

Configuration Pathways for Enhancing Regional Supply Chain Resilience through Digital Intelligence Empowerment: A Study Based on Fuzzy-Set Qualitative Comparative Analysis

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Abstract. In the context of a volatile global environment, digital intelligence empowerment plays a crucial role in the resilience of regional supply chains. Previous scholars have often neglected the grouping role of each element when studying the influencing factors of supply chain resilience, therefore, this paper innovatively adopts the fuzzy-set Qualitative Comparative Analysis (fsQCA) methodology based on China's provincial data in 2022 to deeply explore how digital intelligence can empower the resilience of regional supply chains. The main findings are as follows: (1) No single condition alone can ensure a high level of regional supply chain resilience; (2) There are three configurations of high supply chain resilience, namely, Digitization-Weak & Intelligence-Strong Type, Balanced Digitization & Intelligence Type and Digitization & Intelligence High-Performance Type among which intelligent basic support ability and intelligent innovation level are the core conditions of high regional supply chain resilience. (3) The low-level digitalized economic environment and the intelligent basic support capacity are the basic factors of supply chain resilience in low-level regions, which are asymmetric compared with the high-level group and therefore the smooth transition and rational allocation of various key elements need to be emphasized in their transformation to high levels. This study provides new insights for optimizing the construction of regional supply chain resilience system from the configuration perspective, which enriches the research of supply chain resilience theory, and also provides policy insights for constructing high-level supply chains around the world from the perspective of digital intelligence.

Keywords: Regional supply chain resilience; Digital intelligence; Theory of configuration.

1. Introduction

In the VUCA era, the frequent occurrence of emergencies is prone to supply chain disruptions and cause short-term or long-term negative effects, highlighting the urgency of building a resilient supply chain system. The rise of digital intelligence technology provides a new perspective for building a high-level resilient supply chain, and can provide technical empowerment for supply chain resilience reconstruction. In recent years, China has attached great importance to the supply chain resilience empowered by digital intelligence. In the report of the 20th Party Congress, it is clearly pointed out that we need to focus on improving the resilience of the industrial chain supply chain and the level of security, and the State Council issued the "14th Five-Year Plan" for the development of modern logistics emphasizes the need to promote modern logistics to the upstream and downstream of the supply chain with the help of the number of intellectual empowerment to improve the resilience of the supply chain. In this context, it is of great significance to explore the influence mechanism of digital transformation on regional supply chain resilience to improve the supply chain resilience theoretical system and practical guidance.

In the research field of supply chain resilience influencing factors, scholars used to focus on the micro enterprise perspective and the independent effect of a single element, ignoring the role of multi-factor grouping, and the impact of digital intelligence is often analyzed in the digital and intelligent dimensions, without exploring its inherent synergistic mechanism. Based on this, this paper takes the data of Chinese provinces in 2022 as a sample, and applies the fsQCA method to reveal the core elements of regional supply chain resilience and the role of paths based on the group theory under the

background of digital intelligence, so as to provide policy inspiration for the construction of a resilient supply chain system.

2. Review of Literature

Supply chain resilience generally refers to the ability to withstand risks under external shocks and uncertainties, as well as the ability to quickly and flexibly adjust to adapt to changes to restore the pre-impact state, or even achieve better development^[1]. And digital intelligence as a product of the integration of digitalization and intelligence, can support the supply chain resilience improvement. Currently, most scholars only study the mechanism of digital intelligence on supply chain resilience from a single perspective of digitalization or intelligence.

