indicators are obtained from the China Statistical Yearbook and the China Science and Technology Statistical Yearbook for the years 2014-2022.

Evaluating the digital infrastructure development, digital industrialization development, industrial digitalization development and comprehensive development of digital economy industry in major northern urban agglomerations requires not only the establishment of accessible specific indicators, but also the assignment of weights to each relevant evaluation indicator. Generally speaking, the existing empowerment methods mainly include subjective empowerment method and objective empowerment method. The subjective empowerment method is to artificially assign the relative importance of each indicator through one's own subjective experience, which cannot eliminate the subjective and artificial bias (Wang Jun et al., 2021). Objective assignment method mainly includes cluster analysis method, standard deviation method, entropy value method and extreme deviation method, etc., which is based on the original information of each indicator. In order to avoid the inaccuracy of the assessment value caused by subjective assignment, this paper adopts the entropy value method in the objective assignment method to assign the indicators (Jiang Lei et al., 2017) in an attempt to ensure that the assessment of the level of synergistic development of the digital economy industry in the major northern urban agglomerations is more scientific and reasonable.

When the entropy value method is used for the evaluation of comprehensive indicators, the inconsistency of the units of the indicators and the large difference in values will lead to bias in the measurement results, in order to overcome this measurement bias, this paper refers to Gao Nan et al. (2012) who used the improved entropy value method to determine the weights of each evaluation indicator of the level of digital economic development of the major northern urban agglomerations. In this paper, the evaluation indicators of the level of collaborative development of digital economy industry in the major northern urban agglomerations are all positive indicators, so the polar deviation method is used to normalize the data of each measurement indicator.x_ij Therefore, the polar deviation method is used to quantize the data of each measurement index, so that the indicators are horizontally comparable and practical, in order to ensure the accuracy of the final index measurement. The dimensionless processing formula is as follows:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_{j)} - \min(x_{j)}} \tag{1}$$

In order to avoid the zero value of the indicator after the dimensionless index and lead to the meaninglessness when taking the logarithm, resulting in the incompleteness of the data, therefore, the indicator is non-negative, and the processing formula is as follows:

$$y'_{ij} = x'_{ij} + 0.0001 \tag{2}$$

Then the weights of each secondary evaluation index are calculated by entropy methodw_j Weightw_j reflects the contribution and satisfaction degree of each secondary evaluation index to the established goal, 0≤w_j ≤1.w_j The closer to 1, the higher the degree of contribution and satisfaction of the second-level index, and the closer to 0, the higher the degree of contribution and satisfaction of the second-level index.w_j The closer to 0, the lower the contribution and satisfaction of the second-level indicator.

Calculate each indicator of the level of digital economy industry development in major northern city groups based on weights:

$$S_I = \sum_{j=1}^{n} y'_{ij} \times w_j \tag{3}$$

The above formula calculates the indices of the development level of the digital economy industry in the major northern urban agglomerations, with a value range of [0,1].S_i The larger it is, the higher the development level is; on the contrary, theS_i The smaller, the lower the level of development.

3.2. Coupled harmonization model

This paper adopts the capacity coupling theory and model of physics to measure the level of synergistic development of digital economy and industry in major northern urban agglomerations, i.e., to measure the degree of coupling between digital infrastructure, digital industrialization and industrial digitization of the major northern city clusters, and the coupling degree between the three can reflect the interactions and influences among digital infrastructure, digital industrialization and industrial digitization of the major northern urban agglomerations and city clusters . Referring to the treatment of Miao Long et al. (2021), the coupling degree function is constructed as follows:

$$C = \left[\frac{\prod_1^n S_n}{\left(\frac{\sum_1^n S_n}{n} \right)^n} \right]^{\frac{1}{n}} \tag{4}$$

Where C is the coupling index, the value range is [0,1], the larger C indicates that the coupling role is stronger. When measuring the coupling degree between digital infrastructure, digital industrialization and industrial digitization within the major city clusters in the north, C is the kth level composite index of each city cluster.S_k is the kth level composite indicator of each city cluster; when measuring the coupling between digital infrastructure, digital industrialization, industrial digitization or digital economy industry development among major northern city clusters, theS_k is the kth city cluster's digital infrastructure development index, digital industrialization development index, industry digitization development index or digital economy industry comprehensive development index.

