

Article

Manufacturing Industrial Chain and Supply Chain Resilience in the Yangtze River Economic Belt: Evaluation and Enhancement Under Digitalization and Greening

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Abstract: Considering the potential impacts of digitalization and greening in manufacturing on industrial chain and supply chain (ICSC) resilience, this paper develops a multi-dimensional evaluation index system. The system includes immune resistance, adaptive resilience, autonomous control, innovation competitiveness, and development sustainability. Using the entropy weight method, we measure manufacturing ICSC resilience across provinces and cities in the Yangtze River Economic Belt from 2017 to 2022 and further comprehensively analyze its spatiotemporal evolution and key influencing factors. The findings indicate that though the overall ICSC resilience in the region is relatively high, significant disparities exist between provinces and cities. The average resilience index value of the Yangtze River Delta region remained above 0.4, while that of other provinces was generally below 0.2. The spatial distribution of resilience shifted significantly during the study period, with marked improvements observed in all the regions. The number of high-value areas increased from three to nine, while only two areas had relatively lower values. Furthermore, the financing environment and the degree of digitization exhibited a strong positive correlation with resilience, whereas price fluctuations and excessive government intervention exerted adverse effects. Finally, this paper proposes corresponding policy recommendations to enhance ICSC resilience.

Keywords: industrial chain and supply chain resilience; entropy weight method; spatiotemporal evolution; digitalization and greening



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1. Introduction

Under the trend of de-globalization, the industrial chain and the supply chain (ICSC) are becoming increasingly fragmented and regionalized [1]. This transformation exposes the ICSC to systemic risk. In 2022, the report of the 20th National Congress of the Communist Party of China proposed to stress the innovative development of ICSC resilience and enhance the resilience and security of ICSC operations [2]. This important statement elevates the enhancement of ICSC resilience to the strategic height of safeguarding national industrial security [3–5]. The manufacturing industry is the pillar industry of China's national economy. In 2024, the added value of the manufacturing sector reached USD 4.67 trillion, accounting for a quarter of the national GDP. However, the frequent occurrence of geopolitical conflicts and the impact of the pandemic have further highlighted the deep-seated problems that have long existed in the ICSC. The manufacturing ICSC exhibit a large scale but insufficient strength, having wide coverage but lacking refinement,

while some high-end ICSCs demonstrate high foreign dependence. Against this background, enhancing China's manufacturing ICSC resilience has evolved from an economic requirement to a strategic imperative for risk mitigation, adaptability improvement, and competitiveness maintenance.

The Yangtze River Economic Belt (YREB) is an important east–west economic corridor in China, covering 11 provinces and municipalities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou. The specific geographical location of the YREB is shown in Figure 1. As China's "Golden Economic Belt" with the largest industrial scale and broadest regional influence, the YREB is a key part of China's manufacturing ICSC. In 2023, the regional gross domestic product of the YREB reached USD 3.8 trillion, constituting 46.8% of the national total (<https://www.news.cn/> (accessed on 22 February 2025)). Leveraging its integrated river–sea transportation network, cross-regional resource allocation capabilities, and strategic geographical proximity to global markets, this economic belt has effectively mitigated structural fragmentation in China's manufacturing ICSC while significantly impacting their resilience [6].

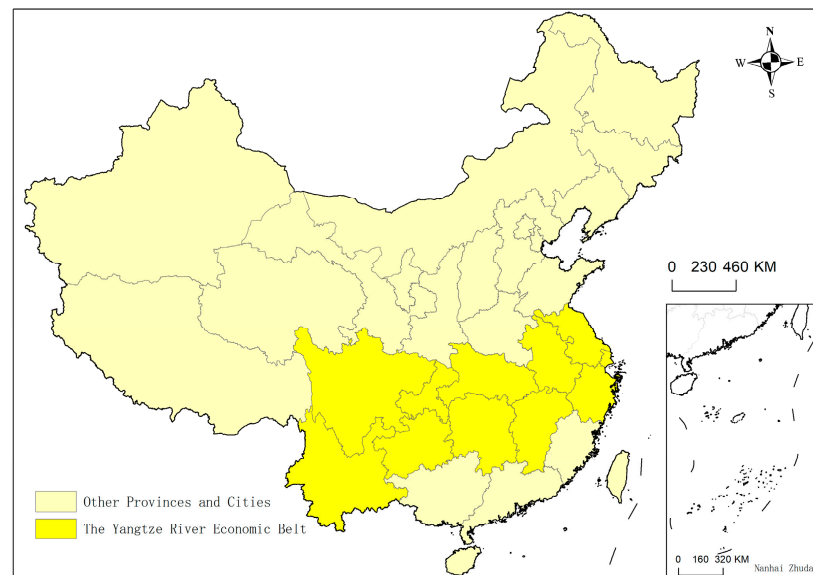


Figure 1. Location map of the YREB.

Enhancing the resilience of the ICSC is critical to achieving sustainable development goals [7]. To further enhance ICSC resilience, the 14th Five-Year Plan for YREB Development emphasizes “digitalization and greening dual-driven transformation” as core mechanisms. This strategy not only aligns with the global sustainable development goals but also holds profound significance for enhancing ICSC resilience. In practice, enterprises are also actively promoting the digitalization and greening of manufacturing (<http://www.citmt.cn/news/202408/107344.html> (accessed on 22 February 2025)). Digitalization can significantly enhance supply chain efficiency by optimizing production processes and promoting technological innovation. Specifically, big data analyses and internet of things technologies enable the real-time monitoring of production processes, precise risk prediction, and rapid plan adjustments, thereby effectively reducing the impact of ICSC disruptions. Moreover, digitalization also promotes information sharing among enterprises, strengthens the collaborative capabilities of upstream and downstream partners, and builds a more adaptable supply chain network. The greening of manufacturing means implementing processes that are technologically advanced, consume fewer resources, and have a smaller environmental impact. This greening can reduce reliance on non-renewable resources, enhance resource utilization efficiency, and thus make the ICSC more resilient

in the face of resource shortages or changes in environmental policies. In short, the advancement of digitalization and greening has become an important support for enhancing manufacturing ICSC resilience.

It can be concluded that digitalization and greening are of significant importance to ICSC resilience in the manufacturing sector. Therefore, when measuring ICSC resilience, the impacts of both digitalization and greening must be taken into account simultaneously. However, this practical problem has been rarely studied in the previous literature. In this paper, we aim to fill this research gap. Specifically, our research aims to answer the following questions: (1) What is the level of YREB's manufacturing ICSC resilience under the digitalization and greening? (2) What are the spatiotemporal distribution characteristics of this region? (3) How to enhance ICSC resilience?

To provide a comprehensive assessment of the YREB's manufacturing ICSC resilience, this study constructs an evaluation index system for resilience based on the core attributes of the ICSC. The entropy weight method is employed to quantify resilience levels, while the spatiotemporal evolution characteristics and key influencing factors are analyzed. Finally, the evaluation results are used to propose actionable countermeasures to improve the level of resilience. The study reaches the following conclusions: Overall, the YREB demonstrates strong ICSC resilience, but significant regional disparities remain. The spatial distribution has also undergone significant changes. Regarding the influencing factors, the financing environment and digitization levels enhance resilience, whereas excessive government intervention and price fluctuations are detrimental.

