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Hypernetwork Symbiosis and Industrial Chain Resilience: A Multilayer Network Perspective

YouXing Ji
School of Business, Hunan University of Science and Technology, Hunan, China

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Abstract

This study aims to explore how hypernetwork symbiosis influences the resilience of industrial chains within the context of increasingly complex global production networks. Drawing on symbiosis theory and a multilayer network perspective, the paper constructs a theoretical framework that conceptualizes cross-national cooperation as an integrated system composed of industrial cooperation, technological collaboration, and trade networks. By examining the structural interactions within and across network layers, the study identifies four key mechanisms through which hypernetwork symbiosis affects industrial chain resilience: intra-layer self-interaction, intra-layer cross-node interaction, inter-layer same-node interaction, and inter-layer cross-node interaction. The analysis shows that intra-layer interactions enhance redundancy, substitutability, and stability within individual networks, while inter-layer interactions promote resource integration, functional complementarity, and coordinated adjustment across networks. Together, these mechanisms strengthen the capacity of industrial systems to absorb shocks, adapt to disruptions, and recover from crises. The findings suggest that hypernetwork symbiosis provides an important structural foundation for improving industrial chain resilience in an increasingly uncertain global economic environment.

Keywords

Hypernetwork symbiosis; Industrial chain resilience; Multilayer networks; Cross-national cooperation; Global production networks

1. Introduction

Against the backdrop of deepening economic globalization, the organization of cross-border production has undergone a profound transformation, shifting from vertically integrated structures toward increasingly networked systems of international division of labor. Represented by Global Value Chains (GVCs), contemporary production networks distribute different stages of production across countries, thereby significantly improving the efficiency of global resource allocation. However, the spatial fragmentation of production activities has also made industrial systems more vulnerable to external shocks. In recent years, the

outbreak of the COVID-19 pandemic, escalating geopolitical tensions, and the resurgence of trade protectionism have substantially increased uncertainty in the global economic environment. As a result, cross-border industrial and supply chains are facing unprecedented disruptions and pressures for restructuring (Baldwin et al., 2022). Under such circumstances, how to enhance the stability and security of industrial chains in an environment characterized by high openness and deep international specialization has become a central concern for both policymakers and scholars.

With the changing operational environment of the global industrial system, academic research has gradually shifted its focus from efficiency alone to the capacity of industrial systems to sustain operations under uncertainty. In this context, the concept of industrial chain resilience has emerged as a key framework for understanding how production networks respond to shocks. Existing studies generally view industrial chain resilience as encompassing not only the ability to withstand disruptions but also the capacity to adjust and recover after shocks occur. In essence, resilience reflects a dynamic process involving resistance, adaptation, recovery, and transformation (Sheffi et al., 2005; Brusset and Teller, 2017). Previous research has explained the formation of industrial chain resilience from several perspectives, including industrial upgrading and diversification, technological innovation and productivity improvement, and institutional environments and policy stability (Hausmann et al., 2007; Hidalgo et al., 2009). Nevertheless, most of these studies treat countries as relatively independent units of analysis, paying limited attention to the systemic effects of multidimensional cooperation among countries.

In reality, within a highly globalized production system, industrial cooperation, technological collaboration, and trade exchanges among countries are increasingly intertwined, giving rise to complex cross-border network structures. A country's industrial chain resilience is therefore determined not only by its domestic industrial base and institutional conditions but also by its structural position and interaction patterns within multiple international cooperation networks. Advances in network science provide new analytical tools for examining such relationships. Compared with traditional single-layer network analysis, complex network and hypernetwork approaches can simultaneously capture multiple relational structures and their coupling mechanisms, and have been widely applied to the study of financial risk transmission, technological diffusion, and international trade (Boccaletti et al., 2014; Kivelä et al., 2014; Aleta et al., 2025). However, the economic implications of collaborative mechanisms within hypernetworks remain insufficiently explored. In particular, there is still a lack of an integrated analytical framework linking hypernetwork structures with industrial chain resilience. Therefore, in the context of profound restructuring of global industrial chains, examining how hypernetwork symbiosis influences industrial chain resilience can

not only deepen the theoretical understanding of network-based economic systems but also shed light on how transnational industrial systems operate under complex and uncertain shock environments.

2. The Concept of Hypernetwork Symbiosis

Drawing on symbiosis theory and the perspective of hypernetworks, cooperation among countries cannot be understood as a single-dimensional interaction. Instead, it reflects a multi-layered structure in which production, innovation, and institutional relationships are intertwined to form different types of symbiotic connections. From a structural–functional perspective, this system mainly consists of three interrelated components: an industrial cooperation network, a technological cooperation network, and a trade cooperation network.

The industrial cooperation network is built upon cross-border industrial division of labor and input–output linkages (Coe et al., 2015). Through upstream–downstream complementarities and transnational collaboration across production stages, it facilitates the efficient allocation of production factors among different economies. Such cooperation not only enhances coordination efficiency along the industrial chain but also strengthens the structural stability of the industrial system.