The coupling degree reflects the coupling degree of digital economy industry synergistic development of major northern city cluster, but it cannot reflect the actual development level, while the coupling coordination degree can reflect the degree of industry synergy of city cluster more scientifically. Therefore, the coupling coordination degree model is applied to assess the coupling coordination degree of digital economy industry development in major northern city clusters (Ma Li et al., 2012), and the coupling coordination degree function is constructed with reference to the treatment of Han Zhao'an et al. (2022) as follows:

$$D = \sqrt{C \times T} \tag{5}$$

$$T = \beta_1 S_1 + \beta_2 S_2 + \cdots \beta_n S_n \tag{6}$$

where T is the comprehensive reconciliation index of digital economy development of city cluster, and β_k is the contribution share, generally taken as $\beta_1 = \beta_2 = \cdots \beta_n = \frac{1}{n}$, D is the coupling coordination index, the value range is [0,1].

Referring to the study of Wang Shujia et al. (2021), the coupling coordination degree is divided into 10 levels, and the division criteria are shown in Table 2:

Table 2. Coupling Coordination Degree Classification Levels and Classification Criteria

Interval of values of coupling coordination degree	level of cooperation	Degree of coupling coordination
0.0≤D<0.1	1	extreme disorder
0.1≤D<0.2	2	severe disorder
0.2≤D<0.3	3	moderate disorder
0.3≤D<0.4	4	on the verge of becoming dysfunctional
0.4≤D<0.5	5	barely in tune
0.5≤D<0.6	6	sue for harmonization

0.6≤D<0.7	7	Primary coordination
0.7≤D<0.8	8	Intermediate level coordination
0.8≤D<0.9	9	good coordination
0.9≤D≤1.0	10	Quality coordination

4. SUMMARY

4.1. Comprehensive development level of the digital economy industry in major city clusters in the northern region

(1) Representing Beijing-Tianjin-Hebei - Shandong Peninsula, (2) Representing Beijing-Tianjin-Hebei - Central Plains, (3) Central Plains - Shandong Peninsula, (4) Beijing-Tianjin-Hebei - Central Plains - Shandong Peninsula.

Using equation (1) to (3), combined with the data related to the digital economy industry in the major northern urban agglomerations, the digital infrastructure development index, the digital industrialization development index, the industrial digitalization development index and the comprehensive development index of the digital economy industry are measured, and the results are shown in Table 3.

Table 3. Digital Economy Industry Development Index for Northern City Groups, 2013-2021

Sector		2013	2014	2015	2016	2017	2018	2019	2020	2021
Digital Infrastructure	(1)	0.508	0.553	0.577	0.736	0.790	0.702	0.752	0.788	0.822
	(2)	0.000	0.027	0.085	0.174	0.213	0.167	0.204	0.226	0.309
	(3)	0.104	0.150	0.207	0.333	0.402	0.285	0.331	0.355	0.303
Digital Industry	(1)	0.376	0.410	0.461	0.501	0.569	0.655	0.744	0.854	1.000
	(2)	0.000	0.001	0.007	0.010	0.014	0.016	0.031	0.043	0.053
	(3)	0.056	0.067	0.069	0.091	0.098	0.117	0.134	0.179	0.230
Digitalization Industry Digitalization	(1)	0.633	0.704	0.403	0.499	0.526	0.419	0.436	0.469	0.476
	(2)	0.011	0.028	0.037	0.128	0.124	0.051	0.047	0.055	0.060
	(3)	0.083	0.097	0.108	0.281	0.305	0.174	0.151	0.166	0.192
Digital Economy Comprehensive Development	(1)	0.583	0.642	0.539	0.640	0.698	0.673	0.737	0.815	0.899
	(2)	0.000	0.015	0.035	0.098	0.107	0.065	0.080	0.094	0.121
	(3)	0.084	0.107	0.126	0.244	0.274	0.198	0.207	0.242	0.267

For this table, (1) for Beijing-Tianjin-Hebei, (2) for Central Plains, (3) for Shandong Peninsula.

The above table lists the digital infrastructure development index, digital industrialization development index, industrial digitalization development index and digital economy industry comprehensive development index of the Beijing-Tianjin-Hebei city cluster, Central Plains city cluster and Shandong Peninsula city cluster from 2013 to 2021, and the following is also an analysis of the development of each city cluster from these four aspects.

