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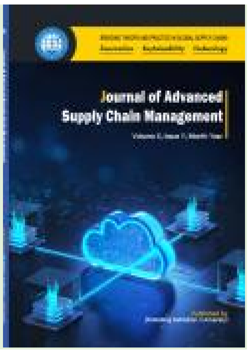

Article

Risk Propagation in Interconnected Supply Chain Networks of Developed and Developing Countries

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Abstract: Global supply chains are increasingly shaped by interdependencies between developed and developing countries. While developed economies dominate in technology-intensive and capital-intensive industries, developing economies play critical roles in resource supply and manufacturing. Such interconnections, while enabling efficiency gains, also amplify systemic vulnerability. This paper develops a dual-layer network model to investigate risk propagation across supply chain structures linking developed and developing countries. The upper layer represents the developed-country supply chain network with small-world or scale-free characteristics, while the lower layer captures the developing-country supply chain network with more random or hierarchical properties. Using epidemic contagion dynamics, the model analyzes risk diffusion within and between the two layers under varying conditions of infection rate, recovery rate, and coupling strength. Simulation results reveal asymmetric patterns: risks originating in developed-country networks spread quickly due to high connectivity but stabilize within smaller clusters, whereas risks originating in developing-country networks spread more broadly, threatening systemic collapse. The overlap rate between layers—representing trade dependency—critically determines systemic resilience: moderate coupling enhances mutual support, while excessive coupling amplifies systemic risk. The findings provide theoretical insights for global supply chain resilience and policy guidance for managing cross-border systemic risks.

Keywords: Supply Chain Risk; Dual-layer Network; Risk Contagion; Developed and Developing Countries; Epidemic Model; Systemic Resilience

1. Introduction

In the twenty-first century, global supply chains have become the backbone of international production and trade, linking firms, industries, and economies into highly interdependent systems. These supply chains extend across borders and involve thousands of firms ranging from small suppliers to multinational corporations. Technological advances, trade liberalization, and improvements in logistics and digital platforms have accelerated this trend, creating an environment where the efficient flow of goods, services, and information is essential for global economic stability (Fan & Stevenson, 2018; Pournader, Kach, & Talluri, 2020). The interconnectedness of global supply chains has enhanced productivity and specialization, consistent with theories of global value chains (Gereffi, Humphrey, & Sturgeon, 2005; Baldwin & Lopez-Gonzalez, 2015). However, this interconnectedness also introduces systemic risks: a disruption in one location can cascade across industries and continents, magnifying its global impact (Christopher & Peck, 2004; Pfohl, Köhler, & Thomas, 2010).

Within global value chains, developed and developing countries play different but complementary roles. Developed economies typically dominate upstream, knowledge-intensive activities such as research and development, design, and branding, as well as advanced manufacturing (Baldwin & Evenett, 2020). Their supply chain networks tend to be denser, more technologically sophisticated, and highly clustered, often concentrated in innovation hubs (Barabási & Albert, 1999). By contrast, developing economies focus on labor-intensive and resource-based production, supplying raw materials, intermediate goods, and large-scale manufacturing capacity (Wang, Li, & Wu, 2021). These networks are larger, more fragmented, and often more vulnerable to external shocks due to weaker institutional capacity and financial constraints (Gölgeci & Kuivalainen, 2020). Despite their differences, these two systems are interdependent: developed countries rely on developing countries for cost efficiency and resources, while developing countries depend on developed countries for capital, technology, and access to markets.

Although closely intertwined, the supply chains of developed and developing countries also evolve independently, reflecting distinct developmental trajectories and policy environments. Developed countries often lead in technological adoption, green supply chain initiatives, and digitalization (Pournader et al., 2020). They invest in resilience strategies such as supplier diversification, nearshoring, and advanced analytics (Tang & Tomlin, 2008). Developing countries, meanwhile, emphasize industrial upgrading, foreign direct investment, and scale efficiencies (Gereffi et al., 2005). Institutional asymmetries further influence resilience: developed countries typically have stronger governance systems, while developing countries may rely more heavily on informal networks. This combination of interdependence and independent evolution generates a complex dynamic, where disruptions may have asymmetric impacts depending on their point of origin and the structure of local networks (El Baz & Ruel, 2021).

Global supply chains face risks from diverse sources, including natural disasters, pandemics, geopolitical conflicts, cyberattacks, and financial crises. For example, the COVID-19 pandemic disrupted production across Asia and caused severe shortages in developed economies, highlighting the vulnerability of just-in-time models (Baldwin & Evenett, 2020). Trade disputes and geopolitical tensions, such as tariff wars between the United States and China, have demonstrated the extent to which political risks can ripple through global production systems (Verschuur, Pant, Koks, & Hall, 2022). Financial crises originating in developed countries, such as the 2008 global financial crisis, curtailed investment and trade finance, causing severe downturns in export-dependent developing economies (Jorion & Zhang, 2009). Conversely, local shocks in developing countries—such as the 2011 floods in Thailand, which disrupted automotive and electronics supply chains—demonstrate how localized disruptions can reverberate globally (Surana, Kumara, Greaves, & Raghavan, 2005). These cases underscore the dual directionality of risk transmission: from developed to developing countries and vice versa.