2.1. The Impact of Digitalization on Supply Chain Resilience

In academia, the facilitating role of digitization on supply chain resilience has been widely recognized as one of the core drivers of resilience enhancement, which can strengthen the supply chain's ability to withstand external shocks (Shushan Zhang and Cheng Gu, 2024^[2]). The first and foremost thing to realize digitalization is to build a good digital foundation, and the improvement of the level of digital foundation can promote the sharing of information transmission and the integration of internal and external resources, and enhance the resilience of the supply chain (Xinting Ge et al., 2024^[3]). In addition, digital development relies on a good digital financial environment, which can improve technological innovation, alleviate financing constraints, and play a key role in supply chain resilience (Cailian Liu, 2023^[4]). In order to further build a highly resilient supply chain, the level of digital innovation is an indispensable key element, which promotes process optimization and efficiency improvement, facilitates the construction of smart supply chain and eco-innovation, and synergizes with intelligence to add impetus to enhance resilience (Shijin Wang et al., 2024^[5]). In summary, digitalization promotes the improvement of supply chain resilience from multiple dimensions, and can play a linkage role through digital innovation drive and intelligence to build a solid foundation for the stable operation and sustainable development of the supply chain.

2.2. The Impact of Intelligence on Supply Chain Resilience

In the field of intelligence research, few scholars directly explore its impact on supply chain resilience from the perspective of intelligence, and most scholars analyze its role in supply chain resilience with specific intelligent applications as an entry point. In the field of artificial intelligence technology, it has a significant advantage as a basic support, which can help enterprises comprehensively grasp the supply chain operating conditions by virtue of its data analysis capability, and provide scientific and reliable support for enterprise strategic decision-making (Huihui Deng et al., 2024^[6]). It can also stimulate the innovation vitality of enterprises, play a key regulatory role in market competition (Shuai Liu, 2025^[7]), realize the optimal allocation of resources, and then actively promote the supply chain resilience enhancement. In the field of logistics, intelligent empowerment optimizes the intelligent logistics model, breaks through the chain domain and geographical time and space limitations, accelerates the flow of information, capital, and commodities, strengthens its ability to withstand external risks and resilience (Shushan Zhang et al., 2023^[8]), and ultimately builds a supply chain system with a high level of resilience. In summary, intelligence provides solid support for the supply chain based on cutting-edge technology, and its application helps the efficient regulation and circulation of information, and promotes the strengthening and improvement of supply chain resilience in the continuous innovation and development.

2.3. Literature Review

The existing literature suggests that digitalization and intelligence are crucial and significantly linked to enhance supply chain resilience, and it is of great research value to integrate them into digital intelligence and explore the benefits of their internal factor combinations. However, most of the

current literature only studies the supply chain resilience of enterprises from a microscopic and single perspective by using benchmark regression, ignoring the benefits and paths of internal factor combinations. In view of this, this paper adopts the fuzzy-set Qualitative Comparative Analysis (fsQCA) method to explore the different paths of Numerical Intelligence on regional supply chain resilience based on the grouping perspective, so as to provide insights for the regional construction of highly resilient supply chains.

3. Theoretical framework and research methods

3.1. Theoretical Frameworks

Taking the resilience level of regional supply chain as the explained variable, based on the existing literature and from the dual perspective of digitalization and intelligence, this study systematically sorted out six key impact indicators, including the level of digital infrastructure, environment for the digital economy, level of digital application, capacity for intelligent support, level of intelligent application and level of intelligent innovation. According to the configuration theory, digitalization and intelligence do not act on regional supply chain resilience in isolation, but produce comprehensive effects through complex interactive and collaborative mechanisms. Accordingly, this study constructs the theoretical analysis framework as shown in Figure 1.

