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# Driving Mechanisms of Green Innovation in Manufacturing Enterprises: A Dynamic Qualitative Comparative Analysis

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**ABSTRACT**

This study examines how technological, organizational, and environmental conditions jointly shape green innovation in manufacturing firms. Drawing on the Technology–Organization–Environment (TOE) framework and the resource-based view, it applies dynamic qualitative comparative analysis (dynamic QCA) to panel data from 116 Chinese listed manufacturing firms. The findings reveal that no single condition is necessary for high green innovation; instead, six sufficient configurations emerge, forming two broad patterns: innovation-led pathways and multi-factor synergy pathways. Digital transformation supports green innovation when combined with complementary technological capabilities and stakeholder attention, and may help compensate for limited organizational slack under certain environmental conditions. Complementary random forest analysis identifies stakeholder attention, technical integration capability, and environmental regulations as important predictors, while revealing nonlinear relationships and a particularly strong interaction between stakeholder attention and technical integration capability. The findings also highlight temporal, regional, and industry heterogeneity, underscoring the need for context-specific green

innovation strategies.

**Keywords:** Technology–Organization–Environment (TOE) framework; digital transformation; gre en transformation; green innovation; dynamic QCA; manufacturing firms.

# 1 Introduction

Amid growing climate change and environmental pressures, green innovation has become an important means for firms to reconcile economic competitiveness with environmental sustainability. Manufacturing firms play a critical role in this transition because they consume substantial amounts of energy and natural resources while providing an important setting for the development and diffusion of green technologies. However, manufacturing firms differ considerably in their green innovation performance, even when facing similar market and environmental conditions. This variation suggests that green innovation cannot be adequately explained by individual factors alone. Understanding how technological capabilities, organizational resources, and external environmental pressures interact to shape green innovation is therefore essential.

Existing research on green innovation has evolved from examining its relationship with firm performance [1–3] to investigating its technological, organizational, and institutional drivers. Previous studies have highlighted the roles of technological capabilities and collaboration [4], organizational structures [5], and institutional and stakeholder pressures [6, 7]. Although these studies have advanced understanding of the determinants of green innovation, three important gaps remain. First, much of the existing literature examines individual drivers and their net effects separately, providing limited insight into how technological, organizational, and environmental conditions combine to generate high green innovation.

Second, although configurational research recognizes that different combinations of conditions can produce similar outcomes [8], limited attention has been paid to how these configurations evolve over time and vary across regions and industry types. Third, existing configurational analyses provide limited information about the relative predictive importance of individual conditions and the nonlinear relationships and interactions that may underlie green innovation. Addressing these gaps requires an integrated approach that captures configurational complexity, temporal dynamics, contextual heterogeneity, and nonlinear relationships.

To address these gaps, this study integrates the Technology–Organization–Environment (TOE) framework with the resource-based view (RBV) to investigate the configurational drivers of green innovation in manufacturing firms. Using panel data from 116 Chinese listed manufacturing firms covering 2018–2024, we employ dynamic qualitative comparative analysis (dynamic QCA) to identify combinations of technological, organizational, and environmental conditions associated with high green innovation and examine their temporal evolution. The Kruskal–Wallis test is further used to assess differences in configurational coverage across regions and industry types. In addition, random forest regression is employed as a complementary analytical method to assess the relative predictive importance of individual conditions, examine nonlinear relationships through partial dependence plots, and explore interactions among antecedent conditions.

This study contributes to the literature in three ways. Theoretically, it integrates RBV and the TOE framework to explain how internal capabilities and external environmental pressures jointly shape green innovation, extending research beyond analyses of isolated determinants. From a configurational and temporal perspective, it identifies multiple pathways to high green innovation and examines their evolution over time, as well as differences across regions and industry types. Methodologically, it combines dynamic QCA with random forest regression to complement configurational analysis with evidence on predictive

importance, nonlinear patterns, and interactions among conditions. This integrated approach provides a more comprehensive understanding of the complex mechanisms associated with green innovation.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and presents the theoretical background. Section 3 describes the research design, including sample selection, variable calibration, and analytical methods. Section 4 presents the dynamic QCA results, robustness checks, and heterogeneity analyses. Section 5 reports the supplementary random forest analysis. Section 6 concludes the study and discusses its practical implications and directions for future research.

# 2 Theoretical framework

## *2.1 Related Research on Green Innovation*

Research on green innovation has grown rapidly in recent years and now spans several connected lines of inquiry. At a broad level, the literature can be organized into four themes: (1) how green innovation is defined and measured, (2) how firms design and implement green innovation through strategy and management practices, (3) what outcomes green innovation produces, (4) which conditions motivate or constrain firms to engage in green innovation. Recent reviews highlight that these themes have advanced the field but also note that findings often remain fragmented across methods and contexts [9].

A first theme focuses on the definition and measurement of green innovation. Recent studies show that green innovation is most commonly measured using green patent data, reflecting firms' technological outputs in environmentally related fields. However, an increasing number of scholars point out that patent-based indicators capture only part of firms′ green innovation efforts and may overlook important non-patented activities, such as process improvements, managerial practices, and organizational innovations related to

environmental sustainability. As a result, recent research calls for combining patent-based measures with complementary indicators to provide a more comprehensive and accurate representation of firms′ green innovation activities and their underlying intensity [10]. A second theme examines firm strategies and organizational behavior that support green innovation. This stream of research emphasizes that green innovation is shaped not only by technological investment, but also by managerial decisions, strategic orientation, and internal coordination mechanisms. Empirical evidence suggests that corporate environmental initiatives and environmental strategies often influence environmental outcomes indirectly by stimulating green innovation, underscoring the mediating role of organizational processes. These findings highlight that green innovation is embedded in broader strategic and organizational contexts, rather than being a purely technical or isolated decision [11].

A third theme focuses on the performance implications of green innovation. Recent meta-analytical studies indicate that green or environmental innovation is, on average, positively associated with firm performance, although the magnitude of this relationship varies across performance dimensions and institutional contexts. Complementary evidence further shows that green innovation tends to enhance environmental performance, with heterogeneous effects depending on the type of innovation, such as green product versus green process innovation. Together, these studies support the view that green innovation can create value for firms, while also explaining why empirical results differ across industries and settings [12]. Finally, a growing body of work examines drivers and constraints of green innovation. Recent studies emphasize external pressures—such as stakeholder demands and environmental regulations—as important triggers that can shape whether firms invest in green innovation and what form that innovation takes. For instance, stakeholder pressure is shown to be closely linked to green innovation and performance through

firms′ capability-building, while regulatory interventions can induce green innovation under certain conditions [13].

Overall, while these research streams provide important insights into green innovation, they tend to examine individual factors in isolation and rely on linear analytical approaches. As a result, they offer limited understanding of how multiple conditions interact to produce high levels of green innovation. This limitation motivates a framework that conceptualizes green innovation as the outcome of interacting technological, organizational, and environmental conditions, rather than the result of a single dominant driver operating independently.

### *2.2 Analytical Framework*

As noted above, existing research on green innovation in manufacturing has identified a wide range of technological, organizational and environmental determinants, but much of this work treats these factors as independent covariates and estimates their linear "net effects". This approach fragments the evidence and obscures how conditions actually work together in practice. Green innovation in manufacturing enterprises, however, is embedded in a multi-dimensional context: it depends on the technological base and innovation inputs available to the firm, on internal organizational resource conditions and managerial arrangements, and on external regulatory and market pressures. An appropriate analytical framework must therefore (1) organize these heterogeneous conditions in a systematic way and (2) be compatible with a configurational, set-theoretic analysis that can capture multiple, equifinal paths to high green innovation.

To meet this need, the present study adopts the Technology–Organization–Environment (TOE) framework as a structural lens for organizing the antecedent conditions of green innovation in manufacturing enterprises. Originally developed to explain organizational innovation adoption, the TOE framework posits

that innovation-related decisions are jointly shaped by conditions in three domains: the technological context, the organizational context and the external environmental context. Applied to green innovation, the technological dimension captures firms' innovation-related inputs and capabilities, such as R&D intensity, technological integration capability and the emphasis placed on digital transformation. The organizational dimension reflects internal structures and resource conditions, here represented by organizational slack as an indicator of available discretionary resources. The environmental dimension encompasses regulatory and market forces and stakeholder pressures, operationalized through environmental regulations, market competition and stakeholder attention. This tri-dimensional structure offers a coherent way to classify the multiple conditions that may influence green innovation in manufacturing enterprises.

At the same time, a purely contextual classification is not sufficient to explain how these conditions generate high green innovation outcomes, nor why different combinations of conditions can lead to similar results. To address this, we complement the TOE framework with a resource-oriented perspective. The resource-based view (RBV) emphasizes that firm-specific resources and capabilities that are valuable, rare, inimitable and non-substitutable form the basis of sustained competitive advantage, and that competitive outcomes depend not only on the stock of resources a firm possesses, but also on how these resources are combined and reconfigured over time. In the context of green innovation, technological inputs (R&D intensity, technological integration capability, digital transformation emphasis), organizational conditions (organizational slack) and environmental conditions (regulatory pressure, market competition, stakeholder attention) can all be interpreted as critical resources and constraints that firms must identify, integrate and redeploy in order to generate green innovation. This resource-based logic suggests that it is not any single condition, but rather configurations of technological, organizational and environmental resources, that underpin high levels of green innovation.