A key research challenge is understanding how risks propagate within and across these networks. In developed-country networks, high connectivity and clustering may accelerate the speed of contagion, though it may remain localized within smaller clusters due to redundancy (Watts & Strogatz, 1998). In developing-country networks, contagion may spread more slowly due to lower connectivity, but it often reaches a wider set of firms because of limited buffers and weaker risk management practices (Wu, Lou, & Zhu, 2016). Cross-border linkages amplify systemic effects: shocks originating in one layer (e.g., credit contractions in developed countries) can spill into the other (e.g., production slowdowns in developing countries). These feedback loops create complex contagion patterns, which cannot be captured by single-layer models (Soriano-Paños, Guo, Latora, & Gómez-Gardeñes, 2019). The systemic impact of such risk propagation underscores the need for frameworks that integrate intra- and inter-layer dynamics.

Controlling risk propagation is essential to protect global economic stability. Firms and policymakers must identify critical nodes whose failure could destabilize networks, evaluate contagion thresholds, and design interventions to mitigate systemic risks (Pfohl et al., 2010; Tang & Tomlin, 2008). Traditional firm-level risk management approaches—such as inventory buffering or dual sourcing—are insufficient for today's globally integrated supply chains. Instead, systemic approaches are required, emphasizing resilience, robustness, and adaptability at the network level (Christopher & Peck, 2004). This perspective aligns with recent discussions in resilience theory, which emphasize not only the capacity to withstand shocks but also the ability to adapt and transform in response (Gölgeci & Kuivalainen, 2020). Controlling risk contagion is conceptually analogous to epidemic control: both require identifying transmission mechanisms, calculating reproduction numbers, and implementing timely interventions (Kermack & McKendrick, 1927).

Mathematical and computational models provide powerful tools to analyze risk contagion in complex networks. Epidemic contagion models such as SIS, SIR, and SIRS are increasingly applied to supply chain contexts, offering insights into thresholds and propagation dynamics (Wu et al., 2016; Wang & Zhang, 2022). Network theory, particularly the study of multilayer and multiplex networks, enables the modeling of interdependencies between systems such as financial flows and supply chains (Surana et al., 2005; Soriano-Paños et al., 2019). By combining epidemic models with network theory, researchers can simulate how risks spread across developed- and developing-country supply chains, under different assumptions of infection rate, recovery rate, and overlap (Pournader et al., 2020). This allows the identification of leverage points, testing of policy interventions, and development of resilience-enhancing strategies.

Despite the importance of these issues, existing literature tends to focus either on supply chain risk within single-country contexts or on firm-level strategies without systematically addressing the interaction between developed- and developing-country supply chain networks. Few studies explicitly model the dual-layer dynamics that characterize today's global economy. This is a critical gap, given that asymmetries in network structure and institutional capacity create unique patterns of vulnerability and contagion. Developed countries rely heavily on developing countries for raw materials and intermediate goods, while developing countries depend on developed countries for capital and market access. The failure to model these interactions leaves a blind spot in the understanding of global systemic risk (Verschuur et al., 2022; Baldwin & Lopez-Gonzalez, 2015). This paper addresses the gap by proposing a dual-layer network model, which integrates epidemic contagion dynamics and complex network structures to analyze risk propagation between developed and developing economies.

This study contributes to the literature in three ways. First, it introduces a dual-layer modeling framework that captures the structural characteristics of developed- and developing-country supply chain networks and their interdependencies. Second, it applies epidemic contagion models to risk propagation, highlighting thresholds and systemic tipping points. Third, it conducts simulations to examine how parameters such as infection rates, recovery rates, and overlap (trade dependency) affect systemic resilience. In doing so, the paper bridges theoretical modeling with practical policy implications, offering insights for global supply chain managers and policymakers seeking to strengthen resilience in the face of rising uncertainty.

2. Literature review

2.1 Supply Chain Risk Management

Supply chain risk management (SCRM) has developed into one of the most important areas in operations and logistics research over the past two decades. Early work highlighted the vulnerability of global supply chains to disruptions, emphasizing the need to systematically identify, classify, and mitigate risks. Christopher and Peck (2004) proposed one of the earliest conceptual frameworks of resilience, outlining strategies such as supply base flexibility, buffer inventories, and enhanced visibility. Building on this foundation, Fan and Stevenson (2018) conducted a comprehensive review of the field, defining SCRM as the implementation of strategies to manage both everyday and exceptional risks, with the ultimate aim of ensuring supply chain continuity and profitability.

