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Anatomizing Resilience: The Multi-Dimensional Evolution and Drivers of Regional Collaborative Innovation Networks

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Abstract

In an era of intensifying global technological competition and systemic disruptions, the resilience of metropolitan innovation networks has emerged as a cornerstone of sustainable regional development. Based on joint invention patents, this study employs a multi-method analytical framework integrating social network analysis, network motif analysis, a random walk algorithm, and the Exponential Random Graph Model (ERGM) to trace the evolution of resilience across node, structural, and community levels in the Shanghai Metropolitan Area (2011–2020). Our findings reveal a significant trajectory of strengthening resilience, marked not only by a shift from a monocentric to a polycentric structure at the node level but also by a qualitative change in collaborative patterns at the structural level, and enhanced integration at the community level. ERGM analysis identifies policy coordination and industrial upgrading as the most potent drivers of this evolution, with a pivotal finding being that digital connectivity, measured by information proximity, has superseded geographic proximity in facilitating collaboration. This study develops and applies a multi-scale resilience framework, while also extending proximity theory by highlighting the growing importance of policy and information dimensions over geographic distance. It offers actionable insights for building resilient innovation ecosystems in policy-driven metropolitan regions.

Keywords: innovation ecosystem; collaborative innovation network; network resilience; Exponential Random Graph Model (ERGM); Shanghai Metropolitan Area (SMA)

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1. Introduction

In an era defined by intensifying global technological competition, volatile supply chains, and recurrent systemic shocks, the capacity of regional innovation systems to withstand, adapt, and transform—collectively termed "resilience"—has become a cornerstone of sustainable development [1–5]. Regional collaborative innovation networks, which channel knowledge flows and resources among cities, firms, and institutions, function not as passive infrastructure but as dynamic "shock absorbers" and "reconfiguring agents" in the face of disruptions [6–8]. This is particularly critical in emerging economies like China, where metropolitan areas are pivotal to national innovation strategies.

The Shanghai Metropolitan Area (SMA), a designated engine for China's "dual-circulation" development model, exemplifies this strategic imperative. As a policy-driven initiative aimed at building a "globally leading innovation community," the SMA's journey

to enhance its collaborative innovation network resilience offers a critical and timely case study [9,10]. However, the SMA also embodies the complex challenges inherent to such a task. It grapples with persistent administrative boundaries between Shanghai, Jiangsu, and Zhejiang provinces, pronounced core–periphery disparities in innovation resources, and risks of "network lock-in" from over-reliance on a few dominant hubs [11]. These internal vulnerabilities, compounded by external shocks, underscore the urgent need for a comprehensive analysis.

Yet, a robust framework for understanding how resilience in such a context evolves is hampered by gaps in the existing literature. First, there is a pronounced lack of multi-dimensional integration. Most studies approach resilience from a single analytical plane—focusing either on the robustness of individual actors (nodes), the stability of the overall network structure, or the cohesion of subnetworks (communities)—overlooking the critical interdependencies across these scales [12]. A holistic understanding requires an anatomization of resilience that systematically dissects and integrates its node-level, structural-level, and community-level dimensions, precisely the dimensions along which the SMA's policy interventions are intended to operate. Second, methodological limitations persist. While social network analysis is common, few studies integrate advanced techniques like Exponential Random Graph Models (ERGM) with granular resilience metrics [13,14]. ERGM's ability to model both the endogenous self-organization of networks and the influence of exogenous drivers such as policy and proximity is crucial for moving from describing correlation to establishing causality in network formation—a key requirement for evaluating the impact of the SMA's coordinated policies. Third, much of the prevailing theory is grounded in the context of market-driven economies in Europe and North America, emphasizing firm-led, bottom-up network evolution [15]. In contrast, the innovation ecosystem of the SMA is strongly shaped by state intervention and top-down metropolitan integration [16]. This contextual gap necessitates an examination of how resilience manifests and is driven within a policy-intensive setting, where factors like coordinated planning may rival or reconfigure the role of traditional proximities.

The Shanghai Metropolitan Area presents a particularly salient case study due to its embeddedness within China's distinct innovation model. This model is defined by strategic state intermediation and accelerated industrial upgrading, representing the globally most significant policy-centric innovation context. As such, the SMA provides a crucial empirical setting to examine the interplay between coordinated top-down metropolitan policies and conventional drivers like geographical distance. Analyzing network resilience under these conditions yields critical insights into the governance of innovation systems operating under pronounced state direction and geopolitical constraints. This examination thereby contributes an essential refinement to prevailing theories of regional adaptation, largely derived from Western contexts emphasizing market mechanisms, by testing their boundaries within an alternative paradigm.

To address these gaps, this study is guided by the core research question: How does the resilience of a policy-driven collaborative innovation network, as exemplified by the SMA, evolve across multiple dimensions, and what are the key drivers of this evolution? We conduct a fine-grained, multi-dimensional anatomy of the SMA's resilience from 2011 to 2020, tracing its trajectory through a period of significant policy intensification. Our research makes three primary contributions. First, we develop and apply a multi-dimensional resilience framework to the SMA, providing a holistic and disaggregated view of its network dynamics. Second, we advance methodology by integrating network motif analysis and ERGM into resilience research, enabling us to decode the SMA's micro-level collaboration patterns and rigorously test the underlying formation mechanisms. Finally, by centering our analysis on the SMA, we extend proximity theory by revealing how geographic, cogni-

tive, and information proximities function within a powerful, policy-driven environment, offering novel insights for both theory and the governance of metropolitan innovation systems. To bridge these gaps, this study is designed to analyze the evolution and drivers of collaborative innovation network resilience in the SMA through a multi-dimensional, multi-method approach.

The remainder sections are organized as follows. Section 2 reviews the literature on the theoretical foundations of innovation networks and resilience, the measurement of network resilience and its drivers, and identifies the key research gaps this study addresses. Section 3 introduces the study area, details the data sources and processing procedures, and outlines the multi-method analytical framework. Section 4 presents the empirical findings on the evolution of collaborative innovation network resilience across node, structural, and community levels in the SMA. Section 5 employs an ERGM to identify and analyze the micro-level drivers of the observed resilience patterns. Section 6 discusses the theoretical and practical implications of the findings and situates them within the broader literature. Finally, Section 7 concludes by summarizing the principal findings and outlining future research directions.

2. Literature Review

2.1. Core Concepts and Distinction

To ensure conceptual clarity and internal consistency, this study distinguishes three interrelated but analytically distinct constructs—resilience, network resilience, and policy coordination—and clarifies their hierarchical relationships within the regional innovation system (RIS) framework.

At the system level, resilience refers to the overarching capacity of a regional innovation system to anticipate, absorb, adapt to, and transform in response to external shocks such as financial crises, technological disruptions, or policy transitions [17]. It reflects the long-term sustainability of a region's innovation performance and structural adaptability [18].

At the network level, resilience captures the capacity of inter-organizational collaboration networks to preserve connectivity, knowledge flow, and functional integrity under stress [19,20]. This construct is operationalized through three measurable dimensions: node resilience (the adaptive capacity of individual actors), structural resilience (the robustness of local relational configurations and motifs), and community resilience (the cohesion and stability of subnetworks) [21,22]. Together, these dimensions provide a multi-scalar anatomy of how resilience manifests and evolves within the RIS.

Policy coordination, in turn, operates as an exogenous but integrative mechanism that influences these network dynamics. It refers to the alignment of administrative rules, strategic investments, and regulatory frameworks across multiple jurisdictions. By fostering institutional proximity, policy coordination enhances the stability and reciprocity of inter-organizational ties, thereby functioning as a governance driver that strengthens network resilience and, ultimately, the system's overall adaptive capacity [23].

In summary, resilience denotes the system's adaptive outcome, network resilience the internal mechanism through which such adaptability emerges, and policy coordination the institutional condition that enables and amplifies this process.

2.2. Theoretical Foundations: From Innovation Networks to System Resilience

The theoretical foundations of this study lie in the convergence of three complementary bodies of literature: the Regional Innovation System (RIS) approach, proximity theory, and system resilience.