The technological cooperation network, by contrast, is centered on firms as key nodes and is supported by collaborative relationships with universities and research institutions. Through mechanisms such as patent licensing, technology transfer, and joint research and development, this network promotes the cross-organizational flow of knowledge and technological resources. In doing so, it accelerates technological diffusion and capability accumulation, ultimately improving innovation efficiency and technological absorption capacity (Cantwell and Mudambi,2005).

The trade cooperation network functions primarily through institutional arrangements and policy coordination. Instruments such as trade agreements, tariff arrangements, and regulatory alignment reduce cross-border transaction costs and policy uncertainty, thereby providing a stable institutional environment for international economic activities (Williamson, 2000).

These three networks are functionally interdependent and mutually embedded: industrial cooperation provides the material foundation for production, technological cooperation drives the diffusion of knowledge and innovation, and trade cooperation establishes stable expectations through institutional frameworks. Together, they form a multilayer interactive structure that can be conceptualized as a hypernetwork-based symbiotic system.

With the deepening of the global division of industrial labor, different forms of cross-national cooperation, including industrial cooperation, technological collaboration, and trade linkages, no longer operate independently. Instead, they interact throughout the processes of value creation, value enhancement, and value

realization, gradually forming a multilayered and embedded cooperation structure. Technological innovation provides the driving force for industrial upgrading, industrial collaboration offers application scenarios and scale foundations for technological diffusion, and trade linkages enable value realization through cross-border circulation and institutional coordination. In this process, different types of cooperation networks become increasingly intertwined, giving rise to a hypernetwork structure. It is important to distinguish between the two concepts: while a hypernetwork emphasizes the structural form resulting from the interconnection of multiple types of networks, hypernetwork symbiosis highlights the collaborative operational mechanism that emerges across network layers through resource allocation, knowledge diffusion, and institutional coordination.

On this basis, this study defines hypernetwork symbiosis as a cross-network co-evolution mechanism formed within a multilayer network system composed of industrial cooperation, technological cooperation, and trade cooperation networks. Through structural embedding, dynamic coupling, and bidirectional feedback among network layers, this mechanism generates synergistic gains across networks by enabling resource sharing, functional complementarity, and risk diversification, thereby jointly promoting structural optimization and functional enhancement of the industrial system. The evolutionary dynamics of hypernetwork symbiosis are driven by the combined influence of four interaction mechanisms among participating countries: intra-layer self-interactions, intra-layer cross-node interactions, inter-layer interactions of identical nodes, and inter-layer interactions among different nodes.

3. Theoretical Mechanisms Through Which Hypernetwork Symbiosis Influences Industrial Chain Resilience

3.1. Intra-layer Self-Interaction Mechanism

Within a hypernetwork symbiotic structure, intra-layer self-interaction refers to the self-reinforcing and self-circulating process through which a single country enhances its capabilities within a specific network layer by optimizing industrial structure, accumulating technological capacity, and adjusting trade patterns. This mechanism mainly manifests in the way a country relies on internal resource reallocation, upstream–downstream coordination, and technological innovation to gradually strengthen the structural stability and functional integration of its industrial system.

On the one hand, reallocating resources across different segments of domestic industries allows production factors to be flexibly substituted when external demand fluctuates or supply channels are disrupted, thereby improving the capacity of the industrial chain to absorb shocks. On the other hand, stronger coordination between domestic upstream and downstream sectors, together with improved local supporting capabilities, helps reduce dependence on a single

external partner and maintain the continuity of industrial operations. Meanwhile, sustained technological innovation and knowledge accumulation can drive industrial upgrading and functional restructuring. As a result, the industrial system may not only recover from disruptions but also achieve structural optimization through technological substitution and value chain upgrading. In this sense, intra-layer self-interaction constitutes the fundamental basis for a country's participation in a multilayer hypernetwork and for maintaining systemic adaptability, and it represents a key endogenous mechanism underlying industrial chain resilience (Domenico et al., 2013; Boccaletti et al., 2014; Kivelä et al., 2014).

3.2. Intra-layer Cross-Node Interaction Mechanism

In a hypernetwork symbiotic system, intra-layer cross-node interaction refers to the dynamic relationships and structural evolution formed among different countries or symbiotic units within the same network layer through flows of resources, information exchange, technological collaboration, and institutional coordination. Unlike intra-layer self-interaction, which emphasizes the internal adjustment of individual nodes, intra-layer cross-node interaction focuses on the formation and strengthening of relational structures among nodes. Its core function is to enhance network connectivity and structural stability through the continuous expansion and optimization of cooperative ties (Domenico et al., 2013; Boccaletti et al., 2014).

Specifically, stable relationships based on reciprocal cooperation help reduce transaction uncertainty and strengthen expectations of sustained collaboration. This stability allows network connections to persist even under external shocks and reduces the likelihood of cascading disruptions. In addition, the expansion of cooperative relationships increases the diversity and redundancy of the network, which enables the system to continue operating through alternative pathways when certain nodes or connections fail. Cross-node interactions also facilitate the rapid diffusion of information and technology through intermediary nodes, thereby accelerating knowledge dissemination and capability accumulation. Through these processes, the network becomes more responsive to shocks and more capable of reorganizing its structure. As a result, intra-layer cross-node interaction reinforces cooperative relationships, increases structural redundancy, and promotes information diffusion. These functions make it a crucial mechanism for maintaining the stability and functional integration of a single-layer network (Domenico et al., 2013; Boccaletti et al., 2014; Kivelä et al., 2014).