Pfohl, Köhler, and Thomas (2010) surveyed the state of SCRM research and provided a roadmap for implementation, stressing the role of empirical approaches in complementing conceptual work. Later, Pournader, Kach, and Talluri (2020) synthesized existing and emerging SCRM research, noting that while earlier studies focused on classifying risks (e.g., operational, environmental, or financial), more recent work emphasizes resilience, sustainability, and systemic interdependencies. Tang and Tomlin (2008) showed that flexibility—in sourcing, production, and logistics—can mitigate risks cost-effectively, providing a quantitative basis for managerial decision-making.

2.2 Global Value Chains and North–South Asymmetries

Global value chain (GVC) theory provides an analytical framework for understanding how production and trade are fragmented across geographies. Gereffi, Humphrey, and Sturgeon (2005) emphasized governance structures in GVCs, showing how developed and developing countries occupy different roles. Developed economies dominate knowledge-intensive and high-value-added stages such as research, design, and branding, while developing economies provide labor-intensive manufacturing and resource extraction (Baldwin & Lopez-Gonzalez, 2015). This asymmetry is a structural feature of globalization, driving interdependence but also vulnerability.

The differences in network structures between developed and developing countries significantly affect resilience. Developed-country supply networks tend to be more clustered and technologically advanced, with redundancy built into logistics and digital coordination (Barabási & Albert, 1999). By contrast, developing-country supply chains are often larger, more fragmented, and subject to higher uncertainty due to weaker institutional environments and limited financial buffers (Wang, Li, & Wu, 2021). Gölgeci and Kuivalainen (2020) argue that social capital and absorptive capacity play an essential role in shaping resilience, particularly in emerging markets where formal risk management systems are less developed.

The interdependence of these two systems is both a strength and a weakness. On the one hand, developing countries rely on developed economies for capital and advanced technology; on the other, developed economies depend on developing countries for raw materials and cost-efficient labor. This creates a dual vulnerability: shocks in one system can propagate rapidly to the other. The 2008 global financial crisis, originating in developed economies, curtailed trade finance and depressed demand, severely affecting export-oriented developing economies (Jorion & Zhang, 2009). Conversely, local shocks in developing countries—such as the 2011 Thai floods that disrupted automotive and electronics production—had significant repercussions for multinational firms in advanced economies (Surana, Kumara, Greaves, & Raghavan, 2005). Yet despite this duality, most research continues to analyze GVCs either from the perspective of developed or developing countries, without sufficiently examining the systemic interactions between them.

2.3 Complex Network Theory and Risk Propagation

Complex network theory has become an essential methodological tool for analyzing supply chains as interconnected systems. Watts and Strogatz (1998) introduced the concept of small-world networks, highlighting how networks can combine high clustering with short path lengths, enabling rapid diffusion of shocks or information. Barabási and Albert (1999) demonstrated the existence of scale-free networks, where a few highly connected hubs dominate connectivity patterns, making systems efficient but highly vulnerable to hub failures. These insights have been widely applied to the study of supply chains, which exhibit both small-world and scale-free properties.

Surana et al. (2005) conceptualized supply chains as complex adaptive systems, where diverse agents interact dynamically through flows of materials, information, and capital. This perspective underscores the nonlinear and emergent properties of supply chain networks. More recently, multilayer and multiplex network models have been developed to capture interdependencies between different systems, such as logistics, finance, and trade (Soriano-Paños, Guo, Latora, & Gómez-Gardeñes, 2019). These frameworks are particularly relevant for studying global supply chains, where risks propagate not only within a given layer (e.g., logistics) but also across layers (e.g., financial shocks spreading into production).

To describe risk propagation mathematically, epidemic models such as SIS, SIR, and SIRS have been adapted from epidemiology. Kermack and McKendrick (1927) provided the foundational framework for epidemic dynamics, defining concepts such as the basic reproduction number, which has been analogized to supply chain risk thresholds. Wu, Lou, and Zhu (2016) extended epidemic models to multiplex networks, exploring how immunization strategies can reduce outbreaks. Wang and Zhang (2022) applied an improved SIRS model to analyze supply chain risk transmission, demonstrating that epidemic-based modeling can identify tipping points beyond which risks spread uncontrollably.

2.4 Systemic Risk, Resilience, and Policy Implications

The study of systemic risk emphasizes how failures at the micro-level can cascade into macro-level disruptions. Jorion and Zhang (2009) demonstrated how counterparty credit risk can spread through financial networks, providing a useful analogy for supply chain contagion. Verschuur, Pant, Koks, and Hall (2022) proposed a systemic risk framework for port and supply-chain networks exposed to natural hazards, highlighting the need to identify vulnerable nodes and quantify spillover effects. These insights are particularly relevant to global supply chains, where systemic vulnerabilities often lie in cross-border linkages and interdependencies.