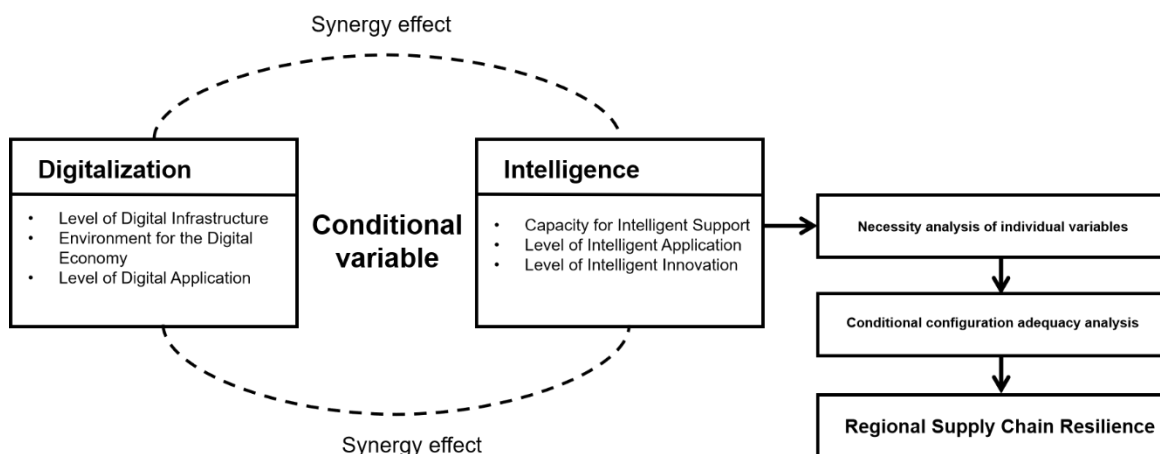


Figure 1. Theoretical analysis framework

3.2. Research Methods

In recent years, fuzzy-set Qualitative Comparative Analysis (fsQCA), as a social science research paradigm integrating quantitative and qualitative, has been widely used and recognized in the field of management. Based on Boolean algebra and group theory, fsQCA can explore the relationship and mechanism between factors and explain complex social problems with multiple concurrent causal factors. The reasons for adopting fsQCA in this paper are as follows: (1) Supply chain resilience stems from the complex interaction of multiple factors, and a single capability improvement is not enough to realize a high level of supply chain resilience, so fsQCA can effectively reveal the causal relationship between factors. (2) This paper takes 30 provinces in China as the sample, which is a smaller sample size and more suitable for using fsQCA than statistical analysis methods. (3) Compared with the category restriction of csQCA and mvQCA, fsQCA is more generalizable as it can deal with the variables with fixed ratio and distance through the degree of affiliation. This paper adopts this method to explore the path of regional supply chain resilience enhancement driven by digital intelligence, which is instructive for each province to build a highly resilient supply chain.

3.3. Definition of Variables

Outcome Variable

Regional supply chain resilience. This paper mainly refers to the method of Xiwen Zhang^[9], divides supply chain resilience into three perspectives of resistance, resilience and reengineering according to the definition to construct an evaluation index system, and then measures regional supply chain resilience through entropy method, as shown in Table.1.

Table.1. Explanation of regional supply chain resilience measures

Outcome Variable	Variable Definitions	Data Sources	References	
Regional Supply Chain Resilience(RSCR)	Resistance	Gross regional product per capita	China Statistical Yearbook	Zhou L et al. ^[10]
	Resilience	fixed-asset investment	China Statistical Yearbook	Yuanling Tan & Jinmei Li ^[11]
	Reengineering	Patent applications	China Statistical Yearbook	Xiwen Zhang ^[9]

Conditional Variable

Digital intelligence, which can be understood as the deep integration and application of digitization and intelligence, can be divided into two dimensions of the level of digitization and the degree of intelligence to construct the evaluation index system^[12], the specific index system is shown in Table.2. Referring to the research of Qun Wu et al^[13] on the level of digitization, it is mainly divided into the level of digital infrastructure, the level of digital application, and the digital economic environment in three aspects for measurement. As for the level of intelligence, reference is made to the research of Jun Liu et al^[14], from the perspective of “foundation-application-innovation”, selecting the level of intelligent basic support capacity, intelligent application level and the level of intelligent innovation as the secondary indicators for measurement.