First, the RIS framework conceptualizes innovation as a collective and embedded process driven by the interactions among firms, universities, research institutes, and gov-

ernments within a specific socio-institutional setting [24,25]. This perspective establishes the networked nature of innovation and highlights how governance structures shape regional adaptive capacity. Comparative studies reveal distinct governance logics between Western and Chinese RIS [26]. In Western economies, innovation networks are typically market-coordinated, with firms acting as autonomous innovators, universities as independent knowledge sources, and governments as facilitators through regulation and incentives [27,28]. By contrast, China's RIS operates within a policy-intensive, state-led framework in which the government acts as a network orchestrator, aligning innovation actors through strategic planning, fiscal instruments, and cross-regional coordination [29]. Rather than emerging organically, innovation linkages are often policy-engineered through mechanisms such as industrial alliances or innovation consortia. Consequently, government intervention functions as a structural accelerator that fosters policy-induced resilience, distinct from the self-organized, market-driven adaptability prevalent in Western systems [30].

To analyze the mechanisms underpinning this resilience, proximity theory provides a multi-dimensional lens that extends beyond geographic proximity to include cognitive, organizational, social, and institutional forms [31]. These dimensions represent relational assets that sustain collaboration and adaptability. For instance, cognitive proximity enhances node-level absorptive capacity, while institutional proximity—often strengthened through coordinated policies—facilitates the integration of subnetworks and the formation of cohesive innovation communities.

Finally, the concept of resilience, transposed from ecology and engineering into regional economic studies [32], reframes innovation from a static efficiency paradigm toward one emphasizing dynamic robustness and reconfigurability. It encapsulates not only recovery from disturbance but also transformation through learning and reorganization. Yet, the multi-scalar anatomy of how resilience operates—across nodes, structures, and communities—remains insufficiently explored. Integrating the RIS perspective on innovation networks, the relational dynamics of proximity theory, and the adaptive logic of resilience theory provides the conceptual foundation for the multi-dimensional analytical framework advanced in this study.

2.3. Research on Network Resilience Measurement and Drivers

The measurement and explanation of innovation network resilience have evolved along several paths, which can be mapped onto the multi-dimensional framework of this study.

At the node level, resilience is often proxied by the centrality and attributes of individual actors such as cities and firms. Metrics like degree, betweenness, and closeness centrality are employed to gauge a node's strategic position and its inferred capacity to access resources, broker knowledge, and recover from shocks [33]. This stream effectively links a node's structural role to its adaptive potential, yet it often treats nodes in isolation, overlooking the broader structural fabric in which they are embedded.

At the structural level, research has pursued two main avenues. The first utilizes global network metrics such as density, centralization, and modularity to infer overall network robustness or fragility [34]. While informative, these macro-descriptors can obscure the micro-mechanisms of resilience. The second, more granular avenue employs network motif analysis to identify the fundamental building blocks of collaboration [7,35]. Certain sub-graph patterns, such as closed triads and redundant tetrads, are theorized to enhance stability by fostering trust, reciprocity, and providing alternative pathways for knowledge flow during disruptions. This study heavily builds on this latter approach, using motif analysis to anatomize the compositional shift in the SMA's network architecture towards more resilient patterns.

At the community level, resilience is often associated with the internal cohesion and modularity of subgroups. Dense, well-connected communities are thought to act as insulating modules, containing shocks and maintaining internal knowledge circulation [36]. The evolution of community structures, therefore, serves as a macro-indicator of regional integration and systemic robustness.

In explaining the drivers of these resilience dimensions, the literature highlights both actor attributes and relational contexts. Resource-based theories suggest that nodes with superior endowments, e.g., high R&D, advanced industry, naturally attract partnerships, creating a "Matthew effect" that shapes the network's core–periphery structure [37]. Simultaneously, multi-dimensional proximity—geographic, institutional, and cognitive—is established as a key facilitator of tie formation [38]. However, a significant methodological gap persists. Most studies rely on correlation-based methods that cannot adequately account for the endogenous nature of networks, for the fact that ties beget ties. The ERGM is specifically designed to overcome this limitation, allowing researchers to disentangle the effects of internal network structures from external node attributes and contextual factors [39]. While ERGM has seen growing application in innovation studies, its integration with an explicit, multi-dimensional resilience framework remains scarce. Furthermore, recent international studies highlight the increasing role of digital connectivity in shaping network resilience, especially after the 2020 global disruptions, suggesting that Information Proximity may now eclipse traditional Geographic Proximity [40,41]. This study fills this gap by employing a dynamic ERGM to rigorously test the drivers shaping the SMA's resilient structure across different periods.

2.4. Research Gaps and the Chinese Context

Synthesizing the above literature, this study is positioned to address three interconnected research gaps.

First, there is a pressing need for theoretical and empirical integration across scales. While existing studies have advanced our understanding of node positions, global structures, or community dynamics in isolation, they seldom integrate these levels into a cohesive analytical framework. This has limited a holistic understanding of how resilience at one level, e.g., robust community structure, interacts with and supports resilience at another, e.g., node recovery. Our research addresses this by proposing and applying a multi-dimensional anatomy that explicitly links node, structural (motif), and community resilience within a single study of the SMA.

Second, a methodological gap exists in rigorously identifying the drivers of resilience. The application of ERGM, a method capable of establishing causality in network formation, to the study of resilience is still in its infancy. By integrating ERGM with resilience metrics derived from SNA and motif analysis, this study provides a more robust, model-based explanation for the evolution of the SMA's innovation network, moving beyond descriptive associations.

Finally, we address a contextual gap. The predominant theories of network evolution and resilience are distilled from market-driven contexts in the West. The SMA, as a paradigmatic case of a policy-driven innovation ecosystem, presents a crucial context for testing and extending these theories. The SMA's experience allows us to investigate whether and how potent policy interventions can reconfigure the roles of traditional drivers like geographic proximity and foster resilience through mechanisms like coordinated institutional rules and strategic infrastructure, thereby contributing a nuanced, context-sensitive extension to the existing body of knowledge.

3. Study Area, Data, and Methods

3.1. Study Area Overview

The Shanghai Metropolitan Area provides a paradigmatic case for anatomizing the multi-dimensional resilience of a policy-driven collaborative innovation network. Formally established under the Spatial Coordination Plan for the Shanghai Metropolitan Area (2022), the SMA's "1 + 8" framework—encompassing Shanghai and eight surrounding cities in Jiangsu and Zhejiang provinces—is explicitly tasked to "jointly build a globally leading innovation community"(see Figure 1). This institutional mandate makes it an ideal living laboratory for investigating how top-down policy coordination interacts with bottom-up market forces to shape network evolution and resilience.



Figure 1. Map of the spatial scope of the Shanghai Metropolitan Area. It is sourced from the officially released Spatial Collaborative Planning of Greater Shanghai Metropolitan Area (2022 Edition) [42].

The SMA's economic scale and innovative capacity underscore its national significance. Encompassing 40 county-level divisions over 56,000 km^2 and hosting 77.42 million people, the region generated a GDP of 12.8 trillion yuan in 2022, accounting for 13.5%

of China's total. Its R&D intensity, at 3.2% of GDP, significantly surpasses the national average, highlighting its role as a primary engine of the country's innovation-driven development. Spatially, the SMA's innovation activities have historically exhibited a distinct "core–periphery" pattern, with planned innovation poles centered on Shanghai, Suzhou, and Ningbo [9]. This inherent spatial inequality, coupled with administrative fragmentation across provincial boundaries, presents a classic set of challenges to regional resilience. However, as the integration of the Yangtze River Delta has developed in depth and been elevated to a national strategy, the construction of an innovation community in the Yangtze River Delta region has been clearly proposed and systematically deployed, and substantial progress has been made in building a modern and international scientific and technological innovation community. In particular, a pivotal shift began with the Development Plan for the Yangtze River Delta Urban Agglomeration in 2016, which accelerated a suite of policy initiatives designed to foster cross-city collaboration, infrastructure sharing, and functional integration. This proactive, policy-driven transformation offers a unique temporal window to observe the deliberate restructuring of an innovation network. Therefore, the SMA is not merely a location but a critical case where the drivers of network resilience, particularly the role of coordinated policy intervention, are being actively tested and can be most clearly observed across node, structural, and community dimensions.