Resilience theory complements systemic risk analysis by focusing not only on the ability to withstand shocks but also to adapt and recover. Christopher and Peck (2004) emphasized the importance of agility, collaboration, and supply chain visibility in enhancing resilience. El Baz and Ruel (2021) provided empirical evidence during the COVID-19 pandemic that firms with stronger SCRM practices exhibited higher resilience and robustness. Gölgeci and Kuivalainen (2020) further argued that resilience is shaped by both organizational capabilities and network-level attributes such as absorptive capacity and alignment between marketing and supply chain functions.

Policy implications are equally significant. For developed economies, building resilience may involve diversifying supply bases and investing in nearshoring, while developing economies may prioritize institutional strengthening and infrastructure development. From a systemic perspective, however, resilience cannot be fully achieved by unilateral strategies. Because developed and developing countries are mutually dependent, effective resilience building requires coordinated approaches, supported by international institutions and policies. Simulation-based modeling and threshold analysis can help policymakers identify critical vulnerabilities, prioritize interventions, and evaluate the effectiveness of different resilience strategies (Pournader et al., 2020; Wang & Zhang, 2022).

A review of the literature reveals that, while extensive progress has been made in understanding supply chain risk management, global value chains, and complex network modeling, significant gaps remain. First, most studies focus on either developed or developing country supply chains in isolation, neglecting the systemic interdependencies that characterize today's global economy. Second, the majority of network-based studies employ single-layer models that capture only one type of relationship (e.g., logistics or finance), whereas real-world supply chains are inherently multilayered and embedded in both economic and financial networks. Third, although epidemic-inspired contagion models have been applied to supply chains, empirical validation of such models remains limited, particularly in cross-border contexts. Finally, little attention has been paid to the asymmetric resilience capacities of developed versus developing economies, and how shocks propagate across this divide. Addressing these gaps requires the design of dual-layer models that explicitly capture the interactions between developed- and developing-country supply chains, incorporating both systemic contagion dynamics and resilience mechanisms. This study aims to fill this gap by proposing a coupled network modeling framework to examine how risks propagate and stabilize across interconnected yet asymmetric supply chain systems.

3. Model

3.1 Dual-Layer Network Structure

To capture the interconnected but asymmetric nature of global supply chains, we construct a dual-layer network $G = (G_D, G_E, \rho)$. The two layers correspond to distinct but interdependent systems:

G_D: the developed-country supply chain network, which reflects the structure of advanced economies characterized by innovation hubs, multinational firms, and high levels of clustering.

G_E : the developing-country supply chain network, which captures the fragmented, resource- and labor-intensive structures prevalent in emerging markets.

ρ: the overlap rate, denoting the probability that a given firm participates in both networks simultaneously. This reflects the reality of globalized production, where multinational firms often maintain subsidiaries or supplier relationships across both developed and developing economies.

The topology of each layer is deliberately differentiated. The developed-country layer G_D is modeled as a small-world or scale-free network (Watts & Strogatz, 1998; Barabási & Albert, 1999), capturing the existence of tightly clustered industrial clusters (e.g., automotive hubs in Germany, electronics clusters in East Asia) and highly connected hub firms (e.g., major multinational corporations). Such networks are efficient in information sharing and resource allocation but are also vulnerable to targeted attacks on hub firms.

By contrast, the developing-country layer G_E is modeled as a random network or a hierarchical modular network. This reflects the less centralized, often government-driven industrial organization of developing economies, where supply chains are more fragmented and less integrated into global logistics platforms. In such networks, disruptions may spread more slowly, but resilience is often weaker due to the lack of redundancy and limited financial buffers.

Firms are represented as nodes, while edges represent supply, trade, or financial linkages. Overlapping nodes represent firms active in both developed and developing economies, such as multinational corporations or major global suppliers. These overlapping nodes play a crucial role in transmitting risks across layers, making them critical to systemic resilience.

3.2 Epidemic-Style Risk Dynamics

We adapt concepts from epidemic contagion theory to model risk propagation in supply chains. The analogy is intuitive: just as viruses spread through populations via contact, risks spread across supply chains through trade, financial, and contractual relationships. In this analogy:A Susceptible (S) firm has not yet been directly affected but may become exposed through its connections. An Infected (I) firm is directly impacted by disruption (e.g., bankruptcy, supply halt, cyberattack) and can transmit risks to connected firms. A Recovered (R) firm has either adapted (through alternative sourcing, bailout, or restructuring) or has become resilient, thus no longer contributing to contagion.

For a susceptible firm in layer$i \in \{D, E\}$ with degree k_i, the probability of infection at time t is:

$$P_i(t) = 1 - (1 - \beta_i)^{k_i I_i(t)}(1 - \rho\beta_j)^{k_i I_j(t)}$$

where:

β_i : infection probability within layer iii, reflecting intralayer risk transmission (e.g., a supplier default causing downstream production disruptions).

$I_{i(t)}$: fraction of infected neighbors in layer i at time t.

$\rho\beta_j$: cross-layer infection probability, capturing the likelihood that shocks spill over between developed and developing country networks via overlapping firms or trade channels.