First of all, it is analyzed from the perspective of digital infrastructure development and and industrialization of city clusters in the northern region.On the one hand, from the aspect of digital infrastructure development index, the development of digital infrastructure of major city clusters in the northern region during the period of 2013-2020 has shown an overall upward trend. Among them, the digital infrastructure of the Beijing-Tianjin-Hebei city cluster widens the gap with the other two city clusters and maintains the leading edge, followed by the Shandong Peninsula city cluster and the Central Plains city cluster; the development rate of the three major city clusters is basically in the same frequency.Starting from 2018, the digital infrastructure development index falls back slightly and rises slowly in the next few years.The digital infrastructure development index of the Central

Plains city cluster in 2021 is the same as that of the Shandong Peninsula city cluster in 2021. The digital infrastructure development index in 2021 is the same, indicating that the digital infrastructure development level of the Central Plains Urban Agglomeration basically catches up with that of the Shandong Peninsula Urban Agglomeration in 2021 (see Table 2 and Figure 1). In summary, the major northern city clusters except Beijing-Tianjin-Hebei should attach great importance to the construction and development of digital infrastructure in order to consolidate the digital economy industry built on top of it and lay a solid foundation for the future development of digital economy. On the other hand, in terms of the digital industrialization development index, the digital industrialization development index of major northern city clusters has been increasing from 2013 to 2021, but there are spatial differences in the level of digital industrialization development of major city clusters. Compared with the city cluster of Central Plains and the city cluster of Shandong Peninsula, the digital industrialization foundation of Beijing-Tianjin-Hebei city cluster has a greater advantage and has been developing at a faster rate, and the digital industrialization level of the Beijing-Tianjin-Hebei city cluster has been maintaining a leading position in the city cluster of the middle reaches of the Yangtze River.During the period from 2013 to 2020, the digital industrialization development index of the city cluster of Central Plains and the city cluster of Shandong Peninsula basically stays in the range of 0-0.2, and the digital industrialization development foundation is extremely weak, and the growth rate is extremely slow; especially in the Central Plains City Cluster, there was almost no improvement in the development of digital industrialization in 2013-2018, and this situation did not improve until the beginning of 2018. In addition, in 2021, the digital industrialization development index of Shandong Peninsula city cluster ushered in a small increase and exceeded 0.2. It can be seen that, although the development foundation and development rate of Shandong Peninsula city cluster and Central Plains city cluster are basically the same, with the passage of time, there is a trend of widening the gap between the digital industrialization level of Shandong Peninsula city cluster and Central Plains city cluster. In general, at present, there is a large gap between the digital industrialization level of the Central Plains Urban Agglomeration and the Shandong Peninsula Urban Agglomeration and the Beijing-Tianjin-Hebei Urban Agglomeration.

Secondly, the comprehensive development level of industrial digitization and digital economy is analyzed: on the one hand, from the point of view of the industrial digitization development index, the industrial digitization development of the major northern city clusters during the study period fluctuates greatly as a whole, and generally shows an upward trend. From the point of view of the development level, compared with the Central Plains City Cluster and Shandong Peninsula City Cluster, the level of industrial digitalization development in the Beijing-Tianjin-Hebei City Cluster is relatively high, especially in 2014, the level of industrial digitization in Beijing-Tianjin-Hebei reached the highest point during the study period, but the level fell sharply in 2015 and faced a low point, but began to show a slight upward trend in 2016 to break through the bottleneck and enter an upward channel. The industrial digitalization development base of Shandong Peninsula City Cluster is better than that of Central Plains City Cluster in every year, and the development of the two is almost in the same frequency; the industrial digitalization development level of the two city clusters is generally similar, but there is still a certain development gap when compared with that of Beijing-Tianjin-Hebei City Cluster. On the other hand, from the analysis of the comprehensive development index of digital economy industry, from the perspective of time, the overall level of digital economy industry development in the major northern city clusters shows a continuous upward trend; from the spatial point of view, the level of industrial digitization in the major northern city clusters has differences. In general, the overall level of digital economy development of the three major northern city clusters in the order from high to low is Beijing-Tianjin-Hebei City Cluster, Shandong Peninsula City Cluster and Central Plains City Cluster, with Beijing-Tianjin-Hebei City Cluster relatively leading in the overall level of digital economy industry development. By calculating the development growth rate of the digital economy industry in major northern city clusters, it can be seen that from 2013 to 2021, the average annual growth rate of the digital economy industry in the Beijing-Tianjin-Hebei City Cluster, Shandong Peninsula City Cluster and Central Plains City Cluster is 5.57%, 142.78%

and 15.45%, respectively, despite the fact that the development foundation of the digital economy industry in the Central Plains City Cluster is relatively weak, and the overall level of the development of the digital economy industry is comparable to that of the Beijing-Tianjin-Hebei City Cluster. Although the development foundation of digital economy industry in the Central Plains City Cluster is relatively weak and the overall development level of digital economy industry has a certain gap compared with that of the Beijing-Tianjin-Hebei City Cluster, the Central Plains City Cluster had a relatively fast growth rate during the study period.