By combining the structural clarity of the TOE framework with the resource configuration logic of the RBV, this study constructs an integrated analytical framework for the drivers of green innovation in manufacturing enterprises. Within this TOE−RBV framework, we conceptualize seven antecedent conditions across the three dimensions—technological resources (R&D intensity, technological integration capability, emphasis on digital transformation), organizational resources (organizational slack) and environmental pressures and supports (environmental regulations, market competition, stakeholder attention)—and treat them as interdependent conditions that may jointly form different configurations sufficient for high green innovation. We explicitly allow for equifinality, that is, the possibility that multiple, qualitatively different configurations can each lead to high green innovation. For example, one type of configuration may be predominantly environment-driven, characterized by strong market competition and high stakeholder attention even in the absence of uniformly strong technological inputs, whereas another type may reflect a multi-factor linkage pattern in which strong technological resources, appropriate organizational slack and supportive environmental conditions co-occur. These configurational expectations underpin the research model presented in Figure 1 and motivate our use of dynamic qualitative comparative analysis (dynamic QCA) to identify empirically the pathways to high green innovation and to trace how their relevance and composition evolve over time.

[Figure 1 about here]

*2.2.1 Technical Dimensions*

Technological conditions form the internal basis through which manufacturing firms convert scientific knowledge into commercially viable applications and, in turn, advance green innovation. In this study, the technological dimension is represented by two complementary aspects: the level of technological innovation

and technological integration capability. Recent research emphasizes that green innovation depends on sustained capability accumulation and purposeful allocation of knowledge resources, rather than one-off investments, because green innovation often requires iterative experimentation, learning, and refinement before it can be scaled within the firm and across markets [13].

Technological innovation captures a firm′ s ability to generate new knowledge and develop novel technologies. From a resource-oriented perspective, green innovation is more likely when firms build distinctive, difficult-to-imitate technological capabilities that can support long-term sustainability-oriented innovation [14]. In practice, however, many firms face low innovation efficiency and persistent technological bottlenecks, which can weaken incentives to invest in green innovation due to uncertain payoffs and delayed returns. Strengthening technological innovation helps to relax these constraints. Specifically, higher R&D intensity broadens firms′ knowledge base and increases the likelihood of eco-innovative outcomes, because eco-innovation often draws on both "green" and conventional R&D portfolios and benefits from diversified technological search [15]. Empirical evidence also suggests that greater R&D intensity can reinforce the effectiveness of green innovation strategies, indicating that R&D strengthens firms′ ability to translate environmental intent into innovation outputs [16]. Moreover, evidence from Chinese manufacturing indicates that increases in green technological innovation are often accompanied by higher R&D investment, consistent with the view that R&D supports green technology development through capability building and resource mobilization [17]. Over time, accumulated R&D also contributes to a more stable technological base that strengthens competitiveness and reduces perceived risk in pursuing green innovation.

Technological integration capability reflects a firm′ s ability to identify, recombine, and coordinate internal and external technological resources, thereby improving the conversion of dispersed information

and knowledge into usable innovation outcomes. In sustainability-oriented settings, scholars increasingly argue that dynamic, reconfiguration-oriented capabilities are central because firms must continuously adjust their resource base and innovation routines in response to shifting technologies, policy signals, and stakeholder demands [18]. Recent work on eco-innovation similarly highlights that firms′ ability to orchestrate resources across organizational boundaries is critical for developing and scaling eco-innovations [19]. In manufacturing, strong integration capability can therefore enhance green innovation by enabling firms to connect new technologies with existing production systems, accelerate internal absorption of external knowledge, and improve adaptation under uncertainty.

Taken together, technological innovation level provides the knowledge-creation engine, while technological integration capability enables effective recombination and deployment. Their joint presence strengthens a firm’ s capacity to generate green technologies and embed them into products and processes, making both conditions important technological foundations of green innovation in manufacturing enterprises.

*2.2.2 Organizational Dimensions*

The organizational dimension shapes how manufacturing enterprises mobilize and deploy internal resources in support of green innovation. In this study, the organizational dimension is captured by two core components: organizational slack and Digital Transformation Emphasis. Both factors influence firms’ ability to absorb uncertainty, reconfigure resources, and sustain long-term investment in environmentally oriented innovation.

Organizational slack refers to the pool of excess resources that firms can draw upon to buffer environmental uncertainty and support strategic experimentation. Recent research grounded in the resource-

based view suggests that moderate levels of organizational slack provide strategic assurance for green innovation by relaxing financial and operational constraints, thereby enabling firms to engage in riskier and longer-horizon sustainability-oriented innovation activities [20]. In the context of manufacturing, where green innovation often involves high upfront costs and uncertain returns, such slack resources can serve as an important internal foundation for sustained innovation efforts.

However, recent studies also indicate that organizational slack may exert nonlinear and ambivalent effects on innovation outcomes. When slack resources exceed a critical threshold, they may reinforce organizational inertia, reduce managerial urgency, and weaken firms' incentives to explore new technological trajectories. Moreover, excessive slack can increase coordination and allocation costs, resulting in resource misallocation and crowding-out effects that ultimately hinder green innovation. Empirical evidence suggests that these counterproductive effects are particularly pronounced in complex manufacturing organizations, where slack resources may be absorbed by routine operations rather than directed toward innovation. These findings underscore the importance of examining organizational slack not in isolation, but in interaction with other organizational and environmental conditions.

Digital Transformation Emphasis reflects the extent to which firms strategically emphasize digital technologies in their resource allocation and organizational transformation. Green innovation is inherently complex and typically requires the integration of heterogeneous resources, including technological knowledge, organizational experience, and external information. Recent studies argue that prioritizing digitalization enhances firms′ ability to acquire, process, and recombine such resources by reducing information asymmetry and strengthening internal coordination mechanisms [21] .From this perspective, digitalization acts as an enabling organizational capability that supports green innovation by improving firms′ absorptive capacity and decision-making quality.

Furthermore, digital technologies facilitate the construction of digital platforms that connect firms with suppliers, customers, and other stakeholders, thereby transcending spatial and temporal constraints in production and exchange processes. This connectivity enables broader recombination and deeper integration of green resources across organizational boundaries, improving the efficiency of resource allocation and accelerating green innovation diffusion. Recent empirical evidence shows that digital transformation can stimulate firms' innovation vitality and increase investment in green innovation activities, particularly when digital technologies are embedded into core strategic priorities rather than treated as peripheral tools.

Collectively, organizational slack offers the essential resource buffer for experimentation, whereas prioritizing digitalization improves the coordination and utilization of those resources. Consequently, their interaction plays a crucial role in determining manufacturing enterprises' ability to pursue green innovation. This underscores the necessity for a configurational perspective that accounts for how various organizational conditions jointly impact green innovation outcomes, rather than presuming uniform or linear effects.

*2.2.3 Environmental dimension*

Internal resource investment alone cannot sufficiently stimulate corporate green innovation momentum. Scholars have increasingly focused on external factors such as institutional constraints, market competition pressures, and stakeholder oversight, which play crucial roles in driving green innovation resource integration and fostering green innovation [22]. This has significantly enriched the research perspectives on green innovation. Therefore, this paper explores green innovation in manufacturing enterprises from three dimensions: environmental regulations, market competition, and stakeholder attention.

As environmental regulations constitute a rigid institutional framework, scholars have identified three distinct impacts on corporate green innovation. The first perspective argues that environmental regulations

impose additional costs, which may reduce corporate R&D investment and create a "crowding-out effect" that suppresses green innovation [23]. The second perspective, grounded in Porter's Hypothesis, suggests that environmental regulations ultimately encourage technological upgrades and stimulate green innovation initiatives. This mechanism channels corporate capital into pollution control activities, reduces environmental remediation costs, and generates a "compensation effect" [24], thereby promoting green innovation. The third perspective posits a nonlinear relationship between environmental regulations and corporate green innovation, requiring consideration of regulatory intensity, the relative magnitudes of the "crowding-out effect" and "compensation effect", as well as industry-specific variations [25]. These findings collectively demonstrate that environmental regulations exert significant influence on corporate green innovation.

As the primary drivers of innovation in market economies, enterprises are profoundly influenced by market competition. Externally, competitive dynamics foster the provision of valuable green resources, expand green demand, and cultivate a conducive innovation ecosystem. Internally, market competition drives companies to proactively identify green opportunities, continuously optimize resource allocation and operational capabilities, stimulate green innovation momentum, and enhance sustainable development capacities [26]. However, excessive competition may raise industry entry barriers and dampen corporate enthusiasm for green innovation. Therefore, manufacturing enterprises require a balanced level of market competition to effectively drive green innovation [27].

In the process of corporate green innovation, enterprises encounter a complex system composed of interdependent stakeholders and their interests. On one hand, investors' attention directly impacts corporate funding sources and capital structure [28]. When investors demonstrate strong interest in green innovation, they can provide robust financial support for corporate green technology R&D. On the other hand, scholars

based on the resource-based view and stakeholder theory argue that companies can treat meeting stakeholder demands as a strategic resource [29]. Under stakeholder pressure, enterprises become more motivated to engage in green innovation activities.

