Supplementary Table S1. Summary of literature in the literature review section.

Author and Year	Research Focus	Core Methodology	Key Findings
Liu (2019)	Definition of the connotation of industrial chain modernization	Theoretical deconstruction and analysis from the element synergy perspective	The core of industrial chain modernization lies in the efficient allocation of key resources, including capital, technology, and talent.
Huang and Ni (2020)	Definition of the connotation of industrial chain modernization	Theoretical deconstruction and analysis from the global value chain perspective	Modernizing industrial chains requires enhancing positions within the global division of labor and developing autonomous and controllable capabilities.
Luo and Meng (2020)	Definition of the connotation of industrial chain modernization	Theoretical deconstruction and analysis from the industrial development perspective	Industrial chain modernization refers to the process of upgrading from low-end manufacturing to high-value-added segments.
Zhang et al. (2022)	Defining the connotation of industrial chain modernization and assessing its level	Theoretical deconstruction from a comprehensive perspective and the construction of a multi-dimensional indicator system	Industrial chain modernization represents a holistic enhancement of capabilities, innovation, resilience, and coordination; a six-dimensional measurement system has been developed to assess the dynamic evolution of China's industrial chain modernization level.
Zheng et al. (2021)	Measuring the level of industrial chain modernization	Construction of a multi-dimensional indicator system (five dimensions) and assessment of the modernization level	Assessing the level of industrial chain modernization in Jiangsu based on the dimensions of innovation, high-end development, sustainability, synergy, and self-reliance.
Liu et al. (2022)	Measuring the level of industrial chain modernization	Construction of a multi-dimensional indicator system (four dimensions) and assessment of the modernization level	Assessing the level of agricultural modernization based on the dimensions of cost, efficiency, sustainable development, and social development.
Liu (2025)	Measuring the level of industrial chain modernization	Construction of a multi-dimensional indicator system (five dimensions) and assessment of the modernization level	Assessing the industrial chain modernization in China based on the dimensions of structure, management, economics, synergy, and sustainability.
Chen and Chen	FDI and industrial chain	Empirical analysis and	OFDI and IFDI can strengthen the division of

(2024); Xing et al. (2024)	modernization	mechanism testing	labor and collaboration within industries, promote synergy between domestic and international economic cycles, and facilitate industrial modernization.
Zheng et al. (2023)	Industrial policy and industrial chain modernization	Empirical analysis and mechanism testing	Reasonable industrial policies have a positive effect on industrial chain modernization, with policy impacts varying across industries and regions due to their inherent heterogeneity.
Meng (2023)	"Chain Chief System" policy and the industrial chain modernization	Empirical analysis and mechanism testing	The "Chain Chief System" enhances industrial chain modernization in regions by optimizing factor allocation and strengthening innovation collaboration across upstream and downstream sectors.
Xing et al. (2023); Zheng (2025)	Human capital and industrial chain modernization	Empirical analysis and mechanism testing	Innovative human capital promotes the industrial chain modernization of the manufacturing sector. The regulatory effects of different talent policies vary.
Zheng and Luo (2024)	Data elements and industrial chain modernization	Empirical analysis and mechanism testing	The aggregation and circulation of data elements accelerate the deconstruction and reconstruction of industrial chains, providing critical support for their modernization.
Huo and Zhang (2024)	Artificial intelligence and industrial chain modernization	Empirical analysis and mechanism testing	Artificial intelligence drives industrial chain modernization by enhancing human capital quality, upgrading industrial structures, and elevating consumer demand.
Xi et al. (2023)	Digital transformation and industrial chain modernization	Empirical analysis and mechanism testing	Digital transformation drives industrial chain diversification and modernization through mechanisms such as trust building and supply chain strengthening.
Zhang and Ren (2023)	Digital economy and industrial chain modernization	Empirical analysis and mechanism testing	The digital economy provides systematic support for industrial chain modernization through factor expansion, carrier transformation, and dynamic innovation.
Silva-Oliveira et al. (2021)	Current research on two-way FDI in emerging economies	Scientific measurement methods	Revealing the knowledge structure and research gaps in the field of two-way FDI in emerging economies from 1994 to 2019.
Caetano et al. (2024)	Drivers of two-way FDI among EU countries	Empirical analysis	Sustainable development and renewable energy are common drivers of two-way FDI among developed countries.
Huang et al. (2010, 2016)	Two-way FDI and social equity in middle-income countries	Empirical analysis	Two-way FDI has a negative impact on income growth among the poorest groups, and its effects on income inequality exhibit regional and institutional heterogeneity.
You and	Two-way FDI and	Empirical analysis at	IFDI exerts a crowding-out effect on domestic