This paper makes three major contributions. First, the indicator framework for assessing ICSC resilience in this study is no longer limited to conceptual definitions and intrinsic attributes but further incorporates considerations of digitalization and greening. Second, although some scholars have assessed manufacturing ICSC resilience, we further explore spatiotemporal differentiation characteristics. Lastly, instead of adopting a national-level framework, our research focuses on the YREB, conducting a detailed assessment of ICSC resilience within this region.

The structure of this article is as follows. After the introduction, Section 2 presents a literature review; Section 3 outlines the research methods, the construction of ICSC resilience evaluation index system, and the data sources used; Section 4 provides the analysis of results and corresponding countermeasures; and Section 5 concludes the paper.

2. Literature Reviews

This paper is closely related to the following three research areas: (i) the concept and connotation of ICSC resilience, (ii) the measurement of ICSC resilience, (iii) the enhancement paths of ICSC resilience. We briefly review the relevant literature in these areas.

2.1. The Concept and Connotation of ICSC Resilience

The concept of resilience has been extensively discussed and refined by scholars in recent years. The term "resilience" is derived from the Latin word "resilire", meaning to rebound. Initially used in physics, "resilience" describes a material's ability to return to its original state after deformation under external forces. In 1973, biologist Holling extends the concept of toughness to ecology [8]. In economics, Reggiani first introduces the concept of resilience in his study on the dynamic evolution of spatial economic systems [9]. Subsequently, regional economic resilience has gradually become a hot topic in economic research. Scholars often focus on urban resilience and economic resilience. Urban resilience refers to a city's ability to resist external shocks, adapt quickly to reduce losses, deploy resources efficiently, and recover rapidly, while potentially achieving breakthrough developments [10–12]. Economic resilience refers to the economic system's ability to re-

spond to external disturbances, resist risk shocks, adjust rapidly, and achieve sustainable, independent economic growth [13–15].

The continuous in-depth exploration of research has resulted in the introduction of the concept of resilience into the domain of industrial economy. The resilience of industrial chains and supply chains has begun to draw attention. Industrial chain resilience is generally defined as the ability of the industrial chain to maintain stability, recover swiftly from disruptions, and even achieve optimization and improvement in the face of external risks [16–18]. From a relatively micro perspective, the related research mainly focuses on supply chain resilience. The primary objective of supply chain resilience is to enable rapid recovery from unanticipated disruptions while also achieving strategic optimization and the systemic enhancement of operations [19–21].

ICSC resilience is a policy concept, and most scholars do not define the differences between the resilience of industrial chains and supply chains. ICSC resilience refers to the comprehensive ability of the ICSC to sustain the normal operation of key functions; rapidly recover to its original state or adapt to a more advanced state; and ensure sustainable development in a dynamic environment when encountering various internal and external disruptions (e.g., natural disasters, pandemics, and market fluctuations) [4,5,22].

Most of the current research on resilience focuses on the qualitative analysis of the concept definition, while quantitative research on the resilience of industrial chains and supply chains is still insufficient [4,5,22]. Therefore, based on the connotation of the ICSC, this paper constructs an evaluation index system to measure their resilience and conducts a systematic quantitative analysis.

2.2. The Measurement of ICSC Resilience

Based on the comprehension of the connotation of industrial chain resilience, scholars have conducted measurements of ICSC resilience from diverse angles. A considerable amount of research has been concentrated on establishing a single indicator or a comprehensive evaluation index system [23–25]. For example, Wu et al. [23] construct a coal ICSC resilience evaluation framework grounded in four core dimensions of resilience: preparedness, absorptive capacity, recovery capacity, and adaptability. Yang et al. [24] proposed a comprehensive framework encompassing multiple factors, including the absorptive capacity, adaptive capacity, and resilience, to assess supply chain resilience at both micro and macro levels. Du et al. [25] established an evaluation index system for the resilience and security of China's lighting industry chain from five dimensions: risk management level, integrity, control power, stability, and competitiveness. Le [26] measured China's manufacturing industry resilience chain from four dimensions: resistance response, adaptive flexibility, independent control, and leading competitiveness, using the entropy weight method for the evaluation. Moreover, some scholars have also measured resilience by using modeling methods. Chen et al. [27] measured industrial chain resilience based on the cost structure of supply chain operations in an environment of disruption. Xia et al. [28] employed an innovative index contribution technique to study manufacturing industry chain resilience in the ever-changing digital economy.

Existing research on the assessment of the resilience of industrial chains and supply chains is mostly based on their connotations [23–25]. In the current context, embedding the assessment of the resilience of industrial chains and supply chains into sustainable development goals is of great significance. Moreover, most existing studies measure the resilience of industrial chains and supply chains at the macro level across multiple industries [26–28]. This paper focuses on the YREB for measurement, which is conducive to more accurately identifying the specific causes of insufficient resilience in industrial chains and supply chains.

2.3. The Enhancement Paths of ICSC Resilience

In recent years, scholars have begun to pay attention to the significant importance of enhancing ICSC resilience [29,30]. To enhance ICSC resilience, scholars have conducted research on the impact of industrial structure, emerging technology, digitalization, and green development on resilience [31–33]. Capello et al. [34] indicated that the rationalization of the industrial structure can continuously expand the potential for industrial development and the capacity to respond to risks, thereby enhancing ICSC resilience. Chatterjee et al. [35] demonstrated that the emerging technologies of companies exert a positive impact on supply chain resilience and corporate performance. Tortorella et al. [36] empirically demonstrated that the digital economy plays a positive role in augmenting resilience. Further, Hao et al. [37] analyzed the historical and current logic of China's industrial security and development and studied how to enhance industrial chain resilience through the digital economy. Li et al. [38] examined the influence mechanism of the synergistic interaction between digitalization and greening in the manufacturing sector on the industrial chain. The research findings suggest that its impact on industrial chain resilience exhibits regional variations.

Moreover, scholars have conducted theoretical research on how to improve ICSC resilience. In terms of digitalization, strategies to enhance resilience include the rational allocation of resources, the optimization of factor combinations, the establishment of dynamic evaluation mechanisms, strengthening support for industrial digitalization, and promoting collaborative technological innovation and the construction of digital intelligence systems [39–41]. In addition, the greening of supply chains plays a crucial role in promoting sustainable development and enhancing resilience. From the perspective of modeling, scholars have studied the optimal decision-making, network design, and coordination contracts for the green supply chain [42–44].

Existing research indicates that digitalization and greening are crucial for enhancing ICSC resilience [36–38]. Therefore, when assessing ICSC resilience, digitalization and greening should be taken into account. Based on this, this article aims to further measure the sustainable development of the ICSC and their ability to cope with future uncertainties through a systematic assessment method, thereby achieving a scientific and reasonable evaluation of ICSC resilience.

