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Research on the Enhancement Path of Enterprises' Green Innovation Capability from an Adaptive Structuration Perspective

-- A Configurational Analysis based on 89 Automotive Manufacturing Enterprises

Ling Luo, Yuan Tang

School of Management, Sichuan University of Science & Engineering, Zigong, Sichuan 643000, China

Abstract

Tariff wars and decoupling policies have triggered profound adjustments in global supply chains. As the core entities within these supply chains, manufacturing enterprises play a crucial role in addressing global sustainable development challenges through their green innovation capabilities. This paper employs Adaptive Structuration Theory as the theoretical analytical framework. Focusing on 89 automotive manufacturing enterprises from 2019 to 2023, it utilizes the dynamic Qualitative Comparative Analysis (QCA) method to explore the enhancement paths driving the green innovation capability of these enterprises from a configurational perspective. The results indicate that: (1) No single antecedent condition can constitute a necessary condition for enhancing enterprises' green innovation capability on its own; (2) Achieving high-level green innovation capability requires specific configurations, where ESG culture is a key factor and the allocation of green attention is an important factor. Specifically, there are five paths leading to high-level green innovation capability, which can be categorized into three driving modes: "Technology-Organization Mutual Construction," "Organization-Led Adaptation," and "Tripartite-Structure Synergy"; (3) The time effect is not significant in the configurations for high-level green innovation capability, while the case effect is significant in some configurations. This research contributes to understanding the complex relationships involved in enhancing corporate green innovation capability and offers theoretical and practical value for automotive manufacturing enterprises striving to achieve green development.

Keywords

Green Innovation Capability; Adaptive Structuration Theory; Dynamic QCA; Automotive Manufacturing Enterprises.

1. Introduction

Amid the ongoing restructuring of the global economic landscape, tariff wars and decoupling policies have not only significantly reshaped global supply chains but also presented unprecedented challenges and opportunities for China's manufacturing sector. At the same time, with the steady advancement of China's "dual-carbon" goals (carbon peak and carbon neutrality), the importance of green and low-carbon development in manufacturing has become increasingly prominent. To improve production efficiency and reduce operational costs, manufacturing companies are urgently seeking to transition toward more efficient and low-carbon production models [1]. As a representative traditional industry, automotive manufacturing is associated with substantial resource consumption, energy use, and pollutant

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emissions, posing a non-negligible negative impact on the ecological environment. In response, the Ministry of Industry and Information Technology released the "Green and Low-Carbon Development Roadmap for the Automotive Industry 1.0", which serves as a guiding policy document to facilitate the achievement of the national dual-carbon objectives within the automotive sector. This roadmap outlines specific goals and pathways for the industry's green transition. Under the continuing influence of policy measures [2], the green transformation of automotive manufacturers is gradually moving from symbolic commitments toward tangible actions. Nevertheless, challenges remain, including inadequate carbon footprint management capabilities, insufficient coordination across industrial chains, and limited application of recycled materials.

Green innovation, as a synergistic integration of "green-oriented" and "innovation-driven" strategies, serves not only as an effective pathway for Chinese enterprises to overcome resource and environmental constraints and achieve green transformation, but also constitutes a fundamental pillar for high-quality development in China's manufacturing sector. Against the backdrop of external pressures from "decoupling" policies and internal imperatives of digitalization and low-carbon transition, enhancing green innovation capabilities is crucial for China's automotive manufacturing industry to strengthen its competitive position in the global value chain. Furthermore, it helps elevate green manufacturing standards, stimulate low-carbon innovation vitality, and ultimately achieve a balance between economic growth and ecological benefits.Compared with conventional technological innovation, green innovation typically requires higher capital investment, involves more complex R&D processes, and entails a longer return-on-investment cycle [3]. These characteristics tend to dampen enterprises' intrinsic motivation to proactively engage in green innovation initiatives [4]. Against this backdrop of multifaceted challenges, how to support automotive manufacturers in accelerating low-carbon transformation, enhancing green innovation capabilities, and effectively implementing green development strategies has become a major focus of discussion among governments, industry stakeholders, and academic researchers.

A review of the literature on corporate green innovation reveals two main observations: First, existing studies predominantly focus on the impact of individual factors-such as digital transformation [5], corporate social responsibility [6], ESG performance [7], organizational slack resources [8-9], and supply chain dynamics [10-11]-on the development of green innovation. However, according to Complex Adaptive Systems (CAS) theory [12], enhancing corporate green innovation capability is a comprehensive process involving the synergy of multiple elements. Research based solely on linear causal relationships falls short in unraveling the complex mechanisms and driving patterns behind corporate green innovation. Second, much of the current research on green innovation in the context of the dual-carbon goals examines manufacturing enterprises as a whole [13] or focuses on industry-leading firms [14]. These findings have limited applicability when extended to the automotive manufacturing sector.The reasons are as follows: Manufacturing enterprises across sectors differ significantly in their core businesses and development strategies, leading to notable variations in operational scope, technological pathways, and resource allocation. On the other hand, industry leaders, with their strong comprehensive capabilities, advanced R&D capacity, and efficient resource integration, have already secured a dominant position. Therefore, applying conclusions drawn from studies on the broader manufacturing sector or leading firms directly to the automotive manufacturing industry requires further critical examination and contextual adaptation.

This paper adopts Adaptive Structuration Theory (AST) as the theoretical framework and examines automotive manufacturing enterprises as the research subject. Utilizing panel data from 2019 to 2023 and applying the dynamic Qualitative Comparative Analysis (QCA) method, it analyzes the enhancement pathways of green innovation capability and the complex causal

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relationships among influencing factors in China's automotive manufacturing industry. Accordingly, the study focuses on the following research questions:

(1) What multi-level factors interact in a coordinated manner to enhance the green innovation capability of automotive manufacturing enterprises?

(2) What synergistic effects and configurational pathways emerge from the interactions among these factors?

(3) Do temporal effects and case-specific variations exist in the pathways leading to high-level green innovation capability in automotive manufacturers?

2. Literature Review and Model Construction

2.1. Literature Review

Corporate innovation is the result of the combined effects of both internal and external environments within an enterprise [15]. Based on the logic of resource orchestration and Adaptive Structuration Theory, this study selects six variables from three dimensions: the advanced information technology structure level, the internal organizational structure level, and the external structural level. These variables are: green digital intelligence capability, innovation and R&D competitiveness, allocation of green attention, ESG culture, sustainable energy supply, and green supply chain preference.

