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Exploration of the level of coupled and coordinated development of digital industrialization and industrial digitization

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Abstract

This paper selects relevant indicators to construct the evaluation index system for the coordinated development of digital industrialization and industrial digitization and explores the coordinated development level of digital industrialization and industrial digitization by using the coupled coordination degree model. After constructing the evaluation index system of digital industrialization and industrial digitization, the entropy value method is used to measure the comprehensive development level of digital industrialization and industrial digitization, and the coupling degree of subsystems is calculated based on the measurement of the degree of interaction between systems by the constructed initial data matrix. It is verified that the coupling coordination degree steadily increases to 0.752 in 2018-2019, while the value of the coupling coordination degree is 0.950 in 2020, indicating that digital industrialization and industrial digitization are in a highly coupled and coordinated stage, and digital industrialization and industrial digitization are developing synergistically and advancing to a new higher level of coupled systems.

Keywords: *digital industrialization; evaluation index; coupling coordination degree model; entropy value method; data matrix*

Introduction

The rapid development of digital industrialization has prompted the traditional industries to open the digitalization process, and guided the whole society to explore the composition and mechanism of the digital economic system (Mugge, Abbu, Michaelis, Kwiatkowski, & Gudergan, 2020). The increase in scale and weakening contribution of digital industrialization coexist, and the scale growth rate of industrial digitization is significantly higher than that of digital industrialization, which has become the main contributing force of the digital economy(FRICKE, 2019; Oliveira et al., 2022). Industrial digitization tends to focus on the supply side, but by the short-term rigid constraints of core technology, key components and professional talents, industrial digitization has entered the bottleneck of development, digital industrialization tends to focus on the demand side, focusing on the realization of the market value of existing products (Ding, Zhang, & Tang, 2021; Øverby, Audestad, & Szalkowski, 2023). Accelerating the network power and digital construction, the digital economy has achieved obvious results, but the digital economy has great potential, the core key digital technology still needs to break through, and the industrial digitalization development space needs to be further expanded (Deev, Gamidullaeva, Finogeev, Finogeev, & Vasin, 2021; Ramos, Ruiz-Pérez, & Alorda, 2021). In this era of the gradual normalization of the intelligent industry, it is an important problem in the development of the economy, which is the cornerstone of the development of the intelligent industry (Chen & Zhu, 2021). In the world, digital economy is more and more an economy, in the case of stagnation of non-physical economic activities, the epidemic has accelerated the process of economic electronization, to the electronic has become the survival strategy of the global economies. Kwan, C proposed that the social workers must be aware of the world's digital economy and actively participate in the action of economic justice, in order to make the social justice can be realized (Kwan, 2023). Shen, W et al. who used the coupled synergy model to analyze the synergistic relationship between the digital economy and high-quality

