

Research on the Impact of Digitalization and Intelligentization on Regional Innovation Capability Based on Provincial QCA Configuration Analysis

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Abstract. Against the backdrop of digitalization and intelligentization, the linkage between regional innovation capabilities and economic development has grown closer and more complex. An in-depth exploration of the multi-dimensional influencing factors of regional innovation capabilities is a prerequisite for accurately grasping the intrinsic link between regional innovation and economic development. However, existing studies are mostly confined to single-dimensional explanatory variables and lack analysis of multi-factor synergistic mechanisms. Using cross-sectional data from 31 Chinese provinces and municipalities in 2023, this study applies the fsQCA method to construct a digital-intelligent factor system with seven core variables and identifies the formation paths of high-level regional innovation capabilities. The study confirms two findings: (1) No single antecedent condition is necessary for fostering high-level regional innovation capabilities. (2) Four typical paths for these capabilities are identified, including the infrastructure-deficient path, the high-level development path, the infrastructure-digital industrialization path, and the digital industrialization-industrial digitalization linkage path, and these conclusions remain robust after robustness tests. This study transcends the traditional single-factor analytical framework and uncovers the dynamic combinatorial logic of digital-intelligent factors through the lens of configurational theory. It provides decision-making implications for "province-specific" regional innovation policies and guidance on resource allocation for enterprises.

Keywords: Regional Innovation Capability, Digitalization, Intelligentization, fsQCA, Configurational Paths.

1. Introduction

Against the dual backdrop of global value chain restructuring and in-depth empowerment by digital technologies, regional innovation capability has become a core engine driving high-quality economic development. Currently, the global industrial division of labor is undergoing profound transformation: developed countries are accelerating the construction of technological barriers, while emerging economies are actively exploring paths for value chain upgrading, leading to intensified competition for innovation resources and technological rivalry among regions. Meanwhile, the widespread penetration of digital technologies such as artificial intelligence and big data has not only reshaped the allocation logic of innovation factors but also significantly improved the efficiency of knowledge circulation and technological integration among innovation subjects. In this context, in-depth analysis of the multi-dimensional influencing factors and operational mechanisms of regional innovation capability holds important theoretical and practical value for addressing the dilemma of unbalanced regional development and enhancing the country's overall innovation efficiency. This study focuses on the multi-dimensional influencing factors and operational mechanisms of regional innovation capability, aiming to reveal its intrinsic upgrading paths and provide a practically feasible decision-making framework for policymakers and enterprises.

There have been some existing studies on the influencing factors of regional innovation capability. For example, He et al. (2025) examined whether the free trade zone policy enhances regional innovation capability [1]. Zhang et al. (2025) verified the synergistic driving effect of human capital agglomeration and financial agglomeration on regional innovation based on Chinese data [2]. Gui and Chen (2025) explored how the development of digital trade affects the improvement of regional

innovation capability, considering the moderating effect of industrial structure upgrading [3]. However, most studies focus only on single-dimensional explanatory variables, lacking research and analysis on the linkage mechanisms of multiple factors. Given the limitations of existing studies, this research can further explain the influencing mechanisms of the dynamic combination of multiple factors on regional innovation capability.

Based on the configurational theory framework and cross-sectional data from 31 provinces and municipalities (excluding Hong Kong, Macao, and Taiwan) in 2023, this study employs the fuzzy set qualitative comparative analysis (fsQCA) method to systematically analyze the operational mechanisms of multi-dimensional factors on regional innovation capability against the backdrop of digital-intelligent transformation. The specific research implementation paths include: In the first stage, two core driving factors—digitalization and intellectualization—are extracted through literature analysis, and seven core explanatory variables are selected to construct a digital-intelligent element system. In the second stage, the fsQCA method is used to identify typical configurational patterns of high-level regional innovation capability, with conclusions verified through robustness analysis. In the third stage, cross-configurational comparative research is conducted to reveal the equivalent substitution laws among different factor combinations. The research findings have academic innovation value in understanding the core influencing factors of regional innovation capability and provide empirical evidence for the design of regionally differentiated policies.