### *2.3 Configurational Drivers of Green Innovation in Manufacturing Enterprises: A TOE Perspective*

Green innovation has become a key driver for manufacturing enterprises to pursue rapid growth and effectively address environmental challenges. Research on its underlying driving factors has expanded beyond internal mechanisms to encompass external pressures. From an internal perspective, existing studies predominantly adopt the resource-based view framework, analyzing how enterprises′ inherent resource endowments and core competencies profoundly influence green innovation activities [30]. Meanwhile, researchers widely employ perspectives such as the resource-based view, market theory, and institutional theory to systematically examine how external factors impact and drive corporate green innovation practices. These discussions primarily focus on the "net effect" of corporate green innovation, laying the foundation for understanding its driving mechanisms. However, green innovation in manufacturing enterprises constitutes a multidimensional and complex process involving interactions across multiple levels and factors. Limiting analysis to linear relationships between single factors not only hinders comprehensive understanding of synergistic mechanisms but also fails to fully uncover the latent driving forces and unique value embedded in green innovation. Specifically, this single-dimensional approach cannot fully reveal how various factors interdependently and mutually reinforce each other during green innovation processes, collectively shaping distinctive innovation pathways and outcomes. Consequently, such limitations restrict the comprehensive enhancement and sustainable development of manufacturing enterprises′ green innovation capabilities.

The configuration perspective emphasizes that individual variables or factors should not be studied in isolation, but rather as an interconnected and interacting complex system, which can better explore the synergistic mechanisms among multiple factors [31]. Secondly, the TOE framework provides a systematic framework for green innovation in manufacturing enterprises, covering three dimensions: technology, organization, and environment. The core of green innovation in manufacturing enterprises lies in green technological innovation, which aligns with the essence of technology application in the TOE framework. Based on the TOE framework and the configuration perspective, this paper argues that green innovation in manufacturing enterprises is influenced by technological development, while also being inseparable from the interaction between internal resources, capabilities, and external pressures. It requires coordinated efforts among the three dimensions: technology, organization, and environment. Specifically, when enterprises face green pressures from institutions, markets, or stakeholders, manufacturing enterprises need to transform external pressures into green innovation strategies and further convert them into green outcomes through technology application and organizational resources. Conversely, when manufacturing enterprises possess innovative technologies, resources, and capabilities, external pressures should motivate them to pursue green innovation. Therefore, this paper explores the complex interactions of the three dimensions—technology, organization, and environment—on green innovation in manufacturing enterprises under the configuration perspective, based on the TOE framework, and reveals potential multi-pathways to promote sustainable development of green innovation. The conceptual model is shown in Figure 1.

# 3 Research Design

### *3.1 Methodology: Dynamic Qualitative Comparative Analysis*

Qualitative Comparative Analysis (QCA) integrates qualitative and quantitative research methods to identify patterns and correlations through comparative analysis of differences between subjects. This study employs configuration analysis to investigate the driving mechanisms of green innovation in manufacturing enterprises, aiming to reveal configurational relationships formed by interactions among exogenous variables. As green innovation in enterprises is a dynamic process, traditional QCA methods lack temporal dimension analysis, making it difficult to demonstrate the varying impacts of exogenous variables across different stages or the evolving trends in green innovation pathways. Therefore, we adopt the dynamic QCA method proposed by Garcia-Castro and Ariño [32], which measures consistency across three dimensions: between-group, within-group, and pooled. By adjusting consistency distances, we assess temporal and case-level stability. Using collected balanced panel data, this study conducts analysis through the SetMethods software package in R.

### *3.2 Sample and Data Sources*

This study sets the sample period from 2018 to 2024, The Environmental Protection Tax Law came into effect in 2018, subjecting manufacturing firms to more standardized and sustained environmental constraints. The subsequent proposal and deepening of the dual-carbon goals made green and low-carbon transformation an increasingly important direction for manufacturing development. This period therefore provides a suitable setting for examining the dynamic evolution of manufacturing firms′ green innovation pathways. To ensure data validity, we exclude ST firms, observations with missing key variables, and observations for which firm

or year information cannot be identified, yielding a final sample of 812 firm-year observations from 116 listed manufacturing firms. Annual report data are obtained from the official websites of the Shanghai and Shenzhen Stock Exchanges; environmental regulation data are obtained from provincial government work reports; green patent and stakeholder attention data are obtained from the CNRDS database; and data for the remaining variables are obtained from the CSMAR database

### *3.3 Variables and Measures*

#### *3.3.1 Outcome Variable*

Green innovation. Scholars predominantly employ indicator systems to measure innovation outcomes, outputs, or multidimensional metrics, such as green patents and pollution emissions [33]. Given the time lag and uncertainty inherent in green patent grants, following Wang Xin [34], this study uses the total number of green patent applications (sum of invention and utility model applications) as a proxy for corporate green innovation levels. To address right-skewed data distribution, the green patent application count is adjusted by adding 1 and then transformed into natural logarithm values to quantify green innovation.

#### *3.3.2 Condition variables*

(1) Level of technological innovation

Previous studies primarily measured technological innovation levels through corporate R&D investment. However, given the significant variations in R&D expenditure among manufacturing enterprises due to differences in operational scales, this paper adopts the approach of Tornatzky [35], using the percentage of corporate R&D investment relative to operating revenue as a metric for technological innovation levels.

(2) Technical integration capability

Existing literature mainly uses questionnaire survey method to collect data and then measures technical integration ability through Likert scale. Due to the availability of data, this study draws on Yan [36] and uses the proportion of internal R&D personnel to measure firms′ technological integration capability.

(3) organizational slack

Existing research identifies two primary methods for assessing organizational slack. The first employs questionnaire surveys with Likert scale scoring, while the second utilizes financial metrics such as the current ratio and cash ratio. Given data availability constraints, this study adopts the current ratio as the measurement tool, following Kim and Bettis [37].

(4) Digital Transformation Emphasis

This study draws on research by Berrone et al. [6] and Song et al. [38]. Using Python, we extracted keywords related to "digital transformation" from annual reports published by listed manufacturing enterprises, calculated their frequency, and manually aggregated these frequencies across years to determine the total annual frequency of digital transformation. To address right-skewed data distribution, we applied a natural logarithm transformation to the total frequency by adding 1, thereby quantifying corporate emphasis on digital transformation.

(5) Environmental regulations

Drawing on Wu et al. [39], this study analyzes provincial government work reports. The methodology involves extracting environmental term frequency per sentence in each city's report, then calculating their proportion of total words to assess the intensity of provincial environmental regulation. To simplify data processing, the environmental regulations intensity variable was scaled by a factor of 100.

(6) Market competition

Drawing on Ghisetti and Rennings [26], this study adopts the Lerner Index as a substitute variable for

market competition, calculated as (revenue-operating costs-selling expenses-administrative expenses) / revenue.

(7) Stakeholder concerns

Stakeholder attention reflects the extent to which external stakeholders monitor and respond to firm-related information. Consistent with prior research, stakeholder attention is proxied by a web search index, which captures the frequency with which stakeholders search for firm-related information online. Given the widespread use of the Internet and search engines as information channels, this indicator provides a useful approximation of stakeholders' attention to corporate activities.

Following established practice, we obtain the web search index from the China Research Data Service Platform (CNRDS) and apply a natural logarithmic transformation to reduce skewness and improve comparability across firms. Detailed definitions and data sources for all variables are reported in Table 1

[Table 1 about here]

### *3.4 Calibration of Sets*

Following prior QCA studies, we employed the direct method of calibration for both the outcome and condition sets. Specifically, the 75th, 50th, and 25th percentiles of the original variables were used as the anchors for full membership, the crossover point, and full non-membership, respectively, and the raw data were transformed into fuzzy-set membership scores ranging from 0 to 1. Because cases with a membership score of exactly 0.5 are treated as neither in nor out of a set and are thus excluded from the analysis, we followed common practice and slightly adjusted memberships of 0.5 to 0.501 to retain these cases. The calibration thresholds for all sets are reported in Table 2.

,[Table 2 about here]

# 4 Results

### *4.1 Analysis of single-condition necessity*

The pooled consistency, between-group consistency, and intra-group consistency obtained through dynamic QCA serve as crucial criteria for assessing necessity. When the pooled consistency reaches or exceeds 0.9, the condition can be deemed necessary. Additionally, dynamic QCA requires utilizing between-group consistency distance to evaluate potential temporal effects. Drawing from existing research, this study establishes a consistency distance threshold of 0.2. If the consistency distance is below 0.2, the pooled consistency demonstrates high precision, allowing determination of necessity through pooled consistency alone. Conversely, when the consistency distance reaches or exceeds 0.2, further investigation into temporal effects becomes necessary.

[Table 3 about here]

According to the dynamic QCA necessity test criterion, when the aggregated consistency coefficient reaches above 0.9, the given condition can be regarded as a necessary condition for the outcome to occur. As shown in Table 3, for both high and non-high levels of green innovation, the aggregated consistency coefficients of all conditional variables failed to reach the 0.9 threshold. This indicates that no single necessary condition exists; that is, green innovation is not driven by any single independent factor, but rather results from the combined effect of multiple conditions. This finding suggests that these conditions play a relatively important role in facilitating high levels of green innovation.