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development and concluded that the synergistic relationship is high and used the Markov chain method (Shen, Xia, & Li, 2022). Wang, X et al. By constructing digital economy indicators and adopting a quadratic fixed-effects model, they study the relationship between digital economy indicators and green innovation capability and analyze the intermediary role of industrial restructuring in it. Corresponding countermeasures are proposed for urban construction and industrial transformation and upgrading (Wang, Sun, Zhang, & Xue, 2022). In the study of product configuration management, Bellalouna, F proposed the idea of introducing augmented reality technology to the industrial field, and provided the practical application of AI in industrial related industries (Bellalouna, 2021). Zuo, Z et al. constructed a multilevel and multilevel model of coupling and coordination between ecological civilization and economy, society and nature by establishing a standard deviation elliptic model and analyzing the role of the model in global warming. They also provide policy suggestions for improving the quality of environmental education from four perspectives: narrowing regional gaps, strengthening inter-regional cooperation and scientific use of resources (Zuo, Guo, Cheng, & Li, 2021). Cho, M. H et al. introduced a new concept of social innovation, i.e., adaptive social innovation, and focused on analyzing the main motivations and effects of government interventions from multiple perspectives, including macroeconomics, social psychology, and political science (Cho & Yi, 2022). Xiang, X study the development of the digital economy in different regions on their low-carbon inclusive growth impact. The analysis shows that the digital economy improves the overall efficiency of resource allocation, but the irrationality of capital factor allocation adversely affects low-carbon inclusive growth. And the downscaling method was applied (Xiang, Yang, & Sun, 2022). In the context of digitization, Petersen, J. A provides an organizational framework to assist in profitable marketing strategies for corporate multinationals in the digital environment. The digital products and processes that are currently emerging in the market are analyzed (Petersen, Paulich, Khodakarami, Spyropoulou, & Kumar, 2022). Sultana, S et al. used literature review, thematic analysis, and other methods, combined with related theories such as dynamic capabilities and market orientation, to carry out an analytics-based research and development process study of a data-driven innovation system (Sultana, Akter, Kyriazis, & Wamba, 2021). Therefore, this paper firstly explored the coupling mechanism of digital industrialization and industrial digitization. Secondly, the data of each measurement index are normalized by the extreme difference method without dimension, and the positive and negative efficacy indicators are proposed, and the data are standardized to obtain the comprehensive scores of digital industrialization and industrial digitization every year. Finally, construct the initial data matrix, and measure the degree of interaction between the systems, calculate the coupling degree of subsystems, and reflect the degree of benign coupling development between subsystems. And through the simulation experiment analysis of the coupling coordinated development, it proves that the digital industrialization and industrial digitization coupling coordinated development towards a new higher level of coupling system (SADEGHI, EBRAHIMI, & ESMAEILI, 2019).

Coupling mechanism of digital industrialization and industrial digitization

Digital industrialization and industrial digitization in the digital economy

With the rapid progress of a new generation of digital technologies and the gradual deepening of cross-border integration, which has promoted the optimization of economic structure and the enhancement of production efficiency, digital transformation has begun to be carried out one after another at all levels of economic development. The framework of the digital economy is shown in Figure 1.

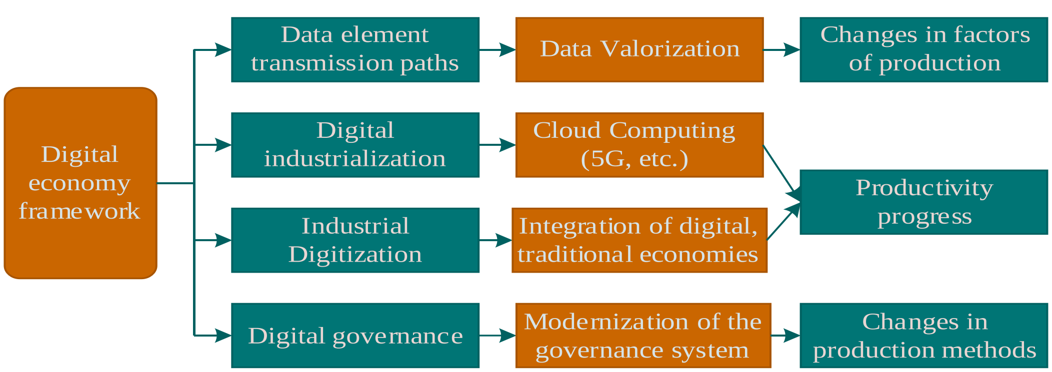

Figure 1 Content framework for the digital economy

Digital governance

The great development of the digital economy triggers the transformation and penetration of digital technology in all aspects of social production inevitably triggers profound changes in the governance of all organizations and groups in society, including government agencies and traditional enterprises, and promotes the upgrading of the governance system (Bressanelli, Adrodegari, Perona, & Saccani, 2018; Gritsenko & Indukaev, 2021; Lawn, 2020). The core of building a more open and positive forward-looking digital government to improve the national governance system lies in how to use modern digital technology in order to realize the efficient governance capacity of orderly collaboration, scientific decision-making, and comprehensive services in all sectors, and the content of digital governance is shown in Figure 2. Relying on the progress of digital technology, in technology and industrial integration to promote greater progress in productivity, thus making changes in the relations of production to adapt to the increase in productivity.