Solomon (2015); Tan et al. (2016); Islam et al. (2022)	domestic investment	the industry, regional, and national levels	investment, with institutional quality playing a moderating role.
Hanson (2010)	Russia's two-way FDI pattern	Empirical analysis	The analysis examines the impact of institutional and policy environments on Russia's two-way FDI patterns.
Goh and Tham (2013)	Malaysia's IFDI and foreign trade	Empirical analysis	This confirms the complementary relationship between IFDI and foreign trade in Malaysia.
Rozen-Bakher (2017)	Two-way FDI and employment structure in developed and developing countries	Empirical analysis	The impact of two-way FDI on employment structure differs between developed and developing countries.
Huang et al. (2018)	Measuring coordinated two-way FDI development	PVAR model, capacity coupling system model, quantitative measure	Validating the endogenous interaction between two-way FDI flows, this study quantifies for the first time the level of interactive development in China's manufacturing sector through two-way FDI.
Xu and Zhou (2021)	Factors Influencing coordinated two-way FDI development	Empirical analysis	Coordinated two-way FDI development is driven by economic growth momentum, industrial structure optimization and technological advancement.
Zou and Chen (2021)	Factors Influencing coordinated two-way FDI development	Empirical analysis	Institutional quality exerts a significant positive influence on coordinated two-way FDI development.
Wang et al. (2019); Gong and Liu (2020)	Coordinated two-way FDI development and environmental governance	Empirical analysis	Coordinated two-way FDI development significantly promotes environmental pollution control.
Ma et al. (2022); Dong et al. (2025)	Coordinated two-way FDI development and efficiency/quality enhancement	Empirical analysis	Coordinated two-way FDI development promotes green total factor productivity growth and enhances the quality of corporate export products.
Huang and Zhang (2022)	Coordinated two-way FDI development and global competitiveness	Empirical analysis	Coordinated two-way FDI development can help elevate a country's position in global value chains.
Song and Chen (2023); Xu et al. (2024)	Coordinated two-way FDI development and innovation capacity	Empirical analysis	Coordinated two-way FDI development significantly enhances innovation capabilities at the national or corporate level.

Supplementary Table S2. Final indicator system and weights.

Dimensional Layer	Guideline Layer	Indicator Preliminary Selection	Weight (%)
		Graded road mileage per 100 square kilometers(V_1)	1.8097