This paper differs from the previous literature in three ways. Firstly, although some scholars have constructed indicator evaluation systems to measure China's ICSC resilience [23–26], they have paid relatively little attention to the impact of digitalization and greening on ICSC resilience. As mentioned earlier, digitalization and greening are of great significance for ICSC resilience. The digitalization and greening of manufacturing are important means to improve manufacturing's productivity, quality, and sustainable development [45]. Hence, this paper differs from the literature by further considering the digitalization and greening of the manufacturing industry. Secondly, most previous studies qualitatively analyze the role of various influencing factors in ICSC resilience [30–33]. This paper differs from the literature by conducting a spatiotemporal evolution analysis and further explores the dynamic differences between regions. Lastly, existing research predominantly examines ICSC resilience at the macro level. This paper differs from the literature by concentrating on the YREB's ICSC resilience. This paper conducts a systematic review of manufacturing development patterns across 11 regions within the economic belt and deeply analyzes the strengths and weaknesses of each region. Based on this, this paper proposes specific solutions for enhancing China's ICSC resilience.

3. Research Design

3.1. ICSC Resilience Analysis Framework

Based on the connotation of ICSC resilience, scholars believe that ICSC resilience refers to the chains' ability to weather disruption, adapt, and recover after suffering a certain degree of damage when exposed to external shocks [4,5,22]. In the context of digital transformation, the ICSC have achieved a dynamic and evolving "high-level resilience" through technological empowerment. This high-level resilience enables the ICSC to break through the traditional framework and leap towards a more efficient and competitive form. Moreover, environmental pressures drive the ICSC to enhance their adaptability in relation to climate crisis mitigation. The ICSC also need to reduce their reliance on and damage to the environment through resource recycling, the application of low-carbon technologies, and the upgrading of green processes. Such greening capacity forms a critical resilience component and represents a strategic pathway for sustainable development goal attainment. Therefore, ICSC resilience is not only reflected in the chains' ability to withstand risks, but also in their capacity to update and upgrade to a better state and achieve sustainable development. Based on the above connotations, this paper categorizes ICSC resilience into five dimensions:

Immune resistance: it manifests in withstanding potential risks and uncertainties via the cooperation of multiple market players, a strong industrial foundation, and a complete closed-loop supply chain ecosystem, thereby preventing disruptions. This is the foundation of ICSC resilience.

Adaptive resilience: Building on immune resistance, it enables the chains to quickly stabilize and recover after being damaged by using their adaptability and rapid-recovery capabilities. It is the key to maintaining overall system resilience under pressure.

Autonomous control: it manifests in governing products, ecosystems, and critical technologies post-recovery, ensuring sustained development and operational continuity after normal conditions are restored.

Innovation competitiveness: It manifests in the leveraging of technological advancements and business model innovation to expand into high-value-added sectors and propel comprehensive advancement. This capacity is pivotal for elevating ICSC resilience.

Development sustainability: It manifests in the enhancement of resource efficiency, the implementation of green governance, the advancement of green and low-carbon initiatives, and the alignment of growth with carbon neutrality objectives. This is indispensable for ensuring long-term resilience.

Based on the above analysis, the five "forces" include immune resistance, adaptive resilience, autonomous control, innovation competitiveness, and development sustainability. These forces synergistically constitute an interconnected and mutually reinforcing whole. Additionally, ICSC resilience is influenced by factors such as price fluctuation, the financing environment, the digitization level, and government intervention. Therefore, the analysis framework for ICSC resilience is illustrated in Figure 2.

3.2. Construction and Selection of Evaluation Index System

3.2.1. Index System for Measuring ICSC Resilience

Based on the theoretical framework of ICSC resilience and its development logic, and referencing indicators from existing studies [23–25], an evaluation system for ICSC resilience was developed as follows:

- (1) **Immune resistance.** In the development process of industrial chains and supply chains, it is necessary to effectively organize and integrate resources and coordinate actions to enhance the ability to respond to risks and challenges. This response capacity mainly relies on "economic strength". Therefore, the selected evaluation indicators

mainly include two aspects: economic scale and economic benefits. The selection of the third-level indicators refers to previous research [23].

- (2) Adaptive resilience. This response capacity mainly relies on “economic potential”. The three aspects of human capital, social factors, and industrial contribution, respectively, correspond to the production subject, production factors, and output efficiency. This not only can measure the current state of the ICSC, but also reflect their future potential, thereby enabling a dynamic assessment of the recovery and adjustment capabilities of the ICSC after being impacted. Therefore, the selected evaluation indicators mainly include three aspects: human capital, social factors, and industrial contribution. The selection of the third-level indicators refers to previous research [24].
- (3) Autonomous control. Market entities drive technological development and industrial upgrading, and their innovation capabilities define ICSC resilience. Upstream–downstream coordination and industrial clustering in the ICSC enhance stability and mitigate breakage risks. Industrial cooperation is a key factor in determining the stability and reparability of the industrial chain. The investment environment can stably guarantee the supply of resources and provide continuous long-term support for technological transformation and business expansion. Through a dynamic cycle of “micro-innovation, meso-synergy, and macro-guarantee”, market entities, industrial cooperation, and the investment environment jointly establish a self-contained ICSC system. Therefore, the selected evaluation indicators mainly include three aspects: market entities, industrial cooperation, and the investment environment.

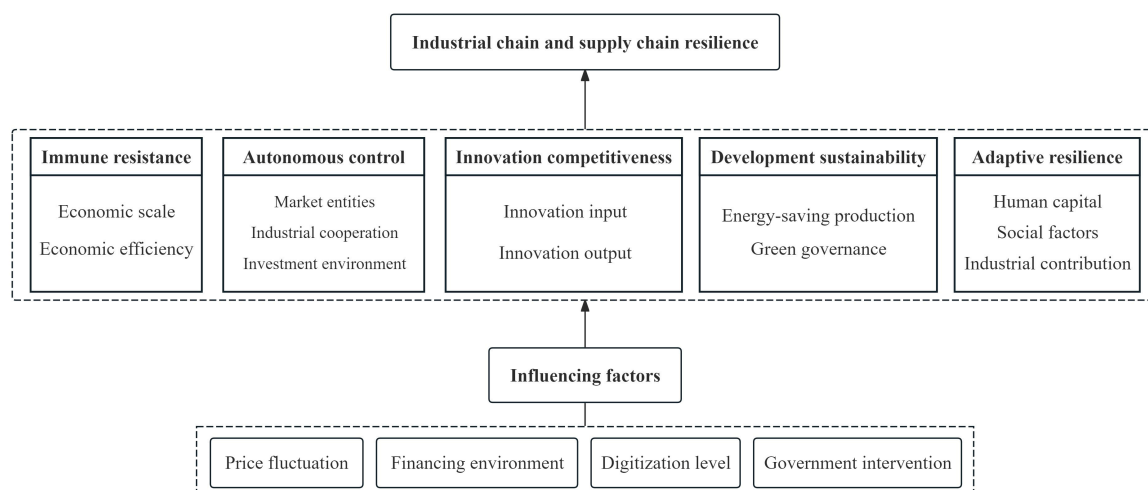


Figure 2. ICSC resilience analysis framework.