Table.2.Explanation of regional supply chain resilience measures

Conditional variables: Digital Intelligence	Short name	Variable definitions	Data Sources	References	
Digitalization	Level of Digital Infrastructure	LDI	Mobile telephone exchange capacity per capita, Internet broadband access ports per capita, fiber-optic cable line density, using the entropy value method to obtain final data	China Statistical Yearbook	Qun Wu,Zhu Jiayi ^[13]

Table2(continued)

	Environment for the Digital Economy	EDE	Digital Economy Index	China Statistical Yearbook, China Labor Statistics Yearbook, etc.	Shengsheng He ^[15]
	Level of Digital Application	LDA	Revenue from software operations	China Statistical Yearbook	Juan Ouyang et al. ^[16]
	Capacity for Intelligent Support	CIS	High-tech manufacturing R&D expenditures, R&D personnel converted to full-time equivalents, using entropy value method to assign values	China High Technology Industry Statistical Yearbook, China Statistical Yearbook	Zhiming Zhu et al. ^[17]
Intelligence	Level of Intelligent Application	LIA	Revenue from the sale of new products in high-tech manufacturing industry, software business revenue, using the entropy value method to assign values	Statistical Yearbook of China's High Technology Industry	Jun Liu et al. ^[18]
	Level of Intelligent Innovation	LII	Number of effective invention patents in high-tech industries	Statistical Yearbook of China's High Technology Industry	Jian Hou & Qing Liu ^[19]

3.4. Data Sources And Calibration

3.4.1 Data Source

The research data of this paper are 30 provinces in China in 2022 (among them, Tibet Province is temporarily excluded from consideration due to the existence of missing values in some of them, and Hong Kong, Macao and Taiwan are also excluded), and the data are mainly sourced from China's "China Statistical Yearbook" and "Statistical Yearbook of China's High-technology Industry".

3.4.2 Data calibration

In order to make the original data have interpretable aggregate meaning, data calibration is needed before using the fsQCA analysis method, i.e. , setting three anchors, namely, full affiliation point, cross-affiliation point and full non-affiliation point. In this paper, according to the method of Dan Wang et al^[20] scholars, the upper quartile, median and lower quartile of the original data are taken as the three calibration anchors for the data condition variable and the outcome variable respectively, and the calibration results are shown in Table.3.

Table.3.Calibration of variables

Conditions and outcome variables	Calibration		
	Full affiliation	Intersections	Not affiliated at all
LDI	0.230	0.183	0.129
EDE	0.217	0.139	0.101
LDA	2803.890	881.012	127.481
CIS	0.110	0.051	0.012
LIA	0.127	0.079	0.012
LII	23415	8599.5	1814.5
RSCR	0.314	0.186	0.082

4. Empirical Analysis

4.1. Necessity Analysis

To test whether a single condition is necessary for the outcome variable, a necessity analysis is performed after calibrating the variable. Generally, when the consistency level is greater than 0.9 and the coverage is greater than 0.5, it is considered that the antecedent condition may be a necessary condition. As shown in Table.4, in the high regional supply chain resilience group, EDE and CIS may be necessary conditions for high regional supply chain resilience; in the non-high regional supply chain resilience group, \sim EDE, \sim CIS, \sim LIA, and \sim LII may be necessary conditions for non-high regional supply chain resilience.

Table.4.Analysis of the need for a single condition

Conditional variable	RSCR		\sim RSCR	
	Consistency	Coverage	Consistency	Coverage
LDI	0.613	0.612	0.481	0.475
\sim LDI	0.475	0.481	0.607	0.608
EDE	0.933	0.934	0.233	0.230
\sim EDE	0.231	0.234	0.934	0.932
LDA	0.810	0.789	0.303	0.292
\sim LDA	0.274	0.284	0.782	0.802
CIS	0.932	0.926	0.226	0.222
\sim CIS	0.217	0.221	0.924	0.930
LIA	0.882	0.908	0.228	0.232
\sim LIA	0.255	0.250	0.910	0.884
LII	0.896	0.928	0.245	0.251
\sim LII	0.277	0.271	0.930	0.898

Note: \sim indicates logical not.

In order to confirm whether it is a necessary condition or not, it is necessary to combine the X-Y scatter plot to make a judgment, and if X is a necessary condition for Y, the scatter will be located below the diagonal. Using fsQCA software to draw the scatter plot of high supply chain resilience group, as shown in Figure 1, where Y is high regional supply chain resilience, and X is digitalized economic environment and intelligent basic support capacity, respectively. As can be seen from Fig. 2, both have about one-third of the scatters located above the diagonal line, and if X is a necessary condition for Y, there is an empty set above the diagonal line, so even though these conditions satisfy a consistency level of greater than 0.9, they still cannot be a necessary condition for high regional supply chain resilience^[21]. Similarly, there is no condition that becomes necessary for non-high

regional supply chain resilience. In summary, regional supply chain resilience is not determined by a single factor and requires a group analysis.