### *4.2 Analysis of Sufficient Configurations*

#### *4.2.1 Overview of Configurational Solutions*

In this study, the original consistency threshold was set to 0.8, the PRI consistency threshold to 0.65, and the case frequency threshold to 2 to construct the truth table. The configurational analysis results are presented in Table 4.

As shown in Table 4, six configurations generate high green innovation, with each configuration demonstrating consistency exceeding 0.75, indicating that these configurations represent sufficient pathways to high green innovation in manufacturing firms. The overall solution consistency is 0.813, the overall PRI consistency is 0.724, and the overall solution coverage is 0.182. Based on the distribution of core conditions, the six configurations are categorized into two patterns. Pattern M1 comprises configurations M1a, M1b, and M1c, in which technological innovation level serves as a core condition and stakeholder attention plays an important role. This pattern is termed "innovation-led." Pattern M2 includes configurations M2a, M2b, and M2c, in which technical integration capability serves as a core condition, while technological innovation level is absent as a core condition. This pattern is classified as "multi-factor synergy," highlighting the role of resource integration, digital transformation emphasis, and external pressures in achieving high green innovation. Three configurations associated with non-high green innovation were also identified: NM1b, NM1c, and NM2. Given the focus of this study, the following discussion concentrates on the configurations leading to high green innovation in manufacturing firms.

[Table 4 about here]

*M1: Innovation-Led Pattern*

Configuration M1a demonstrates that a causal configuration characterized by a high technological innovation level, high technical integration capability, strong environmental regulations, high stakeholder

attention, and the absence of high organizational slack can generate high green innovation. This configuration indicates that manufacturing firms can achieve substantial green innovation even when organizational slack is limited, provided that they possess strong technological innovation and technical integration capabilities. A high technological innovation level provides a foundation for green product development, green process improvement, and the application of pollution-control technologies. Meanwhile, technical integration capability enables firms to identify, absorb, and reconfigure internal and external technological resources, thereby improving green innovation efficiency. Environmental regulations and stakeholder attention further exert external pressure, encouraging firms to shift from passive environmental compliance toward proactive strategic responses and ultimately achieve high green innovation.

Configuration M1b reveals that a causal configuration comprising a high technological innovation level, strong environmental regulations, and high stakeholder attention, together with the absence of high digital transformation emphasis, market competition, and organizational slack, can also generate high green innovation. This configuration suggests that manufacturing firms can achieve high green innovation despite a relatively weak emphasis on digital transformation, limited competitive pressure, and insufficient organizational slack, provided that technological innovation is supported by strong institutional and stakeholder pressures. Environmental regulations exert coercive institutional pressure, encouraging firms to accelerate green technology development and cleaner production. Stakeholder attention further strengthens these incentives through social scrutiny, reputational concerns, and demands for environmental legitimacy. In this pathway, institutional pressure and stakeholder expectations compensate for the limitations associated with digital transformation emphasis and market competition, enabling firms to maintain green innovation despite resource constraints.

Configuration M1c demonstrates that high technological innovation level, high technical integration

capability, and high stakeholder attention, combined with the absence of high organizational slack, constitute another pathway to high green innovation, while environmental regulations play a peripheral role. This configuration indicates that manufacturing firms with strong technological innovation and technical integration capabilities can achieve high green innovation even when external regulatory pressure is relatively weak. Under these circumstances, stakeholder attention encourages firms to translate external environmental expectations into innovation incentives. Through continuous research and development, green knowledge accumulation, and the integration of technological resources, firms can strengthen their internal capabilities and develop sustainable green innovation advantages.

The three configurations share the important roles of technological innovation level and stakeholder attention, while organizational slack is absent as a core condition. This indicates that the innovation-led pattern does not depend primarily on abundant organizational slack. Instead, firms rely on their technological innovation capabilities and leverage stakeholder pressure and institutional incentives to sustain green innovation. Accordingly, these configurations are classified as the "innovation-led" pattern. The findings suggest that the key to achieving high green innovation lies not simply in the availability of resources, but in firms' ability to combine technological innovation, technical integration, and external environmental pressures effectively. Such combinations enable manufacturing firms to overcome resource constraints and develop sustained incentives for green transformation.

Representative firms associated with this pattern include Guodian Nanjing Automation, CHINT Electric, and GEM Co., Ltd. Contemporary Amperex Technology Co., Limited (CATL) provides an illustrative example. CATL has maintained substantial investment in research and development and continuously advanced its green manufacturing initiatives. In 2021, the company launched its carbon-neutrality strategy to promote energy conservation, emissions reduction, and the adoption of clean energy at its production

bases. In 2023, CATL further advanced the development of new products, including its Shenxing superfast-charging battery, improving charging efficiency and product performance. Through sustained technological innovation in power batteries, energy storage batteries, and related materials, the company has upgraded its green products, improved resource utilization efficiency, and sought to reduce environmental impacts throughout product life cycles. These efforts demonstrate how continuous technological innovation and green technology development can support green manufacturing transformation. Meanwhile, stakeholder attention and market competition provide additional incentives for the company to strengthen its green innovation activities and maintain its competitive advantage.

M2: Multi-Factor Synergy Pattern

Configuration M2a demonstrates that a causal configuration characterized by high technical integration capability and strong digital transformation emphasis, together with the absence of high technological innovation level, environmental regulations, market competition, and organizational slack, can generate high green innovation. This configuration indicates that digital transformation and technical integration capability can compensate for limitations in firms′ original technological innovation capabilities, particularly when institutional and competitive pressures are relatively weak. Digital technologies enhance firms′ capacity to acquire, process, and utilize information while improving resource allocation efficiency. Technical integration capability facilitates the recombination and reuse of existing technologies and resources, enabling firms to overcome innovation constraints and improve green innovation performance. Thus, firms can achieve high green innovation by integrating existing technological resources and leveraging digital transformation rather than relying exclusively on original technological breakthroughs.

Configuration M2b reveals that a combination of high technical integration capability, intense market competition, and high stakeholder attention, with the absence of high technological innovation level and

digital transformation emphasis as core conditions, can lead to high green innovation. This configuration suggests that manufacturing firms can achieve high green innovation despite relatively limited original technological innovation capabilities and a weak emphasis on digital transformation, provided that they possess strong technical integration capabilities and face substantial competitive and stakeholder pressures. Market competition encourages firms to differentiate their products and improve operational efficiency, while stakeholder attention reinforces environmental expectations and reputational incentives. These pressures motivate firms to reorganize existing resources, accelerate the adoption of green technologies, and upgrade their products. Consequently, technical integration capability enables firms to translate external competitive and environmental demands into green innovation outcomes.

Configuration M2c demonstrates that high technical integration capability, strong digital transformation emphasis, and intense market competition, together with the absence of high technological innovation level and organizational slack as core conditions, can also generate high green innovation. This configuration highlights a dual-driving mechanism in which digital transformation and market competition jointly promote green innovation. Digital technologies improve information processing, coordination, and resource allocation, while technical integration capability enables firms to reorganize existing technologies and production processes. At the same time, competitive pressure strengthens firms′ incentives to improve environmental performance and develop greener products. Compared with M2a and M2b, this pathway places greater emphasis on the synergistic effects of digital transformation, technical integration, and market competition in facilitating green innovation under resource constraints.

The three configurations share the presence of technical integration capability as a core condition, whereas technological innovation level is absent as a core condition. This indicates that the multi-factor synergy pattern does not necessarily depend on strong original technological innovation capabilities. Instead,

manufacturing firms can achieve high green innovation through resource integration and capability reconfiguration, supported by digital transformation and external pressures. Accordingly, these configurations are classified as the "multi-factor synergy" pattern. The findings highlight the importance of coordinating technological capabilities, organizational resources, and environmental conditions. By integrating existing technologies, resources, and production processes, firms can improve resource utilization and accelerate green innovation even when their original innovation capabilities or organizational slack are limited.

Representative firms associated with this pattern include SANY Heavy Industry, Haier Smart Home, and Inspur Information. SANY Heavy Industry provides an illustrative example. As a manufacturer of large-scale equipment, the company consumes substantial amounts of energy and raw materials during production. Inadequate treatment of wastewater, exhaust gases, and solid waste may also generate considerable environmental impacts, attracting scrutiny from stakeholders such as suppliers, consumers, and social media. In response, SANY has incorporated digital and intelligent technologies into manufacturing, product development, services, and operations to improve energy efficiency, optimize production processes, and promote energy-saving products. These initiatives support the company's green transformation by improving operational efficiency and reducing resource consumption. In addition, SANY has emphasized technological innovation and established research and development capabilities covering intelligent manufacturing, hydrogen fuel technologies, and digital twins, providing technical support for new energy product development. By the end of 2024, the company had introduced more than 80 new energy products and obtained over 30 relevant authorized patents, covering multiple key technological areas. These initiatives illustrate how technical integration, digital transformation, and competitive pressures can work together to support green innovation.