Relevant studies regard digital indicators such as digital technologies and digital economy as core influencing factors: Yuan and Hu (2025) studied the impact of the digital economy on regional innovation capability based on panel data of 30 provinces from 2013 to 2022 [4]. Ma (2025) explored the direct impact and influencing mechanisms of digital technologies on innovation development through theoretical analysis [5]. Cai and Fang (2024) examined the influence mechanism of the digital economy on regional innovation capability by analyzing the role of knowledge flow and regional innovation environment [6]. Jing and Huang (2024) investigated the stimulation and impact of digital innovation ecosystems on regional innovation capability from both temporal and spatial dimensions using the dynamic QCA method [7].

Relevant studies mostly adopt the perspective of intellectualization: Xu et al. (2024) studied the impact of the industrial internet ecosystem on regional innovation capability and found that the industrial internet ecosystem positively affects regional innovation capability by improving the level of human capital and the vitality of the technology market [8]. Wu et al. (2023) explored the impact of industrial intellectualization on regional innovation efficiency as well as its action paths and mechanisms, revealing that human capital level, financial development level, and industrial structure upgrading are the three key channels through which industrial intellectualization enhances regional innovation efficiency [9]. Zhao et al. (2022) studied the impact of industrial intellectualization level on regional industrial competitiveness by constructing a model of intellectualization level and multi-dimensional industrial competitiveness [10]. Lyu et al. (2024) researched the impact of regional digital-intellectualization on the competitiveness of regional innovation ecosystems, finding that digital-intellectualization promotes the competitiveness of regional innovation ecosystems through effects such as the emergence of innovation clusters, acting on links including innovation subjects, innovation support, and innovation resources [11].

Existing studies have laid a solid academic foundation and provided empirical support for exploring the influencing factors of regional innovation capability, but there are still dimensions worthy of expansion: First, most existing quantitative analyses are limited to examining independent influencing factors. However, with the evolution of the economy and society, driving factors have shown characteristics of complexity, and action paths have presented heterogeneity, making it feasible to conduct comprehensive research on multi-dimensional synergistic effects. Second, regarding the interactive linkage mechanisms among the influencing factors of regional innovation capability, the fsQCA method, with its unique advantages in explaining the synergistic mechanisms between variables, can better illustrate the influencing mechanisms of dynamic combinations of multiple factors.

