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Research on the integration level measurement and optimization path of industrial chain, innovation chain and service chain

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ABSTRACT

The contemporary scientific and technological revolution and industrial transformation are accelerating an overall industrial evolution. The integration of industrial, innovation, and service chains (three-chain) has become an important measure for countries around the world for assessing and enhancing international competitiveness. Based on regional economic theory, industrial policy theory, and synergy theory, this study constructs an evaluation index to measure three-chain integration. A model to measure the degree of synergy among the three chains of the composite system is applied using sample data from Zhenjiang, China from 2012 to 2020. The relevant results are threefold. (1) The three chains of Zhenjiang are at a low level of synergy, which exhibits a downward trend. (2) The industrial chain's degree of synergy is the lowest, and must assume more responsibility for addressing the low three-chain integration level. (3) When examining the integration of any two chains, the integration level of the industrial and innovation chains is the highest. Finally, combined with the research results, optimization paths are proposed to promote three-chain integration. This research contributes to the field by integrating industrial, innovation, and service chains into a comprehensive research framework, constructing a universally applicable evaluation index system to empirically test the level of three-chain integration, and proposing optimal paths to provide scientific methods and decision-making reference to advance three-chain research.

Introduction

The contemporary world is undergoing great change that has not been experienced in a century. First, the United States has successively introduced control policies related to Chinese goods, such as the Endless Frontier Act and the 2022 American Competition Act, endeavoring to promote the "de-Chinalization" of key technologies in global industrial and supply chains. The high-end links of China's industrial chain are facing major bottleneck risks and challenges. In addition, black swan events such as the Russian-Ukraine conflict and butterfly effects caused by geopolitical factors have further exacerbated the uncertainty of the global economy, and China's industrial chain could confront a "chain breaking" crisis at any time. In addition, China's economy has moved from high-speed growth to the stage of high-quality development, and the economic structure has undergone major transformations. These circumstances make it urgent to conduct innovation-driven strategic reform in the industrial chain; build a benign interaction between the industrial system, scientific and technological innovation, and service functions; and enhance China's international status and influence. In the post-pandemic era, addressing the problem of integrated development of industrial, innovation, and service chains, which are referred to as the "three chains," and proposing paths for optimizing integrated three-chain development comprise a critically urgent issue to be solved in China.

Accordingly, it is essential to synergize the innovation chain with the industrial chain, optimize the service chain, and promote the deep integration of the three chains. There are complementary and mutually promotional effects among the three chains. The optimization and upgrading of industrial structure and the formation of new industries are inseparable from technological innovation (Chiu & Lin, 2022), and the optimization of technological upgrading and the transformation of innovative achievements cannot be separated from the accelerated growth of industries (Iyigun, 2017; Chen, Huang, Liu, Luan, & Song, 2019). In addition, a series of service synergies, including policy support, talent introduction, technology transfer and transformation, scientific and technological consulting, and entrepreneurship incubation are also necessary (Landini & Malerba, 2017; Xu, Li, Tao, & Zhou, 2022). The coordinated development of the three chains can provide efficient service guarantees for industrial reform

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and upgrading, mobilize the enthusiasm of innovation factors (Varga, Pontikakis, & Chorafakis, 2014), and establish momentum for economic development (Lee, Gao, & Li, 2017; Liao, Hu, & Shih, 2021). Nevertheless, at present, there are limited quantitative studies on the integration of the three chains, and the integration level and optimization path of the industrial, innovation, and service chains require further research and discussion.

Accordingly, based on regional economic development theory, industrial policy theory, and synergy theory, this study takes data from Zhenjiang as the research sample, measures the level of three-chain integration, and proposes the development path for promoting three-chain integration. The contributions of this study are threefold. First, the industrial, innovation, and service chains are integrated into the same research framework, and the integration level of interaction among the three chains is empirically measured. Second, a universal three-chain integration evaluation index system is constructed from the structural characteristics of the industrial and service chains and the chronological logic of innovation activities. Third, it is of considerable practical value to achieve the sustainable innovation of local industry, promote high-quality industry development, and improve science and technology service levels.

The remainder of this paper is structured as follows. The next section reviews the literature on industry, innovation, and service chains. The third section constructs the composite system synergy model and the evaluation index system is designed. The fourth section takes Zhenjiang as an example to measure and evaluate the three-chain integration level. The fifth section proposes the optimization path to promote three-chain integration. Finally, the conclusion summarizes the findings and proposes future research directions.

Literature review

Research on a single chain

The single chain research primarily focuses on examining the connotation and extension of each chain and its development history. The concept of the industrial chain originated from Adam Smith's discussion regarding the division of labor in The Wealth of Nations, and Marshall (1890) then applied it to the resource allocation among enterprises. Hirschman (1958) discussed the concept of an industrial chain from the perspective of the forward and backward linkages of industries. With the rise in supply and value chain research, the industrial chain construct has become a unique academic topic in China. The industrial chain refers to the chain formed by the relationships between upstream and downstream industries (Liu & Ling, 2021); however, from the demander's perspective, the industrial chain is a supply chain, and from the value added perspective, the industrial chain is a value chain (Hipp & Binz, 2020; Zhang & Gallagher, 2016). The concept of an innovation chain was developed from the concepts of industry chain and supply chain. Marshall and Vredenburg (1992) first proposed the concept of an innovation chain, and later research was conducted in a series of studies on the connotations of the innovation chain, constituent links, functional nodes, structural evolution and the economic effects (Hansen & Birkinshaw, 2007; Chen, Liu, &Zhu, 2018; Xu, Wang, Dong, Luo, Yue, & Pang, 2018; Roper, Du, & Love, 2008). The construct is also extended to the concept of an innovation value chain (Tilahun & Berhan, 2022), a global innovation chain (Lin, Liu, Han, & Chen, 2018), and other related concepts. The service chain research lags behind that of the industrial and innovation chains. The service chain refers to effectively organizing service elements to form a complete and orderly system around user needs and provide an overall and whole process service scheme (James, David, & Duance, 2006). Concepts related to service chain include the science and technology service chain and the science and technology intermediary service chain (Howells, 2006) and the e-government service chain (Weerakkody, El-Haddadeh, Sivarajah, Omar, & Molnar, 2019). Many scholars have demonstrated that the service chain has an important role in the process of technological and service innovation (Hargadon,1998; Wang, Wallace, Shen, & Choi, 2015).