Following the existing literature, we used the number of high-tech enterprises as an indicator to measure market entities. “Little Giant” enterprises, as “key nodes” in the ICSC, have significantly enhanced the autonomy, controllability, risk resistance, and global competitiveness of China’s industrial chain through technological breakthroughs, collaborative innovation, and flexible responses to market demands. Therefore, “Little Giant” enterprises play a crucial role in enhancing ICSC resilience. In this paper, the number of “Little Giant” enterprises is also selected as a core indicator when measuring market entities. The selection of the remaining third-level indicators refers to previous research [25].

- (4) Innovation competitiveness. The digital economy era makes it necessary to follow the trend of technological revolution, industrial transformation, and the enhancement of innovation. Accelerating the optimization and improvement of the ICSC is important. Therefore, technological innovation indicators (inputs and outputs) serve as key

yardsticks to measure ICSC improvement. Input indicators ensure continuous investment in breakthrough innovations, whereas output indicators evaluate value-added capabilities. Therefore, the selected evaluation indicators mainly include two aspects: innovation inputs and innovation outputs. The selection of the third-level indicators refers to previous research [26].

- (5) Development sustainability. Energy-saving production promotes the greening of the ICSC through technological means. Green governance, with clear carbon reduction targets and a complete ESG regulatory system, comprehensively facilitates the achievement of carbon reduction goals throughout the entire ICSC. This not only significantly reduces energy dependence but also effectively enhances the resilience and sustainable development capabilities of the ICSC. Therefore, the selected evaluation indicators mainly include two aspects: energy-saving production and green governance.

This paper employs the following indicators for measurement. The unit GDP electricity consumption quantifies the industrial chain's energy efficiency. The industrial solid waste utilization rate measures resource recycling levels and green production substitution effects. The pollution control investment proportion evaluates the enterprise investment intensity and the green transformation implementation capacity. These indicators can systematically assess the sustainable development capacity of the ICSC under the background of carbon neutrality and effectively reflect ICSC resilience.

The system includes 5 primary indicators, 12 secondary indicators, and 24 tertiary indicators, comprising 20 positive indicators and 4 negative indicators. The evaluation index system is presented in Table 1.

Table 1. ICSC resilience evaluation system.

Primary Indicators	Secondary Indicators	Tertiary Indicators	Indicator Category
Immune resistance	Economic scale	Total GDP (X1)	+
		GDP growth rate (X2)	+
	Economic efficiency	GDP per capita (X3)	+
		Industrial added value (X4)	+
		General public budget revenue (X5)	+
		Total profits of industrial enterprises above designated size (X6)	+
Adaptive resilience	Human capital	Urban registered unemployment rate (X7)	—
	Social factors	Average wage of urban unit employees (X8)	+
		Engel coefficient of resident (X9)	—
	Industrial contribution	Growth rate of completed fixed asset investment (X10)	+
Autonomous control	Market entities	Number of national “little giants” firms (X11)	+
		Number of high-tech enterprises (X12)	+
	Industrial cooperation	Total foreign investment (X13)	+
		Number of foreign-invested enterprises (X14)	+
	Investment environment	Total import and export value (X15)	+
		Foreign trade dependence (X16)	—

Table 1. Cont.

Primary Indicators	Secondary Indicators	Tertiary Indicators	Indicator Category
Innovation competitiveness	Innovation input	Full-time equivalent of R&D personnel in industrial enterprises above designated size (X17)	+
		Number of enterprises with R&D activities above designated size (X18)	+
		Expenditure on new product development by industrial enterprises above designated size (X19)	+
	Innovation output	Sales revenue of new products in industrial enterprises above designated size (X20)	+
		Number of patent applications by industrial enterprises above designated size (X21)	+
Development sustainability	Energy-saving production	Power consumption per unit of GDP (X22)	—
	Green governance	Comprehensive utilization rate of industrial solid waste (X23)	+
		Investment in industrial governance as a proportion of industrial added value (X24)	+

Note: “+” is a positive indicator and “—” is a negative indicator.

3.2.2. Index System of Influencing Factors

Following the principles of systematization, objectivity, representativeness, and data accessibility and based on previous studies [46–48], price fluctuation, financing environment, digitization level, and government intervention were selected for analysis. Price fluctuation was operationalized through the producer price index’s volatility, while the financing environment was quantified via aggregate loan balances across financial institutions. The digitalization capacity was proxied by urban employment concentrations in information technology sectors (encompassing software development and data transmission services). The government intervention intensity was measured as the proportion of state-controlled enterprises within the cohort of large-scale industrial manufacturers.

3.3. Research Methods

3.3.1. Entropy Weight Method

Comprehensive evaluation methods systematically assess multiple indicators and units using standardized procedures. Researchers classify these methods into subjective weighting and objective weighting categories based on weight determination mechanisms. Subjective weighting methods depend on expert judgments, which reduces their objectivity. Derived from information entropy theory, the entropy weight method calculates index weight values through data dispersion analyses. This technique eliminates any experiential bias by relying exclusively on quantitative data characteristics, demonstrating particular efficacy in multidimensional system evaluations. Due to its mathematical rigor and strong universality, the entropy weight method has been widely applied in the research of index measurement in various fields [24–26].

To comprehensively assess ICSC resilience, this study employed the entropy weight method. Following standard computation procedures, the method objectively determines index weights through empirical data variability analyses. The calculation process was as follows.

Step 1: Min-Max Normalization.

When the indicator is positive, its standardized formula is

$$x_{ij}^* = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

When the indicator is negative, its standardized formula is

$$x_{ij}^* = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

To prevent the index value from becoming 0 after standardization, the standardized value is adjusted by a translation factor, H ($H > 0$).

$$x_{ij}^{**} = x_{ij}^* + H \quad (3)$$

where H represents the translation magnitude, and 0.001 is used in this paper.

Step 2: Proportional Allocation:

$$P_{ij} = \frac{x_{ij}^{**}}{\sum_i^n x_{ij}^{**}} \quad (4)$$

Step 3: Entropy Quantification:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^n p_{ij} \ln p_{ij} \quad (5)$$

where m represents the number of cities, and n represents the number of indicators, $0 \leq e \leq 1$.

Step 4: Weight Derivation:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^m (1 - e_j)} \quad (6)$$

Step 5: Composite Scoring:

$$z_j = \sum_{j=1}^m x_{ij}^{**} w_j \quad (7)$$

3.3.2. Panel Data Regression Model

We selected the fixed effects regression model based on the Hausman test results, and it is expressed as follows:

$$R_{it} = \alpha + \beta_{i1} * PF + \beta_{i2} * \ln(FE) + \beta_{i3} * DL + \beta_{i4} * GI + \varepsilon_{it} \quad (8)$$

where R_{it} represents the elasticity index of the ICSC in year t for province i . β_{it} is the parameter vector for the independent variables of the influencing factors; PF , FE , DL , and GI represent the price fluctuations, financing environment, digitization level, and government intervention, respectively; α is the constant term; and ε_{it} is the random error term.