2. Research Methods

2.1. Model design

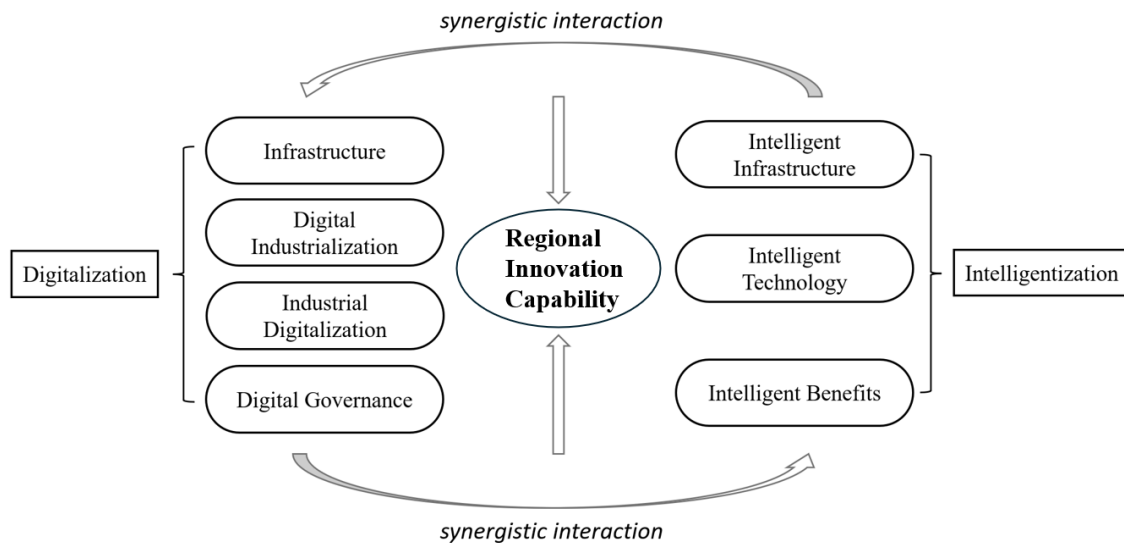


Figure 1. Research Ideas of Influencing Factors

In this study, regional innovation capability is taken as the explained variable. Based on existing research results, seven explanatory variables—including infrastructure, digital industrialization, industrial digitalization, digital governance, intelligent foundation, intelligent technology, and intelligent benefits—are selected and categorized into two dimensions: digitalization and intellectualization, which serve as the main factors affecting regional innovation capability. However, these influencing factors do not act on regional innovation capability independently; instead, they exert an impact through interactive linkage mechanisms among themselves. To this end, this study constructs an association network model among variables, with the research ideas shown in Figure 1.

2.2. Research methods

Although the association network model among variables has been constructed, the specific influence mechanisms between explanatory variables and the explained variable still require in-depth investigation. To analyze their specific action paths, this study adopts the fuzzy set qualitative comparative analysis (fsQCA) method for the following reasons:

First, the fsQCA method effectively combines quantitative data with qualitative analysis, especially compensating for the lack of generalizability in conclusions of traditional qualitative research in small-sample scenarios.

Second, regarding the complex non-linear causal relationships between the seven explanatory variables and the explained variable, the fsQCA method, based on set theory principles, can parse the influence patterns of synergistic combinations of multiple conditional variables on the outcome variable [12], while identifying the necessary conditions for the outcome.

Finally, this method can extract differentiated conditional combination paths of regional innovation capability, focus on case comparisons of typical provinces under each path, and systematically reveal the formation mechanism of high-level regional innovation capability under the linkage effect of multiple conditions.

2.3. Variable indicators

In this study, the measurement of both the explained variable and core explanatory variables is based on the entropy weight method to construct a multi-indicator comprehensive evaluation system, reducing subjective bias through objective weighting. Details are as follows:

Explained variable: Four basic indicators are selected to measure regional innovation capability (comprehensive scientific and technological innovation level index, comprehensive utility value of China’s regional innovation capability, number of domestic patent applications authorized, and number of national-level technology business incubators). After weighting these indicators using the entropy weight method, a comprehensive index of regional innovation capability (RIC) for each province and municipality is generated by integration.

Core explanatory variables: Seven core explanatory variables are selected, each consisting of 1–3 standardized basic indicators. Similarly, the entropy weight method is used for weighting and integration to obtain comprehensive measurement values, reflecting the overall characteristics of the variables. The specific definitions and compositions of variables, data sources, and literature basis are detailed in Table 1.

The entropy weight method is an objective weighting method based on the information entropy of indicators. It determines weights by measuring the degree of dispersion of indicator data, with core steps and formulas as follows:

(1) Let the number of samples be n and the number of indicators be m , with the original data matrix denoted as $X = (x_{ij})_{n \times m}$ (where x_{ij} represents the value of the j -th indicator for the i -th sample). Standardization is performed to eliminate dimensional differences. The processing methods for positive indicators and negative indicators are given by formulas (1) and (2) respectively:

$$y_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{1}$$

$$y_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \tag{2}$$

(2) After standardization, the indicator proportion p_{ij} , information entropy e_j , and entropy weight w_j are calculated in sequence:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^n y_{ij}} \tag{3}$$

$$e_j = -1 / \ln n \sum_{i=1}^n p_{ij} \ln p_{ij} \tag{4}$$

$$w_j = \frac{(1 - e_j)}{\sum_{j=1}^m 1 - e_j} \tag{5}$$

(3) The comprehensive measurement values of both the explained variable and explanatory variables are obtained through weighted summation:

$$S_i = \sum_{j=1}^m w_j y_{ij} \tag{6}$$

Table 1. Index system of regional innovation capability

Condition Variables			Variable Definitions	Variable Sources	References
Digitalization	Infrastructure (IF)	Internet broadband access rate	Internet broadband access ports / year-end permanent population	<i>China Communication Industry Statistical Yearbook</i>	Pan et al., 2021[13]
		Number of internet domain names	Number of internet domain names		
	Digital Industrialization (DI)	Per capita telecommunications business volume	Total telecommunications business volume / year-		