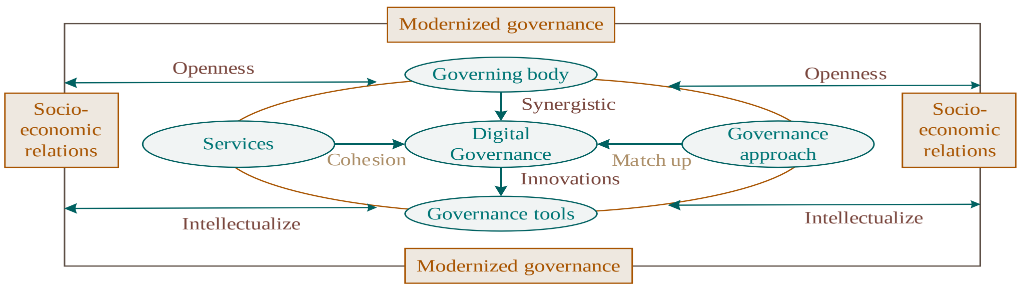

Figure 2 Elements of digital governance

Coupling mechanism

In the economic and social fields, the closely linked economic indicators or social phenomena, through mutual promotion or mutual constraints of the organic combination of the formation of a joint body, the common role of the form or relationship that is the economic and social coupling. Figure 3 shows the coupling relationship between digital industrialization and industrial digitalization. The high-speed development of digital industry and the expansion of industrial scale enrich the application path of digital technology, promote the internal transfer of the structure of the three major industries, make digital technology become an important adhesive for the interpenetration and cross-restructuring of the three major industries, accelerate the adjustment of industrial boundaries through industrial association, and create new development opportunities and more space for digital integration in traditional industries. Innovation capability reflects the development of digital industrialization system, embodies the advanced degree of digital technology, and is the key to realize the structural adjustment of traditional industries and digital transformation of industries. The expansion of the scale of digital convergence on the one hand improves the universality of digital technology, reduces the proprietary nature of digital technology investment, and facilitates the increase of digital industrial subjects. On the other hand, digital technology has been widely used and practically tested, improving the bottleneck of technology application and promoting knowledge innovation, thus making the supporting role of the digital industry continuously strengthened, the scale of the industry continuously expanded, and promoting the construction of an integrated digital industrial system.

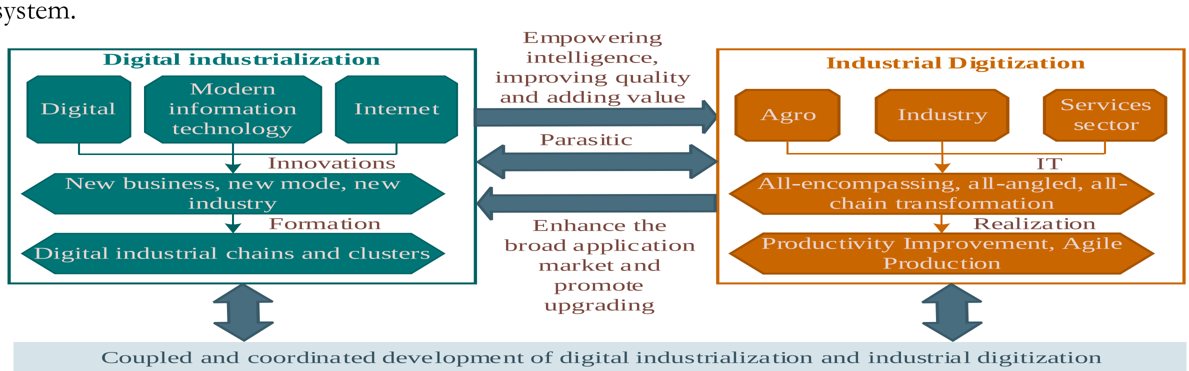

Figure 3 Coupling relationship between digital industrialization and industrial digitization

Digital industrialization and industrial digitalization coupling coordination model construction

In the coupling theory, the whole system develops benignly through the synergy of internal ordinal parameters, and the coupling degree can measure the synergy between the internal ordinal parameters of the system, which reflects the laws and characteristics of the interactions between the systems (Kolluri, Gray, Armstrong, & Fowler, 2020).