3.2. Data Sources and Processing

To ensure a robust and comprehensive analysis, this study integrates multi-source data and employs a standardized processing workflow. The primary data for network construction are joint invention patents, which serve as a reliable proxy for formal collaborative innovation.

3.2.1. Data Source

The core data for constructing the evolving collaborative innovation network were drawn from the official database of the China National Intellectual Property Administration (CNIPA). We collected 24,057 valid joint authorized invention patents filed by entities within the SMA during the 2011–2020 period. Authorized patents were selected over mere applications because their passage through substantive examination confers higher technical validity and indicates a more mature, consequential collaborative effort. Each patent record was meticulously screened to include only those with at least two applicants whose registered addresses could be geocoded to one of the 40 county-level divisions within the SMA's "1+8" framework. This ensures the network nodes represent the official spatial units of policy implementation. Critically, each record includes the patentee's location and the International Patent Classification (IPC) code, enabling the dissection of collaboration patterns not just spatially, but also in terms of their underlying technological domains.

To capture the multi-faceted drivers of network resilience identified by our framework, a comprehensive set of auxiliary data was compiled. These data were chosen to reflect the urban attributes influencing a node's capacity to innovate and attract partnerships, as well as the exogenous factors shaping the likelihood of connection. Key urban socioeconomic indicators, including per capita GDP, the share of the tertiary industry, and per capita government R&D expenditure, were extracted from city statistical yearbooks to measure regional economic strength, industrial structure, and institutional support for innovation. Geographically, city centroids and administrative boundaries obtained from the National Geographic Information Center of China (NGCC) were used to construct a geographic distance matrix, testing the influence of traditional spatial proximity. Furthermore, to address the core hypothesis regarding the evolving roles of digital connectivity versus physical proximity in a modern policy-driven metropolitan context, data on the number

of internet users per 100 people were sourced from the China Statistical Yearbook on Information and Communications Technology to build an information distance matrix, thereby accurately assessing the potentially growing importance of digital connectivity in facilitating collaboration.

3.2.2. Data Processing

To prepare the raw data for network and statistical analysis, a series of procedures were systematically implemented. First, an undirected and weighted 40×40 adjacency matrix was constructed for each year, with each element representing the number of joint patents between two county-level units. This matrix was designed as symmetric, reflecting the inherently shared nature of innovation co-invention activities. Second, to address gaps in the longitudinal socioeconomic panel data, linear interpolation was applied to maintain temporal continuity—a method widely adopted and validated in prior urban research. Finally, all urban attribute variables were normalized using min-max scaling to eliminate dimensional differences before being incorporated into the resilience index and the ERGM. This standardization ensures that variables of varying magnitudes contribute proportionally to composite indicators and model estimates, thereby minimizing potential bias.

3.3. Research Methods

Building on our theoretical framework and data, this study employs a four-part methodological approach to measure and explain the evolution of innovation network resilience at multi-scale levels.

3.3.1. Social Network Analysis (SNA) for Node Resilience

To anatomize resilience at the most granular level, we define node resilience as the capacity of an individual city to maintain its innovation functionality and recover from disruptions. Reflecting the multi-dimensional nature of this capacity, we construct a composite index that synthesizes a city's inherent innovation capability with its strategic position within the collaborative network. This approach allows us to move beyond a singular metric and capture the different facets of a node's adaptive potential.

The index is composed of four dimensions, with their respective weights objectively determined using the Entropy Weighting Method to avoid subjective bias and reflect the intrinsic information contribution of each indicator [43]. A robustness check on the weighting method will be performed during the computation phase.

The selection of indicators is theoretically grounded in the four core phases of network resilience: absorption, recovery, resistance, and transformation. The following operationalization aligns each metric with a specific phase of resilience. To this end, a composite index is constructed to synthesize a city's inherent innovation capability with its strategic position within the collaborative network. The capacity for absorption is reflected by a city's Innovation Capacity, quantified by its total patent count, which represents the foundational resource base enabling it to withstand initial shocks. The ability to resist disruptions is proxied by Degree Centrality, as a high number of direct connections provides multiple alternative channels for resource exchange. The potential for efficient recovery is captured by Closeness Centrality, where a short average path to all other nodes facilitates rapid access to the network's distributed resources to reconnect disrupted functions. Finally, the capacity for transformation is measured by Betweenness Centrality, which signifies a node's role as a broker; this grants it the potential to reconfigure flows and catalyze structural adaptation by bridging disconnected parts of the network. The weights of these four normalized indicators are objectively determined using the Entropy Weighting Method to minimize subjective bias, resulting in an overall node resilience score computed

as their weighted sum, thus providing a nuanced and theoretically coherent measure of a city's adaptive potential [44].

The multi-dimensional index is calculated as the weighted sum of these four normalized components, providing a nuanced measure of node resilience.

$$C_{RD_i} = \frac{1}{N-1}\sum_{j\in N} x_{ij} \tag{1}$$

$$C_{RP_i}^{-1} = \frac{1}{N-1}\sum_{j\in N} d_{ij} \tag{2}$$

$$C_{RB_i} = \frac{2}{N^2-3N+2}\sum_{j\in N}\sum_{k\in N}\frac{g_{jk}(i)}{g_{jk}} \tag{3}$$

where C_{RD_i} denotes degree centrality, the more connections a node has, the greater its degree centrality is, and the stronger its resistance and recovery capabilities are; N is the number of nodes; x_{ij} stands for the number of effective connections between city i and j; $C_{RP_i}^{-1}$ indicates the closeness centrality, the larger it is, the stronger the ability to restart and innovate connections and the resilience will be; d_{ij} is the shortest path between node i and node j; C_{RB_i} signifies betweenness centrality, the larger this value is, the stronger the network node's control and transformation capabilities are, and the greater its resilience is; g_{ik} refers to the shortest path between nodes j and k that are connected to regional node i; and $g_{jk}(i)$ represents the path connecting nodes j and k via node i. This multi-dimensional index thus provides a nuanced measure of node resilience, quantifying not just how much a city innovates, but how it is embedded in the network to withstand, recover from, and drive systemic adaptation.

3.3.2. Network Motif Analysis for Structural Resilience

To anatomize resilience at the structural level, we move beyond global network metrics to examine the micro-architectural patterns that constitute the network's fabric. We employ network motif analysis to identify these foundational building blocks. A network motif is a recurring, statistically significant sub-graph pattern that occurs far more frequently in the empirical network than in randomized counterparts with equivalent macro-properties [45]. These motifs represent the fundamental, stable circuits of collaboration, and their prevalence and type directly determine the network's capacity to sustain and reroute knowledge flows under stress.

We focus on analyzing triadic (3-node) and tetradic (4-node) motifs to capture the evolution from simple to complex collaboration patterns. For instance, the analysis distinguishes between fragile, linear chains of knowledge transfer and robust, reciprocal structures that facilitate redundant and resilient interactions.

The statistical significance of each motif i is evaluated by calculating its Z-score, which compares its frequency in the empirical network against its distribution in an ensemble of random networks [44]. The formula is defined as:

$$Z_i = \frac{N_{real_i} - N_{rand_i}}{\sigma_{rand_i}} \tag{4}$$

In the formula, N_{real_i} represents the number of occurrences of motif i in the actual network, N_{rand_i} denotes the average number of occurrences of motif i in the random networks, and σ_{rand_i} is the standard deviation of the frequency in the random ensemble. Motifs with $|\text{Z-score}| > 2.0$ are considered statistically significant and are retained for further analysis.