2.1.1. The Relationship between AST Elements and Corporate Green Innovation

Adaptive Structuration Theory (AST) is rooted in Giddens' Structuration Theory [16] and was formally proposed by DeSanctis and Poole (1994) within the theoretical frameworks of rational decisionism and institutionalism [17]. The theory posits that behaviors related to information technology are shaped by the interplay of factors at three levels: the advanced information technology structure, the internal organizational structure, and external structural environments. Unlike the Technology-Organization-Environment (TOE) framework, AST not only provides a categorical structure for influencing factors but is also underpinned by a robust theoretical foundation [18]. Numerous studies have been conducted based on the AST framework. For example, research by Ju Yanhui, Xu Yan, et al. [19] from an adaptive structuration perspective demonstrated that social media applications can significantly enhance the success rate of crowdfunding projects for rural community libraries.Luna-Reyes et al. [20] analyzed the digital government transformation process from the perspective of the co-evolution of technology, organization, and institutions, emphasizing that governments at all levels should choose appropriate paths for information technology application based on their specific contexts. Liu Rui and Zhang Weijing [21], from the perspective of industrial adaptive adjustment, found that spatial agglomeration in manufacturing significantly enhances the resilience of China's manufacturing sector. Fan Bo and Yu Yuanting [22], using data from the Government Service Hotline 12345, explored factors influencing the quality of governmental data from a structural perspective. They proposed strengthening governance supervision and institutionalizing data management processes to improve the capacity and effectiveness of governmental data quality governance.

Based on the AST theoretical framework, researchers can not only clearly delineate the application contexts of technological structures, internal organizational structures, and external structures, but also gain deeper insights into the dynamic processes through which enterprises achieve high-level green innovation under the interaction of these three dimensions. AST provides solid theoretical support and clear practical guidance for enterprises to promote green innovation through the synergistic effects of technology, internal structure, and external structure.

(1) Advanced Information Technology Structure Level

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Based on Adaptive Structuration Theory (AST), the advanced information technology structure emphasizes institutional rules and encompasses the structural features and technical conditions inherent in technology application. In this study, conditions at this level specifically include green digital-intelligent capability and innovation R&D competitiveness, which reflect the heterogeneity in enterprises' technological resources.

Digital intelligence has become a new driving force for manufacturing enterprises to enhance green innovation capability and gain a competitive edge in the market within the context of the green economy. As a distinctive resource, digital technology serves as a key indicator of an enterprise's level of digital intelligence and a critical element for its green innovation development. Driven by the stringent emission and energy consumption standards of the "China National Stage 6 Motor Vehicle Pollutant Emission Standards," automotive manufacturers are continuously improving production processes, promoting lightweight automotive materials, and reducing waste emissions to facilitate the innovation and application of low-carbon technologies.

Today, the deep integration of smart technologies—such as the Internet of Things, cloud computing, and AI—with traditional manufacturing technologies like internal combustion engines has given rise to intelligent connected vehicles equipped with autonomous driving capabilities. This convergence has created new application scenarios, transforming the conventional automobile from mere transportation into an intelligent platform that enhances smart management, marketing, and services [23]. The widespread adoption of these digital technologies not only strengthens enterprises' ability to acquire external knowledge resources [24] but also advances green and intelligent manufacturing capabilities [25], thereby driving the industry toward high-quality and sustainable development.

Thus, green digital-intelligent capability in production and manufacturing constitutes a critical resource that enables automotive enterprises to accelerate green innovation and achieve high-quality development.

In the process of advancing green innovation, enterprises require abundant innovation resources and strong R&D support. As a form of self-investment, R&D expenditure serves as a vital driver for enhancing independent innovation capability and core creative capacity, and it plays a key role in transforming corporate strengths into market competitiveness [26]. A virtuous cycle exists between R&D investment and innovation capability [27], with "R&D-driven innovation" being particularly conducive to strengthening a company's core competitiveness. Innovation through R&D is a process wherein research personnel translate theoretical knowledge and practical experience into new products, providing technological momentum for enterprises striving for high-quality green development. By increasing investment in R&D, companies are essentially investing in their future development blueprint. Such investment not only enhances core competitiveness but also secures a strategic advantage in future market competition. Therefore, innovation and R&D competitiveness constitute a critical resource that supports automotive manufacturers in accelerating green innovation and achieving high-quality development.

(2) Internal Organizational Structure Level

Based on Adaptive Structuration Theory (AST), the internal organizational structure focuses on managerial cognition, corporate resources, and cultural associations, encompassing aspects such as management structure, human resources, and organizational culture. In this study, it specifically includes the conditions of green attention allocation and ESG culture, reflecting the emphasis an enterprise places on green development.

The human potential of executives and their allocation of attention are key drivers for achieving green innovation [28]. According to the attention-based view of Upper Echelons Theory [29], corporate behavior and decision-making are, to some extent, a reflection of how top managers

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allocate their attention. As the core decision-makers in production and operations, the green attention of the executive team significantly and positively influences the implementation of corporate green innovation strategies. The intensity of executives' focus on green development strategies determines whether such strategies enter the corporate decision-making agenda and further shape organizational behavior [30]. When executives allocate more attention to green development, the implementation of green innovation strategies accelerates, advancing the enterprise's green transformation. Moreover, once managers have invested attention in green innovation, they are more motivated to actively promote it to avoid the sunk cost effect associated with discontinuing these efforts.Given the current national emphasis on "energy conservation and carbon reduction," enterprises require executives to continuously strengthen the allocation of green attention in strategic planning and rationally coordinate internal resources to accelerate the green transition. Therefore, the allocation of green attention by top management is a critical factor in enhancing the green innovation capability of automotive manufacturing enterprises.