Due to the complex and intertwined relationship between the digital industrialization system and the industrial digitization system, considering the relevance, coordinated development degree and mutual constraints between the two, in order to measure the synergistic effect of the two systems, this section establishes a coupling degree measurement model to assess the degree of mutual influence between the coupled elements of the two systems in terms of the coupling degree (L. Li, Fan, Feng, Yuxin, & Keyu, 2022).

The degree of coordinated development of sequential parameters within the system is measured from the time logic, and the coupling degree of coordination model is constructed to calculate the coupling degree of coordination of digital industrialization and industrial digitization, to achieve the purpose of reflecting both whether the subsystems have a better level and the interaction relationship between the systems (X. Li, Lu, Hou, Zhao, & Zhang, 2022; Yu, Qi, Yu, & He, 2022).

Construction of the indicator system

By comparing the existing theoretical and empirical studies, and also in order to accurately and objectively reflect the level of digital industrialization, 16 indicators are selected from four aspects, to quantitatively describe the level of development of digital industrialization.

The scale level mainly measures the development level of digital industrialization from the perspectives of operation scale and output scale, and the industrial scale level is an important measurement standard for the government in formulating industrial policies. Economic efficiency is the fundamental starting point of all economic activities, and the evaluation index system of digital industrialization is shown in Table 1.

Table 1 Evaluation index system of digital industrialization

Level 1 indicators	Secondary indicators	Unit
Level of informatization	Internet penetration	%
	Mobile phone penetration	Ministry/hundred
	Number of sites	10,000
	IPV4 ADDRESS NUMBER	10,000
	Mobile Internet access traffic	Million GB
Level of innovation	ICT industry R&D personnel equivalent to full-time equivalent	Year of the man
	ICT Industry R&D Funding Internal Expenditure	Billion
	Number of valid invention patents in the ICT industry	Item
	Funding for new product development in the ICT industry	Billion
Scale level	Investment in fixed assets in the ICT industry	Billion
	Number of ICT industry enterprises	Piece
	Number of employees in the ICT industry	10,000 people
Level of efficiency	Digital industrialization scale	Billion
	Digital industrialization accounts for the proportion of GDP	%
	ICT industry profits	Billion
	ICT industry profits	Billion

The level of empowerment is to reflect the digital empowerment benefits from both industrial digitalization scale and industrial production benefits, and the industrial digitalization evaluation index system is shown in Table 2.

Table 2 Evaluation index system of industrial digitalization

Level 1 indicators	Secondary indicators	Unit
Level of infrastructure	Cable route length	10,000 km
	Total number of Internet broadband access ports	10,000
	Fixed broadband average access rate	Mbps
	Number of mobile communication base stations	10,000
	Online payment penetration	%
Level of innovation	GEM total market capitalization	Billion
	R&D expenditure of industrial enterprises on the plan	Billion
	The number of valid invention patents of industrial enterprises on the scale	Item
Application level	The number of industrial Internet platforms at the provincial level and above	Piece
	The numerical control rate of key processes in industrial enterprises is standardized	%
	The penetration rate of key control software in industrial enterprises is on the plan	%
	Internet application coverage of industrial enterprises on the plan	%
	Agricultural informatization coverage	%
	Online retail transaction volume	Billion
	Third-party mobile payment transaction volume	Trillion yuan
Empowerment level	The scale of industry digitalization	Billion
	Industrial digitalization as a percentage of GDP	%
	Average energy consumption level of industrial added value	Tons of standard coal/10,000 yuan
	Labor productivity of industrial enterprises on the regulations	Million yuan/person per year
	Amount of industrial solid waste generated	Tons of tons