Research on the integration of any two chains

Scholars have often examined the interactions of combinations of any two chains among the industrial, innovation, and service chains. First, there are the two chains of the relationship between mutual promotion. For example, Eswaran and Kotwal (2002) constructed a mathematical model to assess the reciprocal effects between service and manufacturing industries. Wu and Liu (2021) used the spatial Durbin model to test the positive spatial spillover effect of technological innovation on industrial structure upgrading. Conducting a case study on Huawei, Lin et al., (2018) explored the impact of global innovation chain development on industrial chain upgrading. Xing, Duan, Yan, and Baykal-Gürsoy (2021) constructed a framework to examine the integration of innovation and industry chains to match market and technology needs based on manufacturing firms' different requirements for innovation. Second, there is research on approaches for promoting the integration of two chains. As found by Landini and Malerba (2017), Lee, Gao, and Li (2017), industrial policies and government actions can promote the integration of industrial chains and innovation by improving the ability to integrate technology. Yu and Zhao (2021) constructed an evolutionary game model to analyze the strategic choices of the government and upstream and downstream enterprises in the process of collaborative innovation.

Research on the integration of three chains

Generally, most research on three-chain integration has used a theoretical perspective to explore the mechanism and evolutionary path of three-chain integration. For example, Zhang and Zhao (2019) proposed the integration route of the industrial, innovation, and service chains from four aspects based on the construction of Vein Industrial Park. Some scholars have also explored the integration level of four chains, including the capital chain. For example, Che and Huang (2004) evaluated Taiwan's high-tech industrial parks by considering the degree of integration of the industrial, innovation, service, and capital chains. Kim (2009) investigated research and development (R&D) in information and communications technology (ICT) and global competitiveness in Japan, deeply exploring the new collaborative system between the ICT industry chain, technology R&D, government services, and financial support, reflecting the idea of integrating the four chains.

The literature review reveals that academic research on the structure and connotation of single chains and the collaboration between industry and innovation chains has become relatively mature; however, few studies have examined three-chain integration or have focused on a theoretical analysis of the mechanism, lacking empirical analysis and testing. However, neither technological innovation nor industrial upgrading can be separated from the collaboration of a series of services such as scientific and technological consulting and innovation results incubation. Few scholars have included service, industrial, and innovation chains in the same research category as the current research, leading to insufficient comprehensive research. Therefore, the study constructs a scientific indicator system to measure and evaluate the three-chain integration level to theoretically bridge the gap between scientific and technological innovation and industrial development, enriching the current literature on three-chain integration and providing theoretical guidance value for expanding this research paradigm.

Model construction and evaluation index system design of three-chain integration

This study endeavors to investigate three-chain integration. Referencing the synergy theory proposed by the physicist Harken, three chains are regarded as a composite system, and three-chain integration indicates symbiotic coordination among the subsystems of industrial, innovation, and service chains. The measure of this symbiotic coordination is the level of synergy or integration of the composite system (Meynhardt, Chandler, & Strathoff, 2016; Bai, Chen, Gao, & Luo, 2018), which primarily depends on the degree of order of each subsystem and the degree of integration matching between subsystems. Therefore, referring to Park and Kim (1997), and based on the literature review, combining the structural characteristics of the industrial and service chains and the time sequence logic of innovation activities, this study constructs a three-chain integration evaluation index system, measuring the integration level using the synergistic degree model of a composite system.

Composite system synergy model

The composite system synergy model is constructed based on synergy theory, which is used to measure the degree of three-chain composite system synergy and evaluate the integration level. The model building process is described below.

We first construct a three-chain composite system ($S = \{S_1, S_2, S_3\}$), where S_j represents the jth subsystem of the composite system (S), S_1 is the industrial chain subsystem, S_2 is the innovation chain subsystem, and S_3 is the service chain subsystem. Each subsystem is composed of several order parameters, and the order parameter of the subsystem is defined as e_{ji}, $e_{ji}=(e_{j1}, e_{j2}, \ldots\ldots, e_{jm})$ $m \geq 1$, $\beta_{ji} \leq e_{ji} \leq \alpha_{ji}$, $i \in [1, m]$. It is assumed that the greater the value of the order parameters $(e_{j1}, e_{j2}, \ldots\ldots, e_{jl})$ is, the higher the degree of order the subsystem is; otherwise, the lower the degree of order the lower the subsystem is. It is also assumed that the larger the value of e_{j1}, e_{j2}, $\ldots\ldots$, e_{jm} is, the lower the order of the system is; otherwise, the higher the order of the system is.