The development of digital economy industry is a systematic project, and the internal structure of digital economy industry, i.e., the level of synergistic development among digital infrastructure, digital industrialization, and industrial digitization, has a crucial impact on the overall level of digital economy industry in the major northern urban agglomerations, therefore, the coupling and coordination degree of digital infrastructure, digital industrialization, and industrial digitization of major northern urban agglomerations is analyzed by applying Eqs. (4) to Eq. (6) to measure the coupling coordination degree of digital infrastructure, digital industrialization, and industrial digitization in the major northern urban agglomerations, and n in Eq. (4) and Eq. (6) is taken as 3.

As can be seen from Figure 1,the coupling coordination between digital infrastructure, digital industrialization and industrial digitization of the three major northern city clusters is generally increasing from 2013 to 2021, which indicates that the three major northern city clusters are paying more attention to the synergistic development within the digital economy industry. The Beijing-Tianjin-Hebei city cluster has the highest degree of coupled coordination among digital infrastructure, digital industrialization and industrial digitization during the study period, from 0.560 (barely coordinated) in 2013 to 0.782 (moderately coordinated) in 2021; followed by the Shandong Peninsula City Cluster, from 0.121 (severely dislocated) in 2013 to 0.304 (on the verge of being dislocated) in 2021; and finally the Central Plains City Cluster that goes from 0.003 (extremely dysfunctional) in 2013 to 0.164 (severely dysfunctional) in 2021. However, overall, except for the Beijing-Tianjin-Hebei city cluster, which is relatively well developed, the coupling coordination degree of the Shandong Peninsula city cluster and the Central Plains city cluster, although it has increased over the past few years, is still at a very low level, unable to reach the most basic degree of coordination. In addition, in 2018, the coupling coordination degree within the three major city clusters had a small decline, and then the Beijing-Tianjin-Hebei city cluster and the Central Plains city cluster recovered to the pre-decline level in 2019 and 2020, but the Shandong Peninsula city cluster has not recovered to the pre-decline level until 2021, so that the three major city clusters should focus on the speed of development, and at the same time need to pay more attention to the quality of development. At the same time, the average growth rate of each of the three major city clusters during the study period is not high, indicating that the development of internal coupling and coordination requires a large cost of time.

Similarly, equations (4) to (6) are applied to measure the coupling coordination degree of digital infrastructure, digital industrialization, industrial digitization and integrated development of digital economy industry among the Beijing-Tianjin-Hebei city cluster, the Central Plains city cluster and the Shandong Peninsula city cluster. When measuring the coupling coordination degree between two city clusters, n is taken as 2, and when measuring the coupling coordination degree between three city clusters, n is taken as 3. Based on this method, Table 4 is obtained; the following analysis is based on Table 4.

In terms of digital infrastructure development, the coupling and coordination degree of digital infrastructure among the three major northern city clusters generally improves from 2013 to 2021, and reaches a barely coordinated level in 2021. Among them, in 2021, the coupling and coordination degrees of the Beijing-Tianjin-Hebei city cluster and the Shandong Peninsula city cluster, and its coupling and coordination degree with the Central Plains city cluster are almost equal, indicating that the Beijing-Tianjin-Hebei city cluster has a relatively good coordinated development relationship with the other two major city clusters (see Table 4). As for the digital industry, the level of digital

industrialization coupling coordination degree between the major northern city clusters during the study period is generally improving, and the development trend is relatively close, the level of coupling coordination degree is steadily increasing before 2018, and the increase is larger after 2018, and the coupling coordination degree of the digital economy industry of each city cluster has been greatly improved.2021 Beijing-Tianjin-Hebei City Cluster and the Shandong Peninsula City Cluster with the digital industrialization coupling coordination degree is higher than 0.6, reaching the primary coordination level, while the digital industrialization coupling coordination degree between the Beijing-Tianjin-Hebei City Cluster and the Central Plains City Cluster and the three major city clusters is around 0.4, reaching only the level of barely coordination. Overall, the digital industrialization coupling coordination degree between the Beijing-Tianjin-Hebei city cluster and the Shandong Peninsula city cluster is higher than that between the other city clusters.