Constructing the coupling model

Let S_t be the composite ordinal parameter of the tnd subsystem and t be taken as 1 and 2. The data X_{tj} of each measure is normalized in a dimensionless manner using the extreme difference method, and $min(X_{tj})$ and $max(X_{tj})$ are used to denote the minimum and maximum values of the indicator values of the tth subsystem, respectively, and different algorithms are used to standardize the data for the positive efficacy indicators and the negative efficacy indicators. S_{tj} denotes the result after the dimensionless normalization of the jth secondary indicator value of the tth subsystem, then for the positive efficacy indicator i.e:

$$S_{tj} = \frac{X_{tj} - min(X_{tj})}{max(X_{tj}) - min(X_{tj})} \quad (1)$$

For negative efficacy indicators i.e:

$$S_{tj} = \frac{max(X_{tj}) - X_{tj}}{max(X_{tj}) - min(X_{tj})} \quad (2)$$

S_{tj} reflects the degree of convergence and satisfaction of each secondary indicator to the established goal, the closer $0 \leq S_{tj} \leq 1$ and S_{tj} are to 1, the higher the contribution of the secondary indicator and the higher the degree of satisfaction, and the closer S_{tj} is to 0, the lower the contribution of the secondary indicator and the lower the degree of satisfaction. Since the subsystems have a certain degree of heterogeneity, the linear weighted sum method is used to reflect the comprehensive contribution of the sequential covariates within the subsystems to the whole subsystem, i.e.:

$$\begin{cases} S_1 = \sum_{j=1}^{n} W_{1j} S_{1j} \\ S_2 = \sum_{j=1}^{n} W_{2j} S_{2j} \end{cases} \quad (3)$$

Where S_1、S_2 represents the integrated sequential coefficients of digital industrialization and industrial digitization respectively, and W_{1j} and W_{2j} represent the weight coefficients of each secondary index.

The entropy value method is used to measure the comprehensive development level of digital industrialization and industrial digitization, and the initial data matrix is constructed as follows:

$$\begin{cases} X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \\ X = \{x_{ij} | 0 \le i \le m, 0 \le j \le n\} \end{cases} \quad (4)$$

The weighting of the indicator value for year i under indicator j is calculated as follows:

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} (0 \le y_{ij} \le 1) \quad (5)$$

Obtain the weighting matrix of the data $Y = \{y_{ij}\}_{m*n}$.

Calculate the information entropy value of item j as:

$$e_j = -K \sum_{i=1}^{m} y_{ij} \, ln \, y_{ij} \quad (6)$$

$$w_j = \frac{d_j}{\sum_{i=1}^{m} d_j} \quad (7)$$

Coupling and coupling coordination measurements

Coupling is a measure of the degree of interaction between the systems, and after calculating the composite score of the subsystems, equation (8) can be used to calculate the coupling between the two in each year:

$$C = 2\sqrt{U_s \times U_c}/(U_s + U_c) \quad (8)$$

The coupling degree C value of the binary system is not uniformly distributed in the interval [0,1], and is mostly concentrated at the 1 end. In order to improve the validity of the use of the coupling degree, the modified coupling degree model is used, this model will be distributed as much as possible dispersed C value in [0,1], increase the differentiation of the C value, the calculation is as follows:

$$C_{sc} = \sqrt{\left[1 - \sqrt{(U_2 - U_1)^2}\right] \times \frac{U_1}{U_2}} = \sqrt{[1 - (U_2 - U_1)] \times \frac{U_1}{U_2}} \quad (9)$$

Where $U_1 = min\{U_s, U_c\}$, $U_2 = max\{U_s, U_c\}$.