*4.2.2 Within-Group Results Analysis*

Table 4 shows that the within-group consistency of each individual configuration exceeds 0.2, suggesting that the six configurations may exhibit case-specific effects associated with differences in regional distribution and product types within the manufacturing sector. Such differences can be further examined by comparing the within-group coverage of each configuration across regions and product types. As dynamic QCA does not yet provide a specific indicator for measuring these differences, and the assumptions required for one-way analysis of variance (ANOVA) are not satisfied, this study employs the Kruskal–Wallis rank-sum test to investigate whether the coverage of each configuration differs significantly across regions and product types [47]. Specifically, manufacturing industries are classified into three categories: textile manufacturing, resource-processing industries, and mechanical and electronic manufacturing. The regions in which these firms are located are classified as eastern, central, and western China. The corresponding results are presented in Tables 5 and 6.

[Table 5 about here]

[Table 6 about here]

Table 5 shows that all six configurations leading to high green innovation differ significantly across industry types. Further analysis of the mean configurational coverage by industry type (Table 7) reveals differences in configurational preferences among firms producing different types of products. Mechanical and electronic manufacturing exhibits relatively high coverage across the configurations, followed by resource-processing industries. This suggests that industries with greater technological intensity or stronger resource and environmental constraints may be more likely to achieve higher configurational coverage through innovation-led and multi-factor synergy pathways. In contrast, textile and light manufacturing exhibits relatively low configurational coverage, indicating greater dispersion in its green innovation

pathways.

As shown in Table 6, significant regional differences are observed in all configurations except M2c, indicating substantial regional heterogeneity in the pathways to high green innovation. Overall, the mean coverage results presented in Table 8 show that the eastern and central regions tend to exhibit higher configurational coverage. By contrast, M2c displays no statistically significant regional differences, suggesting that this pathway may be more broadly applicable across regions.

[Table 7 about here]

[Table 8 about here]

*4.2.3 Between-group Result Analysis*

As shown in Table 4, the consistency distance between periods for each configuration is below 0.2, indicating that temporal variations remain below the specified threshold. Nevertheless, annual consistency scores reveal dynamic fluctuations across configurations. Figure 2 illustrates these temporal patterns. From 2018 to 2023, consistency scores generally fluctuated between 0.85 and 0.95, showing an initial increase followed by stabilization and gradual decline, before dropping markedly in 2024. This decline may be associated with heightened global economic uncertainty, rising cost pressures, and weakening market demand, which may constrain firms′ willingness to sustain long-term green innovation investments.

Across configurations, Configurations 2 and 4 exhibited relatively high consistency during 2018−2020, highlighting the relevance of multiple-condition combinations in explaining high green innovation. During 2021−2022, Configurations 4 and 6 maintained comparatively high consistency, suggesting greater temporal stability in these configurational pathways. After 2023, the configurations diverged, with Configuration 5 experiencing a pronounced decline. This variation suggests that the consistency of configurational pathways

may be sensitive to changing external conditions. Overall, the findings highlight the temporal dynamics of green innovation pathways and suggest an increasing need for firms to coordinate technological integration, digital management, and organizational resources.

[Figure 2 about here]

### *4.3 Robustness Checks*

This study conducts two robustness checks to assess the stability of the configurational results (see Table 10). First, the case frequency threshold is increased from 2 to 4. The resulting configurations exhibit clear subset relationships with the original configurations, indicating that the main configurational findings remain robust to changes in these parameter settings

[Table 9 about here]

# 5 Further Analysis

To complement dynamic QCA, this study employs random forest regression to examine feature importance, nonlinear relationships, and interactions among the antecedent conditions of green innovation. The dataset is divided into training and test sets at an 8:2 ratio, with cross-validation and hyperparameter tuning used to improve model generalization.

Feature importance rankings, partial dependence plots, and interaction-strength heatmaps are used to assess the relative predictive contributions of individual conditions, nonlinear patterns, and interaction effects. The results identify stakeholder attention, technical integration capability, and environmental

regulations as important predictors, while revealing a strong interaction between stakeholder attention and technical integration capability. These findings complement the configurational pathways identified by dynamic QCA. However, random forest results indicate predictive associations rather than causal relationships.

[Figure 3 about here]

[Figure 4 about here]

Figure 5 illustrates the partial dependence of green innovation on the antecedent conditions, revealing distinct nonlinear relationships. For most variables, the predictive effects are relatively weak at low levels but strengthen after certain thresholds, with marginal effects diminishing at higher levels. Specifically, stakeholder attention exhibits a threshold effect, as external scrutiny, market evaluations, and social pressure strengthen firms′ incentives for green innovation. Technical integration capability similarly promotes green innovation by facilitating knowledge integration, resource allocation, and cross-functional coordination. Digital transformation emphasis shows a staged effect, with its positive association becoming more pronounced as digital capabilities develop before gradually leveling off. Environmental regulations and organizational slack exhibit similar patterns, suggesting that regulatory pressure and resource buffers can support green innovation, although their marginal contributions may diminish at higher levels.

[Figure 5 about here]

The partial dependence results suggest that improvements in green innovation are not driven by the linear accumulation of a single factor. Rather, stronger predictive effects emerge when external stakeholder attention, technological capabilities, digitalization, environmental regulations, and organizational resources

reach appropriate levels. This highlights the need for firms to shift from expanding factor inputs toward optimizing resource allocation and strengthening coordination. Enhancing technical integration capability, engaging stakeholders, improving digital governance, and refining environmental management can help sustain green innovation.

Furthermore, an interaction-strength heatmap is used to examine synergies among antecedent conditions. Figure 7 shows that the interaction between stakeholder attention and technical integration capability is particularly strong, suggesting that external stakeholder pressure may be more strongly associated with green innovation when combined with firms′ internal integration capabilities. Interactions between stakeholder attention, organizational slack, and environmental regulations are also evident, indicating that external scrutiny may be more effectively translated into green innovation when aligned with resource availability and institutional constraints.

Overall, the interaction analysis complements the configurational findings of dynamic QCA, suggesting that green innovation is associated with combinations of interdependent conditions rather than isolated factors. Stronger interactions may identify strategically important combinations, whereas weaker interactions may depend more on complementary conditions. Manufacturing firms should therefore coordinate stakeholder engagement, technical integration capability, and environmental management to support green innovation.

[Figure 6 about here]

[Figure 7 about here]

# 6 Conclusions and Implications

Drawing on the resource-based view and the Technology – Organization – Environment (TOE) framework, this study employs dynamic qualitative comparative analysis (dynamic QCA) to examine the configurational pathways to green innovation using data from 116 Chinese listed manufacturing firms from 2018 to 2024. The results show that none of the seven antecedent conditions constitutes a necessary condition for high green innovation. However, stakeholder attention plays a prominent role, appearing as a core condition in all six configurations leading to high green innovation. These configurations can be classified into two patterns: the innovation-led pattern and the multi-factor synergy pattern. The former emphasizes technological innovation and technical integration capabilities, whereas the latter highlights the coordinated effects of technological, organizational, and environmental conditions.

The findings also reveal heterogeneity across industry types and regions, with mechanical and electronic manufacturing generally exhibiting higher configurational coverage and all configurations except M2c showing significant regional differences. Furthermore, random forest analysis identifies stakeholder attention, technical integration capability, and environmental regulations as important predictors of green innovation. Partial dependence plots reveal nonlinear relationships, while interaction analysis highlights the interaction between stakeholder attention and technical integration capability. Overall, green innovation is associated with multiple configurational pathways rather than a single dominant condition, and its development involves the interplay of internal capabilities and external pressures.

Manufacturing firms should select green innovation strategies according to their technological

capabilities and resource conditions rather than pursue a single universal pathway. Firms with strong R&D capabilities can prioritize green technology development and commercialization, whereas firms with more limited original innovation capabilities can focus on technical integration, resource reconfiguration, and the adoption of existing technologies. The observed industry and regional differences further suggest that green innovation strategies should be adapted to firms′ industrial characteristics, technological resources, and institutional environments.

Efficient resource allocation and stakeholder engagement are also essential. The findings suggest that abundant organizational slack is not necessary for achieving high green innovation. Firms should therefore allocate resources strategically to green R&D, cleaner production, and process upgrading while avoiding inefficient resource accumulation. They should also strengthen environmental disclosure and stakeholder communication, translating external expectations into innovation initiatives through improved technical integration capabilities.

For policymakers, the findings underscore the importance of effective environmental governance and stakeholder participation. Regulatory measures and innovation support should be tailored to firms′ technological capabilities and regional conditions. Strengthening the coordination between environmental requirements, technological development, and resource allocation can help manufacturing firms overcome innovation constraints and achieve sustained green transformation.

# Additional Information

*Data Availability*

The data used in this study were compiled from publicly available sources, including corporate annual reports, green patent records, and government work reports. The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

*Author Contributions*

Yue Sun conceptualized the study and developed the research framework.Xujia Guo collected and organized the data and conducted the empirical analysis. Yue Sun and Xujia Guo interpreted the results and drafted the manuscript. Lexin Yun reviewed and edited the manuscript. All authors read and approved the final manuscript.

*Competing interests*

The authors declare no competing interests.