Foundation	Flow capacity	Operational railway mileage per 100 square kilometers(V_2)	2.3672
		Volume of cargo turnover(V_3)	4.1603
		Length of long-distance fiber optic cable per 10,000 people per unit area(V_4)	4.9705
Digitalization	Enterprise digitization	Computers per 100 population(V_5)	1.8288
	Industrial digitalization	E-commerce sales as a share of GDP(V_6)	3.2718
		Primary business revenue from electronic information manufacturing as a share of the manufacturing industry(V_7)	2.9361
Innovation	Innovative inputs	Full-time equivalent of R&D personnel in industrial enterprises above designated size(V_8)	6.2137
	Innovation outputs	Accepted PCT international patent applications(V_9)	13.4691
		Proportion of new product sales revenue in the primary business income of industrial enterprises above designated size(V_{10})	1.6763
Resilience	High-end leadership	Share of fixed-asset investment in productive services in the tertiary sector(V_{11})	1.1991
		Primary business income from high-tech manufacturing(V_{12})	7.1093
		The share of high-tech manufacturing in the total main business income of the manufacturing industry (V_{13})	1.8577
		Industrial structure rationalization(V_{14})	0.3435
		Industrial structure advancement(V_{15})	2.1038
	Chain control	Number of top 100 transnational corporations(V_{16})	11.0593
		Number of China's top 500 manufacturing companies(V_{17})	5.0729
		Number of China's most valuable brands(V_{18})	6.4518
	Profitability	Cost per 100 yuan of operating revenue for industrial enterprises above designated size(V_{19})	1.1946
		Main business revenue per 100 yuan of assets for industrial enterprises above designated size(V_{20})	1.4496
		Profit margin on operating revenue for industrial enterprises above designated size(V_{21})	0.0529
Synergy	Financial synergies	Balance of loans to financial institutions(V_{22})	3.3600
	Innovative synergies	External R&D expenditure for industrial enterprises above designated size(V_{23})	7.0356
		External R&D expenditure for industrial enterprises above designated size as a share of GDP(V_{24})	2.5970
	Industrial synergies	EG index of manufacturing and productive service industries' synergistic agglomeration(V_{25})	0.3106
Sustainability	Energy efficient production	Energy consumption per unit of GDP(V_{26})	0.4494
		Electricity consumption per unit of industrial value added(V_{27})	0.2249

Pollutant emission	Sulfur dioxide emissions per unit of industrial added value(V_{28})	0.1687
Green governance	Overall utilization rate of general industrial solid waste(V_{29})	1.1070
	Investment in industrial pollution control projects completed this year as a percentage of industrial value added(V_{30})	4.1489



Supplementary Figure S1. Spearman correlation coefficient heatmap for selected indicators from Table 1.

The construction process of the indicator system is as follows:

First, the preliminary indicators undergo dimensionless processing and directional alignment. Given that the indicator system includes both absolute and relative indicators, as well as positive and negative ones, their dimensions and magnitudes vary considerably. Direct integration may lead to weight imbalances or biased results. Therefore, standardization is essential to eliminate dimensional disparities and enhance comparability across indicators. Simultaneously, directional alignment ensures a uniform optimization direction for all indicators, thereby avoiding distortion in the comprehensive evaluation. Following the principle of applying a unified normalization formula to indicators of the same attribute and maintaining a consistent mapping range across different indicator types, all indicators are scaled to the [0,1] interval to ensure scientific rigor in the integration process. The standardization procedure is as follows:

The first category includes positive indicators, where higher values mean better outcomes. Min-Max normalization is applied to all such indicators—absolute or relative—to ensure comparability and consistency.

$$X'_{ij} = \frac{X_{ij} - \min\left(X_j\right)}{\max\left(X_j\right) - \min\left(X_j\right)} \tag{S1}$$

According to Equation (S1), positive relative and absolute indicators are normalized using their extreme value ranges and scaled to the [0,1] interval, eliminating dimensional differences and ensuring comparability.

The second category includes negative indicators, where lower values mean better outcomes. Reverse Min-Max normalization is applied to all such indicators—absolute or relative—to ensure consistent directional alignment and evaluation consistency.

$$X'_{ij} = \frac{\max\left(X_j\right) - X_{ij}}{\max\left(X_j\right) - \min\left(X_j\right)} \quad \text{(S2)}$$

According to Equation (S2), negative relative and absolute indicators are standardized using their extreme values and scaled to the [0,1] interval. This reverse Min-Max method removes dimensional differences, normalizes values, and aligns negative indicators in the same direction, preventing evaluation bias from conflicting directions.