The order degree of the three-chain subsystem is calculated as follows:

$$U_je_{ji}\begin{cases} \dfrac{\left(e_{ji}-\beta_{ji}\right)}{\left(\alpha_{ji}-\beta_{ji}\right)} & i \in [1, l] \\ \dfrac{\left(\alpha_{ji}-e_{ji}\right)}{\left(\alpha_{ji}-\beta_{ji}\right)} & i \in [l+1, m] \end{cases} \tag{1}$$

where α_{ji} and β_{ji} respectively correspond to the upper and lower limits of the order parameter components at the critical point of system stability. According to equation (1), for $U_je_{ji} \in [0, 1]$, the larger the value is, the greater the contribution of the order parameter is to the order degree of the subsystem.

In general, the order effect of order parameter e_j on subsystem S_j can be achieved through the integration of U_je_{ji}. This study adopts the geometric mean method for integration. The equation for subsystem ordering degree is as follows:

$$U_je_j = \sqrt[m]{\prod_{i=1}^{m} u_j(e_{ji})} \quad j = 1, 2, 3 \tag{2}$$

where for $U_je_j \in [0, 1]$, the higher the value is, the higher the degree of order the subsystem is; otherwise, the lower the degree of the subsystem's order.

Taking the base period as the starting point, assuming that the initial time is t_0, the order degree of the subsystems at t_0 is $u_j^0(e_i)$, and with the dynamic evolution of the composite system to time T1, the order degree of each subsystem is $u_j^1(e_i)$. The equation for the coordination degree of the composite system is as follows:

$$= \theta \sqrt[3]{\left| \prod_{j=1}^{3} \left[u_j(e_{ji}) - u_j^0(e_i) \right] \right|} \tag{3}$$

where $\theta = \frac{\min[u_j^1(e_i) - u_j^0(e_i)]}{|\min[u_j^1(e_i) - u_j^0(e_j)]|}$

According to equation (3), for $C \in [0, 1]$, the larger the value, the higher the degree of coordination of the three-chain composite system, the better the fusion level; otherwise, the lower the value, the worse the fusion level. In addition, the composite system synergy model starts from the base period to investigate the characteristics and change trends of the synergistic evolution of composite systems. This paper takes 2012 as the base period.

In addition, to evaluate the three-chain integration level objectively and reasonably, the synergy degree of the composite system is classified into five levels according to value, as shown in Table 1.

Evaluation index system design

To accurately measure the three-chain integration level, it is essential to select accurate and reasonable subsystem order parameters. Based on the reality of China's industrial development, technological innovation, and scientific and technological service level, referencing the construction of the synergy degree index system in the existing research, six first-level indicators and 13 second-level subdivision indicators are formed according to the structural characteristics of the industrial chain and service chain and the chronological logic of innovation activities. The evaluation index system for the level of industrial, innovation, and service chain integration is presented in Table 2.

Contemporary industrial competition has been transformed into industrial chain competition, and an industrial chain index system must include the integration degree and competitiveness of the industrial chain itself. In this study, the construction of the industrial chain subsystem evaluation index system primarily considers the integration degree and advancement of the industrial chain. The industrial chain integration degree is measured using the number of high-tech enterprises, the proportion of high-tech enterprises among industrial enterprises above a designated size, and the proportion of the output value of high-tech products in the total industrial output value above a designated size. The upgrading of the industrial chain emphasizes the transformation of the traditional industrial chain by means of science and technology and technological innovation, completing the evolution of the industrial chain from low to high level, and obtaining high added value, high technology, and high intensification of the industrial chain (Humphrey & Schmitz, 2002). In this study, the ratio of the added value of the tertiary industry to the added value of the secondary industry and the ratio of the sum of the added value of secondary and tertiary industries to GDP are used to measure industrial chain upgrading.

The innovation chain has obvious process characteristics, including basic research, application research, product development and trial production, commercialization, and industrialization. The innovation chain

Table 1
Classification of composite systems' synergistic degree

Value of *C*	[-1,0]	(0,0.3]	(0.3,0.7]	(0.7,1)	1
System state	No synergy	Low synergy	General synergy	High synergy	Consistent synergy

Table 2
Three-chain synergy evaluation index system

General system	Subsystem	Primary index	Secondary index	Symbol
Three-chain composite system	Industrial chain (S1)	Integration	Number of high-tech enterprises	e11
			Proportion of high-tech enterprises among industrial enterprises above a designated size	e12
			Proportion of the output value of high-tech products in the total output value of industries above a designated size	e13
		Advance	Ratio of the added value of tertiary industry to the added value of secondary industry	e14
			Ratio of the sum of the added value of the secondary and tertiary industries to GDP	e15
	Innovation chain (S2)	R&D stage	Personnel who are engaged in R&D activities throughout the year and whose accumulated working hours account for 90% or more of the total working hours	e21
			R&D as a share of GDP	e22
			Number of invention patent applications authorized	e23
		Achievement transformation stage	New product sales revenue	e24
	Service chain (S3)	Competitive power	Proportion of government funding for science and technology services in total government funding for science and technology	e31
		Resource allocation	Value added of the service sector to GDP	e32
			Proportion of service labor force in each industry	e33
			Proportion of service output value among industries	e34

can be divided into R&D and achievement transformation stages. Referencing Wiermeier, Thoma, & Senn, (2012) and Bi, Huang, & Wang, (2016) on innovation chain performance and scientific and technological innovation output, the R&D stage is measured by full-time equivalent of R&D personnel, the proportion of R&D in GDP, and number of invention patent applications granted, and the achievement transformation stage is measured by sales revenue of new products.

Industrial innovation development is inseparable from the aggregation of service organizations and a series of services, such as innovation incubation, policy consultation, talent training, and technology transfer. According to the characteristics of the service chain structure, this study measures the competitiveness and resource allocation capabilities of the service chain. The competitiveness of the service chain is measured by the proportion of financial allocation for science and technology services in the total financial allocation for science and technology. The resource allocation capability of the service chain is measured by the proportion of the added value of the service industry in GDP, the proportion of the labor force in the service industry, and the proportion of the output value of the service industry in each industry.