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## Tables

Table 1. Operationalization and Data Sources of Outcome

| Outcome | Measurement | Data source |
|---|---|---|
| Green Innovation | The natural logarithm of the sum of the company's green patent applications | CNRDS |
| Technological innovation level | Corporate R&D investment/Corporate operating revenue | CSMAR database |
| Technical integration capability | Enterprise R&D personnel ratio | CSMAR database |
| Organizational slack | Enterprise current ratio | CSMAR database |
| Digital transformation emphasis | The natural logarithm of the sum of total word frequencies in digital transformation | Annual Report of Listed Companies |
| Environmental regulations | The proportion of words containing environmental-related terms in the sentence to the total word count | Local Government Reports |
| market competition | Lerner Index | CSMAR database |
| Stakeholder attention | The network search index takes the natural logarithm | CNRDS |

Table 2. Calibration of Outcome and Condition Sets

| Outcome | Full membership (75%) | Crossover point (50%) | Full non-membership (25%) |
|---|---|---|---|
| Green Innovation | 3.178 | 2.303 | 1.609 |
| Technological innovation level | 7.465 | 4.960 | 3.670 |
| Technical integration capability | 25.843 | 17.015 | 12.545 |
| Organizational slack | 1.911 | 1.462 | 1.164 |
| Digital transformation emphasis | 3.258 | 2.485 | 1.609 |
| Environmental regulations | 0.988 | 0.888 | 0.787 |
| market competition | 0.181 | 0.123 | 0.076 |
| Stakeholder attention | 13.411 | 12.887 | 12.364 |

Table 3. Necessary condition test results

| condition variable | High Green Innovation | | | | Non-high green innovation | | | |
|---|---|---|---|---|---|---|---|---|
| | Consistency Summary | Summary coverage | between-group consistency | Within-group consistency | Consistency Summary | Summary coverage | between-group consistency | Within-group consistency |
| High level of technological innovation | 0.567 | 0.565 | 0.051 | 0.644 | 0.513 | 0.520 | 0.106 | 0.655 |
| Low level of technological innovation | 0.518 | 0.511 | 0.038 | 0.687 | 0.571 | 0.574 | 0.093 | 0.644 |
| High technology integration capability | 0.577 | 0.578 | 0.096 | 0.633 | 0.500 | 0.511 | 0.090 | 0.655 |
| Low technical integration capability | 0.512 | 0.501 | 0.067 | 0.698 | 0.587 | 0.586 | 0.071 | 0.644 |
| High organizational slack | 0.511 | 0.514 | 0.048 | 0.644 | 0.551 | 0.565 | 0.074 | 0.644 |
| Low organizational slack | 0.567 | 0.554 | 0.058 | 0.665 | 0.525 | 0.523 | 0.035 | 0.655 |
| High Digital Transformation Emphasis | 0.528 | 0.528 | 0.115 | 0.676 | 0.542 | 0.553 | 0.164 | 0.589 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Low Digital Transformation Emphasis | 0.553 | 0.543 | 0.080 | 0.633 | 0.537 | 0.537 | 0.164 | 0.687 |
| High environmental regulations | 0.518 | 0.571 | 0.058 | 0.687 | 0.477 | 0.536 | 0.038 | 0.709 |
| Low environmental regulations | 0.578 | 0.521 | 0.048 | 0.633 | 0.617 | 0.566 | 0.055 | 0.611 |
| High market competition | 0.618 | 0.609 | 0.099 | 0.644 | 0.484 | 0.485 | 0.125 | 0.665 |
| Low market competition | 0.477 | 0.476 | 0.138 | 0.655 | 0.610 | 0.619 | 0.115 | 0.611 |
| High stakeholder attention | 0.550 | 0.547 | 0.077 | 0.611 | 0.535 | 0.543 | 0.096 | 0.622 |
| Low stakeholder attention | 0.540 | 0.533 | 0.093 | 0.644 | 0.553 | 0.556 | 0.106 | 0.633 |

Table 4. Sufficiency analysis results

| condition variable | High green innovation | | | | | | Non-high green innovation | | |
|---|---|---|---|---|---|---|---|---|---|
| | M1a | M1b | M1c | M2a | M2b | M2c | NM1b | NM1c | NM2 |
| Technological innovation level | ● | ● | ● | ⊗ | ⊗ | ⊗ | ⊗ | ● | ⊗ |
| Technical integration capability | ● | | ● | ● | ● | ● | ⊗ | ● | ⊗ |
| organizational slack | ⊗ | ⊗ | ⊗ | ⊗ | • | ⊗ | ● | ● | ● |
| Digital Transformation Emphasis | | ⊗ | ⊗ | ● | ⊗ | ● | ● | ● | ⊗ |
| Environmental regulations | ● | ● | • | ⊗ | ⊗ | • | ⊗ | ⊗ | ● |
| market competition | ⊗ | ⊗ | | ⊗ | ● | ● | ⊗ | ⊗ | ⊗ |
| Stakeholder focus | ● | ● | ● | • | ● | • | ⊗ | ⊗ | ⊗ |
| consistency | 0.815 | 0.885 | 0.813 | 0.858 | 0.824 | 0.823 | 0.842 | 0.849 | 0.854 |
| PRI | 0.728 | 0.813 | 0.722 | 0.784 | 0.704 | 0.732 | 0.745 | 0.738 | 0.720 |
| coverage | 0.107 | 0.069 | 0.111 | 0.097 | 0.044 | 0.115 | 0.081 | 0.067 | 0.046 |
| Unique coverage | 0.021 | 0.016 | 0.013 | 0.031 | 0.006 | 0.030 | 0.008 | 0.021 | 0.019 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| between-group consistency | 0.125 | 0.125 | 0.135 | 0.115 | 0.131 | 0.061 | 0.096 | 0.058 | 0.045 |
| Within-group consistency | 0.318 | 0.287 | 0.318 | 0.287 | 0.287 | 0.348 | 0.333 | 0.318 | 0.318 |
| Overall consistency | | | 0.814 | | | | 0.827 | | |
| ensemble PRI | | | 0.739 | | | | 0.741 | | |
| Overall coverage | | | 0.196 | | | | 0.169 | | |

Note: ⊗and ●indicates the presence or absence of core conditions, ⊗indicates the absence of edge conditions, ●indicates the presence of edge conditions, and blank indicates optional conditions

Table 5. Kruskal-Wallis Rank Sum Test (Product Type)

| configuration | Mean | SD | Chi-square | P |
|---|---|---|---|---|
| Configuration M1a | 0.099 | 0.059 | 187.436 | <0.001*** |
| Configuration M1b | 0.097 | 0.056 | 182.111 | <0.001*** |
| Configuration M1c | 0.098 | 0.060 | 183.850 | <0.001*** |
| Configuration M2a | 0.173 | 0.113 | 121.127 | <0.001*** |
| Configuration M2b | 0.098 | 0.058 | 84.562 | <0.001*** |
| Configuration M2c | 0.142 | 0.090 | 121.077 | <0.001*** |

Table 6. Kruskal-Wallis Rank Sum Test (Regional Distribution)

| configuration | Mean | SD | Chi-square | P |
|---|---|---|---|---|
| Configuration M1a | 0.099 | 0.059 | 14.951 | <0.001*** |
| Configuration M1b | 0.096 | 0.056 | 16.048 | <0.001*** |
| Configuration M1c | 0.098 | 0.060 | 15.378 | <0.001*** |
| Configuration M2a | 0.172 | 0.113 | 14.600 | <0.001*** |
| Configuration M2b | 0.098 | 0.058 | 33.540 | <0.001*** |
| Configuration M2c | 0.141 | 0.090 | 4.164 | 0.125 |

Note: 1) * denotes significance at the 1%, ** at the 5%, and *** at the 10% significance levels; 2) P-values are indicated in parentheses.

Table 7. Average product type coverage

| product type | Configuration M1a | Configuration M1b | Configuration M1c | Configuration M2a | Configuration M2b | Configuration M2c |
|---|---|---|---|---|---|---|
| Light textiles | 0.042 | 0.042 | 0.042 | 0.079 | 0.033 | 0.060 |
| Resource processing | 0.050 | 0.051 | 0.050 | 0.089 | 0.065 | 0.071 |
| Mechatronics manufacturing | 0.111 | 0.108 | 0.110 | 0.192 | 0.107 | 0.159 |

Table 8. Average regional coverage

| product type | Configuration M1a | Configuration M1b | Configuration M1c | Configuration M2a | Configuration M2b | Configuration M2c |
|---|---|---|---|---|---|---|
| Eastern Region | 0.098 | 0.095 | 0.097 | 0.167 | 0.102 | 0.141 |
| Central Region | 0.111 | 0.110 | 0.110 | 0.203 | 0.091 | 0.150 |
| Western Region | 0.062 | 0.062 | 0.062 | 0.129 | 0.041 | 0.110 |