Subsequently, the Overall Structural Resilience (SR) index is quantified as a weighted sum of the frequencies of these significant motifs. The weighting scheme assigns greater importance to more complex and redundant motifs (e.g., a fully connected tetrad) based on their number of edges, acknowledging that these intricate structures provide more alternative pathways and are thus more critical to withstanding link or node failures than simpler, linear chains. This method provides a nuanced, bottom-up measure of the structural robustness embedded within the network's local interaction patterns.

3.3.3. Random Walk Algorithm for Community Resilience

To complete the multi-dimensional anatomy, we examine resilience at the meso-scale by analyzing the stability and cohesion of innovation communities—subgroups within the network characterized by denser internal connections. Community resilience refers to the capacity of these subgroups to maintain robust internal collaboration and function as semi-autonomous innovation modules during systemic stresses [46]. We employ the Random Walk Algorithm for community detection, a method particularly suited to innovation networks as it identifies communities based on the flow of knowledge, modeled by the likelihood of a random walker transitioning between nodes. This approach effectively captures the underlying collaborative landscape that is shaped by both policy linkages and market interactions [47]. The algorithmic procedure is as follows.

Based on the adjacency matrix A and degree matrix D of the network, the probability transition matrix P is calculated.

$$\mathrm{P} = \mathrm{D}^{-1}\mathrm{A},\ \mathrm{P}_{ij} = A_{ij}/d_i \tag{5}$$

Here, d_i represents the degree value of node i; P_{ij} signifies the probability that a random walker moves from node i to node j in one step.

Define the distance between nodes as follows:

$$r_{ij} = \sqrt{\sum_{k=1}^{n} \frac{\left(P_{ik}^{t} - P_{ik}^{t}\right)^2}{d(k)}} \tag{6}$$

where r_{ij} denotes the distance between nodes; P_{ik}^{t} is the probability that node i reaches node k after t random walks; k stands for the intermediate node; and $d(k)$ is the degree of the intermediate node. A smaller r_{ij} indicates that nodes i and j are structurally similar and more likely to belong to the same community.

The community distance formula is derived based on the node distance formula:

$$r_{c_1c_2} = \sqrt{\sum_{k=1}^{n} \frac{\left(P_{c_1k}^{t} - P_{c_2k}^{t}\right)^2}{d(k)}} \tag{7}$$

the algorithm then iteratively merges the two closest communities. The merging decision is guided by minimizing the increase in the total squared distance within the new community structure, quantified by $\Delta\sigma(c_1,\ c_2)$.

$$\Delta\sigma(c_1,\ c_2) = \frac{1}{n}\left(\sum_{i\in c_3} r_{ic_3}^2 - \sum_{i\in c_2} r_{ic_2}^2 - \sum_{i\in c_1} r_{ic_1}^2\right) \tag{8}$$

Here, $c_1,\ c_2$ denote the communities to be merged, and c_3 represents the new community formed after merging. This process repeats until all nodes are merged into a single community, producing a hierarchical structure of community partitions.

3.3.4. Exponential Random Graph Model (ERGM) for Driving Mechanisms

To move beyond descriptive correlation and toward a causal understanding of the multi-dimensional resilience evolution, we employ a dynamic ERGM. ERGM is an advanced statistical method designed specifically for network data, which models the probability of a tie (collaborative link) existing between two nodes, conditional on the network's endogenous structure and exogenous node and dyadic attributes [48]. This approach allows us to rigorously test the micro-level drivers that collectively shape the resilient network structure observed at the node, motif, and community levels.

The basic form of the ERGM is as follows:

$$P_\theta(\mathrm{Y} = y) = \frac{1}{k} exp\left\{\sum_H \theta_H g_H(y)\right\} \quad (9)$$

where Y is the observed network, and y is a particular realization of it; each H represents a configuration, defined as the set of possible edges between nodes in a subset of nodes of G; $g_H(y) = \prod_{y_{ij} \in H} y_{ij}$, which equals 1 if configuration H appears in y, and 0 otherwise; the non-zero value θ_H indicates that Y_{ij} is dependent on all node pairs $\{i, j\}$ in H given the remaining part of the graph; $k = k(\theta)$ is the normalization index.

Our ERGM specification is designed to holistically explain the formation and resilience of the innovation network by integrating variables across three categories. First, to capture the endogenous, structural tendencies of network self-organization, we include the "Edges" term to model the baseline probability of tie formation and the "Mutual" term to test for reciprocity—a key indicator of balanced and stable collaboration that underlies structural resilience. Second, to examine urban node attribute effects, we incorporate factors such as per capita GDP, industrial structure, government S&T expenditure, FDI, and education investment. These variables test the principles of homophily and the "Matthew effect," analyzing whether cities with similar or superior resource endowments are more likely to form partnerships, thereby shaping the distribution of node-level resilience. Finally, the model accounts for exogenous network effects by incorporating several key proximity measures. Geographic distance is included as the Euclidean distance between city centroids to capture the fundamental friction of space. Administrative proximity is introduced as a binary variable based on shared provincial affiliation, thereby assessing the influence of political and administrative boundaries. Furthermore, information proximity is quantified using the absolute difference in internet users per 100 people between cities, serving to evaluate how digital connectivity may help overcome the inherent barriers posed by physical distance and institutional divisions in fostering collaboration.

To capture the temporal dynamics and the impact of the SMA's key policy interventions (e.g., the 2016 Yangtze River Delta Urban Agglomeration Development Plan), we estimate separate ERGMs for two periods: 2011–2015 and 2016–2020. This dynamic setup allows us to discern how the relative importance of these drivers shifted in response to the intensifying policy-driven integration.

The model parameters are estimated using the Markov Chain Monte Carlo (MCMC) maximum likelihood estimation method. Model convergence and goodness-of-fit are rigorously assessed by examining the stability of MCMC chains and comparing the simulated networks against the observed network using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), ensuring that our model provides a robust representation of the underlying network formation processes.

4. Resilience Evolution of the Collaborative Innovation Network in the Shanghai Metropolitan Area

4.1. Evolution of Innovation Network Node Resilience

Our anatomical analysis begins at the micro-level by examining the evolution of node resilience across the SMA. The findings reveal a fundamental structural transformation: a shift from a concentrated, monocentric configuration to a distributed, polycentric architecture, reflecting a deepening and broadening of the region's adaptive capacity.

In 2011, the SMA's innovation network was dominated by a "Shanghai single core". Shanghai's paramount position was evidenced by a node resilience value of 0.78 (see Figure 2), which can be largely attributed to its immense concentration of innovation resources, including the Zhangjiang Science City and policies of the Pilot Free Trade Zone. In stark contrast, Suzhou, the second-ranked city, trailed significantly with a resilience value of only 0.46. This pattern underscored a severe core–periphery disparity, where approximately 75% of the cities, particularly peripheral nodes like Zhoushan (0.01), exhibited low resilience, indicating limited collaborative integration beyond the dominant core.