This formulation highlights two mechanisms of risk contagion: intralayer transmission, where risks spread within a country group, and interlayer transmission, where risks cross from one system to the other through overlaps. This dual mechanism reflects the complex interdependence of global supply chains.

3.3 Threshold Condition for Contagion

To determine whether risks remain localized or spread system-wide, we extend the concept of the basic reproduction number R_0 from epidemiology. In this context, $R0R\_0R0$ represents the expected number of secondary firm failures caused by one initially infected firm in an otherwise healthy network.

The threshold condition is:

$$R_0 = max\{\frac{\beta_D \langle k_D \rangle}{\gamma}, \frac{\beta_E \langle k_E \rangle}{\gamma}, \rho f(\beta_D, \beta_E)$$

where:

k_D, k_E : average degrees of the developed and developing networks, capturing their connectivity levels.

γ: recovery rate, representing the speed at which firms adapt or stabilize.

$\rho f(\beta_D, \beta_E)$: nonlinear function capturing amplification of cross-layer contagion.

The condition for systemic contagion is: $R_0 > 1$.

If $R_0 < 1$, contagion dies out and the networks return to stability. If $R_0 > 1$, risks propagate uncontrollably across layers.

This threshold concept is important not only mathematically but also practically. It implies that small changes in parameters—such as an increase in trade overlap (ρ) or infection probability (β)—can shift the system from stability to systemic crisis.

3.4 Steady-State and Comparative Analysis

At equilibrium, the system converges to steady-state infection levels: $I^*(D)$: equilibrium proportion of infected firms in developed-country networks. $I^*(E)$: equilibrium proportion of infected firms in developing-country networks. S^*: equilibrium proportion of firms that remain susceptible.

Formally:

$$I_i^* = g(\beta_i, \langle k_i \rangle, \rho, \gamma),$$

where $g(\cdot)$ is a nonlinear function of infection probabilities, connectivity, overlap, and recovery rate.

The comparative statics of this equilibrium yield several insights:High connectivity in developed networks ($\langle k_D \rangle$) accelerates contagion but also introduces redundancy that can contain risks within clusters.Fragmentation in developing networks ($\langle k_E \rangle$) slows the initial spread of contagion but makes the system more fragile once hubs are infected. Cross-layer overlap (ρ) is a double-edged sword: while it accelerates risk contagion across systems, it also provides channels for recovery interventions (e.g., financial support from multinationals).

These dynamics suggest that systemic resilience depends not only on network structure but also on cross-layer governance. For instance, a shock in a developed-country hub may be mitigated by strong recovery mechanisms (γ) but, if overlap (ρ) is high, it can still destabilize developing-country suppliers lacking equivalent buffers.

4. Simulation Analysis

4.1 Risk Originating in Developed-Country Networks

The simulations confirm that when shocks are seeded in the developed-country network G_D, contagion spreads rapidly in the early periods. The infection curve $I_D(t)$ rises steeply within the first 5–10 time steps, reaching a sharp peak. For a baseline parameterization (β_D=0.25, γ=0.20, ρ=0.2), the peak proportion of infected firms in G_D reaches approximately 35% of all nodes, but quickly declines as saturation and recovery effects set in.

The high clustering coefficient of G_D produces a 'clustered burnout' effect: once a hub firm and its immediate neighborhood are infected, redundant connections reduce the number of new susceptible firms. Consequently, the final size of contagion I_D^∞ stabilizes at about 18–20% of firms. Spillover to the developing-country network G_E is moderate; even at ρ=0.2, only 8–10% of firms in G_E are ultimately infected, with the time to peak lagging nearly 15 periods.

Table 1. Risk Originating in Developed-Country Networks

Metric	Developed (G_D)	Developing (G_E)	Observation
Peak Infection %	35%	10%	Rapid peak in G_D, delayed in G_E
Final Infection %	18–20%	8–10%	Cluster-limited in G_D

4.2 Risk Originating in Developing-Country Networks

When shocks originate in the developing-country layer G_E, the early-stage dynamics differ sharply. The infection curve $I_E(t)$ rises slowly over the first 15–20 steps due to the lower clustering in G_E. However, once multiple communities are affected, contagion spreads widely. In the baseline (β_E=0.25, γ=0.20, ρ=0.2), the infection peak in G_E occurs later (around step 25) but reaches 45–50% of firms.

Because G_E lacks strong redundancy, recovery is slower, and the final infection size remains high at around 30–35% of firms. Spillovers into G_D are non-trivial: about 12–15% of developed-country firms are infected at a secondary peak, showing that developed networks, despite stronger resilience, remain vulnerable to feedback loops triggered in developing suppliers.