Table 9. Robustness test

| Antecedent Conditions | Case Frequency Threshold = 4 | | | | |
|---|---|---|---|---|---|
| | Y | | | | |
| | Configuration 1 | Configuration 2 | Configuration 3 | Configuration 4 | Configuration 5 |
| Technological Innovation Level | ● | ● | ● | ⊗ | ⊗ |
| Technical Integration Capability | ● | | ● | ● | ● |
| Organizational Slack | ⊗ | ⊗ | ⊗ | ⊗ | • |
| Digital Transformation Emphasis | | ⊗ | ⊗ | ● | ⊗ |
| Environmental Regulations | ● | ● | • | ⊗ | ⊗ |
| Market Competition | ⊗ | ⊗ | | ⊗ | ● |
| Stakeholder Attention | ● | ● | ● | • | ● |
| Consistency | 0.844 | 0.853 | 0.859 | 0.828 | 0.838 |

| | | | | | |
|---|---|---|---|---|---|
| PRI Consistency | 0.759 | 0.753 | 0.773 | 0.73 | 0.741 |
| Coverage | 0.092 | 0.078 | 0.071 | 0.062 | 0.043 |
| Unique Coverage | 0.023 | 0.019 | 0.009 | 0.022 | 0.02 |
| Between-Group Adjusted Consistency Distance | 0.131 | 0.093 | 0.119 | 0.157 | 0.119 |
| Within-Group Adjusted Consistency Distance | 0.273 | 0.262 | 0.240 | 0.240 | 0.218 |
| Overall Solution Consistency | | | 0.815 | | |
| Overall Solution Coverage | | | 0.726 | | |
| Overall Solution PRI | | | 0.176 | | |

Note: ⊗and ●indicates the presence or absence of core conditions, ⊗indicates the absence of edge conditions, ●indicates the presence of edge conditions, and blank indicates optional conditions