Corporate green culture serves as an incubator and nurturing environment for green innovation, functioning as a vital means to promote both green technological innovation and green management innovation performance [3]. ESG (Environmental, Social, and Governance) represents a key carrier and external manifestation of corporate green culture-a holistic development concept that integrates environmental protection, social responsibility, and sound corporate governance. Implementing ESG principles at the micro-enterprise level is a powerful lever for achieving sustainable socio-economic development and driving high-quality corporate growth [31]. For automotive manufacturing enterprises, which attract significant attention in capital markets, ESG ratings and scores can enhance both the quantity and quality of green innovation through the following internal mechanisms: alleviating financing constraints, optimizing principal-agent relationships, and increasing R&D investment [7]. Specifically, a strong ESG rating sends positive signals to capital markets regarding a company's commitment to environmental protection, social responsibility, and robust corporate governance. This enables the enterprise to channel more resources into key areas such as green technology R&D, eco-friendly product design, and the optimization of green production processes, thereby facilitating breakthroughs in green technological and managerial innovation. Hence, a strong ESG culture is a critical influencing factor in enhancing the green innovation capability of automotive manufacturing enterprises.

(3) External Structural Level

Based on Adaptive Structuration Theory (AST), the external structural level primarily involves the broader environment in which an organization operates, including policies and regulations, industry conditions, and market competitiveness and uncertainty. In this study, it specifically includes the secondary conditions of sustainable energy supply and green supply chain preferences, highlighting disparities in the external environment faced by enterprises.

Resource constraints have become a significant factor limiting green innovation among Chinese enterprises [32]. China's commitment to the "dual-carbon" goals has placed higher demands on the construction of a new energy system [33], underscoring the importance of energy conservation and pollution control [34]. As a critical component of this new energy system, the level of clean energy supply serves as a fundamental foundation for corporate green innovation, and its green transformation is a core pathway toward achieving the dual-carbon objectives.The supply of green and clean energy has a significant positive effect on enterprises' green technology innovation. Without stable support for green energy, a company's green transition may be hindered by insufficient energy supply security. A stable green energy supply not only reduces energy costs but also enhances production efficiency through optimized energy structure, thereby providing essential material and technical support for green

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technology innovation.Therefore, a sustainable energy supply is an important factor in enhancing the green innovation capability of automotive manufacturing enterprises.

The pressure on the automotive industry's supply chain stems from a dual set of driving factors: binding requirements from upstream suppliers regarding green production, and growing preference among downstream consumers for environmentally friendly products. The structure of collaborative networks within China's automotive industry remains relatively simplistic in both upstream and downstream sub-networks, and a comprehensive green innovation system across the entire industrial chain has yet to be fully established [35]. In particular, contractual relationships between upstream suppliers and manufacturers are significantly influenced by the cost-investment coefficient of green innovation and the degree of downstream consumers' preference for green technologies. This market-driven environmental constraint is further transmitted to automotive manufacturers, ultimately shaping the green supply chain innovation ecosystem of the entire industry [36]. At the same time, as the direct demand side of end products, consumer preferences not only determine purchasing decisions but also profoundly influence corporate strategic orientation and market positioning [37]. Amid increasing environmental responsibility awareness and growing preference for eco-friendly attributes among both upstream and downstream supply chain actors, automotive manufacturing enterprises must urgently establish a sustainable development strategy system centered on green innovation. Aligning with the prevailing trend of green development, companies need to continuously enhance their green technological capabilities and overall competitiveness. Therefore, green supply chain preference is an important factor in strengthening the green innovation capacity of automotive manufacturing enterprises.

2.2. Theoretical Model Construction

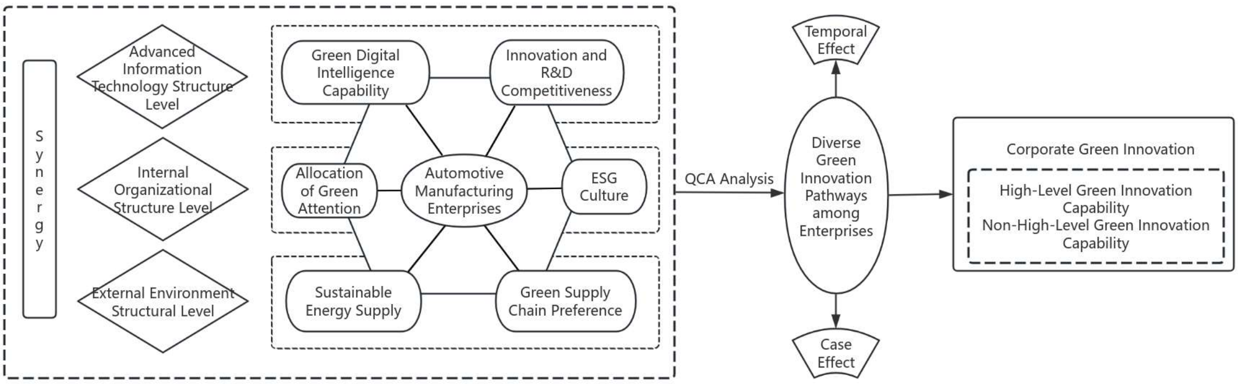

Figure 1. Research Model Based on the Adaptive Structuration Theory (AST) Framework

The enhancement of corporate green innovation capability is the result of synergy and adaptive development among multiple elements within the organizational system. These elements encompass a wide range of factors, including investment in green digital-intelligent technologies, competitiveness in innovation and R&D, mechanisms for allocating green attention, organization-led adaptive culture, external energy environments, market demand feedback, and collaboration across upstream and downstream segments of the industrial chain. Together, they form a complex dynamic system during the green innovation process, adapting to external stimuli and internal developmental needs. Through multidimensional synergy and self-optimization mechanisms, they generate diverse pathways for green innovation development, leading to temporal or case-specific effects, and ultimately achieving different levels of green innovation capability. Using Adaptive Structuration Theory (AST) as the research framework and incorporating insights from Resource Orchestration Theory and

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Complex Adaptive Systems Theory, this study identifies key variables as components of the model and constructs the research model shown in Figure 1.