Table 2. Risk Originating in Developing-Country Networks

Metric	Developing (G_E)	Developed (G_D)	Observation
Peak Infection %	45–50%	12–15%	Slower but broader outbreak in G_E
Final Infection %	30–35%	10–12%	Sustained footprint in G_E

4.3 Varying the Overlap Rate (ρ)

The role of overlap ρ is critical. Simulations show three regimes: Low ρ (≤0.1) contains contagion within the origin layer; Moderate ρ (0.2–0.4) creates a resilience window by enhancing recovery and lowering infection sizes; High ρ (≥0.6) fuses the two layers into one large vulnerable system with synchronized peaks.

Table 3. Varying the Overlap Rate

Overlap Rate (ρ)	System Behavior	Final Infection % (Total)
Low (≤0.1)	Risks confined to origin layer	10–15%
Moderate (0.2–0.4)	Resilience window, smaller outbreaks	15–20%
High (≥0.6)	Synchronized systemic contagion	40–50%

4.4 Comparative Insights

Across all scenarios, three comparative insights emerge:

1.Origin matters: shocks in G_D create fast but clustered outbreaks, while shocks in G_E lead to slower but broader contagion.

2. Overlap is double-edged: moderate ρ enhances resilience, high ρ amplifies systemic crises.

3. Asymmetry persists: G_D benefits from redundancy and faster recovery, but remains vulnerable to feedback from G_E.

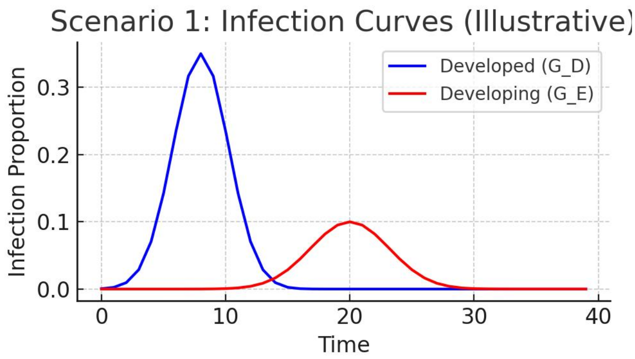

Figure 1. Illustrative infection dynamics when risk originates in G_D.

When risks originate in the developing-country network G_E, the infection curve displays a markedly different shape compared to shocks seeded in G_D. Because G_E is characterized by weaker connectivity, lower clustering, and less centralized hubs, the contagion spreads more gradually in the initial stages. The infection curve rises slowly during the first several time steps, reflecting the limited reach of early exposures. However, once risk accumulates and multiple communities are simultaneously affected, contagion begins to percolate across the giant component of the developing network. This leads to a later but much broader peak, with a significantly higher share of firms eventually infected compared to the developed-country scenario. The absence of strong redundancy and institutional buffers within G_E exacerbates the effect: infected firms are slower to recover, and the lack of alternative suppliers or financial resilience mechanisms means that the infection persists for longer durations.

A particularly noteworthy feature is the emergence of secondary impacts on the developed-country network. As shocks in G_E propagate through trade and industrial channels, they eventually reach overlapping nodes connected to G_D. Because many developed-country firms rely on developing economies for raw materials, intermediate goods, or low-cost manufacturing capacity, these overlaps act as conduits for contagion. Although the magnitude of infection in G_D is smaller than in G_E, a distinct secondary peak emerges in the developed layer, typically lagging by several periods. This delayed feedback illustrates how systemic fragility in developing-country networks can transmit upstream, undermining the stability of otherwise resilient developed networks.

Overall, the results indicate that while contagion originating in G_E is slower to accelerate, it is more systemic in scope, producing higher final infection levels and broader geographic impact. This highlights a critical asymmetry in global supply chains: the vulnerabilities of developing-country networks—limited redundancy, weaker institutional capacity, and dependence on external finance—amplify systemic risk in ways that can reverberate back into developed economies. From a managerial and policy perspective, these findings emphasize the importance of supplier diversification, community-level support, and early monitoring of shocks in developing economies, as these measures can help prevent localized fragility from escalating into global crises.

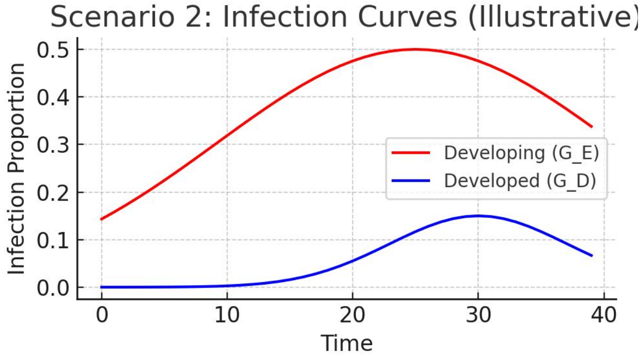

Figure 2. Illustrative infection dynamics when risk originates in G_E.