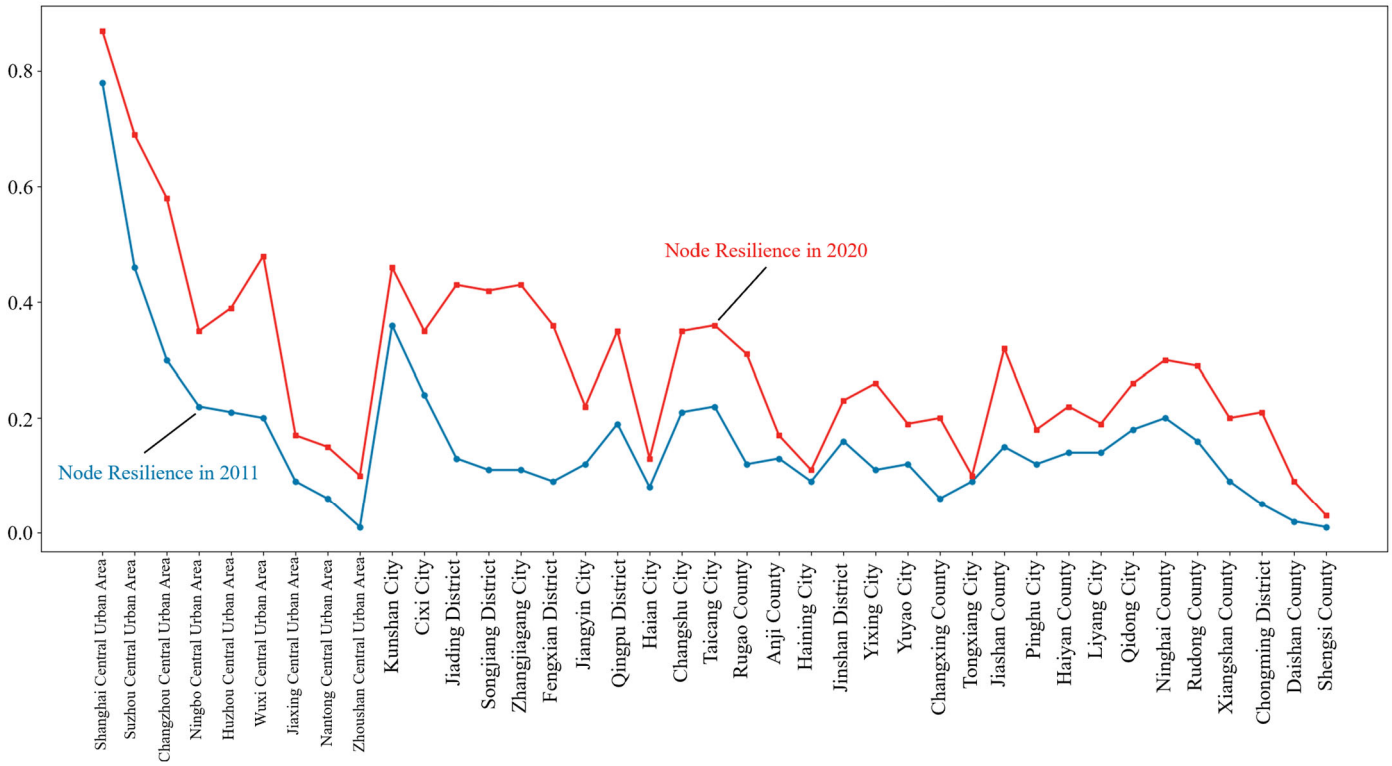


Figure 2. Node resilience of innovation network in the Shanghai Metropolitan Area from 2011 to 2020.

By 2020, this landscape had radically reconfigured into a "Shanghai–Suzhou–Changzhou–Wuxi" multi-core pattern. This transition was not merely a dilution of Shanghai's dominance but a qualitative enhancement of the network's structure, driven by a combination of market-driven industrial specialization and proactive policy-enabled integration. Suzhou solidified its status as a primary hub, forming a "contiguous innovation cluster" with Shanghai through the "Shanghai–Suzhou Integration" strategy and deep synergies in industrial parks. Changzhou demonstrated the most dramatic growth, with its resilience value surging by 90% from 0.30 to 0.58. This leap was strategically fueled by its focus on the new energy vehicle (NEV) industry and targeted collaborative projects with core cities. Wuxi emerged as a critical "knowledge transfer hub", particularly in the

digital technology network, with its resilience value rising from 0.20 to 0.48, bolstered by its integrated circuit (IC) cluster.

This polycentric evolution also facilitated positive spillover effects to other peripheral cities. Jiaxing and Huzhou, for instance, saw their resilience nearly double, a growth directly linked to improved physical connectivity, such as the opening of intercity railways, which enhanced cross-city R&D mobility. However, this growth was not universal. Zhoushan remained a low-resilience outlier, underscoring that geographic proximity alone is insufficient. Its persistent low resilience is attributed to a "functional mismatch" between its tourism-dominated economic base and the SMA's manufacturing and technology-oriented innovation network, leaving it structurally decoupled from the primary collaboration flows.

4.2. Evolution of Innovation Network Structural Resilience

Moving from the micro to the structural level, our anatomical analysis employs network motif analysis to reveal how the very fabric of collaboration, the recurring micro-circuits of interaction, evolved to enhance the network's overall robustness. The findings demonstrate a significant strengthening of the SMA's structural resilience, marked by a qualitative shift from fragile, linear chains to robust, redundant motifs (see Figure 3). The enhancement of structural resilience was driven by a fundamental re-composition of the network's building blocks. We observed a marked decline in the prevalence of simple, linear motifs such as Motif 16, which represent unidirectional knowledge flows and are vulnerable to disruption. Conversely, more complex and reciprocal motifs saw a significant increase in frequency. This qualitative shift is exemplified by two key motifs. Motif 239, a fully connected and reciprocal triad, became markedly more prevalent. This motif embodies balanced, multi-lateral partnerships that foster trust and stability, making local collaborations more robust to the failure of any single link. At a higher order of complexity, Motif 4999, a core-led yet densely interconnected tetrad, also increased in frequency. This structure provides substantial pathway redundancy, effectively mitigating "single-point failure" risks. For instance, the presence of Motif 4999 within the network enabled Wuxi to swiftly find alternative suppliers from within its collaborative cluster when Shanghai's supply chains were disrupted during the COVID-19 pandemic, thereby reducing regional production losses. The rise of such motifs signifies a network that is not only more connected but also intelligently woven with built-in buffers.

The consolidation of these resilient motifs into the network's architecture drove a substantial increase in the overall Structural Resilience (SR) index, which rose from 3.84 in 2011 to 5.26 in 2020. Crucially, this growth was not linear but occurred in two distinct phases, revealing the powerful influence of policy intervention on structural evolution.

The period from 2011 to 2015 was characterized by moderate growth. This initial, slower pace was primarily constrained by persistent administrative barriers and uncoordinated policies across provincial boundaries. Inconsistent intellectual property (IP) protection regimes, for example, created uncertainty that hindered the formation of the very reciprocal and complex ties that underpin structural resilience.

A pronounced acceleration occurred from 2016 to 2020. This inflection point aligns directly with the implementation of the Yangtze River Delta Urban Agglomeration Development Plan. This coordinated policy package, which standardized cross-city collaboration mechanisms, established unified IP protection platforms, and promoted inter-city R&D platforms, acted as a catalyst. By systematically reducing the institutional friction to collaboration, it actively encouraged the formation of the redundant, reciprocal motifs like M239 and M4999 that are fundamental to structural resilience, thereby engineering a more rapid maturation of the network's shock-absorbing capacity.

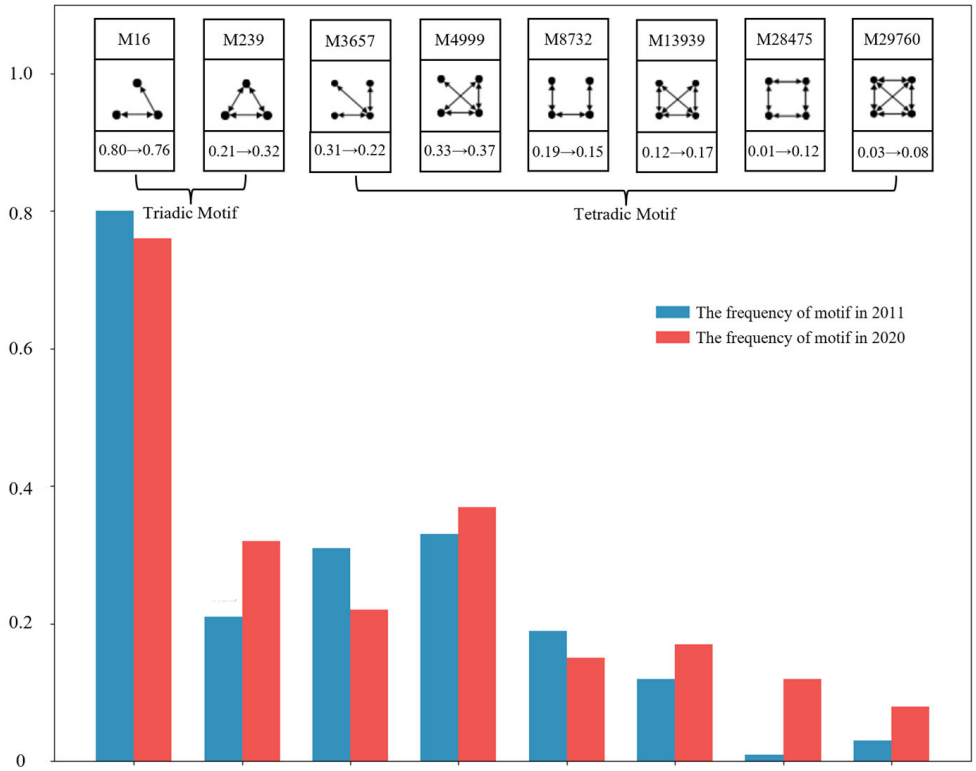


Figure 3. The frequency of motif structures in the innovation network of the Shanghai Metropolitan Area from 2011 to 2020.