2.3. Research Methodology

Enhancing the green innovation capability of automotive manufacturing enterprises is a dynamic evolutionary process characterized by continuity and long-term effects, involving complex causal relationships. As Du Yunzhou [38] pointed out, Qualitative Comparative Analysis (QCA) is a suitable method for examining such causal complexities. However, traditional QCA approaches face limitations in handling panel data, particularly in capturing temporal dynamics and case-specific variations, which may lead to an incomplete representation of temporal and case effects.To address this issue, this study employs a dynamic QCA method based on the set-theoretic approach for panel data proposed by Garcia-Castro and Ariño [39]. This method enhances traditional QCA by decomposing consistency into three dimensions: overall consistency, between-group consistency, and within-group consistency. This refinement allows for more precise identification of temporal effects and case-specific effects within institutional configurations. The distance between between-group consistency and within-group consistency reflects temporal heterogeneity and case heterogeneity in the panel data, helping to determine whether the dominant variation in the sample stems from time-related dynamics or cross-sectional differences. This, in turn, improves the accuracy of QCA results. The analysis was implemented using RStudio to perform QCA on panel data.

2.4. Sample Selection and Data Sources

This study focuses on publicly listed companies in the automotive manufacturing sector traded on the Shanghai and Shenzhen A-share markets. After initial screening, 259 companies met the basic criteria. Following the exclusion of companies with incomplete data, insufficient key information, less than five years since listing, and those classified as ST or *ST (indicating financial anomalies or delisting risks), a final sample of 89 companies was obtained. The data cover the period from 2019 to 2023.

2.5. Outcome Measurement

Green Innovation Capability.

Green patents serve as a core reflection of corporate green technological innovation, enabling breakthroughs in areas such as energy conservation, emission reduction, clean energy, and resource recycling. The number of green patent applications and grants is a key indicator of a company's current green innovation capability and activity level. Drawing on the research of Xu Jia and Cui Jingbo [40], this study uses the number of green patent applications to measure corporate green innovation capability.

2.6. Measurement of Conditions

Green Digital Intelligence Capability

This refers to the comprehensive ability of an enterprise to integrate green development principles with digital and intelligent technologies during its green transformation. Drawing on the research of Wang Yonggui et al. [41], this study measures it using the proportion of intangible assets related to green digitalization and low-carbon intelligent technologies relative to the total intangible assets.

Innovation and R&D Competitiveness

With reference to the study by Yu Minggui [42], this construct is measured by the ratio of the enterprise's annual R&D expenditure to its annual operating revenue.

Allocation of Green Attention

Based on the methodological approach of Li Yabing et al. [43], this study employs text analysis techniques implemented in Python to extract and analyze keywords related to green development, innovation strategy, and low-carbon development in corporate annual reports. The frequency of these keywords as a proportion of the total word count is used to indicate the degree of green attention allocation.

ESG Culture

This is measured using the percentile ESG disclosure score provided by the enterprise.

Sustainable Energy Supply

Measured by the ratio of green and renewable energy production to total energy production in the province or municipality where the enterprise is located.

Green Supply Chain Preference

The green preference of upstream and downstream supply chain partners can be reflected through the financial performance influenced by market mechanisms. Operating profit margin, as a key indicator of corporate profitability, effectively captures the impact of green preferences on corporate performance. In line with the research of Wan Xiaole et al. [44], this study uses operating profit margin to measure green supply chain preference.

3. Data Analysis and Results

3.1. Variable Calibration and Descriptive Statistics

Data calibration refers to the process of assigning set membership to sample cases. In line with the approach of Zhang Ming et al. [45] and tailored to the specific context of the sample cases, this study standardized the data in Excel and applied the direct calibration method. Calibration anchors were set at the 25th percentile for full non-membership, the 50th percentile for the crossover point, and the 75th percentile for full membership, thereby transforming all variables into set memberships within the interval [0, 1]. To address specific configurational issues, the approach of Fiss [46] was adopted, whereby membership scores exactly equal to 0.5 were adjusted to 0.501. Calibration details and descriptive statistics for all variables are summarized in Table 1.

Table 1. Calibration results and descriptive statistics

	Conditions and outcomes	Fuzzy set calibration			Descriptive statistics			
		Full membership	Crossover point	Full non-membership	Mean	Standard deviation	Minimum	Maximum
result	Green Innovation Capability	15	3	0	30.166	75.6	0	493
Advanced Information Technology Structure Level	Green Digital Intelligence Capability	0.099	0.051	0.026	0.077	0.086	0	0.76
	Innovation and R&D Competitiveness	6.06	4.68	3.64	5.14	2.813	0.89	30
Internal Organizational Structure Level	Allocation of Green Attention	0.045	0.033	0.024	0.037	0.019	0	0.14
	ESG Culture	28.907	24.75	21.322	25.634	6.84	9.28	46.67
External Structural Level	Sustainable Energy Supply	0.457	0.371	0.222	0.357	0.136	0.07	0.71
	Green Supply Chain Preference	0.085	0.049	0.017	0.041	0.133	-1.24	0.44

3.2. Necessity Analysis

Necessity analysis in QCA aims to identify whether a single condition or a combination of conditions is indispensable for the occurrence of a specific outcome. When applying dynamic QCA with panel data, the necessity of an individual condition must simultaneously satisfy three

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criteria: the aggregate consistency of both the condition and its negation should exceed 0.9, the aggregate coverage should be greater than 0.5, and the adjusted distance between between-group and within-group consistency should be less than 0.2 [39]. As reported in Table 2, the aggregate consistency values for all six conditions and their negations fall below the 0.9 threshold; however, the adjusted between-group consistency distance exceeds 0.2 in certain cases, and the adjusted within-group consistency distance generally surpasses 0.2, indicating the need for further analysis to clarify the necessity of these conditional variables.

Table 2. Analysis of Necessary Conditions

Conditions	High-level green innovation capability				~High-level green innovation capability			
	Aggregate consistency	Aggregate coverage	Adjusted distance of between-group consistency	Adjusted distance of within-group consistency	Aggregate consistency	Aggregate coverage	Adjusted distance of between-group consistency	Adjusted distance of within-group consistency
Green Digital Intelligence Capability	0.568	0.546	0.038	0.614	0.517	0.556	0.07	0.614
~Green Digital Intelligence Capability	0.538	0.499	0.041	0.652	0.578	0.599	0.038	0.585
Innovation and R&D Competitiveness	0.592	0.569	0.104	0.604	0.498	0.535	0.067	0.604
~Innovation and R&D Competitiveness	0.516	0.479	0.11	0.595	0.598	0.621	0.075	0.595
Allocation of Green Attention	0.632	0.6	0.235	0.547	0.468	0.496	0.281	0.624
~Allocation of Green Attention	0.469	0.441	0.33	0.614	0.623	0.654	0.22	0.528
ESG Culture	0.661	0.623	0.145	0.422	0.462	0.487	0.255	0.537
~ESG Culture	0.455	0.431	0.145	0.556	0.642	0.679	0.162	0.422
Sustainable Energy Supply	0.557	0.484	0.096	0.624	0.615	0.597	0.055	0.576
~Sustainable Energy Supply	0.536	0.555	0.11	0.652	0.469	0.542	0.072	0.71
Green Supply Chain Preference	0.483	0.457	0.046	0.614	0.607	0.642	0.041	0.585
~Green Supply Chain Preference	0.622	0.586	0.035	0.624	0.486	0.512	0.043	0.652

Note: "~" denotes the logical operation "not" (the same applies to the following tables).