Measurement and evaluation of three-chain integration level

Three-chain integration level measurement

Zhenjiang City is used as an example for measuring the three-chain integration level, with Zhenjiang City data from 2012 to 2020 obtained from the Zhenjiang Statistical Yearbook, the Zhenjiang Yearbook, and the Zhenjiang High-Tech Industry Main Data Statistical Annual Report. The specific data calculation process is described below.

Due to the inconsistent measurement units of the original data, to eliminate the impact of specific dimensions on the empirical results, the data are first standardized. See Tables 3 and 4 for the results of the original data collation and the standardized processing of order variables.

The process then multiplies the maximum and minimum values of the normalized data of the order variable component by 110% to obtain the upper and lower limits, respectively, of the normalized data of the parameter order component, substituting the upper and lower limits and the normalized data in Table 2 into equation (1) to obtain the order degree of the order variables of each subsystem of the three chains, as shown in Table 5. As noted previously, the larger the order value of the order parameter is, the greater the contribution of the order parameter is to the order of the subsystem.

The data in Table 5 are next substituted into equation (2) to obtain the order degree of each subsystem, as shown in Table 6 and Figure 1. The higher the ordering degree of the subsystem is, the higher the ordering degree of the subsystem is.

Finally, taking 2012 as the base year, the data of the order degree of each subsystem is substituted into equation (3) to obtain the composite system synergy degree of Zhenjiang's industrial, innovation, and service chains, representing the three-chain integration level, as shown in Table 6 and Figure 2.

Table 3
Original data collation results

Year	Industrial chain (S1)					Innovation chain (S2)				Service chain (S3)			
	e11	e12	e13	e14	e15	e21	e22	e23	e24	e31	e32	e33	e34
Unit	number	%	%	/	/	Person / year	%	piece	Ten thousand yuan	%	%	%	%
2012	252	10.30	45.71	1.2186	0.0822	17380	2.31	9235	7972654	16.60	4.52	39.27	41.59
2013	327	11.76	46.80	1.5765	0.0815	18810	2.35	9808	8517256	9.70	4.99	40.06	43.26
2014	427	14.53	48.20	2.8332	0.0705	23155	2.53	12707	18392167	10.19	5.21	41.29	45.26
2015	528	18.57	48.60	1.5950	0.0665	26812	2.55	14136	20333333	9.77	4.09	43.16	46.17
2016	619	23.49	49.10	1.5158	0.0996	28380	2.59	13836	22887253	9.28	6.00	44.33	47.51
2017	630	30.79	49.30	0.9289	0.0738	21096	2.58	14825	14840262	11.56	3.55	46.07	47.50
2018	750	36.69	47.50	1.4295	0.0348	17691	2.54	15348	9897605	5.75	2.05	47.57	47.90
2019	947	48.49	45.64	1.5122	0.0566	15187	2.22	12639	9688082	5.38	3.41	49.22	48.61
2020	1188	59.16	46.20	2.9507	0.0317	18822	2.30	19814	12235687	2.75	2.37	50.33	49.33

Note: Due to the lack of data, underlined numbers are replaced by predicted values from the existing years.

Table 4
Normalized processing results of sequence variables

Year	Industrial chain (S1)					Innovation chain (S2)				Service chain (S3)			
	e11	e12	e13	e14	e15	e21	e22	e23	e24	e31	e32	e33	e34
2012	-1.2657	-1.0461	-1.2182	-0.7370	0.7129	-0.7681	-0.9097	-1.3901	-1.0669	1.8886	0.3780	-1.3328	-1.8576
2013	-1.0144	-0.9610	-0.4551	-0.2202	0.6825	-0.4483	-0.6450	-1.2074	-0.9682	0.1748	0.7390	-1.1357	-1.2062
2014	-0.6794	-0.7988	0.5251	1.5947	0.1856	0.5233	0.6192	-0.2829	0.8204	0.2957	0.9076	-0.8275	-0.4234
2015	-0.3410	-0.5627	0.8051	-0.1934	0.0055	1.3411	0.7582	0.1728	1.1720	0.1919	0.0507	-0.3588	-0.0682
2016	-0.0361	-0.2752	1.1552	-0.3078	1.4963	1.6918	1.0362	0.0771	1.6346	0.0697	1.5123	-0.0651	0.4530
2017	0.0007	0.1515	1.2952	-1.1554	0.3352	0.0629	0.9667	0.3925	0.1771	0.6372	-0.3550	0.3722	0.4484
2018	0.4028	0.4964	0.0350	-0.4324	-1.4192	-0.6986	0.6887	0.5593	-0.7182	-0.8077	-1.5040	0.7474	0.6059
2019	1.0628	1.1860	-1.2672	-0.3130	-0.4387	-1.2585	-1.5352	-0.3046	-0.7561	-0.8990	-0.4671	1.1617	0.8833
2020	1.8703	1.8099	-0.8751	1.7644	-1.5600	-0.4456	-0.9792	1.9835	-0.2947	-1.5514	-1.2615	1.4385	1.1648