3.4. Data Sources

This article selected the period from 2017 to 2022 as the research period. During this period, major events, such as the Sino-US trade friction, the COVID-19 pandemic, and the Russia-Ukraine conflict, successively impacted the global supply chain. A five-year time span enabled the effective capture of policy implementation effects and revealed significant variations in resilience across the pre-treatment and post-treatment periods, thereby

fulfilling the longitudinal comparison and dynamic analysis requirements. Moreover, this period coincided with the critical phase of the digital economy and green technology deeply empowering manufacturing industries. The YREB features both industrial gradient differences and the characteristics of the world's largest manufacturing cluster. Its policy, technological, and crisis response logic, which combines regional particularity and overall representativeness, provides crucial empirical evidence for the upgrading of China's ICSC. Therefore, this study spanned 2017–2022, focusing on 11 provinces and cities along the YREB. Data sources included the *China Statistical Yearbook*, *China Science and Technology Statistical Yearbook*, *China Energy Statistical Yearbook*, *China Environmental Statistical Yearbook*, and reports from the National Bureau of Statistics, as well as provincial statistical yearbooks and the Statistical Bulletin of National Economic and Social Development. The missing data were filled by using provincial records or linear interpolation techniques.

4. Results and Analysis

4.1. Analysis of Temporal Changes in ICSC Resilience

4.1.1. Comparative Analysis of ICSC Resilience in Different Provinces

The values of ICSC resilience for provinces and cities in the YREB from 2017 to 2022 were calculated by using the entropy weight method. Based on the resilience measurements, the time weights were determined by adopting the “emphasizing the present over the past” weighting method. Then, we applied a secondary weighting based on time weights to ICSC resilience indicator values. The results are shown in Table 2.

Table 2. Evaluation of ICSC resilience.

Province	2017	2018	2019	2020	2021	2022	Quadratic Weighting
Shanghai	0.3327	0.3249	0.3642	0.3715	0.4393	0.4797	0.3854
Jiangsu	0.5086	0.5524	0.5824	0.6427	0.7366	0.8224	0.6409
Zhejiang	0.3597	0.3982	0.4514	0.5187	0.6231	0.7296	0.5135
Anhui	0.1539	0.1619	0.1807	0.2057	0.2491	0.2871	0.2064
Jiangxi	0.0901	0.0960	0.1232	0.1288	0.1611	0.1680	0.1279
Hubei	0.1388	0.1594	0.1762	0.1793	0.2373	0.2858	0.1962
Hunan	0.1273	0.1367	0.1537	0.1747	0.2247	0.2533	0.1784
Chongqing	0.1001	0.1024	0.1137	0.1296	0.1569	0.1704	0.1289
Sichuan	0.1171	0.1317	0.1489	0.1760	0.2100	0.2393	0.1705
Yunnan	0.0456	0.0550	0.0770	0.0869	0.0895	0.0988	0.0755
Guizhou	0.0429	0.0539	0.0622	0.0769	0.0765	0.0951	0.0679

From 2017 to 2022, the overall levels of the YREB's ICSC resilience ranked as follows: Jiangsu, Zhejiang, Shanghai, Anhui, Hubei, Hunan, Sichuan, Jiangxi, Chongqing, Yunnan, and Guizhou, from the highest to the lowest (Table 2). The YREB's ICSC resilience exhibited a steady upward trajectory during the study period (Figure 3). Government-policy-driven initiatives drove this improvement. The State Council's 2017 Guiding Opinions on Supply Chain Innovation and Application enhanced industrial collaboration through servitization and intelligentization. From 2019 to 2020, the China–US trade conflict escalation and COVID-19 pandemic temporarily stagnated resilience growth, with some regions experiencing declines. However, from 2020 to 2022, the recovery measures combining epidemic prevention with enterprise resumption operations maintained ICSC stability while strengthening industrial linkages. During this period, the provincial implementation of three policy measures underpinned resilience enhancement: industrial infrastructure consolidation, supply chain efficiency pilot programs, and emergency support capacity

development. These coordinated efforts significantly mitigated the pandemic's impacts across YREB regions.

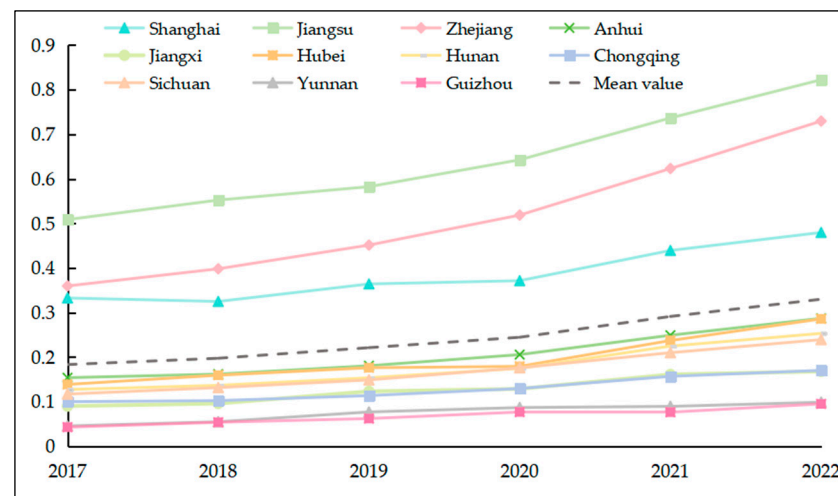


Figure 3. The evolution of manufacturing ICSC resilience in the YREB by province.

Specifically, manufacturing ICSC resilience in Jiangsu, Zhejiang, and Shanghai was consistently above average and steadily increased. Jiangsu Province particularly stood out. Its ICSC resilience index rose steadily from 0.5086 in 2017 to 0.8224 in 2022. It maintained the top position for six consecutive years. Zhejiang Province ranked second during the same period. Its resilience index increased from 0.3597 in 2017 to 0.5135 in 2022. In contrast, the average resilience levels of the other provinces in the YREB, except for the Yangtze River Delta region, were all below 0.2, with a significant disparity.

From the perspective of core indicators, in terms of the economic scale, Jiangsu's GDP rose from USD 1.18 trillion to USD 168.5 billion, with an average annual growth rate of 7.4%. Its industrial added value exceeded USD 666.4 billion, 1.8 times the combined total of Anhui, Guizhou, and Hubei. Disparities in innovation investment were even more pronounced. In 2022, the full-time equivalent of R&D personnel in Jiangsu's large and medium-sized industrial enterprises was 656,000 person-years, 3.6 times that of Anhui. The comparative analysis of economic benefits and energy-saving production revealed substantial regional disparities across the YREB provinces and cities. As a recipient of industrial transfers, Anhui recorded USD 32.7 billion in total profits of industrial enterprises above a designated size in 2022, only 26% of Jiangsu's USD 124.27 billion in the same year. Guizhou's industrial added value in 2022 was USD 75.3 billion, less than 16% of Jiangsu in 2017. Moreover, its power consumption per USD 1371 of the GDP was 864 kWh, reflecting a resource-dependent profile. This efficiency gap was particularly evident during periods of economic stress. During the 2020 pandemic, Shanghai's industrial added value rebounded due to a 25.7% increase in new product development funding. Meanwhile, Hubei's profits from large and medium-sized enterprises surged to USD 60.6 billion in 2021, driven by automotive industry recovery. These confirm that a diversified industrial structure is crucial for risk mitigation.