Table 3. Causal configurations with an adjusted between-group consistency distance greater than 0.2

Case	Causal configuration	Metric	Years				
			2019	2020	2021	2022	2023
Case1	Allocation of Green Attention	Between-group consistency	0.495	0.508	0.655	0.745	0.766
	High-level green innovation capability	Between-group coverage	0.661	0.615	0.634	0.619	0.503
Case2	Allocation of Green Attention	Between-group consistency	0.308	0.387	0.538	0.55	0.559
	~High-level green innovation capability	Between-group coverage	0.49	0.511	0.451	0.466	0.562
Case3	~Allocation of Green Attention	Between-group consistency	0.618	0.597	0.433	0.357	0.333
	High-level green innovation capability	Between-group coverage	0.428	0.472	0.52	0.438	0.33
Case4	~Allocation of Green Attention	Between-group consistency	0.787	0.709	0.564	0.55	0.506
	~High-level green innovation capability	Between-group coverage	0.65	0.611	0.586	0.688	0.768
Case5	ESG Culture	Between-group consistency	0.318	0.399	0.487	0.538	0.563
	~High-level green innovation capability	Between-group coverage	0.437	0.471	0.43	0.486	0.583

Table 3 reports five causal configurations where the adjusted distance of between-group consistency exceeds 0.2. First, by examining the consistency and coverage values across different years for these five configurations, it is observed that the between-group consistency in all cases falls below 0.9. This indicates that the conditional variables do not constitute necessary conditions for driving high-level corporate green innovation capability. Thus, enhancing high-level corporate green innovation capability results from the combined effects of multiple antecedent conditions, necessitating further analysis of the configurations.

3.3. Sufficiency Analysis

The core of QCA lies in examining how different combinations of conditions influence the outcome variable, with the consistency level of sufficient condition configurations serving as the key criterion. Following prior research [2] and considering the specific context of this study, the thresholds were set as follows: consistency level ≥ 0.8, PRI (Proportional Reduction in Inconsistency) ≥ 0.7, and case frequency ≥ 5 for constructing the truth table. The truth table itself is not presented here due to space limitations. To ensure comprehensiveness and scientific rigor, and to avoid biases from unwarranted assumptions, no prior directional assumptions were imposed on the variables. Using RStudio, the data were analyzed to derive the intermediate, parsimonious, and complex solutions. The intermediate solution served as the primary basis for interpretation, supplemented by the parsimonious and complex solutions. Conditions appearing in both the intermediate and parsimonious solutions were identified as core conditions, while those only present in the intermediate solution were classified as peripheral conditions. The resulting configurational outcomes for achieving high-level green innovation capability are summarized in Table 4.

3.3.1. Configurational Paths to High-Level Corporate Green Innovation Capability

Table 4. Configurations for High-Level Corporate Green Innovation Capability

Conditions		High-level green innovation capability				
		M1			M2	M3
		H1	H2	H3	H4	H5
Advanced Information Technology Structure Level	Green Digital Intelligence Capability	●		●	⊗	⊗
	Innovation and R&D Competitiveness		●	●	⊗	●
Internal Organizational Structure Level	Allocation of Green Attention	●	●		●	•
	ESG Culture	●	●	●	●	●
External Structural Level	Sustainable Energy Supply			⊗	⊗	●
	Green Supply Chain Preference	⊗	⊗	⊗		
	Consistency	0.811	0.845	0.852	0.835	0.821
	PRI	0.745	0.784	0.78	0.747	0.724
	Coverage	0.187	0.191	0.111	0.126	0.124
	Unique Coverage	0.046	0.005	0.04	0.019	0.027
	Adjusted Distance of Between-Group Consistency	0.113	0.116	0.128	0.067	0.125
	Adjusted Distance of Within-Group Consistency	0.297	0.211	0.182	0.24	0.182
	Overall Consistency	0.808				
	Overall PRI	0.744				
	Overall Coverage	0.394				

Note: ① "•" indicates the presence of a condition variable, "⊗" indicates the absence of a condition variable, and a blank space indicates that the condition variable is irrelevant; ② "●" and "⊗" denote core conditions, while "•" and "⊗" denote peripheral conditions (the same applies below).

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Overall, five distinct configurations were identified as sufficient for achieving high-level corporate green innovation capability, which can be categorized into three models: M1, M2, and M3. Both individual and overall solution consistency levels exceed the threshold of 0.75, and the overall solution coverage is above the standard of 0.3 [44], indicating strong explanatory power of the identified paths. The adjusted between-group consistency distances are all below 0.2, suggesting the absence of significant temporal effects across these configurations. However, the adjusted within-group consistency distances exceed 0.2 for configurations H1, H3, and H4, indicating the presence of case-specific effects in these paths that warrant further discussion.

3.3.2. Typical Case Analysis

Based on the results of the sufficiency analysis, a table of typical cases corresponding to each configuration leading to high-level green innovation capability was constructed, as shown in Table 5. Under Model M1, configuration H1 is represented by companies such as Foton Motor, configuration H2 by enterprises like Weichai Power, and configuration H3 by firms including Seres Group. In Model M2, configuration H4 is exemplified by cases such as Yutong Bus. Under Model M3, configuration H5 is represented by companies like BYD.