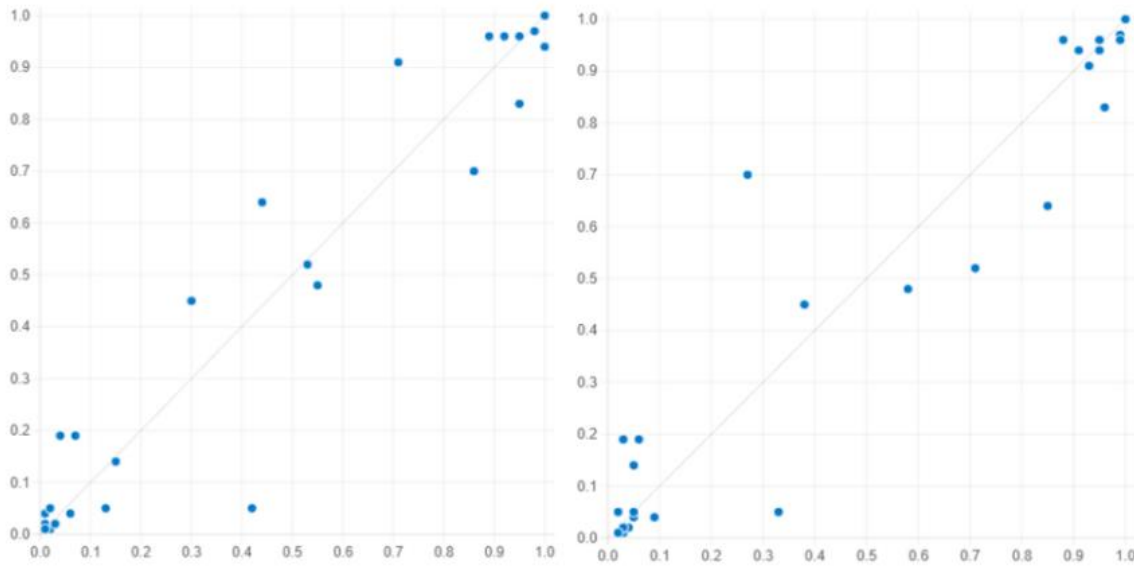


Figure 2. EDE-RSCR scatterplot (left) and CIS-RSCR scatterplot (right)

4.2. Configuration Analysis

Grouping analysis focuses on exploring the adequacy of the grouping composed of multiple conditional variables to make the outcome variable, aiming to reveal the path of action of multiple combinations of conditions affecting the outcome variable. On the basis of data calibration and truth table construction using the fsQCA tool, due to the small sample in this study, the frequency threshold was set to 1 and the consistency value threshold to 0.8, drawing on the research of Liu Wei et al [22], after which the core and auxiliary conditions of each grouping were determined based on the output parsimonious and intermediate solutions and plotted in Table 5.

Table 5. Regional supply chain resilience configuration analysis

Configuration	RSCR			~RSCR			
	1	2	3	1	2	3	4
LDI	⊗	⊗			⊗	●	●
EDE		●	●	⊗	⊗	⊗	●
LDA	⊗	●	●	⊗	●	●	●
CIS	●	●	●	⊗	⊗	⊗	●
LIA	●		●	⊗	⊗	●	●
LII	●	●	●	⊗	●	⊗	⊗
Consistency	0.932	0.933	0.962	0.974	0.989	0.995	0.959
Configuration	RSCR			~RSCR			
	1	2	3	1	2	3	4
Raw Coverage	0.182	0.294	0.769	0.745	0.121	0.127	0.109

Table5(continued)

Unique Coverage	0.057	0.016	0.491	0.656	0.022	0.015	0.007
Overall solution consistency		0.958				0.972	
Overall solution coverage		0.842				0.847	

Note: ● or ● indicates that the condition exists, ⊗ or ⊗ indicates that the condition is missing; ● or ⊗ indicates core conditions, ● or ⊗ indicates auxiliary conditions.