Second, this study conducts correlation analysis and indicator screening. To mitigate information redundancy caused by high intercorrelations among indicators within the same criterion layer, Spearman correlation analysis is performed on the primary indicators standardized using the Min-Max method, with an absolute correlation coefficient threshold of 0.8. Indicators exceeding this threshold are excluded. Correlation coefficients for selected indicators are shown in Table 2. The analysis shows that the correlation coefficients between V_{10} and V_{11}, V_{12} and V_{13}, V_{12} and V_{14}, V_{15} and V_{16}, and V_{19} and V_{21} are 0.837, 0.899, 0.979, 0.823, and 0.936, respectively—all above the threshold—indicating substantial multicollinearity that necessitates further indicator screening. V_{10}, an absolute measure of electronic information industry scale, has limited capacity to reflect technological integration, whereas V_{11}, a relative indicator, better captures digital empowerment; thus, V_{11} is retained and V_{10} excluded. V_{12} reflects R&D personnel density, collaboration efficiency, and sustained innovation, showing stronger links to innovation outputs than funding-based indicators. V_{13} and V_{14}, though measuring capital investment, are affected by management efficiency and equipment procurement, weakening their accuracy in representing innovation input; therefore, V_{12} is retained. V_{15}, with standardized criteria and rigorous review, accurately captures core technological value and global deployment, closely aligning with high-quality innovation outputs. V_{16} is distorted by transaction authenticity issues and policy subsidies, leading to inaccurate measurement of technological value; hence, V_{15} is retained and V_{16} excluded. V_{21} covers China's high R&D, technology-intensive industries, reflecting high-tech development comprehensively and aligning with OECD standards for strong international comparability. V_{19} reflects China-specific statistical definitions, limiting global comparability; therefore, V_{21} is retained and V_{19} excluded.

Third, this study conducts discriminant ability analysis and indicator screening. This analysis assesses each indicator's contribution to measuring industrial chain modernization over time, with effectiveness evaluated by calculating the internal consistency coefficient. Following established research standards, indicators with a coefficient above 2 are excluded; others are retained [50]. The results show that thirteen indicators—V_4, V_7, V_8, V_{20}, V_{23}, V_{30}, V_{31}, V_{33}, V_{36}, V_{37}, V_{38}, V_{39}, and V_{40}—exceed this threshold and are therefore removed during screening.

Fourth, this study conducts rational screening and analysis of the indicators. Based on correlation and internal consistency coefficient analyses, redundant or poorly discriminative indicators are removed, and an initial evaluation index system for

industrial chain modernization is established. However, relying solely on statistical criteria may overlook the economic meaning of indicators, risking the exclusion of key variables with practical significance. Therefore, building on the quantitative screening results, this study integrates theoretical logic with practical representativeness to rigorously assess the indicators and reintroduces seven critically important ones: V_{23}, V_{31}, V_{36}, V_{37}, V_{38}, V_{39}, and V_{40}. The reasons are as follows:

V_{23} directly measures high-end empowerment and leadership across three dimensions — industrial chain collaboration, factor allocation, and supply-demand matching. It supports industrial chain resilience by enabling control over high-end segments, regulating risk transmission, and governing technological iteration. Excluding this indicator would weaken the assessment of strategic controllability and distort the evaluation of resilience relative to actual operational dynamics.

V_{31} directly reflects revenue-to-profit conversion efficiency, capturing the industrial chain's profit stability and resilience to risks such as cost fluctuations and market changes. Compared with excluded V_{30}, V_{31} emphasizes operational resilience more strongly and better aligns with the industrial chain's day-to-day risk response mechanisms.

V_{36} quantifies the level of collaborative agglomeration between manufacturing and producer services. It effectively captures collaborative characteristics such as functional complementarity, resource sharing, and enhanced collaboration efficiency, making it a key variable for characterizing industrial linkage relationships.

V_{37}, V_{38}, V_{39} and V_{40} can effectively reflect the performance of the industrial chain in energy-saving production, pollution discharge and green governance. They not only demonstrate their current resource utilization efficiency and environmental impact level, but also their sustainable development capacity and green governance level in the long-term operation to break away from the high-consumption and high-pollution mode. The four indicators complement each other's functions and have different focuses, jointly constructing a multi-dimensional assessment framework for the sustainability of the industrial chain.