Table 5
Order degree of order parameters for each subsystem

Year	Industrial chain (S1)					Innovation chain (S2)				Service chain (S3)			
	U1 (e11)	U1 (e12)	U1 (e13)	U1 (e14)	U1 (e15)	U2 (e21)	U2 (e22)	U2 (e23)	U2 (e24)	U3 (e31)	U3 (e32)	U3 (e33)	U3 (e34)
2012	0.0367	0.0333	0.0623	0.1662	0.7225	0.1899	0.2754	0.0375	0.0359	0.9501	0.6125	0.0437	0.0559
2013	0.1095	0.0604	0.3331	0.3272	0.7134	0.2884	0.3690	0.0867	0.0691	0.4972	0.7214	0.1084	0.2518
2014	0.2067	0.1120	0.6808	0.8922	0.5656	0.5878	0.8159	0.3358	0.6710	0.5291	0.7722	0.2095	0.4873
2015	0.3048	0.1872	0.7802	0.3355	0.5121	0.8398	0.8651	0.4586	0.7893	0.5017	0.5139	0.3632	0.5941
2016	0.3931	0.2787	0.9044	0.2999	0.9555	0.9479	0.9634	0.4328	0.9450	0.4694	0.9544	0.4596	0.7509
2017	0.4038	0.4145	0.9540	0.0360	0.6101	0.4460	0.9388	0.5178	0.4545	0.6194	0.3916	0.6030	0.7495
2018	0.5204	0.5243	0.5070	0.2611	0.0883	0.2113	0.8405	0.5628	0.1532	0.2375	0.0453	0.7261	0.7969
2019	0.7117	0.7438	0.0450	0.2983	0.3800	0.0388	0.0543	0.3300	0.1405	0.2134	0.3578	0.8620	0.8803
2020	0.9458	0.9424	0.1841	0.9451	0.0464	0.2893	0.2508	0.9466	0.2957	0.0410	0.1184	0.9528	0.9650

Table 6
Ordering degree and system synergy degree of three-chain subsystems

Year	Industrial chain (S1) U1 (e1)	Innovation chain (S2) U2 (e2)	Service chain (S3) U3 (e3)	Synergy C
2012	0.0982	0.0916	0.1942	–
2013	0.2199	0.1589	0.3145	0.0995
2014	0.3803	0.5734	0.4519	0.3272
2015	0.3773	0.7161	0.4857	0.3704
2016	0.4905	0.7818	0.6270	0.4894
2017	0.3228	0.5603	0.5754	0.3424
2018	0.3167	0.3518	0.2809	0.1702
2019	0.3063	0.0994	0.4906	0.0784
2020	0.3727	0.3775	0.2585	0.1715

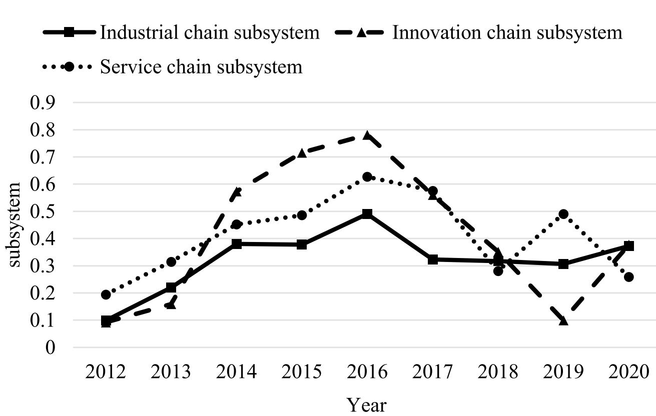

Figure 1. The three-chain subsystem order degree

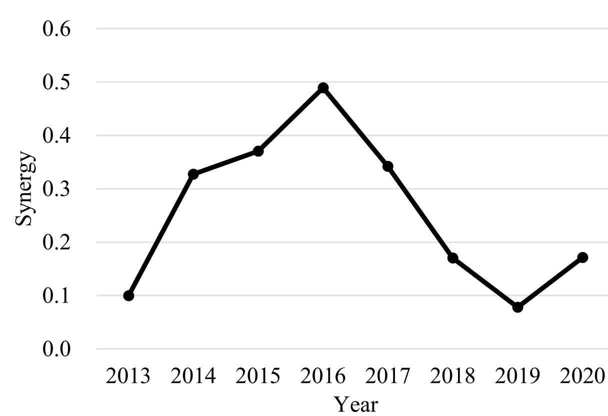

Figure 2. Three-chain composite system synergy

Table 7
Coordination degree of any two-chain composite system

Year	Synergy between industry and innovation chains	Synergy between industry and service chains	Synergy between innovation and service chains
2013	0.0905	0.1210	0.0900
2014	0.3687	0.2696	0.3524
2015	0.4175	0.2852	0.4267
2016	0.5204	0.4121	0.5466
2017	0.3245	0.2926	0.4227
2018	0.2384	0.1376	0.1502
2019	0.0403	0.2484	0.0481
2020	0.2801	0.1329	0.1356
Average synergy	0.2850	0.2374	0.2715

In addition, by substituting the order degree of three chains into equation (3), the integration levels of the industry and innovation chains, industry and service chains, and innovation and service chains are obtained, as shown in Table 7 and Figure 3.