As can be seen from Table.5, the consistency of each grouping with the final model solution is higher than 0.8, and the coverage of the complete solution is also higher than 0.8, indicating that the results have a certain degree of reliability and explanatory strength. Among them, the distribution of each group state within the high regional supply chain resilience group has a certain degree of variability, which is mainly divided into the following types:

Digitization-Weak & Intelligence-Strong Type. Corresponds to group state 1 in Table.5, in which CIS and LII are the core conditions, and the auxiliary conditions are ~ LDI, ~ LDA and LIA. This grouping indicates that provinces with a high level of intelligent infrastructure support capacity, intelligent application level, and intelligent innovation level can also achieve a breakthrough and reach a high level of regional supply chain resilience by increasing the investment in intelligence in the case of insufficient digitalization construction. Taking Jiangxi Province as an example, the province has shortcomings in digital infrastructure, technology application, talent training, etc., and faces dilemmas such as lagging digitalization level, imperfect data resource integration and sharing mechanism, and insufficient integration with traditional industries. However, Jiangxi reconstructs the supply chain toughness through intelligent technology, realizes the three-dimensional optimization of efficiency, cost and reliability, makes up for the digital short board, improves the supply chain toughness, and lays the foundation for regional economic development and industrial competitiveness enhancement.

Balanced Digitization & Intelligence Type. Corresponds to grouping 2 in Table.5, in which CIS and LII are the core conditions, and the auxiliary conditions are ~ LDI, EDE and LDA. This pattern reveals that even if there are certain shortcomings in the level of digital infrastructure, a high level of regional supply chain resilience can still be achieved if we can focus on improving the level of digital application, actively creating a favorable digital economic environment, and at the same time attaching great importance to intelligent infrastructure and vigorously promoting innovation. Taking Shandong as an example, in 2022, there are structural shortcomings, low hardware adaptation rate and data silos and other digital infrastructure issues. In the face of infrastructure constraints, Shandong line application traction combined with the ecological reconstruction strategy, digital applications by “chain leader system” to build a platform to enhance the efficiency of synergies, the digital economy, the introduction of a program to build a regulatory system to strengthen the digital economy environment, risk warning. At the same time committed to intelligent transformation, the development of kinetic energy from traditional factor inputs to data-driven intelligence, in the infrastructure of the non-optimal state of the supply chain resilience of the qualitative change.

Digitization & Intelligence High-Performance Type. It corresponds to grouping 3 in Table.5, where CIS and LIA are the core conditions and EDE, LDA, and LIA are the auxiliary conditions. Among the three types, it is able to explain 76.9% of the cases, which is the type that can explain the most cases. This type shows good development in both digitalization and intelligence dimensions and successfully achieves a higher level of supply chain resilience. Guangdong Province is a typical case, where digitalization has been developed by improving infrastructure, deepening industrial integration, constructing an industrial Internet marking system, driving big data transformation of enterprises, and building a blockchain credit system to strengthen risk resilience. In the field of intelligence, IoT and artificial intelligence empower logistics monitoring and demand forecasting, innovative platforms promote industry chain synergy, and build system resilience to cope with shocks. It realizes a high level of resilience in two-dimensional synergy, effectively resists external risks and guarantees the sound operation of the regional economy.

As for the non-high-region supply chain group, it can be intuitively seen from Table.5 that it has asymmetry with the high-region supply chain group. Among them, the ~EDE and ~CIS of group state 1, and the auxiliary conditions are ~LDA, LIA, and ~LII. and the original coverage of group state 1 is 0.745, which indicates that it can explain 74.5% of the cases, and it is the group path that can explain the most cases in this group. Taking it as an example, compared with the high regional supply chain resilience group, it can be seen that good intelligent basic support capability and high level of intelligent innovation play a key role in building a high level regional supply chain resilience system. However, in the non-high regional supply chain resilience group, the situation shows significant differences, and its supply chain resilience is mainly constrained by the impact of an adverse digital economic environment and weak intelligent basic support capacity.