4.3. Evolution of Innovation Network Community Resilience

Completing the multi-scale anatomical analysis, we examine resilience at the meso-level through the lens of community structure. The evolution here reveals the SMA's transition from a fragmented collection of localized clusters toward a more integrated and robust regional innovation ecosystem, a process profoundly shaped by policy-driven integration.

Our analysis identifies a decisive shift in the SMA's community architecture between the two study periods (Table 1). During 2011–2015, the network was partitioned into four distinct, spatially segregated communities. These subgroups largely adhered to provincial administrative boundaries, with minimal cross-community collaboration. For instance, one community was predominantly composed of cities in Jiangsu province, while another was almost exclusively made up of cities from Zhejiang province, reflecting the "balkanization" of the innovation landscape.

In stark contrast, the period of 2016–2020 witnessed a consolidation into two integrated communities. This restructuring was not a minor adjustment but a fundamental reorganization. A dominant core community (Community 1) emerged, seamlessly integrating key innovation nodes from Shanghai, Jiangsu, and Zhejiang. The share of cross-provincial patents within this core community grew to nearly half of its total collaborations, signaling a breakthrough in administrative barriers. This integration was physically and institutionally facilitated by major policy-driven infrastructure projects, such as the Shanghai–Nantong Yangtze River Bridge and the accelerated development of the Shanghai–Ningbo High-Speed Railway, which effectively shrank the functional distance between previously disconnected cities.

Table 1. Innovation communities in the Shanghai Metropolitan Area from 2011 to 2020.

Stage	Innovation Community Tier	Involved Regions
2011–2015	1	Shanghai Central Urban Area, Suzhou Central Urban Area, Wuxi Central Urban Area, Changzhou Central Urban Area, Ningbo Central Urban Area, Kunshan City, Nantong Central Urban Area, Jiading District, Songjiang District
	2	Jiaxing Central Urban Area, Huzhou Central Urban Area, Cixi City, Changshu City, Zhangjiagang City, Fengxian District, Jiangyin City, Qingpu District, Taicang City, Jinshan District
	3	Yuyao City, Haian City, Qidong City, Liyang City, Rugao City, Anji County, Haining City, Yixing City, Deqing County, Tongxiang City, Rudong County, Jiashan County, Pinghu City, Haiyan County
	4	Zhoushan Central Urban Area, Changxing County, Ninghai County, Xiangshan County, Chongming District, Daishan County, Shengsi County
2016–2020	1	Shanghai Central Urban Area, Suzhou Central Urban Area, Wuxi Central Urban Area, Changzhou Central Urban Area, Ningbo Central Urban Area, Kunshan City, Nantong Urban Area, Jiading District, Songjiang District, Jiaxing Urban Area, Huzhou Urban Area, Cixi City, Changshu City, Zhangjiagang City, Fengxian District, Jiangyin City, Qingpu District, Taicang City, Yuyao City, Haian City, Rugao City, Anji County, Haining City, Jinshan District, Yixing City, Deqing County, Changxing County, Tongxiang City, Jiashan County, Pinghu City
	2	Zhoushan Central Urban Area, Haiyan County, Liyang City, Qidong City, Ninghai County, Rudong County, Xiangshan County, Chongming District, Daishan County, Shengsi County

The process of community merging significantly enhanced the network's meso-scale resilience through three primary mechanisms. First, the formation of a large, dense core community substantially increased internal connection density, establishing a high-capacity structural backbone that accelerated knowledge circulation and enabled more efficient recombination of ideas and resources across the region, a critical capacity for adaptive response during crises. Second, by integrating peripheral cities into the core community, these previously marginal nodes gained significantly improved access to regional innovation resources, narrowing the resilience gap between core and periphery. This integration also strengthened collective risk pooling, allowing localized shocks, such as a city-specific R&D investment downturn, to be absorbed and offset by the distributed capacity of the community, as evidenced during the 2019 regional economic slowdown. Finally, this structural consolidation mitigated systemic fragmentation risk by reducing the network's susceptibility to division along traditional administrative boundaries. With fewer, larger, and more densely interconnected communities, the innovation ecosystem became less likely to disintegrate into isolated components under stress, thereby preserving the functional integrity of the metropolitan-wide collaborative network.

5. Driving Mechanism of the Collaborative Innovation Network Resilience in the Shanghai Metropolitan Area Based on ERGM

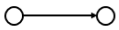
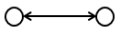
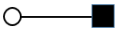
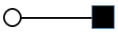
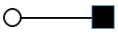
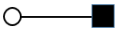
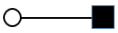
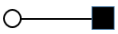
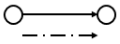
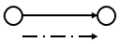
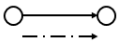
5.1. Model Selection for the Driving Mechanism of Regional Innovation Network Resilience

Following the multi-dimensional anatomy of resilience evolution, this study delves into the causal factors underpinning these dynamics. Traditional econometric methods, which assume independence among observations, are ill-suited for modeling interdependent network ties. To address this fundamental issue and rigorously test the drivers hypothesized in our framework, we employ the ERGM. ERGM is a state-of-the-art statistical method that treats the entire observed network as a single data point, modeling the probability of its formation by simultaneously accounting for endogenous structural self-organization, node attributes, and exogenous dyadic factors. This approach allows us to move beyond correlation and toward a causal understanding of the micro-foundations of network resilience.

5.2. Variable Selection and Interpretation for the Network Resilience Driving Mechanism

Our ERGM specification is designed to test a comprehensive set of drivers derived from regional innovation theory and the specific context of the SMA. The variables, summarized in Table 2, are categorized into three groups that map onto our analytical framework.

Table 2. Driving factors of innovation network resilience.

Driving Factors	Structural Variables	Schematic Diagram	Variable Meaning	Mechanism	Explanation
Network Self-Organization Effect	Edges		Number of Edges	Fundamental Effect	The basic tendency of network nodes to form connections
	Mutual		Reciprocity	Reciprocity Effect	Whether network nodes tend to form interactive connections?
Individual Attribute Effect	Nodefactor (gdp. high)		Economic Driver	Matthew Effect	Whether nodes with high economic development level tend to form connections?
	Nodefactor(indust.high)		Industrial Structure	Matthew Effect	Whether nodes with high industrial structure level tend to form connections?
	Nodefactor(service.high)		Sci-Tech Services	Matthew Effect	Whether nodes with high sci-tech service levels tend to form connections?
	Nodefactor(input.high)		Government Supply	Matthew Effect	Whether nodes with high government supply level tend to form connections?
	Nodefactor(fdi.high)		Opening-Up	Matthew Effect	Whether nodes with high opening-up level tend to form connections?
	Nodefactor(edu.high)		Education Input	Matthew Effect	Whether nodes with high education input level tend to form connections?
Exogenous Network Effect	Edgecov.geo		Geographic Distance Network	Dependence Effect	Whether the resilient network has dependence on the geographic distance-associated network?
	Edgecov.admin		Administrative Distance Network	Dependence Effect	Whether the resilient network has dependence on administrative adjacency?
	Edgecov.internet		Information Distance Network	Dependence Effect	Whether the resilient network has dependence on the information network?