Table 5. Typical Cases Corresponding to Each Configuration

Configuration	Configuration Designation	Typical Cases
H1	"Technology-Organization Co-construction" Driving Mode	Foton Motors (2020-2023), Great Wall Motors (2021-2023), SAIC Motor (2022-2023), Dongfeng Motor Corporation (2019-2023)
H2	"Technology-Organization Co-construction" Driving Mode	Weichai Power (2021-2023), JAC Motors (2020-2022), Lizhong Group (2020-2021)
H3	"Technology-Organization Co-construction" Driving Mode	Seres Group (2019-2023), Wanliyang Group (2020-2022), Changan Automobile (2022-2023)
H4	"Organization-Led Adaptation" Driving Mode	Sinoretech (2020-2023), Yutong Bus (2021-2022), Great Wall Motors (2022-2023), Aerospace Science and Technology Corporation (2020-2022
H5	"Tripartite-Structure Synergy" Driving Mode	BYD (2020-2023), Seres Group (2020-2022), Harbin Dongan Auto Engine Co., Ltd. (2021-2023), JAC Motors (2022-2023)

(1) M1: Technology-Organization Co-construction Driving Mode

This mode comprises configurations H1, H2, and H3, each demonstrating consistency levels exceeding 0.8, and accounting for 18.7%, 19.1%, and 11.1% of the sample cases, respectively. Across all three configurations, technological conditions and corporate ESG culture consistently serve as core conditions, while green supply chain preference is consistently absent as a core condition. The distinctions lie in the specific interactive mechanisms: Configurations H1 and H2 emphasize the synergistic effect between green attention allocation by executives (internal organizational structure) and ESG culture. Configuration H3 highlights the interplay between green digital-intelligent capability and innovation R&D competitiveness (advanced information technology structure). This mode underscores that the co-evolution of technological and organizational factors is critical to driving high-level green innovation capability, albeit through distinct causal pathways.

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Analysis based on the model reveals that enterprises achieve high-level green innovation through the dynamic alignment of advanced low-carbon technology applications and green organizational systems. This finding corroborates conclusions from existing research, confirming that the application of advanced digital-intelligent technologies can effectively enhance corporate green innovation performance [24], thereby facilitating enterprises' green transformation.

(2) M2: Organization-Led Adaptive Driving Mode

This mode corresponds to configuration H4, which demonstrates a consistency level of 0.835 (exceeding the 0.8 threshold) and explains 12.6% of the sample cases. In configuration H4, both green attention allocation and ESG culture (internal organizational structure level) serve as core conditions, while green digital-intelligent capability, innovation R&D competitiveness, and sustainable energy supply are absent as core conditions. This indicates that enterprises can achieve high-level green innovation capability primarily by strengthening internal green management and operational practices, even without relying heavily on technological resources or external energy supply conditions. The results emphasize the critical role of organizational initiative and adaptive internal governance in driving green innovation.

Nevertheless, despite gaps in advanced information technology and external resource development within this mode, high-level corporate green innovation capability can still be achieved when green organizational system conditions are well-developed. This finding validates that executive green attention and green culture serve as crucial mechanisms influencing corporate green innovation [3].

(3) M3: Tripartite-Structure Synergy Driving Mode

This mode corresponds to configuration H5, which demonstrates a consistency level of 0.821 (exceeding the 0.8 threshold) and explains 12.4% of the sample cases. In configuration H5, innovation R&D competitiveness, ESG culture, and sustainable energy supply simultaneously serve as core conditions, while green attention allocation functions as a peripheral condition, and green digital-intelligent capability is absent as a core condition. This indicates that enterprises can achieve high-level green innovation capability by adopting a multi-pronged development path that synergistically leverages technological innovation, organizational culture, and external resource support. The results highlight the effectiveness of a coordinated approach across multiple structural dimensions in driving green innovation, even when specific technological capabilities are not dominant.

Overall, the M3 mode represents a comprehensive and integrated development approach. In this mode, elements across different structural dimensions within the adaptive structuration framework interact synergistically to collectively enhance high-level green innovation capability. This integrated pathway provides a solid theoretical and practical foundation for corporate green innovation through multi-dimensional collaboration.

Analysis of the three modes of corporate green innovation capability reveals that, under the AST framework, different combinations of variables from the three dimensions—advanced information technology structure, internal organizational structure, and external structural environment—can lead to the same outcome of high green innovation performance. On one hand, compared to M1 and M2, the M3 mode highlights the role of the energy environment. Energy infrastructure not only provides essential resource inputs for green innovation but also enhances efficiency by optimizing resource allocation. On the other hand, technological rules and organizational institutions play more prominent roles compared to other dimensions. Specifically, ESG culture appears as a core condition in all five configurations across the three modes, while green attention allocation is present in four configurations. This indicates that ESG culture serves as a core structural element in green innovation through institutional and cultural reproduction mechanisms, whereas green attention allocation facilitates strategy

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implementation through the structuring of managerial cognition. Both are critical factors influencing corporate green innovation capability.

3.3.3. Analysis of Between-Group Results

As shown in Table 4, the adjusted between-group consistency distances for all five configurations identified in this study are below 0.2, indicating no significant differences in the explanatory power of these configurations across different years-that is, temporal effects are not significant. As illustrated in Figure 2, the between-group consistency of the five configurations generally exhibits a fluctuating downward trend. The period between 2020 and 2022 shows particularly notable fluctuations, with configurations H4 and H5 demonstrating significantly more pronounced volatility compared to the others.