4.3. Robustness Testing

Drawing on the practice of Shi Jialing et al^[23], after raising the consistency threshold from 0.8 to 0.85, robustness tests were conducted for the high-region supply chain resilience group and the non-high-region supply chain resilience group respectively. The results show that after replacing the consistency threshold, the configurations, core conditions and auxiliary conditions of each group state do not change significantly, and the consistency of each group state is greater than 0.9, which shows that the research conclusions have strong stability.

5. Conclusions and Implications of the Study

5.1. Conclusions

In recent years, the global environment has been complex and volatile, and enhancing supply chain resilience has become the focus of academia. This study analyzes the influencing factors of China's regional supply chain through qualitative comparison and draws the following conclusions: first, a single conditional variable cannot constitute a necessary condition for high regional supply chain resilience, indicating that under the background of digital intelligence, high-level regional supply chain resilience is formed by the interdependent and synergistic effects of multiple factors. Secondly, the results of fsQCA group analysis show that intelligent basic support capability and intelligent innovation level are the core conditions for high regional supply chain resilience, and three influencing paths are found: Digitization-Weak & Intelligence-Strong Type, Balanced Digitization & Intelligence Type and Digitization & Intelligence High-Performance Type. Among them, Digitization & Intelligence High-Performance Type has the strongest explanatory power. Third, the supply chain resilience group of high and non-high regions is asymmetric. Intelligent basic support capacity and intelligent innovation level are the key to build high-level regional supply chain resilience, but in the non-high-level regional supply chain resilience group, supply chain resilience is mainly constrained by the digitalized economic environment and intelligent basic support capacity.

5.2. Policy Recommendations

First, strengthen the intelligent support investment mechanism. The government should guide enterprises to focus on the research and development of core technologies of digital intelligence through special planning, research funds and tax incentives, focusing on supporting the innovation of intelligent algorithms, digital twins and multi-source data fusion, and fostering composite technology teams. Second, build an innovation-driven ecosystem. The government needs to play the role of policy leadership and resource coordination, and stimulate the innovation vitality of multiple subjects through the establishment of special funds, the construction of industry-university-research platforms, the improvement of talent mechanisms and the strengthening of intellectual property rights protection and other initiatives. Focus on promoting the deep integration of intelligent technology and supply chain, improve the overall level of intelligence and resilience, and realize the transformation and upgrading and risk resilience synergistic enhancement. Third, make up the short boards to drive the resilience improvement. For low-level supply chain resilience regions, priority should be given to

strengthening the digital economic environment and intelligent support capacity of the double short board. On this basis, relying on intelligent innovation drive, promote the supply chain to intelligent, efficient and cooperative evolution, and ultimately building a highly resilient supply chain system.

5.3. Theoretical Contributions

First, this study constructs a regional supply chain resilience analysis model based on fsQCA, revealing the synergistic mechanism of multi-factors and asymmetric differences between regions, and providing new perspectives and group analysis support for supply chain resilience formation theory. Second, the introduction of fsQCA breaks through the limitations of traditional single-factor analysis, and analyzes the compound effects of digitalized factors on supply chain resilience from a group perspective. This study expands the theoretical boundaries, innovates the methodological paradigm, and promotes the cross-fertilization of management, economics and complex systems science. Third, the study breaks through the single-factor determinism through the group state analysis, identifies the multi-path driving mechanism of supply chain resilience in high regions, and reveals the asymmetric characteristics of high and non-high resilience regions. The study provides a theoretical basis and practical guidance for differentiated enhancement strategies for low-toughness regions.

5.4. Research Shortcomings and Prospects

This study is based on the cross-section data of Chinese provinces, which fails to capture the dynamic evolution of regional supply chain resilience and the consideration of international regional differences. Future research can introduce time series data and adopt dynamic analysis methods, and expand cross-country comparative studies to reveal the general rules and special phenomena of global supply chain resilience.

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