Network self-organization effects variables capture the internal structural logic of the network. The Edges parameter models the baseline density, while Mutual tests for reciprocity—a key endogenous mechanism that signifies balanced, stable partnerships and is a direct contributor to structural resilience at the motif level.

Urban individual attributes variables test the "Matthew Effect" and node-level capacity arguments. We examine whether cities with superior economic development (gdp), advanced industrial structure (indust), strong sci-tech services (service), high government R&D input (input), significant openness (fdi), and substantial education investment (edu) are more active in forming ties, thereby influencing the distribution of node resilience (see Table 3).

Table 3. Selection of urban individual attribute variables and explanation of measurement indicators.

Variable	Indicators	Meaning	Reference
Economic Driver	Per capita GDP	Reflecting a city's capacity to fund innovation activities and recover from economic shocks	[15,49]
Industrial Structure	The proportion of the tertiary industry	A more advanced industrial structure often correlates with higher innovation dependence and adaptability	[22,50]
Technological Services	The number of employees in the sector	Indicating the availability of skilled talent for innovation and knowledge transfer.	[38,51]
Government Support	Per capita local fiscal expenditure on science and technology	Reflecting the institutional attention and financial buffering capacity during crises	[34,52]
Opening Up	Actual utilized FDI	Capturing a city's integration into global value chains and its access to external knowledge	[26,53]
Education Investment	Per capita local fiscal expenditure on education	A foundational long-term driver of human capital development for the innovation system	[27,54]

Exogenous network effects variables probe the role of different forms of proximity in bridging or separating nodes. Geographic distance tests the friction of physical space. Administrative proximity examines the legacy effect of provincial boundaries. Most critically, Information proximity, which is operationalized as the inverse of internet user difference, quantifies the role of digital connectivity—a potential substitute for geographic proximity in fostering collaboration and enhancing community integration.

5.3. Analysis of Network Resilience Driving Mechanism

The ERGM results for two periods of 2011–2015 and 2016–2020, detailed in Table 4, reveal significant temporal shifts in the drivers of the SMA's collaborative network, illuminating the mechanics behind its resilience evolution.

Table 4. Results of Exponential Random Graph Model analysis.

Variable	2011–2015		2016–2020	
	Model I	**Model II**	**Model I**	**Model II**
Edges	−3.83 *** (−15.28)	−3.45 *** (−22.50)	−4.03 *** (−6.18)	−5.55 *** (−196.13)
Mutual	−1.10 *** (−3.28)	−0.97 *** (−5.88)	1.19 *** (4.99)	0.26 *** (17.206)
Nodefactor (gdp.high)	0.67 (18.84)	0.45 *** (4.89)	−3.30 (−28.90)	−1.30 *** (−8.90)
Nodefactor (indust.high)	1.17 *** (9.98)	1.56 *** (6.23)	1.17 *** (7.87)	3.42 *** (42.87)
Nodefactor (service.high)	1.62 (12.90)	0.50 (7.66)	−0.54 ** (−19.88)	0.15 (0.299)
Nodefactor (input.high)	−0.28 (−7.67)	1.14 ** (1.42)	0.03 (3.68)	1.10 *** (18.93)
Nodefactor (fdi.high)	0.39 *** (1.19)	0.68 (1.14)	1.10 *** (18.93)	2.06 *** (79.36)
Nodefactor (edu.high)	0.98 *** (2.60)	0.93 (6.53)	−1.11 * (−1.94)	−0.72 *** (−12.68)
Edgecov.geo		−0.01 * (−1.92)		−0.01 (−1.26)
Edgecov.admin		−0.14 * (−0.05)		0.11 (10.23)
Edgecov.internet		0.02 *** (0.99)		0.01 *** (3.98)
AlC	1021	1013	1145	1096
BlC	1376	1211	1451	1426

Note: ***, **, and * represent the significance levels of 1%, 5%, and 10%, respectively; the values in parentheses are t-values; the blank items indicate that this model does not have such items.

5.3.1. Driving Role of Network Self-Organization

The significantly negative coefficient for Edges in both periods confirms the overall sparsity of the network and the non-random, costly nature of forming innovation partnerships. The most telling shift is observed in the Mutual parameter. It was negative and significant in the early period but became positive and highly significant after 2016. This pivotal reversal indicates that reciprocal collaboration evolved from a suppressed to a dominant organizing principle of the network. This maturation towards balanced, two-way knowledge exchange is a core ingredient of the structural resilience observed in the motif analysis and was likely catalyzed by policy frameworks that encouraged sustained and equitable partnerships.

5.3.2. Driving Role of Urban Individual Attributes

The analysis reveals that Industrial Structure and Openness (FDI) were consistently positive and significant drivers across both periods. This underscores that cities with advanced producer services and global knowledge pipelines are perennial anchors of the network. A notable "U-turn" is observed for the Economic Driver (GDP). Its effect shifted from positive to significantly negative, suggesting that as the network matured, sheer economic scale became less critical for forging new ties than specialized capabilities and openness, signaling a diversification of partnership logics. The variable for Government Support also underwent a crucial transition, from an insignificant or negative effect to a positive and significant driver in the later period. This transformation is a direct statistical signature of the SMA's policy success. It indicates that whereas uncoordinated local government spending initially created inefficiencies, the later-period coordinated,

cross-jurisdictional science and technology policies effectively translated into stronger collaborative ties, directly driving the observed integration at the community level.

5.3.3. Driving Role of Exogenous Networks

The results on exogenous factors provide compelling evidence for the evolving geography of innovation in the SMA. The negative effect of Geographic Distance was significant only in the early period and faded thereafter. Conversely, Information Proximity emerged as a positive and significant driver in both periods, with its importance growing over time. This provides robust, model-based evidence that digital connectivity has effectively supplanted physical proximity as a key enabler of collaboration, facilitating the dense, cross-boundary interactions that define a resilient network. Interestingly, the Administrative Proximity effect was statistically weak and unstable, which in itself is a significant finding. It reflects the relative success of SMA policies in consciously dismantling the "invisible walls" at provincial boundaries, fostering a metropolitan identity that overrides traditional administrative divisions.

6. Discussion

6.1. The Policy-Engineered Resilience: A Comparison with Market-Driven Models

The multi-dimensional resilience evolution observed in the SMA—the transition to a polycentric node structure, the ascendancy of complex structural motifs, and the consolidation of communities—presents a stark contrast to the typically slow, organic, and market-led evolution observed in established Western metropolitan regions. Our findings underscore the distinctiveness of the policy-driven model.

6.1.1. The Accelerated Dual-Core Formation and Contextual Lock-In

Our finding that the SMA's innovation network evolved from a single-core to a multi-core structure aligns with recent studies on polycentric innovation clusters in Chinese metropolitan areas [55]. However, we extend this work by pinpointing policy-driven acceleration as a distinct and powerful mechanism—a force less prominent in the market-led evolution documented in Western regions [56,57]. For instance, the dramatic resilience growth of cities like Changzhou and Wuxi was not an organic, slow-burning process but was actively accelerated by the SMA's strategic policy framework, which provided targeted subsidies and infrastructure to channel knowledge and resources [58]. In contrast, regional innovation in Western economies such as the United States or Germany typically unfolds through bottom-up, market-coordinated processes, where firms, universities, and research institutes interact through competition, knowledge spillovers, and entrepreneurial ecosystems rather than administrative coordination [59,60]. Innovation clusters such as Silicon Valley and Bavaria's high-tech region have evolved through venture capital networks, industrial specialization, and university–industry partnerships, with governments acting primarily as facilitators that shape enabling environments rather than direct orchestrators of network formation [61–63]. This contrast underscores two distinct pathways to resilience. In China's policy-driven systems, resilience stems from institutional coordination and strategic intervention. Conversely, in Western contexts, it emerges through self-organized adaptability and market-based learning.