			end permanent population		
		Proportion of digital industry employees	Number of legal entities in information transmission, software and information technology services / urban unit employees	National Bureau of Statistics	
	Industrial Digitalization (ID)	E-commerce sales	E-commerce sales	Statistical Yearbooks of various provinces	
		R&D expenditure intensity	R&D expenditure of industrial enterprises above designated size	National Bureau of Statistics	
		Digital inclusive finance index	Peking University Digital Inclusive Finance Index	Peking University	Guo et al., 2020[14]
Digital Governance (DG)	Government internet service capability	Government e-service capability index	<i>Report on Government E-service Capability Index</i>	Zhang and Sun, 2024[15]	
Intelligentization	Intelligent Infrastructure (II)	Intelligent infrastructure	Telecommunications fixed-asset investment	<i>China Communications Industry Statistical Yearbook</i>	Yang et al., 2022[16]
	Intelligent Technology (IT)	Intelligent talents	Number of software R&D personnel	<i>China Software Industry Statistical Yearbook</i>	
		R&D investment of software enterprises	R&D expenditure of software enterprises		
		Software business revenue	Software business revenue		
	Intelligent Benefits (IB)	Revenue of electronic information manufacturing industry	Revenue of electronic information manufacturing industry	<i>Electronic Information Manufacturing Industry Statistical Yearbook</i>	

3. Configuration results

3.1. Measurement and Calibration

Before conducting QCA analysis, it is necessary to determine the full membership points, cross-over points, and full non-membership points for condition variables and the outcome variable. Drawing on the views of Du Yunzhou (2017) et al. and combining with the characteristics of case data, the calibration standards for sample data are determined as follows: the 0.95 quantile for full

membership, the 0.5 quantile for cross-over point, and the 0.05 quantile for full non-membership [17]. The calibrated data for each variable are obtained after transforming the original data, as detailed in Table 2.

Table 2. Variable calibration

Variable	Full Membership	Crossover Point	Full Non-Membership
IF	0.449	0.093	0.020
DI	0.508	0.132	0.065
ID	0.651	0.179	0.037
DG	0.851	0.426	0.023
II	0.631	0.264	0.006
IT	0.357	0.013	0.000
IB	0.568	0.051	0.001
RIC	0.894	0.426	0.103

3.2. Analysis of Necessary Conditions

In conducting the necessity analysis, to avoid the influence of condition variables on the subsequent fsQCA truth table results, it is first necessary to test each condition variable to determine whether it is a necessary condition for RIC. According to the fsQCA method, consistency is the key criterion for testing necessary conditions. When the consistency value is greater than 0.9, it means that the condition is a necessary condition. The results of the necessary condition analysis are shown in Table 3.

Table 3. Necessary conditions for regional innovation capability

	RIC		~RIC	
	Consistency	Coverage	Consistency	Coverage
IF	0.862	0.900	0.433	0.453
~IF	0.475	0.455	0.904	0.868
DI	0.826	0.881	0.429	0.459
~DI	0.493	0.463	0.889	0.837
ID	0.833	0.940	0.359	0.406
~ID	0.474	0.424	0.947	0.851
DG	0.844	0.870	0.418	0.432
~DG	0.449	0.435	0.874	0.849
II	0.780	0.792	0.490	0.498
~II	0.505	0.497	0.795	0.784
IT	0.799	0.949	0.333	0.396
~IT	0.492	0.424	0.957	0.827
IB	0.774	0.980	0.316	0.401
~IB	0.526	0.434	0.984	0.814

Note: In the table, "~" denotes the negation of the corresponding condition.

The results in Table 3 indicate that the consistency values of all condition variables are lower than 0.9, suggesting that no single antecedent condition is sufficient to serve as a necessary condition for high RIC. This implies that a single antecedent condition cannot directly lead to a high level of RIC; therefore, it is necessary to conduct configurational analysis of condition variables to explore the impact of multiple path combinations on the target variable.