Evaluation of three-chain integration level

Overall level of three-chain integration

The above calculation of the synergy of the composite system of Zhenjiang's industrial, innovation, and service chains reveals that the integrated development level of Zhenjiang's three chains from 2012 to 2020 was not high overall, exhibiting a fluctuating trend of first rising, then falling, and then rebounding. Specifically, the synergy of the composite system of Zhenjiang's industrial, innovation, and service chains is in the range of [0.0784–0.4894], and the average synergy is 0.2561, which is relatively low. According to the classification criteria of the composite system synergy presented above (Table 1), the three-chain integration level in 2013, 2018, and 2020 was at a low level, and the three chains in 2014 and 2017 were at a general level. Although individual subsystems' order degree is relatively high in some years, according to the barrel effect theory, the three-chain integration development level, representing the order degree of the whole composite system, should comprehensively consider the shortest path of the subsystems' order degree. From 2012 to 2016, although the order degree of the innovation chain continued rising and reached a high level, those of the industrial chain and service chain subsystems were at a low development level, resulting in a low degree of synergy for the whole composite system, and a low level of integration. From 2017 to 2020, the orderliness of the three-chain subsystem exhibited a downward trend, and the decline of the innovation chain subsystem was particularly evident, leading to low synergy across the entire composite system. The overall low level of integration and development indicates that the benign integration and development mechanism among the three chains of Zhenjiang is not fully formed, which also highlights the urgency and necessity of actively promoting three-chain integration.

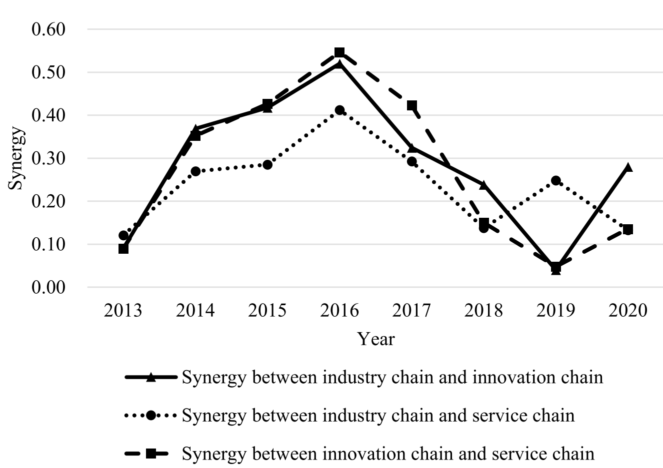

Figure 3. Integration of any "two chains"

In past years, the highest level of three-chain integration was in 2016, and each subsystem's order degree also reached the maximum in 2016. Among them, the order degree of the innovation and service chain subsystems were 0.7818 and 0.6270, respectively. Although the industrial chain subsystem's order degree was the highest over the years, it only reached 0.4905, leading to the low synergy of the composite system. The lowest level of three-chain integration was in 2019, and the low level of order of the innovation chain system in 2019 limited the level of collaborative development across the whole complex system, resulting in a low level of three-chain integration in 2019. In addition, in 2013, the order degree of each subsystem of the three chains was low, revealing a synergy degree of the composite system lower than 0.1, with a low level of integration.

Three-chain integration development trend

Based on the dynamic development process of the synergy evolution of the three-chain composite system in Zhenjiang, from 2012 to 2020, the synergy of the composite system was in a fluctuating evolutionary state of first rising, then falling, and then rebounding, revealing an overall downward trend. Specifically, taking 2012 as the base period, the overall three-chain integration level continued to rise from 2013 to 2016, with large increases. The value of synergy degree rose from 0.0995 in 2013 to 0.4894 in 2016, and the three-chain integration development level reached its height in 2016, but continuously declined from 2017 to the lowest in 2019. In 2020, the level of three-chain integration once again indicated an upward trend.

Development of each three-chain subsystem

The above analysis reveals that each subsystem's order degree determines the degree of coordination within the three-chain composite system. The higher the subsystem's order degree, the greater composite system's coordination degree and the better the synergy level. Based on the changes in each subsystem's order degree, the industrial chain order degree fluctuated between [0.0982–0.4905], with the lowest value of 0.0982 in 2012 and the highest value of 0.4905 in 2016. From 2012 to 2016, the order degree of the industrial chain showed a gradually increasing development trend. The development pattern gradually declined from 2016 to 2020. In general, the industrial chain order degree was low and the overall fluctuation range was not large. Compared with the industrial chain with a relatively stable fluctuation range, the innovation chain order degree fluctuated considerably, with a fluctuation range of [0.0916–0.7818]. It continued to rise from 2012 to 2016, and then continuously declined after reaching a peak in 2016. From 2014 to 2017, the order of the innovation chain reached a high level, indicating that the innovation chain experienced a high level of development during these four years. The service chain order degree fluctuated between [0.01942–0.0627], gradually fluctuating from 2012 to 2016 and exhibiting a downward trend after reaching the highest value in 2016. The order degree development of the three-chain subsystem reveals common points for all subsystems. First, the three-chain subsystem order degree showed an upward trend from 2012 to 2016 and a downward trend from 2017 to 2020. Second, the minimum value of the three-chain subsystem order degree appeared in 2012, and the maximum value appeared in 2016. This indicates that the three chains of Zhenjiang City are in a stage of gradual development, and the development circumstance in 2016 was the most ideal. In recent years, development level has fallen to a certain extent, and urgently requires the strategic policy attention of the government and relevant departments.

Integration of any two chains

Table 3 indicates that Zhenjiang's industrial chain and innovation chain integration from 2012 to 2020 is similar to that of the innovation and service chains, revealing the same fluctuating trend of first rising, then falling, and then rebounding. Both systems had the highest integration level in 2016, which then continued to decline until 2019, after which it exhibited an upward trend. This integration development is consistent with the three-chain integration trend. The industrial chain and service chain integration level had different characteristics. The industrial chain and service chain integration development trend was more volatile, indicating a familiar continuous fluctuation of first rising, then falling, then rising, and then falling. In 2019, the industrial and service chain integration level increased, indicating that the integration development level of the industrial chain and the innovation chain in Zhenjiang City in 2019 was better than that of the industrial and innovation chains and the innovation and service chains. This also demonstrates that the overall three-chain integration level in 2019 was primarily due to the innovation chain's low development level in that year. In addition, comparing the average fusion level between the two systems reveals that the fusion level of any two chains is at a low level of collaboration. In general, the integration of industrial and innovation chains was the best, followed by innovation and service chains, and the integration level is low. This suggests that Zhenjiang City is actively pursuing the policy of deploying the innovation chain around an industrial chain and laying out an industrial chain around the innovation chain.