Table 4. Degree of coupling and coordination of northern urban agglomerations, 2013-2021

Sector		2013	2014	2015	2016	2017	2018	2019	2020	2021
Digital Infrastructure	(1)	0.356	0.413	0.465	0.602	0.660	0.560	0.606	0.632	0.612
	(2)	0.054	0.257	0.357	0.491	0.539	0.475	0.520	0.548	0.615
	(3)	0.024	0.138	0.225	0.348	0.403	0.322	0.366	0.390	0.411
	(4)	0.072	0.226	0.308	0.441	0.496	0.412	0.459	0.486	0.510
Digital Industry Digitalization	(1)	0.260	0.285	0.302	0.341	0.369	0.415	0.457	0.530	0.613
	(2)	0.039	0.100	0.164	0.190	0.220	0.245	0.308	0.359	0.409
	(3)	0.015	0.041	0.065	0.083	0.094	0.106	0.136	0.171	0.204
	(4)	0.050	0.097	0.138	0.163	0.185	0.210	0.257	0.308	0.362
Industry Digitalization	(1)	0.371	0.406	0.325	0.483	0.508	0.384	0.373	0.397	0.418
	(2)	0.216	0.291	0.239	0.376	0.381	0.266	0.266	0.286	0.296
	(3)	0.080	0.114	0.130	0.292	0.300	0.178	0.163	0.178	0.195
	(4)	0.179	0.229	0.194	0.343	0.355	0.236	0.228	0.247	0.262
Digital Economy Comprehensive Development	(1)	0.358	0.400	0.388	0.512	0.552	0.491	0.518	0.568	0.611
	(2)	0.064	0.235	0.271	0.390	0.416	0.357	0.394	0.432	0.485
	(3)	0.024	0.098	0.137	0.252	0.273	0.203	0.220	0.249	0.281
	(4)	0.079	0.200	0.225	0.343	0.372	0.307	0.335	0.374	0.418

For this table, (1) Representing Beijing-Tianjin-Hebei - Shandong Peninsula, (2) Representing Beijing-Tianjin-Hebei - Central Plains, (3) Central Plains - Shandong Peninsula, (4) Beijing-Tianjin-Hebei - Central Plains - Shandong Peninsula.

In terms of industrial digitization, the overall trend of industrial digitization coupling and coordination between major city clusters in the North from 2013 to 2021 shows a fluctuating upward trend, but the level of coupling and coordination between different city clusters still varies, but largely maintains a relatively similar development trend. In 2021, the degree of coordination of industrial digital coupling between the major city clusters in the north is basically above 0.2, basically at the level of moderate dislocation, and not yet out of the category of dislocation. In the comprehensive level of digital economy industry, the coupling and coordination degree of the comprehensive development of digital economy industry among the city clusters in the north from 2013 to 2021 shows an overall rising trend. By 2021, the coupling coordination degree of digital economy industry synergistic development between the main three major city clusters in the north reaches 0.418, reaching the level of barely out of dissonance. The level of digital economy synergistic development between the main two two city clusters in the north is, in descending order, Beijing-Tianjin-Hebei city cluster-Shandong Peninsula city cluster (0.611), Beijing-Tianjin-Hebei city cluster-Middle Plains city cluster (0.485), and Middle Plains city cluster-Shandong Peninsula city cluster (0.281). Although the digital economy synergistic development between the Beijing-Tianjin-Hebei city cluster and the other two city clusters have all reached the level of barely dislocated and above, it can be seen that the level of digital economy industry synergistic development in the Central Plains city cluster is much lower than that of the Beijing-Tianjin-Hebei city cluster and the Shandong Peninsula city cluster (see Table 4).