Coupling degree can only reflect the degree of synchronization between subsystems, can not indicate the state of development level between the systems, there will be when the two systems are synchronized at a low level of development stage coupling degree value is very high. The coupling coordination degree of two subsystems is calculated using formula (10) as follows:

$$D_{sc} = \sqrt{C_{sc} \times G_{sc}}, G_{sc} = aU_s + bU_c, a + b = 1 \quad (10)$$

As digital industrialization plays a fundamental and pioneering role in supporting the development of industrial digitization, the scale of digital industrialization and industrial digitization are both expanding, but the growth rate of industrial digitization scale is slightly faster in comparison, so in the actual calculation, a and b are assigned the values of 0.4 and 0.6, respectively. In order to reflect the level of coupling coordinated development in a more intuitive manner, the degree of coupling coordinated is divided into four intervals and is evaluated against Table 2 by using the coupling coordinated degree measured by the entropy method.

Test of the level of coupled and coordinated development

Comprehensive Assessment and Score Analysis

Taking Province A as the research unit, the data used mainly comes from the website of government departments in Province A. The development level of digital industrialization in Province A has achieved steady improvement, and the overall scale of digital industrialization in the province has always been in the forefront, while the digitalization of industries in Province A started earlier and developed faster, and the digitalization of industries has become a major driving force for pulling the economy of Province A to grow. From the perspective of innovation level, from 2016 to 2020, the regional innovation capacity of Province A has always ranked among the top 3, with the intensity of investment in research and experimental development reaching 2.7%, and the number of invention patents owned by 10,000 people reaching 26. From the level of benefit, the benefit of digital industry in Province A has been steadily improving, and the growth rate of business income of the Internet and related service industry has always remained above 12%. From the level of empowerment, the scale of industrial digitization in Jiangsu has been expanding year by year, and the proportion of industrial digitization in GDP by the end of 2020 exceeds 28%. The labor productivity of industrial enterprises has improved year by year, and the average energy consumption level of industrial added value has continued to decline. Table 3 shows the comprehensive score of digital industrialization and industrial digitization in Province A using the entropy value method as follows:

(1) The comprehensive score of digital industrialization increased from 0.096 to 0.902 in 2016-2020, with the development speed increasing year by year, and showing the trend of a more moderate development speed in 2016-2018 and a more rapid development in the period of 2019-2020. It is mainly due to the big data development action plan released in 2018, the digital economy, and policies such as the coupled and coordinated development of digital industrialization and industrial digitalization.

(2) The comprehensive score of industrial digitization in Province A increased from 0.088 to 0.901 in 2016-2020, showing an overall trend of increasing growth rate year by year, which developed rapidly and reached a new level in the period of 2018-2020. As can be seen by comparing the data in the table, the comprehensive development level of digital industrialization in Province A has been higher than the comprehensive development level of industrial digitization in 2016-2017, and the comprehensive development level of industrial digitization in Province A surpassed the comprehensive development level of digital industrialization for the first time in 2018, and it has been maintained in this state. At the same time, the traditional industries themselves are large in scale, and the application of digital technology has inspired the traditional industries to improve their productivity and output, and industrial digitization has gradually become the main engine of digital economic growth and has also pulled the deep development of digital industrialization from another direction.

Table 3 Composite Score for Province A, 2016-2020

	Year	**2016**	**2017**	**2018**	**2019**	**2020**
Digital industrialization	Composite Score	0.096412	0.264968	0.317502	0.568553	0.902354
	Informatization	0.000004	0.057661	0.102045	0.222486	0.345189
	Innovation	0.000004	0.041010	0.098531	0.141780	0.258862
	Scale	0.058757	0.085992	0.044292	0.054404	0.104021
	Benefits	0.034689	0.081945	0.077048	0.159201	0.183455
Industrial digitization	Composite Score	0.088319	0.174960	0.432858	0.635150	0.901337
	Infrastructure	0.000001	0.053622	0.134270	0.166362	0.215543
	Innovation	0.000002	0.038151	0.070127	0.095411	0.114852
	Application	0.000004	0.068774	0.133665	0.214837	0.310450
	Empowerment	0.090270	0.019344	0.080010	0.148008	0.264112