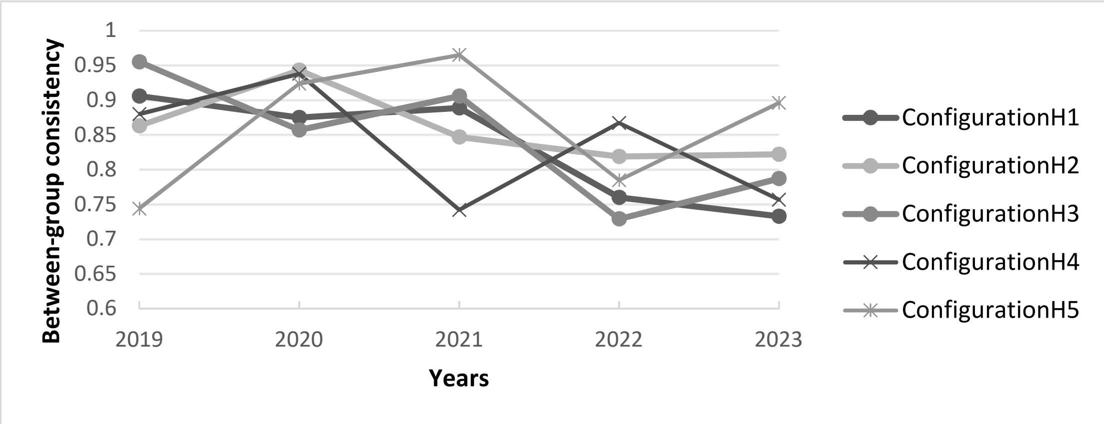

Figure 2. Variation in between-group consistency

Potential reasons for these observations are speculated as follows: First, the overall fluctuating downward trend may stem from the inherently dynamic and enabling nature of green innovation. This dynamism implies that fluctuations in corporate green innovation processes are normal and expected. Second, the significantly increased volatility across all configurations during the 2020–2022 period is likely closely related to the impact of the COVID-19 pandemic. The outbreak disrupted the implementation and execution of some green innovation policies, suppressed consumer demand for green products and services, and consequently weakened enterprises' willingness to invest in green innovation. Third, the more pronounced fluctuations in configurations H4 and H5 compared to others may be attributed to differences in the functional emphasis of their conditional combinations. Each configuration emphasizes distinct elements, and when applied to highly heterogeneous automotive manufacturing enterprises, their mechanisms and effects inevitably exhibit significant variations.

3.3.4. Analysis of Within-Group Results

As indicated in Table 4, the adjusted within-group consistency distances for configurations H1, H2, and H4 exceed 0.2, suggesting differences in the explanatory power of these configurations across different enterprises-that is, case-specific effects may be present in this study. The within-group consistency levels for each configuration are shown in Figure 3.

Most enterprises exhibit high consistency levels under the various configurations, while a small number show relatively lower consistency. This implies that the configurations for high-level green innovation capability demonstrate strong explanatory power for the majority of enterprises, whereas a few atypical enterprises may require alternative pathways to achieve high-level green innovation. This phenomenon may be attributed to multiple factors, including external conditions such as the level of economic development, geographical location, and resource endowment of the region where an enterprise is located, as well as internal factors

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such as the enterprise's own development experience. Firstly, the external environment significantly influences corporate green innovation development. Regional economic development in China is uneven, with central and western regions generally less developed than eastern regions. For example, companies like Foton Motor and BYD, which demonstrate high levels of green innovation, are located in economically advanced regions such as Beijing and Guangdong Province. These enterprises benefit from geographical advantages in terms of government policies, investor attention, and industry regulations compared to companies in other regions.

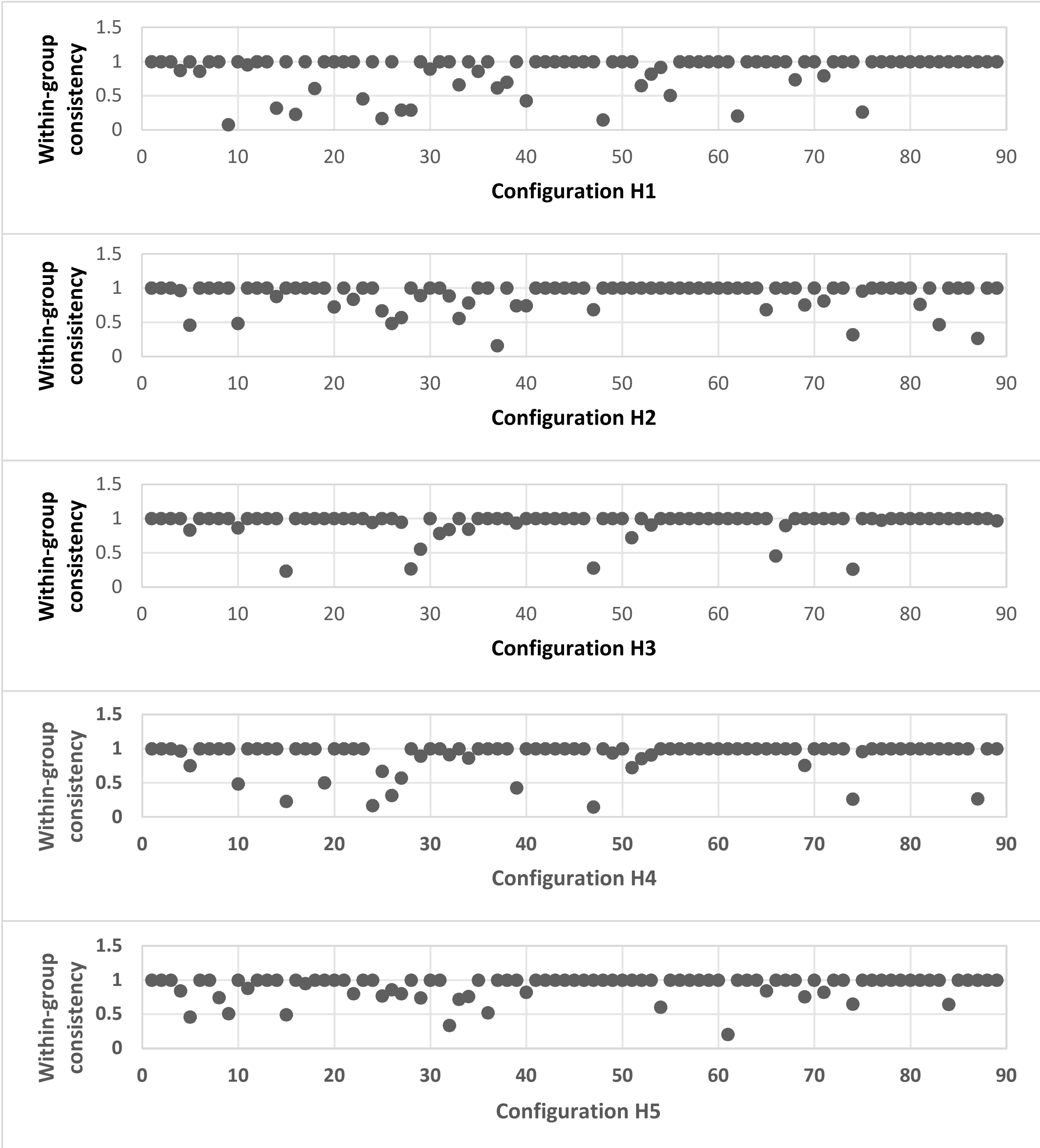

Figure 3. Within-group consistency of configurations H1 to H5

Note: The horizontal axis represents the enterprise serial number. The sample comprises 89 enterprises.