Indicator system validation test

To confirm the reasonableness of the indicator system, it is necessary to first consider whether redundant indicators are evident, to verify that indicators are highly relevant. Second, it is essential to determine whether the indicator system is universally applicable. The independence and redundancy test is measured by the redundancy degree (RD) of the indicator system, and the spatial universality test of the indicator system is measured using sensitivity degree (SD) (Fu & Liu, 2009).

Redundancy degree test

Testing the RD of an indicator system measures the independence of the system and the redundancy of indicators. Let the correlation coefficient matrix of indicator system X be R and n be the number of indicators. The equation is expressed as follows:

$$R = \begin{bmatrix} 1 & r_{12} & \cdots & r_{1n} \\ r_{21} & 1 & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & 1 \end{bmatrix} \tag{4}$$

The average correlation coefficient is used to measure the redundancy of the indicator system. The RD calculation formula is as follows:

$$RD = \frac{\sum_{n}^{i=1} \sum_{n}^{j=1} \left| r_{ij} \right| - n}{n^2 - n} \tag{5}$$

where 0 < RD < 1, with smaller RD values indicating less redundant information in the indicator system. Due to the complexity of socioeconomic systems, indicators measuring socioeconomic development cannot be completely independent, and redundancy is considered acceptable as long as the average correlation between indicators is low. In general, when RD is less than 0.5, the redundancy of indicator system is considered to be low and can be accepted. In contrast, when RD is greater than 0.5, its redundancy cannot be accepted. This study calculates RD = 0.48, which is less than 0.5, and the redundancy does not exceed the critical value, confirming the streamlined and independent nature of the indicator system.

Sensitivity degree test

Sensitivity degree analysis of an indicator system is a method to test the extent to which errors in the evaluation process affect the evaluation results. It is used to measure the generalizability of the indicator system to different evaluation objects and is the primary approach for testing the reliability of the evaluation results. This study analyzes the extent to which small changes in indicators affect the evaluation results. If the evaluation results are consistent before and after the changes, this indicates that the evaluation results are insensitive to errors; otherwise they need to be adjusted.

For a system of evaluation indicators, the SD of the evaluation results to indicator X_i is defined as follows:

$$SD_i = \frac{\frac{\Delta V(X_i)}{V}}{\frac{\Delta X}{X_i}} \tag{6}$$

The formula for calculating the sensitivity of the indicator system is as follows:

$$SD = \frac{1}{n} \sum_{i=1}^{n} SD_i \tag{7}$$

The SD test shows the impact of a relative change in the evaluation result per unit relative change (e.g., 1%) in one or more of the indicators in the system. The larger the absolute value of SD is, the more sensitive the indicator system is and the less universal it is. From the perspective of confirming an indicator system's rationality, its absolute value should not exceed 5. According to the equation, this study calculated SD = 1.83, which is less than 5, indicating that the index system has strong universality. Combined with the results of the RD test, the indicator system constructed in this study is reasonable.

Optimizing paths

Strengthening the resilience of each chain

Based on the above findings, the strength of any chain will have enormous impact on the level of three-chain integrated development. In the process of promoting this development, it is crucial to enhance the resilience of each chain, stabilize, complement, and strengthen the chain, and effectively drive and enhance three-chain integration and mutual promotion. To do so, first independently cultivate leading industrial chains by developing regional comparative advantage industries, cultivating iconic industrial chains, and actively exploring industrial transformation and upgrading paths that align with local realities and regional industry characteristics. For example, Zhenjiang should promote the development of four key industrial clusters, including high-end equipment manufacturing, life and health, digital economy, and new materials, to develop new competitive advantages by cultivating leading industrial chains. Second, forging and strengthening innovation chains. Set up a number of national, provincial, and ministerial R&D institutions, innovation centers, and laboratories in response to market demands for key and core technologies common to the industrial chain, and encourage enterprises to invest more in R&D, particularly basic research. Promote the formation and establishment of consortiums for integrating key technologies, focus on breaking through bottlenecks in the industrial chain, develop a collaborative database for integrating key and core technologies, establish a dynamic innovation cooperation network and a community of shared interests, and promote the free flow of innovation elements along all chains. Third, consolidate interconnected service chains. Guided by the development needs of industrial upgrading and technological innovation, conduct and improve a series of service supporting measures that focus on supporting the development and growth of science and technology service enterprises. Finally, vigorously support the development of science and technology service demonstration zones such as high-tech zones and new science and technology cities.