## Figure legends

Figure 1. Analytical Framework

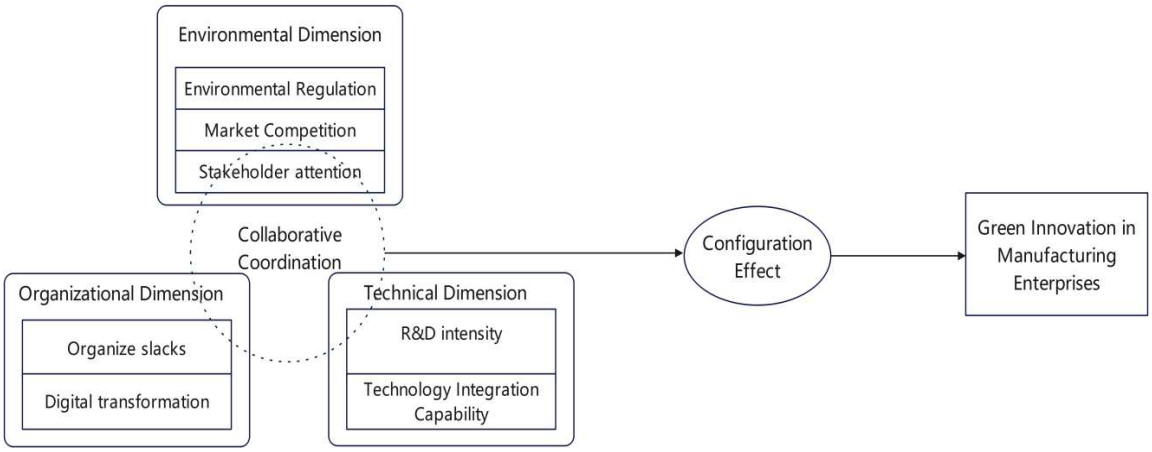



Figure 1 Analytical Framework

Figure 2. Configuration time dimension line chart

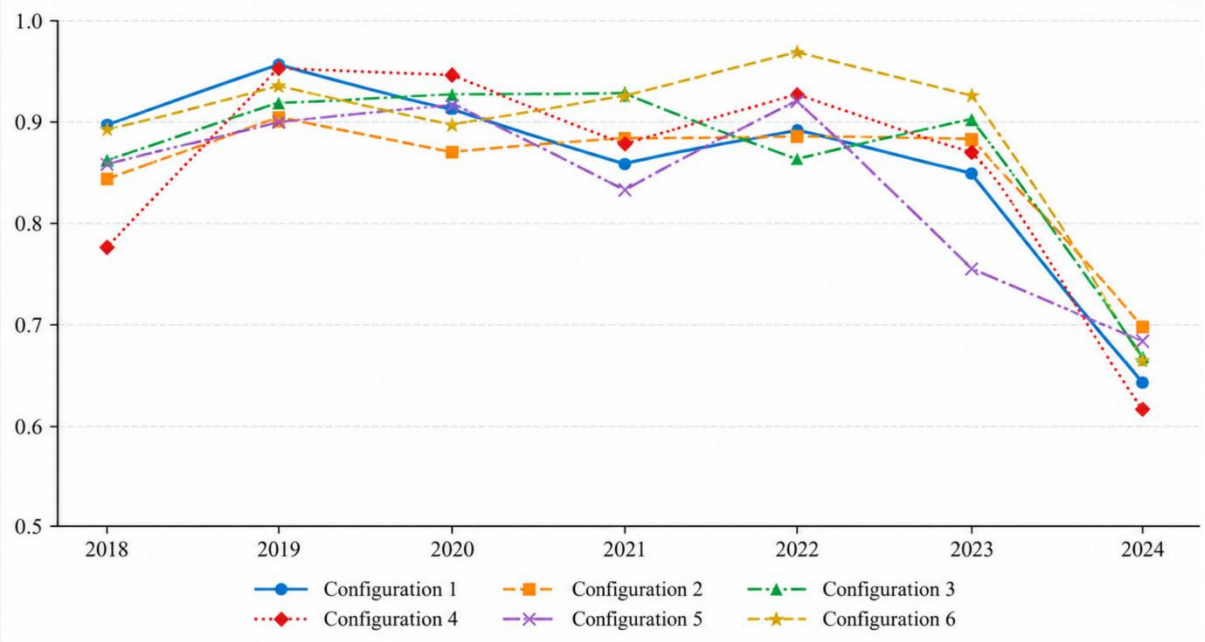



Figure 2 Configuration time dimension line chart

Figure 3. Node Purity by Variable

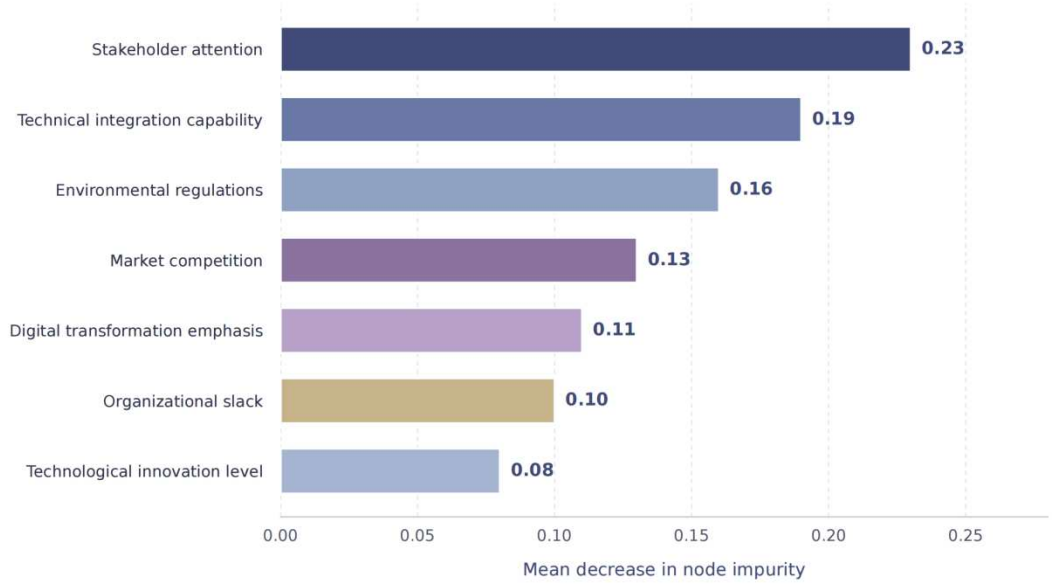



Figure 3. Node Purity by Variable

Figure 4. Percentage Increase in Mean Squared Error

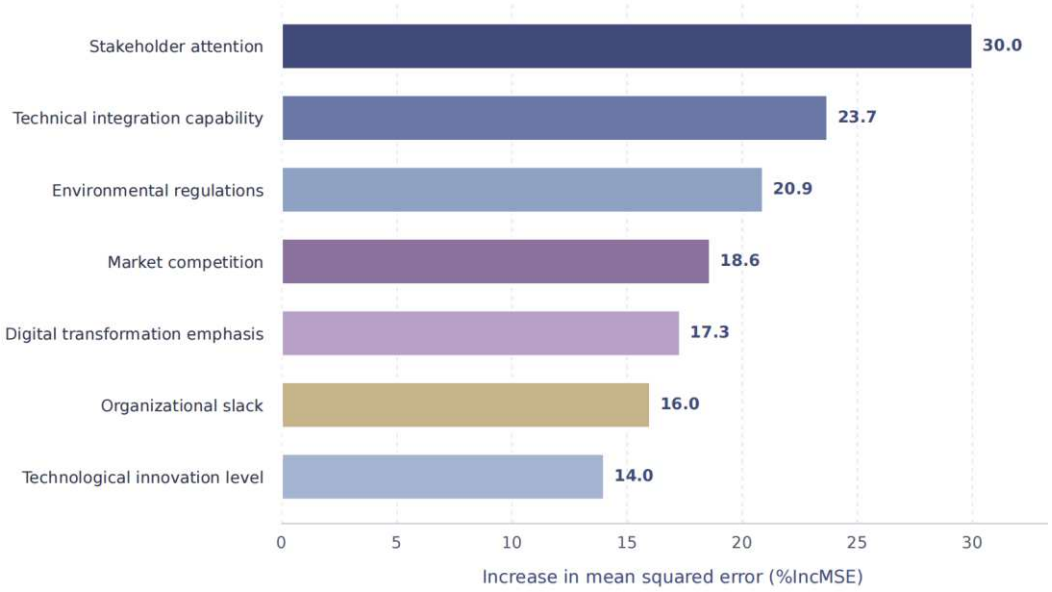



Figure 4 Percentage Increase in Mean Squared Error

Figure 5. Partial Dependence of Green Innovation on Antecedent Conditions

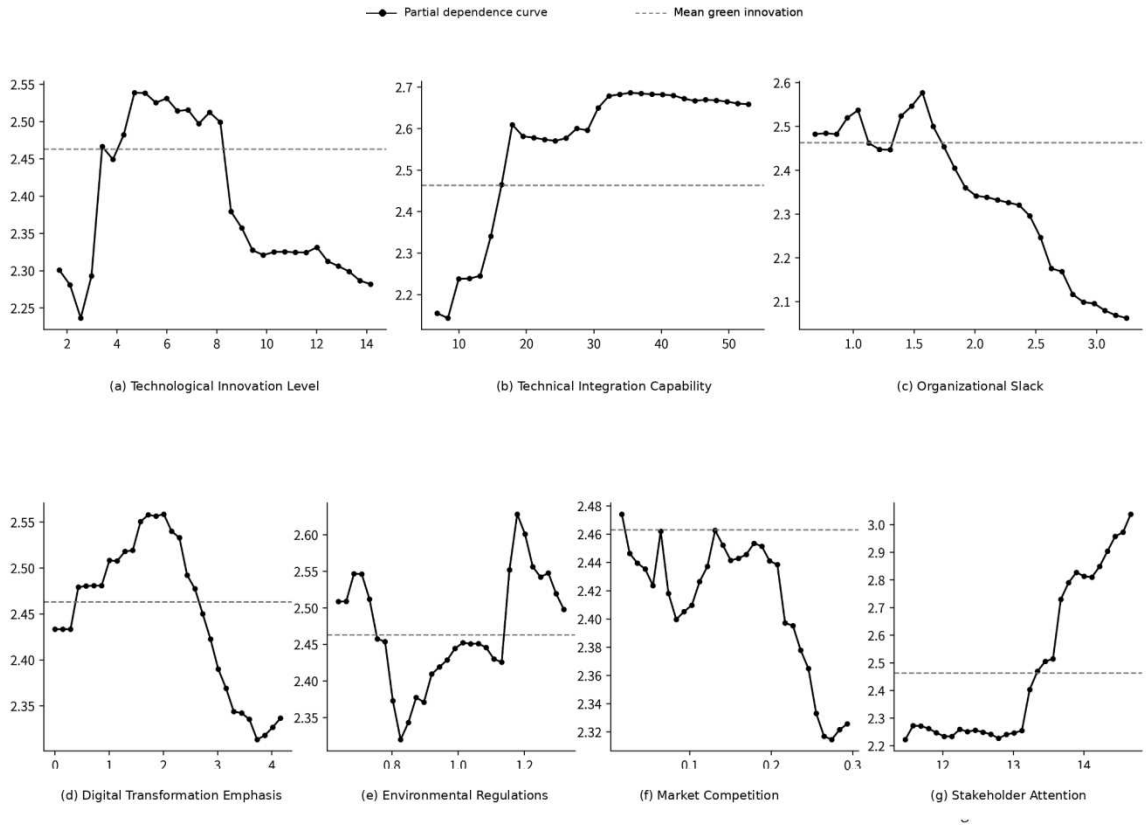



Figure 5 Partial Dependence of Green Innovation on Antecedent Conditions

Figure 6. Interaction Strength Heatmap of Pairwise Condition Variables

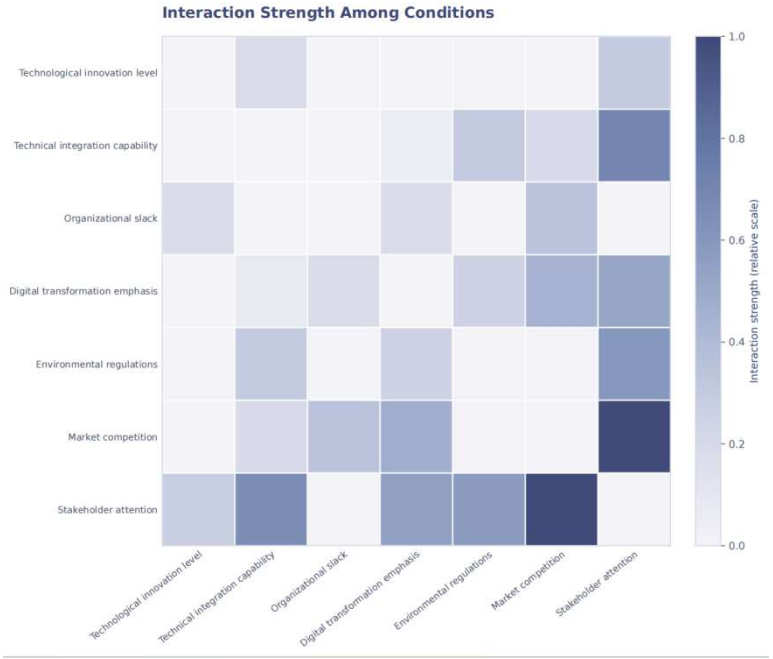



Figure 6. Interaction Strength Heatmap of Pairwise Condition Variables

Figure 7. Strongest Interaction: Technical Integration Capability and Stakeholder Attention

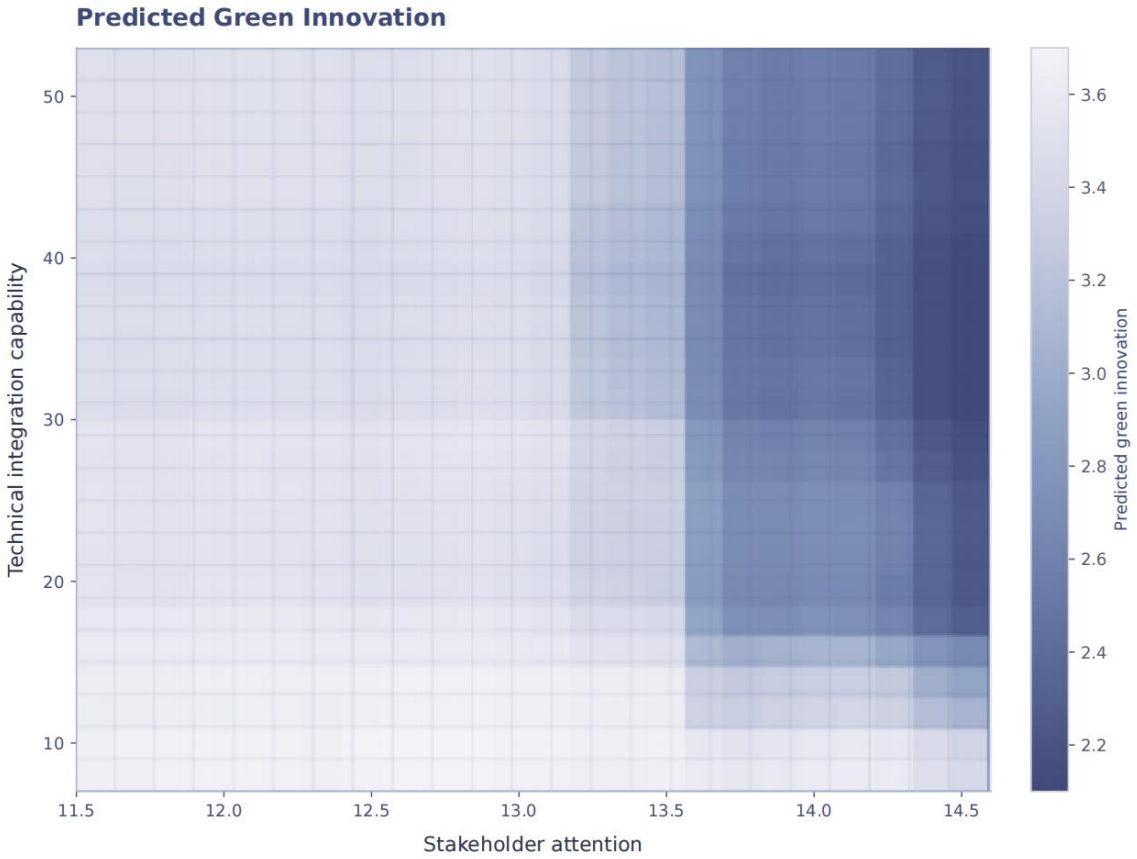



Figure 7 Strongest Interaction: Technical Integration Capability and Stakeholder Attention