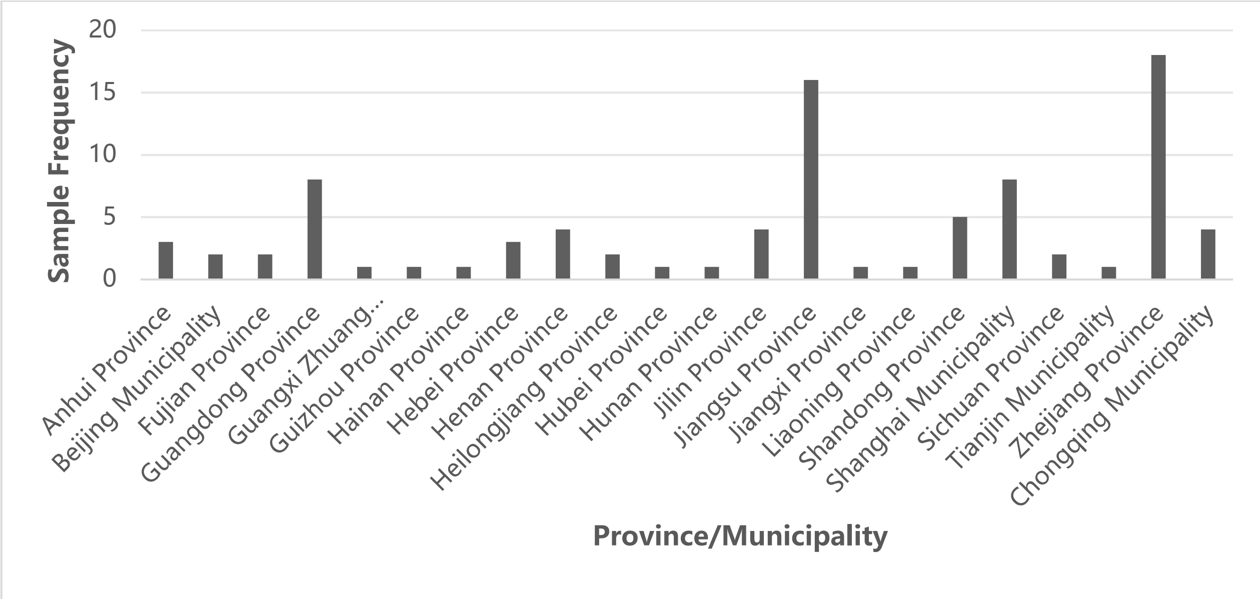

Figure 4. Proportion of Enterprises by Province/Municipality

Therefore, as shown in Figure 4, even though the research sample covers 22 provinces, municipalities, and autonomous regions, significant case-specific effects are observed in the green innovation development of automotive manufacturing enterprises. These variations arise from differences in regional resource consumption levels, implementation of low-carbon strategies, government support for green development policies, and industry competition dynamics.

Furthermore, the enterprises studied exhibit heterogeneity in their founding and listing dates, which range from 1992 to 2018. Over decades of economic development, disparities in initial capital accumulation have naturally emerged. Such differences may create “barriers” when empowering enterprises to pursue new green development pathways, thereby limiting the full potential of configurational drivers.

3.3.5. Robustness Test

This study conducted robustness tests on the configurations leading to high-level green innovation capability in automotive manufacturing enterprises. Following the approach of Du Yunzhou [38], robustness was examined by adjusting the following thresholds: raw consistency threshold, case frequency threshold, and PRI consistency threshold. Specifically, the raw consistency threshold was increased from 0.8 to 0.85, the case frequency threshold was reduced from 5 to 4, and the PRI consistency threshold was raised from 0.7 to 0.72. After these adjustments, the overall consistency values of the configurations generating high-level green innovation capability changed to 0.811, 0.797, and 0.813, respectively-only minor deviations from the original value of 0.808. Moreover, the configurations yielding high-level green innovation capability remained largely unchanged. Therefore, based on established evaluation criteria [45], the findings of this study are considered robust.

4. Research Conclusion

This study yields the following main conclusions:

(1) In terms of necessary conditions, enhancing green innovation capability in automotive manufacturing enterprises involves complex causal relationships. None of the conditions-green digital intelligence capability, innovation and R&D competitiveness, allocation of green attention, ESG culture, sustainable energy supply, or green supply chain preference-can

individually serve as a necessary condition for driving the improvement of green innovation capability, indicating that single driving conditions have limited explanatory power.

(2) Regarding the configurations for high-level green innovation capability, antecedent conditions from the advanced information technology structure, internal organizational structure, and other external structural levels exhibit "multiple conjunctural" causality, forming three types of driving paths with a total of five configurations: the technology-organization co-construction driving mode, the organization-led adaptation driving mode, and the tripartite-structure synergy driving mode. Furthermore, this study finds that ESG culture appears as a core condition in all five configurations, while the allocation of green attention is present in four configurations. The former is a key factor influencing enterprises' green innovation capability, and the latter is an important factor affecting corporate green innovation; both play more significant roles in the configurations compared to other antecedent variables.

(3) From the between-group results, temporal effects were not significant in the configurations leading to high-level green innovation capability. The five identified pathways generally exhibited a fluctuating downward trend, with particularly pronounced volatility during the 2020–2022 period. Configurations H4 and H5 showed noticeably stronger fluctuations compared to the others, likely attributable to the inherent dynamism of green innovation, disruptions caused by the pandemic, and differences in conditional combinations.

(4) From the within-group results, although case-specific effects were significant in some configurations for high-level green innovation capability, the explanatory power remained strong for most enterprises. A comparative case analysis reveals an imbalance in the enhancement of green innovation capability among automotive manufacturing enterprises in China, which is primarily driven by regional disparities in innovation development and enterprise heterogeneity. These variations reflect the uneven development of regional innovation capabilities and the divergent levels of progress among automotive manufacturers, underscoring the need for in-depth exploration of how to foster diversified and flourishing green innovation pathways across enterprises and how to effectively address regional development imbalances.

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