Overall, the internal coupling coordination level of the major northern city clusters is very poor, except for the Beijing-Tianjin-Hebei city cluster, which performs better, and the Central Plains city cluster and the Shandong Peninsula city cluster, both of which have very poor internal coordination levels. In addition, the level of coupling coordination of digital infrastructure, digital industrialization, industrial digitization, and digital economy industry among the major northern city clusters is increasing, and the level of digital economy industry synergy among the three major northern city clusters in 2021 is 0.418. Specifically, the level of coupling coordination of digital infrastructure (0.510) > digital economy industry (0.418) among the three major northern city clusters. coupling coordination degree of industrialization (0.362) > coupling coordination degree of industrial digitization (0.262). It can be seen that the level of coupled development of digital infrastructure among the three major city clusters in the north has played a large role in improving the overall level of coupled development of digital economy industry in the major city clusters in the north, but the level of coupled coordination of industrial digitization among the three major city clusters in the north restricts the overall level of coupled development of digital economy industry among the three city clusters, and the level of industrial digitization in the major city clusters in the north exists. The major northern city clusters have the phenomenon of industrial digitalization development level lagging behind digital infrastructure construction and industrial digitalization development level. At the same time, in the case that the level of digital economy industry synergy among the three major city clusters in the north is only barely out of tune with the level, the integrated development of the major city clusters in the north can embark on the high-quality synergistic development of the digital economy industry in order to improve the overall digital economy industry synergistic level. Therefore, each of the major northern city clusters should further increase the development of industrial digitization, pay special attention to the synergistic development of digital industrialization and industrial digitization between each city cluster, and promote the synergistic development of the digital economy industry of the major northern city clusters to move towards a new development stage of a more advanced state of coordination.

5. MAIN CONCLUSIONS AND POLICY RECOMMENDATIONS

Regarding the level reached by the coordinated development of the digital economy industry in major northern city clusters, this paper obtains the following conclusions: first, from the viewpoint of the foundation of the development of the digital economy industry in major northern city clusters, the level of digital economy development in major northern city clusters in the period of 2013-2021 is improving, and the level of the digital economy industry in the Beijing-Tianjin-Hebei city cluster is higher than that in the Central Plains City Cluster and the Shandong Peninsula City Cluster, especially the digital industrialization Second, from the point of view of the degree of synergy of the digital economy industry content of the major northern city clusters, the coupling and coordination degree of the digital economy industry of the major northern city clusters from 2013 to 2021 is improving, and the digital economy industry of the Beijing-Tianjin-Hebei city cluster will reach the intermediate level of coordination in 2021, and the degree of coordination of the other two city clusters will also have a certain degree of improvement. economy industry spatial coordination degree, in 2021, the digital economy coordination between the major northern city clusters only reaches the level of barely dislocation, the three major city clusters have the best degree of digital infrastructure synergy between them, digital industrialization synergy is second to the degree of digital industry synergy, the degree of industry digitalization synergy between the three major city clusters is obviously lagging behind the level of the overall synergy of the digital economy.

In view of the above analysis, this paper makes the following policy recommendations:

First, accelerate the top-level design for the collaborative development of the digital economy and industry in major northern city clusters. The collaborative development of digital infrastructure, industrial digitization and digital industrialization within a city cluster is a systematic project, so it is

necessary to plan as a whole, accelerate top-level design, build an architectural system for the collaborative development of the digital economy industry in major northern city clusters, and promote the collaborative governance of the digital economy industry chain in major northern city clusters. At the same time, from the perspective of the whole industry chain of digital economy, it is necessary to promote the synergistic development of digital infrastructure construction, industrial digitization and digital industrialization at a higher level within the city cluster.

Secondly, the establishment of institutional mechanisms to support the collaborative development of the digital economy industry in city clusters. Firstly, a better institutional system should be established for the collaborative development of the digital economy industry in major city clusters in the north, and the communication and coordination mechanism and the compensation mechanism for benefits should be improved, so as to break the institutional constraints of "administrative barriers" and "information islands" in major city clusters in the north. The innovation and industrial chain of digital economy industry should be formed in close cooperation within the city cluster, the collaborative layout of digital industry should be explored with the city cluster as the spatial scale, and the spatial optimization distribution and gradient reasonable transfer of digital economy industry chain of major northern city clusters should be pushed forward according to the comparative advantages of the digital economy of each region within the city cluster. Secondly, provinces and cities should take the city cluster digital economy industry synergy as a strategic guideline, scientifically plan the layout of digital economy industries in the five provinces and cities to avoid inefficient synergy and homogenized competition; and accelerate the construction of the Northern Major City Cluster Digital Economy Industry Alliance. Finally, promote the development of digital industrialization in the city cluster with greater efforts, increase the investment in digital industrialization, accelerate the development of strategic emerging industries such as integrated circuits, new types of displays, quantum communications and intelligent terminals in the major city cluster in the North, push forward the integration and development of new industries represented by big data, artificial intelligence, the Internet of Things, cloud computing and other industries in the city cluster, and cultivate the application scenarios of the new-generation digital technologies, so as to build the major city cluster in the North into a national-level digital industry cluster. city clusters into national-level digital industry clusters.

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