Furthermore, we identify a novel mechanism of "functional lock-in" in the case of Zhoushan. This extends prior research that primarily attributed peripheral exclusion to geographic remoteness [64,65]. Our findings demonstrate that despite geographic proximity to Ningbo, Zhoushan's tourism-specialized economy was fundamentally misaligned with the SMA's manufacturing and technology-oriented innovation chain. This highlights that economic-structural compatibility, not just physical distance, is a critical determinant of

a node's integrative capacity and resilience within a policy-driven metropolitan network, offering a crucial refinement to core–periphery theory.

6.1.2. The Structural Power of Motifs and Policy Leverage

The significant rise in structural resilience, driven by the ascendancy of specific motifs like the reciprocal triad Motifs 239 and the redundant tetrad Motifs 4999, provides robust, micro-architectural evidence for theories linking complexity and redundancy to system robustness [66,67]. Our study quantifies this link, demonstrating that multi-node, densely interconnected motifs are superior shock-absorbers compared to simpler structures.

The non-linear trajectory of this structural evolution, specifically the marked acceleration post-2016, serves as a powerful testament to policy leverage. It demonstrates that well-designed, coordinated top-down interventions, such as unified IP platforms, can actively engineer a more resilient network architecture by incentivizing the formation of robust collaboration patterns. This accelerates a process that would likely unfold more slowly and haphazardly under purely market-driven dynamics [68], highlighting the unique capacity of strategic governance to sculpt the very fabric of the innovation system for enhanced resilience.

6.2. Theoretical Extensions: Proximity, Policy Coordination, and the Digital Shift

6.2.1. The Digital Supremacy and Proximity Theory Extension

Our dynamic ERGM analysis yields novel insights into the shifting drivers of network formation. The finding that the constraining effect of geographic distance diminished post-2016, while information proximity emerged as a powerful and sustained driver, offers compelling empirical evidence that in a modern, digitally supported metropolitan context, virtual connectivity can effectively substitute for physical co-location. This result is strongly supported by recent international studies (post-2022) showing the crucial role of digital proximity in maintaining network resilience during global supply chain disruptions.

This finding necessitates a significant extension to Boschma's proximity framework [69], suggesting a re-evaluation of the hierarchy of proximities in the digital age. We propose that Information Proximity has transitioned from a supporting factor to a critical relational asset that dictates the potential for cross-regional collaboration, especially when policy coordination minimizes institutional friction [70,71].

6.2.2. Policy Coordination as a Paramount Catalyst

The evolution of the Government Support variable from an insignificant or negative influence to a positive and significant driver in the later period is a contextually profound result. It captures a statistical signature of a successful governance transition: from fragmented, potentially inefficient local interventions to a strategic, metropolitan-scale policy coordination.

This outcome directly supports the GPN 2.0 framework, which posits that the State is not merely an external regulator but an internal driver of network formation. This demonstrates that while uncoordinated government action may initially hinder network formation, a unified and strategic policy approach can become a paramount catalyst for building a cohesive and resilient innovation ecosystem, overriding traditional administrative barriers and accelerating structural integration [72–74].

6.3. Theoretical and Practical Implications

6.3.1. Theoretical Contributions

This study makes three key theoretical contributions. First, it introduces and validates a multi-dimensional resilience framework that integrates node, structural, and community levels, providing a more holistic and anatomized understanding of how resilience operates

across different scales of a complex system. Second, it significantly advances proximity theory by empirically demonstrating the declining role of geography and the ascendancy of information proximity, while also proposing policy proximity—achieved through coordinated institutional rules and governance—as a distinct and potent dimension that can override traditional barriers. Finally, by pioneering the methodological integration of network motif analysis with ERGM in resilience research, it provides a rigorous template for future studies to decode the micro-foundations and causal drivers of network dynamics.

6.3.2. Practical Implications

For policymakers, our findings offer three key, evidence-based strategies for optimizing metropolitan innovation network resilience.

Targeted resilience enhancement for peripheral cities. Policymakers should move beyond a "one-size-fits-all" approach to peripheral development. Cities like Jiaxing, with a compatible industrial base, should be supported with innovation vouchers and infrastructure that facilitates innovation spillover from core cities. Conversely, for cities like Zhoushan, with a functional mismatch, strategies should focus on aligning their economic specialization with the core network through targeted collaborative projects, such as a "Marine Innovation Corridor" that connects its marine economy with the SMA's broader innovation chain [75].

Structural optimization via resilient motif promotion. Policy should be designed to actively foster the formation of robust network structures [76]. This can be achieved by funding multi-city R&D projects that require collaboration among a minimum of three partners, thereby directly promoting the formation of resilient motifs such as Motif 239 and Motif 4999. Policies such as a 25% subsidy for projects meeting a minimum city-partner threshold could serve as a powerful incentive. Furthermore, strategic investment in redundant physical and digital infrastructure, including but not limited to new high-speed railways, can effectively transform vulnerable, linear supply chains into resilient, multi-path networks [77].

Strengthened policy coordination. Our findings underscore the paramount importance of coordinated governance. Policymakers should prioritize establishing metropolitan-wide institutions, such as a dedicated SMA Innovation Resilience Fund, and standardize rules (e.g., IP protection) across the entire region to eliminate collaboration costs and create a seamless, resilient innovation ecosystem [78].

7. Conclusions

This study has systematically investigated the evolution and drivers of collaborative innovation network resilience in the SMA from 2011 to 2020. By developing a multi-dimensional analytical framework and employing an integrated methodology combining social network analysis, network motif analysis, a random walk algorithm, and the ERGM, we have dissected the trajectories of resilience across node, structural, and community levels.

The core findings demonstrate that the SMA's innovation network successfully transitioned towards a more resilient architecture during this period. At the node level, the resilience configuration evolved from a Shanghai-centric monopolar core to a robust, polycentric structure characterized by multiple hubs, notably Shanghai, Suzhou, Changzhou, and Wuxi. At the structural level, a qualitative shift occurred in the network's micro-architecture, moving from fragile, linear chains of collaboration towards complex and robust motifs, such as reciprocal triads and redundant tetrads, which form the bedrock of structural resilience. At the community level, resilience was enhanced through the integra-

tion of previously fragmented, administratively bounded subgroups into a highly cohesive core innovation community, marking a structural breakthrough in regional integration.

Our ERGM analysis further reveals that this multi-dimensional resilience evolution was driven by the synergistic effects of policy coordination, industrial upgrading, and information proximity. A pivotal finding is that the role of information proximity has surpassed that of geographic proximity as a more critical bond sustaining cross-regional collaboration. Furthermore, top-down policy intervention successfully transformed from a potential hindrance in the early stage to a key catalyst for network integration and maturation in the later period.

Based on these insights, we propose that policies aimed at enhancing metropolitan innovation network resilience should focus on guiding and funding multilateral R&D collaborations that inherently form robust network motifs; formulating differentiated integration strategies for peripheral cities based on their functional profiles to overcome "functional lock-in"; and establishing permanent cross-regional governance platforms and a resilience fund to institutionalize policy coordination.

Despite these contributions, this study has certain limitations that suggest directions for future research. While joint patents provide a reliable measure of formal collaboration, they may not capture informal or emergent knowledge exchanges; integrating firm-level or survey-based data could enrich the network representation. Treating all patents as homogeneous might also obscure sectoral heterogeneity. Future analyses could employ IPCs to compare resilience dynamics across high-tech and traditional industries. Although the two-period ERGM effectively captures structural evolution, applying a continuous-time temporal ERGM or other dynamic network models would allow finer-grained observation of short-term adaptive responses. Addressing these limitations would not only refine the empirical precision of resilience measurement but also deepen theoretical understanding of how innovation networks evolve and recover under complex, rapidly changing environments.

In summary, this research provides and validates a refined, multi-dimensional anatomical framework for understanding innovation resilience in policy-driven contexts. By integrating novel methodologies and contextualizing the analysis, it extends the theory of proximity and offers both a theoretical foundation and practical pathways for building more adaptive, shock-resistant, and sustainable metropolitan innovation ecosystems.

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