3.3. Analysis of Configuration Results

Table 4 presents four configurational paths for high RIC. Each column represents a possible condition configuration. The consistency index of each individual configuration is higher than 0.9,

which indicates that there is a high level of consistency between these condition configurations and a high level of RIC.

Table 4. Configuration analysis

Antecedent Conditions	RIC Configurations			
	Path 1	Path 2	Path 3	Path 4
IF	p	C	C	C
DI			C	C
ID	C	C	p	C
DG	C	C	p	p
II	p	P	P	P
IT	C	C	p	p
IB	C	C	p	C
Raw Coverage	0.256	0.585	0.286	0.268
Unique Coverage	0.038	0.331	0.033	0.004
Consistency	0.993	0.997	0.921	0.974
Overall Solution Coverage		0.716		
Overall Solution Consistency		0.961		

Note: C indicates the presence of a core condition in the configuration, while c indicates the absence of a core condition; P indicates the presence of a peripheral condition, and p indicates the absence of a peripheral condition. A blank space indicates that the condition is optional.

A vertical analysis of these four configurational paths reveals that the RIC of all provinces and municipalities is jointly influenced by the two dimensions of digitalization and intellectualization. To further identify the synergistic effects of various factors on regional innovation capability, the specific patterns can be summarized as follows:

IF-deficient Path: Corresponding to Configuration 1 in Table 4, the core conditions are ID, DG, IT, and IB, with the peripheral conditions being the lack of IF and II. This configuration indicates that without considering DI, when a province or municipality has low levels of IF and II, a high level of RIC can still be achieved by focusing more on ID, DG, IT, and IB. The representative provinces and municipalities are Tianjin and Chongqing. Taking Tianjin as an example, despite its relatively weak IF and II with no comparative advantages, it has achieved innovative breakthroughs through the closed-loop path of ID-DG-IT-IB. In recent years, Tianjin has focused on port and manufacturing transformation in industrial development, built a "zero-carbon" smart port, and cultivated smart factories and digital workshops, forming a high-quality coordinated development pattern among digital development, logistics industry growth, and high-quality economic development [18]. In terms of digital governance, it has realized the full-process integration of grassroots governance and government services through platforms such as "Jinzhitong". In terms of intelligent technology and benefits, it has formed technical support with general large models as the core, combined with open-source ecology and security control, accelerating the development of new industrialization and informatization.

High-level Development Path: Corresponding to Configuration 2 in Table 4, the core conditions are IF, ID, DG, IT, and IB, with the peripheral condition being II. This configuration suggests that without considering DI, a province or municipality can achieve a high level of RIC by focusing more on IF, ID, DG, IT, and IB. The representative provinces include Guangdong, Zhejiang, and Shandong. Taking Guangdong as an example, it has built the largest number of 5G base stations in the country and laid out computing power hubs in the Guangdong-Hong Kong-Macau Greater Bay Area, providing underlying support for transformation. Although the digital transformation of its advanced manufacturing and high-tech manufacturing industries faces short-term efficiency paradoxes, their long-term potential is significant [19]. Industrial digitalization focuses on traditional fields such as automobiles and home appliances, promoting the transformation of tens of thousands of industrial enterprises above designated size and cultivating multiple national-level industrial internet platforms.

Digital governance has realized the integration of government services through platforms like "Yueshengshi". In terms of intelligent technology, a semiconductor fund has been established to support the implementation of large model technologies in vertical scenarios. In terms of intelligent benefits, its comprehensive scale ranks among the top in the country.

IF-DI Path: Corresponding to Configuration 3 in Table 4, the core conditions are IF and DI, with the peripheral conditions being II and the lack of ID, DG, IT, and IB. This configuration indicates that a province can achieve a high level of RIC by focusing on IF and DI. The representative province is Hebei. Despite its relatively weak ID, DG, IT, and IB with no comparative advantages, Hebei has achieved a leap in regional innovation by strengthening IF and focusing on DI. Although the application of its industrial internet platforms is still in the primary stage, the construction of data center clusters has provided important support for digital industrialization [20]. The province has built large-scale data center clusters in Zhangbei and Huailai, with server scale ranking among the top in the country. It has also laid out 5G base stations and focused on developing industries such as big data, cloud computing, and modern communications, laying a computing power and network foundation for digital industrialization.