This regional disparity arises from differences in economic conditions. Coastal provinces, such as Jiangsu, Zhejiang, and Shanghai in the lower Yangtze River region, possess geographic advantages, robust industrial foundations, efficient supply chain networks, abundant innovation resources, and a significant developmental potential [49]. Meanwhile, the central and western provinces actively respond to national policies aimed at transforming the manufacturing sector. However, historical industrial development patterns have contributed to regional imbalances. These areas remain dominated by tra-

ditional industries, with a limited presence of emerging sectors and a predominance of low-end manufacturers over high-end ones. Consequently, the structural gap between these regions and Jiangsu, Zhejiang, and Shanghai hinders ICSC efficiency, thereby reducing the resilience of the central and western provinces and cities.

4.1.2. Comparative Analysis of ICSC Resilience in Different Dimensions

The levels of the YREB's manufacturing ICSC resilience from 2017 to 2022 were calculated based on five key dimensions: immune resistance, adaptive resilience, autonomous control, innovation competitiveness, and development sustainability. The results are shown in Figure 4.

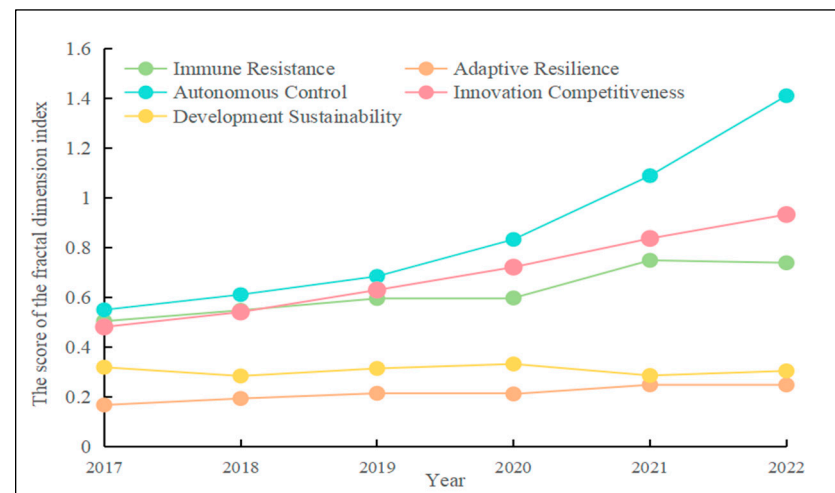


Figure 4. Fractal evolution of manufacturing ICSC resilience in the YREB.

From 2017 to 2022, the manufacturing ICSC in the YREB exhibited an overall upward trend in immune resistance from 0.503 (2017) to 0.738 (2022). However, the resilience index saw notable declines in 2020 and 2022, primarily due to external economic pressures. In 2020, the intensification of the US–China trade conflict and the COVID-19 pandemic significantly disrupted economic stability, which led to a dip in resilience. Similarly, in 2022, the index dropped again, falling from 0.74 to 0.73, which reflects challenges such as demand contractions, supply chain disruptions, and weakened economic expectations.

Despite these challenges, autonomous control and innovation competitiveness showed steady growth. Specifically, the autonomous control capability rose rapidly from 0.549 to 1.41, while innovation competitiveness increased from 0.48 to 0.93. This progress was driven by implementing national policies, leveraging industrial strengths, increasing technological innovation efforts, and reducing dependence on foreign trade. However, due to the destabilizing effects of the global economic downturn and anti-globalization trends, adaptive resilience indices ranged from 0.16 to 0.25 and development sustainability indices remained at approximately 0.3. These two dimensions' indices remained low. This hindered the YREB's recovery and long-term sustainable development.

4.2. Analysis of Spatial Variation in ICSC Resilience

This study further examined regional disparities in levels of ICSC resilience across YREB provinces and cities. It analyzed spatial variations in resilience levels during 2017, 2020, and 2022. Using a natural break point classification approach, resilience levels were categorized as follows: low-value (0.042–0.045), lower-value (0.045–0.100), medium-value (0.100–0.127), higher-value (0.127–0.154), and high-value (0.154–0.508). The spatial distribution and evolution of these levels are illustrated in Figure 5.

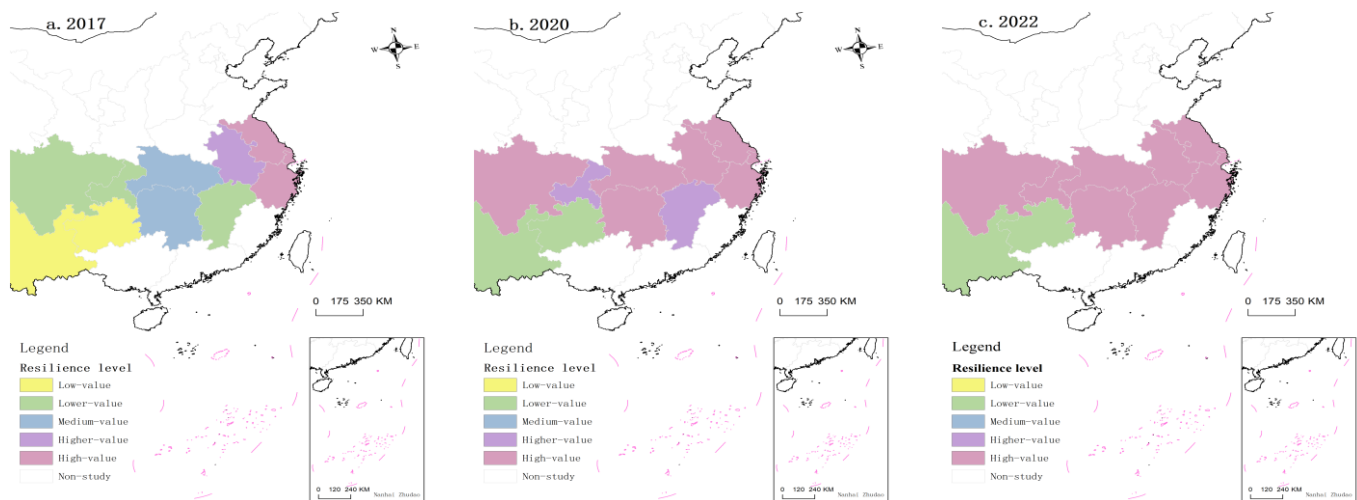


Figure 5. Evolution of spatial pattern of levels of ICSC resilience.

From 2017 to 2020, the spatial pattern of manufacturing ICSC resilience in the YREB underwent significant changes. High-value areas increased from three to seven, while low- and lower-value areas disappeared, decreasing from two to zero, and higher-value areas remained unchanged. Between 2020 and 2022, the pattern stabilized: high-value areas expanded further, increasing from seven to nine; higher-value areas were eliminated, decreasing from two to zero; and lower-value areas persisted unchanged.