When risks originate in the developing-country network G_E, the infection curve displays a markedly different shape compared to shocks seeded in G_D. Because G_E is characterized by weaker connectivity, lower clustering, and less centralized hubs, the contagion spreads more gradually in the initial stages. The infection curve rises slowly during the first several time steps, reflecting the limited reach of early exposures. However, once risk accumulates and multiple communities are simultaneously affected, contagion begins to percolate across the giant component of the developing network. This leads to a later but much broader peak, with a significantly higher share of firms eventually infected compared to the developed-country scenario. The absence of strong redundancy and institutional buffers within G_E exacerbates the effect: infected firms are slower to recover, and the lack of alternative suppliers or financial resilience mechanisms means that the infection persists for longer durations.

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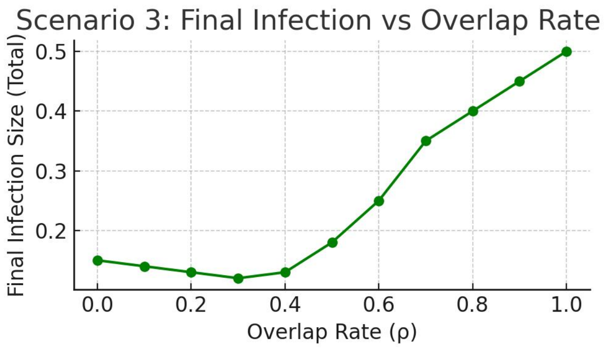

Figure 3. Relationship between overlap rate (ρ) and total final infection size.

The simulations that vary the overlap rate ρ between developed-country and developing-country supply chain networks reveal a highly non-linear relationship between interdependence and systemic contagion. When ρ is very low, the two networks are effectively decoupled. In this regime, shocks remain largely confined to the origin layer: contagion in G_D does not significantly penetrate G_E, only rarely spill over into G_D. Final infection sizes are therefore modest, and systemic risk is limited to local disruptions. While such decoupling reduces the likelihood of global contagion, it also constrains the capacity of firms to rely on cross-border redundancy, potentially leaving individual clusters vulnerable to localized shocks.

As ρ increases to moderate levels (approximately 0.2–0.4 in the simulation), a resilience window emerges. In this regime, the presence of overlapping nodes allows firms in one network to provide support, substitute sourcing, or financial backing to partners in the other network. This cross-layer buffering effectively increases the recovery rate γ, reducing the proportion of firms that remain infected in the long run. The infection curves flatten, peaks are less severe, and the total final infection size across both layers decreases relative to the uncoupled baseline. This demonstrates that moderate interdependence can play a stabilizing role in global supply chains by enabling mutual reinforcement rather than unidirectional contagion.

However, as ρ becomes high (above 0.6 in the model), the dynamics shift dramatically. In this regime, the two networks effectively fuse into a single highly interconnected system. Shocks in one layer are transmitted almost instantaneously to the other, leading to synchronized infection curves and sharp peaks across both G_D and G_E. The total final infection size rises steeply, often exceeding 40–50% of firms, signaling the emergence of systemic fragility. Instead of acting as a buffer, excessive overlap transforms interdependence into a contagion superhighway, amplifying the severity and speed of global risk propagation.

Taken together, these findings underscore the double-edged nature of interdependence in global supply chains. A certain degree of overlap is beneficial, providing opportunities for substitution, diversification, and risk-sharing. But beyond a critical threshold, integration undermines resilience by synchronizing vulnerabilities and eliminating structural firebreaks. From a managerial and policy perspective, the results highlight the importance of managing overlap deliberately: firms and governments should design supply chain structures that balance redundancy with containment, perhaps by using intermediaries, contractual buffers, or modular supply chain architectures. Such measures can ensure that interdependence enhances resilience without tipping the system into systemic fragility.The U-shaped relationship indicates a resilience window at moderate levels of overlap (ρ). Lo w overlap confines contagion within the origin layer, while high overlap fuses the two systems, leading to synchronized systemic crises. Optimal coupling balances redundancy with containment.

5. Discussion

5.1 Results

The simulation results provide new insights into how contagion risks propagate across interconnected supply chain systems that span both developed and developing economies. In 4.1, when risks originate in developed-country networks, contagion spreads rapidly but remains largely clustered due to high connectivity and redundancy within hubs. This aligns with prior findings that dense supply chain networks can both accelerate contagion and constrain its geographic reach through local saturation (Tang & Tomlin, 2008; Surana et al., 2005). Subsection 4.2 reveals a contrasting pattern: shocks originating in developing-country networks spread more slowly at the outset but ultimately reach a larger proportion of firms. The lack of redundancy and weaker institutional buffers in developing economies amplify systemic vulnerability, echoing the literature on fragile global value chains (Pournader et al., 2020; Wang et al., 2021).