3.3. Inter-layer Same-Node Interaction Mechanism

Within a hypernetwork symbiotic structure, inter-layer same-node interaction refers to the process of vertical coupling and functional integration that occurs when the same node, such as a country or an industrial symbiotic unit, participates

simultaneously in different network layers (Domenico et al., 2013; Boccaletti et al., 2014). Unlike intra-layer interactions, which primarily emphasize horizontal relationships within a single network, inter-layer same-node interaction reflects the multiple roles that a node performs across different networks, including industrial cooperation, technological collaboration, and trade relations. It also captures the mechanisms through which resources are coordinated among these networks (Kivelä et al., 2014).

More specifically, when the same node operates across different network layers, it can generate cross-layer synergies through resource integration, functional coupling, and information feedback. On the one hand, heterogeneous resources such as technological capabilities, production capacity, and market connections can be jointly mobilized across different layers. When one network layer experiences disruption, resources from other layers can provide complementary support, thereby strengthening the system's ability to absorb shocks. On the other hand, functional linkages among different networks can create a dynamic cycle that connects technological innovation, industrial upgrading, and trade expansion, which improves the efficiency of post-shock recovery. In addition, cross-layer feedback mechanisms enable nodes to adjust resource allocation and development strategies in response to changes in their positions within different networks. This process supports structural reconfiguration and functional upgrading. As a result, inter-layer same-node interaction enhances the collaborative capacity of nodes embedded in multilayer networks through resource integration, functional coupling, and adaptive feedback. It therefore represents an important vertical mechanism through which hypernetwork symbiosis contributes to system stability and evolutionary adaptation (Domenico et al., 2013; Boccaletti et al., 2014; Kivelä et al., 2014).

3.4. Inter-layer Cross-Node Interaction Mechanism

In a hypernetwork symbiotic system, inter-layer cross-node interaction refers to the multi-actor and multi-level coupling relationships formed when different nodes are connected across distinct network layers (Domenico et al., 2013; Boccaletti et al., 2014). Unlike inter-layer same-node interaction, which emphasizes the vertical integration capacity of a single node, inter-layer cross-node interaction reflects the intertwined structural relationships among different actors across multiple networks and represents a system-level mechanism of cross-layer coordination (Kivelä et al., 2014).

Under this mechanism, different nodes assume differentiated roles in industrial cooperation, technological collaboration, and trade networks, and are linked through cross-layer connections that create multidimensional patterns of division of labor and coordination. First, the cross-layer flow of resources and information enables technological, production, and market factors to be allocated across nodes, thereby dispersing risks and enhancing the system's resilience to shocks. Second,

the structural coupling of multiple networks provides the system with multiple adjustment pathways, allowing disruptions in one layer to be mitigated through coordinated responses in other layers. Furthermore, cross-layer and cross-node linkages can trigger cascading adjustment processes, encouraging nodes to jointly reconfigure their division of labor, technological trajectories, and trade flows. Through such coordinated adjustments, the system can achieve structural optimization and functional upgrading after shocks occur. Therefore, by facilitating resource flows, structural coupling, and coordinated adaptation across networks, inter-layer cross-node interaction strengthens systemic synergy among multilayer networks and serves as a crucial mechanism through which hypernetwork symbiosis promotes the stable operation and evolutionary transformation of industrial systems (Domenico et al., 2013; Boccaletti et al., 2014; Kivelä et al., 2014).

4. Conclusion

Industrial chain resilience cannot be explained by a single economic variable. Instead, it reflects the structural relationships through which economies are embedded in global production networks. This section addresses the central question of how hypernetwork symbiosis influences industrial chain resilience. The discussion develops along two main lines. The first clarifies the conceptual foundation of hypernetwork symbiosis. The second examines the mechanisms through which it affects resilience. On this basis, an integrated theoretical framework linking hypernetwork symbiosis and industrial chain resilience is constructed.

Countries and industries often respond differently to external shocks. These differences mainly arise from variations in their positions and connections within network structures, especially in terms of risk absorption, shock buffering, and functional reconfiguration. From this perspective, the structural implications of hypernetwork symbiosis and its influence on resilience can be understood through two dimensions: intra-layer symbiosis and inter-layer symbiosis. Intra-layer symbiosis strengthens relationships within individual networks such as industrial cooperation, technological collaboration, and trade linkages. Stronger ties within these networks increase substitutability and redundancy among nodes, reduce dependence on a single market or partner, and enhance the capacity of industrial chains to absorb risks. Inter-layer symbiosis emphasizes the functional complementarity and structural coupling among different cooperation networks. Through these cross-layer connections, technological diffusion, resource allocation, and market adjustment become mutually reinforcing processes. This interaction improves the adaptability and recovery capacity of industrial chains under disruptive conditions. The two forms of symbiotic interaction operate together and form the structural foundation through which hypernetwork symbiosis enhances industrial chain resilience.

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