The southern regions of the YREB demonstrated higher manufacturing ICSC resilience than the central and western regions. Jiangsu, Zhejiang, and Shanghai consistently maintained a high-value status due to their strong industrial foundation, strategic geographical location, advanced transportation infrastructure, high degree of openness, robust development of Sino–foreign joint ventures, and resilient manufacturing ICSCs. From 2017 to 2020, the resilience levels of Sichuan Province, Hubei Province, and Hunan Province rose significantly, transitioning from medium-value zones to high-value zones. This upward shift reflects their accelerated industrial upgrading, increased investment in infrastructure, and strengthened integration with the more developed middle and lower reaches of the YREB. Hubei, in particular, benefited from targeted policy support and a surge in industrial profits, while Sichuan and Hunan leveraged industrial transfer opportunities and actively cultivated emerging manufacturing clusters, improving their adaptive resilience and immune resistance.

Between 2017 and 2022, Jiangxi Province and Chongqing Municipality also experienced steady improvements, moving from lower-value zones into high-value zones. This progress can be attributed to enhanced regional connectivity, increasing digital transformation efforts, and the gradual optimization of their industrial structures. Both regions improved their innovation capacity and supply chain integration by actively participating in interprovincial industrial cooperation and attracting high-tech investments. Meanwhile, Guizhou Province, despite starting from a disadvantageous base, advanced from a bottom-tier position to the lower-value zone. This was primarily due to increased R&D activities and policy-driven support. Though its development sustainability remained relatively weak, the province showed upward momentum in resilience indicators.

Overall, by 2022, all the provinces within the YREB demonstrated varying degrees of improvement in ICSC resilience. This widespread enhancement was driven by a combination of national policy incentives, inter-regional industrial collaboration, infrastructure improvements, and efforts to reduce regional disparities in manufacturing capabilities.

Through an analysis of the spatiotemporal differences among various regions in the YREB, it might be found that changes in the financing environment, digitalization level, government intervention, and price fluctuations have an impact on ICSC resilience. Based on this, the following analysis will focus on these four key factors and evaluate their mechanisms of action on manufacturing ICSC resilience in the YREB.

4.3. Analysis of Influencing Factors

The variance inflation factor (VIF) test results are shown in Table 3. The results reveal that all the VIF values are below 10. This indicates that there is no multicollinearity among the selected influencing factor indices.

Table 3. Collinear diagnosis results.

Variable	VIF	1/VIF
Financing environment	2.95	0.340
Digitization level	2.52	0.397
Government intervention	1.40	0.716
Price fluctuations	1.05	0.950
Mean VIF	1.98	

To analyze the overall resilience and the resilience at each level across the 11 provinces and cities in the YREB, a fixed-effect regression analysis was conducted by using Stata 18.0 on panel data. The results of this analysis are presented in Table 4.

Table 4. Regression results of influencing factors on ICSC resilience.

Variable	Overall Resilience	Immune Resistance	Adaptive Resilience	Autonomous Control	Innovation Competitiveness	Development Sustainability
Price fluctuations	−0.0003 (−0.38)	0.0003 (1.18)	−0.003 ** (−2.40)	−0.0002 (−0.35)	−0.0004 (−1.09)	0.0002 (0.44)
Financing environment	0.0003 *** (19.63)	0.0000 *** (7.80)	0.0000 (0.62)	0.0001 *** (12.55)	0.001 *** (25.19)	−0.0000 (−0.47)
Digitization level	0.0133 ** (2.04)	0.0001 (0.39)	0.0004 *** (4.15)	0.0021 *** (4.55)	−0.0011 *** (−4.81)	−0.0002 (−0.52)
Government intervention	−0.4240 * (−1.85)	−0.0856 (−1.20)	−0.087 *** (−2.72)	−0.2889 *** (−1.79)	−0.1859 ** (−2.40)	0.2241 *** (2.16)
Constant	0.0877 (0.84)	−0.0061 * (−0.19)	0.0504 *** (3.45)	−1.254 *** (0.191)	−0.0458 (1.30)	−0.0029 (−0.06)

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The findings reveal that the overall resilience of manufacturing industrial symbiosis clusters in the YREB is significantly influenced by the financing environment and digitization level, with the financing environment having the greatest impact. A robust financing environment alleviates enterprise capital constraints and reduces supply chain disruption risks from funding shortages. Furthermore, a favorable financing environment provides financial support for enterprises to upgrade their technologies, promoting digital innovation and technological investment, and addressing the bottleneck issues caused by core and key technologies. With financing support, not only can resource allocation be optimized, but also the collaborative cooperation among ICSC networks can be strengthened. Therefore, a beneficial financing environment enhances the ability of the ICSC to cope with risks and shocks, thereby increasing ICSC resilience.

In this digital and information age, digitalization has been widely recognized as a fundamental trend for building ICSC resilience. Digitalization enables the ICSC systems to

proactively sense environmental changes and predict potential disruptions, allowing them to mitigate supply chain risks before they escalate into destructive events. Additionally, digitalization can promote collaboration, trust, and flexibility among organizations and their members, which in turn leads to better responses after disruptions. Therefore, the improvement of digitalization levels can effectively enhance the overall ICSC resilience. Conversely, government intervention has a detrimental effect on resilience. State-owned enterprises often rely on government support when facing operational challenges due to internal or external environmental shifts, which hinders their ability to develop independent risk management capabilities. Stronger government intervention further impedes resilience improvement.

The analysis also revealed that the financing environment positively impacts immune resistance, autonomous control, and innovation competitiveness. Digitization levels significantly improve adaptive resilience, autonomous control, and innovation competitiveness. In contrast, government intervention negatively affects all resilience dimensions except immune resistance. Price fluctuations also harm adaptive resilience by causing supply reduction and demand contraction due to market instability.

5. Conclusions and Policy Recommendations

5.1. Conclusions

This study investigated manufacturing ICSC resilience in 11 provinces and cities along the YREB, including Shanghai, Jiangsu, Zhejiang, Anhui, Hunan, Hubei, Sichuan, Chongqing, Jiangxi, Yunnan, and Guizhou. A comprehensive evaluation system was developed to assess key aspects, such as immune resistance, adaptive resilience, autonomous control, innovation competitiveness, and development sustainability. Using the entropy weight method, we quantified regional resilience levels from 2017 to 2022. Subsequently, we employed ArcGis (10.8.1) for spatial analyses to identify spatiotemporal patterns and regional disparities in resilience. Additionally, a fixed effects model was utilized to identify critical influencing factors.