Smooth the circulation of the entire chain

Three-chain integration is expected to be a process in which all chains interact with one another and collaborate to achieve circular and sustainable development. Only when the chains circulate smoothly can the system's integrated development be achieved. To do so, first, deploy innovation chains around industrial chains, focusing on key industrial chains. Deploy innovation chains to address key weaknesses and pain points, and strengthen applied basic research through consolidation. Implement "horse racing" and "unveiling the leader" systems for key and core technologies, strengthen the synergy between innovation and industrial chains, encourage scientific research institutions to innovate and transform scientific and technological achievements to meet industrial needs, and improve the ability to supply science and technology to key links in the industrial chain. Second, deploy the industrial chain around the innovation chain. For key R&D projects at national, provincial, and ministerial levels, leading enterprises should be organized to actively develop and put into production, promote the transformation and expedient deployment of technological achievements, and accelerate the cultivation and development of emerging industries. The exploration of frontier technological innovation should be more inclusive and fault-tolerant, encourage leading users to engage exploratory and developmental products, accelerate the application and industrialization of frontier technological achievements, leverage industrial transformation and upgrading with scientific and technological innovation, empower traditional industries, and promote new business forms and forms of industrial command. Third, optimize and improve the service chain around the industrial and innovation chains for support. Vigorously support the construction of specialized service institutions, provide basic conditions for scientific R&D and scientific and technological achievements, and provide design and development, professional marketing, intellectual property protection, and other services to improve innovative achievements. Focusing on the development of strategic emerging industries and the transformation and upgrading of traditional industries, establish a number of intermediary service institutions and enterprises that can provide information services, technical services, and policy advice and inject external impetus into industrial innovation and development.

Improve the three-chain integrated development mechanism

Three-chain fusion development requires effective policy support to strengthen top-level design, adjust measures to local conditions to support policies, accelerate the development of an information communication platform, optimize the talent introduction mechanism, leverage the role of the new national system preview layout and the development of three-chain fusion to provide the best service. First, accelerate the construction of a three-chain financing platform. Accelerate the transfer of R&D and innovation resources from developed regions to benefit less developed regions, improve regional innovative resource sharing, promote the free diffusion and optimal allocation of scientific and technological innovation resources and service elements, and fill the gap between technology R&D and enterprise production. Second, strengthen personnel training and management capabilities. The government should prioritize the cultivation and introduction of high-end talent and cultivating local talent, increase the introduction of skilled talent matching local industry, improve the flow and incentive mechanism for innovative talent, attract more high-end talent, and provide strong intellectual support for integrated three-chain development. Third, the government should break down regional administrative barriers and integrate innovative development across regions. In congruence with the development trend toward a "national unified big market," policymakers must accelerate innovation resources' docking between local and surrounding cities, advance the free flow of innovation and service factors between regions, open and share scientific and technological resources among innovation entities, and promote the transfer and transformation efficiency of innovation achievements.

Discussion

This study constructed an evaluation index system to assess the integration of industrial, innovation, and service chains, measured and evaluated Zhenjiang's three-chain integration level using a composite system synergistic degree model, and proposed an optimization path to promote three-chain integration.

Our study incorporated industrial, innovation, and service chains into the same research framework, considering the interactive relationships between industrial development and technological innovation as well as the bonding effect of scientific and technological services on the industrial and innovation chains. This research supports the view of Luoma-aho and Halonen (2010) that organization, technology, knowledge, capital, and other relevant factors catalyze and promote one another in a system to achieve symbiosis and continuity. It also supplements the existing research that has only considered the interaction between industry and innovation (Lin et al., 2018; Xing et al., 2021).

This study proposed a universal three-chain integration evaluation index system. Based on existing research (Humphrey & Schmitz, 2002; Bi et al., 2016), our study considers the structural characteristics of the industrial and service chains and the chronological logic of innovation activities, establishing six first-level indicators, including the industrial chain's degree of integration and upgrading, the innovation chain's R&D and achievement transformation stage, and the service chain's competitiveness and resource allocation capabilities. The methodology and findings are expected to provide an insightful reference for relevant research on three-chain integration and development.

Our study proposed the optimal path for promoting three-chain integration. Combined with the research conclusions of this study and the practical challenges to be urgently solved in China (Ma, Zhang, & Lin, 2022), the optimization path was proposed to integrate aspects of enhancing chain toughness, unblocking chain circulation, and improving the integration mechanism. It is of considerable practical value to achieve continuous innovation, promote high-quality development of industry, and advance the improvement of scientific and technological service levels.

Conclusion

Based on regional economic development, industrial policy, synergetic theories, and other relevant perspectives, this study reviewed the relevant literature regarding the aspects of the connotation and extension of three chains, integration relationships, and the processes of integration. A three-chain integration evaluation index system was constructed, combining the structural characteristics of the industrial and service chains and the time sequence logic of innovation activities; finally, 6 first-level indicators and 13 second-level indicators were developed. Taking Zhenjiang City as an example, data from 2012 to 2020 were selected to measure and evaluate the three-chain integration level using the composite system synergistic degree model. The relevant research results are threefold. (1) The overall three-chain integration level is low. In 2012–2016, the level of integration increased annually. From 2017, the level of integration exhibited a downward trend, until 2020, when the downward trend eased. The three-chain integration level in Zhenjiang has considerable space for improvement. (2) Among the three chains, the industrial chain subsystem had the worst order degree and should assume more responsibility for the low three-chain integration level. The industrial chain subsystem is the key factor restricting collaborative three-chain evolution. (3) Regarding the integration of any two chains, the level of integration of the industrial and innovation chains is the highest, indicating that China's development strategy of deploying the innovation chain around the industrial chain and laying out the industrial chain around the innovation chain has been effectively implemented. In this regard, this study proposed an optimization path to promote three-chain integration order and provide decision-making reference for each city to implement the innovation-driven development strategy and make greater strides in promoting high-quality economic development.

This study has expanded the discussion at theoretical and practical levels, leaving room for future exploration to be conducted. First, this study measured and evaluated the integration level of industrial, innovation, and service chains. Future studies could explore the economic effects generated by three-chain integration, such as whether the integration promotes high-quality economic development. Second, this study focused on the level of exploration after three-chain integration and lacked a process perspective in this regard. Future research can explore how to accelerate and solidify connections and integrate the three chains from a procedural perspective.

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