DI-ID Linkage Path: Corresponding to Configuration 4 in Table 4, the core conditions are IF, DI, ID, and IB, with the peripheral conditions being II and the lack of DG and IT. This configuration suggests that a province can achieve a high level of RIC by focusing on IF, DI, ID, and IB. The representative province is Henan. In recent years, Henan has built large-scale 5G base stations and data centers, laying a foundation for computing power and networks. Its manufacturing industry has cultivated digital leading enterprises through the "7+28+N" industrial chain clusters, promoting in-depth transformation [21]. Meanwhile, Henan has focused on digital industrialization and industrial digitalization, developed core industries such as big data and intelligent terminals, cultivated smart factories, and promoted the integration of digital technologies with the real economy.

3.4. Robustness Test

Drawing on the views of Du et al. (2017), this study adopts the method of adjusting calibrated anchor points for robustness testing [16]. After modifying the anchor points for full membership, cross-over point, and full non-membership in data calibration to 0.9, 0.5, and 0.1 respectively, the results are shown in Table 5, where the configuration path results are basically consistent with the previous ones. It can thus be concluded that the research results are robust.

Table 5. Changing calibration anchors and robustness test

Antecedent Conditions	RIC Configurations			
	Path 1	Path 2	Path 3	Path 4
IF	p	C	C	C
DI			C	C
ID	C	C	p	C
DG	C	C	p	p
II	p	P	P	P
IT	C	C	p	p
IB	C	C	p	C
Raw Coverage	0.216	0.612	0.251	0.238
Unique Coverage	0.046	0.397	0.019	0.004
Consistency	0.979	0.991	0.891	0.945
Overall Solution Coverage		0.737		
Overall Solution Consistency		0.946		

Note: C indicates the presence of a core condition in the configuration, while c indicates the absence of a core condition; P indicates the presence of a peripheral condition, and p indicates the absence of a peripheral condition. A blank space indicates that the condition is optional.

4. Conclusions

Drawing on cross-sectional data from 31 Chinese provinces in 2023, this study applies the fuzzy set qualitative comparative analysis (fsQCA) method to systematically explore the configurational formation paths of high-level RIC in the context of digitalization and intelligentization. It aims to address the inadequacy of existing RIC studies in analyzing multi-factor synergistic mechanisms and to break through the limitations of traditional single-factor analytical frameworks. The key findings reveal that no single antecedent variable constitutes a necessary condition for high-level RIC, as all consistency values are below 0.9. This directly verifies that high-level RIC is driven by the synergistic effect of multiple factors rather than individual conditions. Configurational analysis identifies four typical paths to high-level RIC, each with distinct factor combinations and applicable scenarios: the infrastructure-deficient path, represented by Tianjin and Chongqing, where regions with weak IF and II achieve innovative breakthroughs through the closed-loop synergy of ID, DG, IT, IB; the high-level development path, demonstrated by provinces such as Guangdong and Zhejiang, and relies on strong infrastructure support to drive full-chain linkage among ID, DG, IT, and IB, forming a high-level innovation paradigm; the IF-DI path adopted by Hebei Province, concentrating resources to strengthen the linkage between IF and DI to compensate for shortcomings in ID and IT; the DI-ID linkage path realized by Henan Province, leveraging IF to simultaneously promote DI and ID, and converting IB into high-level innovation. The core theoretical innovation of this study lies in revealing that there is no universally optimal path for improving regional innovation; instead, the effectiveness of a path depends on the dynamic adaptation between factors and the complementary effect of core conditions, which provides a configurational perspective for understanding regional innovation divergence. Future research could extend in two dimensions: expanding the research period to panel data analysis to explore the dynamic evolution of configurational paths over time and identify whether factor combinations exhibit stage-specific characteristics; additionally, incorporating external environmental factors, such as policy shocks or inter-regional spillovers, into the configurational framework could enrich the analysis of complex causal relationships.

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