The results indicate a steady increase in manufacturing ICSC resilience across the YREB, particularly in recent years. Regionally, Jiangsu, Zhejiang, and Shanghai exhibited higher resilience, while other areas lagged behind, which reflects uneven development. Upstream regions have developed strong frameworks for supply chain stability, whereas midstream and downstream regions need further improvement. Specifically, Jiangsu Province particularly stood out. Its ICSC resilience index rose steadily from 0.5086 in 2017 to 0.8224 in 2022. Zhejiang Province ranked second during the same period. Its resilience index increased from 0.3597 in 2017 to 0.5135 in 2022. In contrast, the average resilience levels of the other provinces in the YREB, except for the Yangtze River Delta region, were all below 0.2, with a significant disparity. In terms of specific dimensions, the manufacturing ICSC in the YREB showed a general upward trend in immune resistance. However, resilience levels dropped notably in 2020 and 2022 due to external economic pressures. Autonomous control and innovation competitiveness were consistently improved, with autonomous control showing the most significant progress. Meanwhile, adaptive resilience and development sustainability remained relatively weak. Specifically, from 2017 to 2022, the manufacturing ICSC in the YREB exhibited an overall upward trend in immune resistance from 0.503 to 0.738. The autonomous control capability rose rapidly from 0.549 to 1.41, while innovation competitiveness increased from 0.48 to 0.93. Adaptive resilience indices ranged from 0.16 to 0.25, and development sustainability also remained at approximately 0.3.

The spatial distribution of resilience shifted significantly during the study period, with marked improvements observed in all the regions. From 2017 to 2020, the spatial pattern of manufacturing ICSC resilience in the YREB underwent significant changes. High-

value areas increase from three to seven, while low- and lower-value areas disappeared, decreasing from two to zero, and higher-value areas remain unchanged. Between 2020 and 2022, the pattern stabilized: high-value areas expanded further, increasing from seven to nine; higher-value areas were eliminated, decreasing from two to zero; and lower-value areas persisted unchanged. Key factors for influencing resilience include a favorable financing environment and an advanced digitization level, which enhance resilience. On the other hand, excessive government intervention and price fluctuations negatively affect resilience levels.

5.2. Policy Recommendations

Based on our findings, we propose the following strategies to address the identified challenges and enhance ICSC resilience.

5.2.1. Build a Three-Level Promotion Strategy for Technological Breakthroughs, Industrial Upgrading, and the Regional Coordination of the YREB, Led by the Yangtze River Delta

For the high-value Yangtze River Delta area, leveraging its strong industrial foundation and innovative resources is critical. This involves developing key sectors, such as integrated circuits and emerging fields like artificial intelligence and quantum computing, through pilot research areas and industrial hubs. Additionally, by leveraging the institutional innovation strengths of the Shanghai Free Trade Zone Lingang New Area, we can promote the establishment of a robust ICSC cooperation mechanism and build an international intelligent supply chain management center.

In the midstream provinces (Anhui, Hubei, Hunan, Sichuan), seizing opportunities from the industrial transfer and the digital revolution is essential. A detailed analysis of the ICSC should identify key enterprises and technologies to accelerate green technology development and support traditional industry transformation. Attracting high-end manufacturing can drive regional upgrades. Though the upper reaches remain a low-value area, leveraging the Chengdu–Chongqing Twin City Economic Circle can effectively absorb the industrial spillover from the Yangtze River Delta region while fostering the development of intelligent logistics hubs. This collaboration can help mitigate the impact of high inland transportation costs on supply chains, thereby optimizing regional economic integration.

Finally, enhancing the coordination among ICSCs in the YREB requires comprehensive digital mapping and risk warning systems to ensure smooth operations. Building collaborative ecosystems for production, supply, and marketing is vital. Integrating enterprises across tiers (upstream, midstream, downstream) and types (large firms, “little giants”) through innovation mechanisms will create a resilient system based on shared risks and benefits. This approach will strengthen the Yangtze River Delta’s global supply chain position and revitalize the central and western regions, which will drive cohesive development across the entire economic belt.

5.2.2. Strengthen the Industrial Foundation of the New Development Pattern and Enhance the Resilience of the Industrial and Supply Chains in the YREB

Establish a favorable financing environment: Integrating the capital chain with the ICSC necessitates the creation of a conducive financing environment. First, fostering the advancement of supply chain finance is critical. Supported by the creditworthiness of core enterprises, this mechanism reinforces ICSC stability through coordinating the management of capital, logistics, and information flows across both central and ancillary enterprises. Second, it is crucial to incentivize financial institutions to utilize fintech innovation. Fintech solutions can address inadequate collateral and non-standardized financial documentation by capitalizing on “data-driven credit” and “asset-backed credit” frameworks. These

measures broaden financing opportunities for non-core enterprises while optimizing the operational efficacy of the ICSC.

Increase digitization and integrate the digital economy: The integration of the digital economy with the ICSC requires a concerted effort toward digitization. First, prioritizing the development of digital infrastructure is crucial. Building the next generation of digital infrastructure is crucial for enhancing industrial resilience and advancing digitalization. This requires collaboration among governments at all levels, cross-departmental institutions, and various sectors of society to develop a comprehensive infrastructure strategy. This strategy should integrate strategic planning, construction, governance, technological integration, and practical implementation to ensure sustainable development. Second, accelerating the development of innovative models for cultivating digital talent is essential. In emerging industries, strengthening core and interdisciplinary fields in advanced manufacturing will help train professionals with innovation-driven skills and practical expertise. Simultaneously, reforming talent incentive mechanisms should be prioritized by introducing performance-driven evaluations based on innovation criteria and quality standards. Equitable income distribution systems should also be designed to reflect the true value of knowledge and technological innovation.

Restructure the government–enterprise relationship: To minimize the adverse effects of administrative intervention on operational autonomy, reconfiguring the government–enterprise relationship is essential. Regulatory authorities should refrain from prescribing technical pathways or engaging in operational decision-making. Furthermore, institutionalizing accountability mechanisms requires the integration of “ICSC security KPIs” into the performance evaluation frameworks of state-owned enterprises. Enterprises should be obligated to submit detailed annual contingency plans for critical supply chain nodes.

Stimulate private enterprise vitality: To stimulate the vitality of private enterprises and integrate the value chain with the ICSC, it is essential to optimize service levels. The government enforces the unified national negative list system for market access and supports private capital in key sectors. The government also enhances fair competition mechanisms to ensure that private enterprises have equitable access to inclusive policies in finance, taxation, and technology. Additionally, due to the high demand for land by private enterprises in strategic emerging industries, the government should optimize land guarantees. Simultaneously, the government should encourage private enterprises to develop renewable energy with corresponding preferential policies.

5.3. Limitation and Future Research

There are a few interesting topics for further research. First, this paper employed provincial panel data from the YREB to conduct a macro-level analysis of ICSC resilience. To further enhance ICSC resilience, empirical analyses using city-level panel data across provinces remain to be conducted. Second, this paper evaluated ICSC resilience under the context of digitalization and greening. Furthermore, government reports propose the development of more intelligent ICSCs. Therefore, the impact of intelligent technologies on ICSC resilience deserves further research. Lastly, this paper focused solely on manufacturing ICSC resilience. Under the context of digitalization and green transition, ICSC resilience in other sectors also merits further investigation.

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Abbreviations

The following abbreviations are used in this manuscript:

ICSC Industrial Chain and Supply Chain
YREB Yangtze River Economic Belt

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