Overall coupling coordination analysis

The comprehensive score of digital industrialization and the comprehensive score of industrial digitization of Province A are sequentially substituted into equations (9) and (10) to obtain the overall coupling coordination degree of digital industrialization and industrial digitization in Province A. The results of the calculation are shown in Table 4.The coupling coordination degree of digital industrialization and industrial digitization of Jiangsu Province increases year by year from 2016 to 2020.The value of the coupling coordination degree in 2016 is 0.301, and the coupling coordination degree between digital industrialization and industrial digitization are at a lower level of coupling coordination stage, indicating that the level of industrial digitization development in province A is low at this stage, digital industrialization is relatively fast, and digital industrialization is constrained by the backward industrial digitization while pulling the development of industrial digitization. This requires accelerating the digital, networked and intelligent development of traditional industries, promoting the digital transformation of traditional industries, and prompting the coordinated development of digital industrialization and industrial digitization. The value of the degree of coupling and coordination in 2017 rose rapidly to 0.420, and digital industrialization and industrial digitization were in the medium coupling and coordination stage, and industrial digitization in Jiangsu at this stage gradually entered the stage of rapid and stable development, and the limited digital industrialization In 2018-2019, the degree of coupling coordination steadily increased to 0.752, at which time digital industrialization and industrial digitization were at a higher level of coupling coordination stage, at which stage digital industrialization and industrial digitization of Province A began to enter the friction stage, and digital industrialization was in a new stage of development, with industrial digitization scoring more than digital digitization for the first time. Industrialization comprehensive score and gradually occupy the dominant position in the digital economy, digital industrialization and industrial digitization into a new stage of coordinated development. 2020 coupling degree of coordination value of 0.950, digital industrialization and industrial digitization in a high level of coupling and coordination stage, the stage of the overall balanced development of the digital economy in province A, digital industrialization and industrial digitization coordinated development, to the new higher level of coupling system towards.

Table 4 Coupling harmonization in Province A, 2016-2020

Year	Digital Industrialization Composite Score	Industrial Digitization Composite Score	Coupling (physics)	Degree of coupling coordination	Stage
2016	0.096	0.088	0.968	0.301	Low coupling stage
2017	0.265	0.175	0.791	0.420	Medium coupling stage
2018	0.318	0.433	0.830	0.563	High coupling stage
2019	0.569	0.635	0.931	0.752	High coupling stage
2020	0.902	0.901	0.985	0.950	Extreme coupling stage

Sub-coupling coordination analysis

In order to further analyze the interaction between the level of informatization, innovation, scale and efficiency of digital economy digital industrialization and digital economy industry digitization in Province A, the degree of coupling and coordination between the first-level indicator system and industry digitization is shown in Figure 4. Among them:

(1) the coupling degree between the two indicators of digital industrialization informatization level and innovation level and industrial digitization in province A in 2016-2020 starts low, grows fast, and maintains a high level of coupling degree, and the corresponding coordination degree grows from a low coordination degree to a high coordination degree. This shows that the two indicators of digital industrialization informatization level and innovation level in Province A always show high correlation with industrial digitization, but the development pace is not coordinated.

(2) During the period from 2016 to 2018, under the advancement of the 2016-2018 action program for the construction of the smart economy, the level of informatization and the level of innovation in Province A develops faster, but the development of industrial digitization in Province A is relatively slow, and the industrial digitization fails to better match the level of informatization and the level of innovation during the same period. During the period from 2018 to 2020, the development of industrial digitization in Province A accelerates and gradually fit with the level of informatization and the level of innovation in the same period. During the period from 2016 to 2020, the level of digital industrialization scale and the level of efficiency in Province A started at a higher level of coupling with industrial digitization and grew slower, and the degree of coupling as well as the coordination was relatively weak.