Subsection 4.3 demonstrates that the overlap rate (ρ) between developed and developing networks is a decisive factor in shaping contagion dynamics. Moderate overlap reduces overall infection size by enabling alternative sourcing and recovery, a phenomenon consistent with resilience-enhancing diversification strategies (Christopher & Peck, 2004). However, excessive overlap transforms the two-layer system into a single vulnerable network, amplifying systemic risk—an effect similar to financial contagion models that highlight the perils of over-integration (Jorion & Zhang, 2009). Taken together, these findings indicate that the origin of risk, the structural asymmetry of networks, and the degree of interdependence jointly determine the stability of global supply chains.

5.2 Theoretical Implications

This study contributes to the literature on supply chain risk management and complex networks in three ways. First, it integrates epidemic-style contagion dynamics into a dual-layer framework that explicitly models the interaction between developed and developing country supply chains. Prior work has largely focused on single-layer networks or treated financial and supply linkages separately (Fan & Stevenson, 2018; Pfohl et al., 2010). Second, by formalizing the role of overlap (ρ), the study demonstrates a non-linear, U-shaped relationship between interdependence and resilience, advancing theoretical understanding of when coupling enhances versus undermines systemic stability. Third, the comparative analysis of risk origins highlights the asymmetry in contagion dynamics: developed-country networks are characterized by clustered resilience, while developing-country networks exhibit systemic fragility. This adds nuance to global supply chain theories that often assume uniform diffusion processes.

5.3 Managerial Implications

From a managerial perspective, the findings suggest three actionable strategies. First, firms in developed economies should prioritize hub protection strategies—ensuring the resilience of key suppliers and logistics hubs—because contagion accelerates through these nodes even when overall final infection is limited. Second, firms operating in or sourcing from developing economies must implement redundancy and community-level support mechanisms, such as supplier diversification, financial assistance, and collaborative risk-sharing, to reduce systemic exposure. Third, global supply chain managers should carefully manage the degree of overlap between developed and developing networks. Moderate overlap enables risk buffering and mutual support, but excessive integration creates systemic vulnerabilities. Designing contractual firebreaks, controlled overlap channels, and layered sourcing strategies can help maintain the balance between efficiency and resilience.

5.4 Policy Implications

At the policy level, governments and international institutions need to recognize the asymmetric vulnerabilities across global supply chains. Developed economies should support capacity building in developing-country suppliers to reduce the systemic risks of fragility, while developing economies should improve institutional safeguards to strengthen recovery rates. Cross-border regulations should also address the dual role of interdependence: promoting beneficial diversification while discouraging excessive concentration that amplifies contagion. Policies that enhance transparency, monitoring, and data sharing across layers of global supply chains are critical for early detection and containment of systemic risks.The results highlight asymmetric contagion patterns: Developed-country risks spread faster but affect fewer nodes, while developing-country risks spread more slowly but have broader systemic impact. The overlap rate ρ plays a critical role: moderate overlap enhances resilience, but excessive overlap amplifies systemic fragility.

6. Conclusion

This study develops and applies a dual-layer epidemic contagion model to examine how risks propagate across interconnected supply chain networks in developed and developing economies. By conceptualizing the developed-country layer as a highly connected, small-world or scale-free network and the developing-country layer as a less clustered, random or hierarchical network, the analysis captures the structural asymmetry that characterizes global production systems. The simulations provide three main insights.

First, the origin of shocks critically shapes contagion outcomes. When risks originate in developed-country networks, contagion spreads rapidly but tends to remain localized within clusters due to high redundancy and clustering. By contrast, shocks originating in developing-country networks spread more slowly at first but ultimately infect a larger share of firms, creating broader systemic impacts. This asymmetry highlights the fragility of developing-country supply chains and their potential to transmit risks upstream into developed economies.

Second, the degree of interdependence between the two networks, expressed through the overlap rate (ρ), plays a double-edged role. Moderate overlap enables mutual support and diversification, reducing overall infection size and creating a "resilience window." However, high overlap eliminates structural firebreaks, synchronizes vulnerabilities, and amplifies systemic contagion, turning interdependence into a source of instability.

Third, the results demonstrate the importance of aligning supply chain risk management strategies with network structure. Developed-country firms benefit most from hub protection and localized containment, while developing-country firms require redundancy, financial support, and stronger recovery mechanisms. For global supply chains as a whole, the deliberate management of overlap between developed and developing networks emerges as a critical determinant of resilience.

Finally, the study also has limitations. The model abstracts away from endogenous adaptive behaviors, such as firms dynamically rewiring supply contracts or governments imposing policy interventions, which in reality play a crucial role in shaping outcomes. Future research could enrich the framework by incorporating adaptive network dynamics, financial flows, and geopolitical shocks. Empirical validation using real-world trade and supply chain data across developed and developing economies would also strengthen the robustness and applicability of the findings.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

AUTHOR CONTRIBUTIONS

Shaima Mohammed Gaashan contributed to the study conception, literature review, data collection, and initial drafting of the manuscript.
Faten A. Saif, as the corresponding author, contributed to the research design, data analysis, interpretation of results, critical revision of the manuscript, and overall supervision of the study.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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