(3) In 2016, the scale level and benefit level of digital industrialization in Province A showed high correlation with industrial digitization, the reason is that Province A, as one of the most developed provinces in the ICT industry, has an early start in the development of digital industrialization, with a certain degree of scale and profitability, which effectively promotes the development of industrial digitization. During the period from 2017 to 2020, the large economic scale and sound industrial system of Province A provide a huge digital dividend for the development of digital industrialization, and the correlation and coordination between the level of scale and profitability of its digital industrialization and the level of industrial digitization gradually increase.

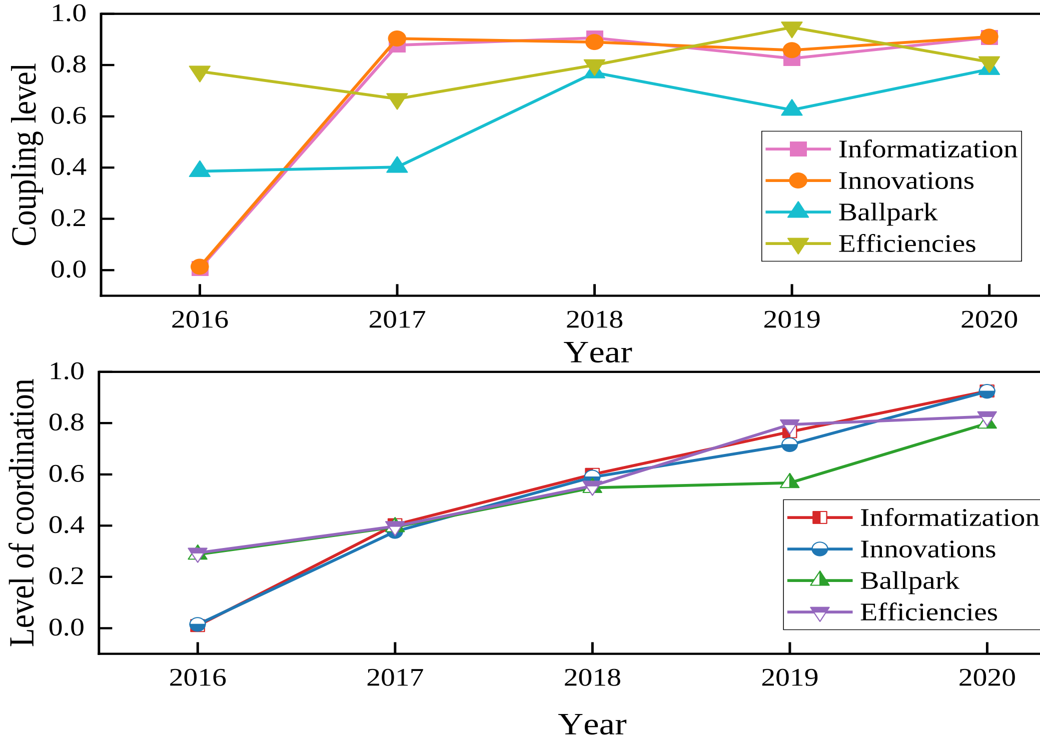

Figure 4 Analysis of coupling and coordination

Conclusion

Finally, the results of the coupling coordination show that after the release of the big data development action plan, digital economy and the coupled and coordinated development of digital industrialization and industrial digitization and other policies, the digital economic camp in province A presents a good policy environment. The comprehensive score of the digital industrialization from 2016 to 2020 increased from 0.096 to 0.902, and the comprehensive score of the industrial digitization from 0.088 to 0.901, and the overall growth rate increased from 0.088 to 0.901, and the comprehensive score of the industrial digitization from 0.088 to 0.901. The overall trend shows that the growth rate increases year by year. It proves that digital industrialization and industrial digitization show a high degree of correlation, and it is necessary to accelerate and improve the construction of new infrastructure for the digital economy and establish a mechanism for the integration of digital industrialization and industrial digitization to promote the coupled and coordinated development of digital industrialization and industrial digitization.

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