

From Maritime Disruption to Firm-Level Resilience: Risk Transmission Mechanisms in Supply Chains

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Abstract:

Global production and trade are structurally dependent on maritime transport, while geopolitical conflict, extreme weather, port congestion, and restrictions at major chokepoints have increased uncertainty in transport services. Maritime route disruptions are initially reflected in rerouting, schedule revisions, changes in port calls, and higher transport costs. Their impacts enter firm-level supply chains when these transport changes create procurement fulfilment deviations that interfere with purchasing and production plans. This study applies integrative literature analysis and inductive reasoning to explain how risks are transmitted from the maritime network to firm operations. The analysis distinguishes between disruption that remains locally contained and disruption that develops into a wider ripple effect. It then examines resilience through four interrelated capabilities: visibility, redundancy, flexibility, and collaboration. The synthesis suggests that maritime disruption does not necessarily produce an interruption in production or delivery. Subsequent transmission depends on disruption duration, the concentration of suppliers and transport routes, inventory coverage, the feasibility of alternatives, and spare capacity in the external transport network. On this basis, the study develops a risk-oriented ABC classification, dependency mapping, supply chain digital twin, differentiated redundancy, and trigger-based coordination as managerial responses to maritime disruption.

Keywords: Maritime Disruption; Risk Transmission; Supply Chain Resilience; Ripple Effect; Digital Twin

1. Introduction

1.1 Research Background and Problem Statement

Maritime transport links raw-material locations, manufacturing centers, distribution nodes, and consumer markets, making it a core infrastructure of global supply chains. For firms that rely on imported inputs and cross-border component sourcing, changes in maritime services can extend procurement lead times and require adjustments to inventory, production schedules, and delivery performance.

Many firms have adopted JIT-oriented practices to reduce routine operating costs, including centralized procurement, lean inventories, and fixed transport schedules. Such arrangements improve operational efficiency under normal circumstances, yet reduce firms' capacity to absorb unforeseen disturbances. Christopher and Peck argued that supply chain design should balance efficiency with resilience rather than being assessed solely by cost and speed [1].

Recent events, including security risks in the Red Sea and drought-related restrictions at the Panama Canal, have highlighted persistent instability in maritime transport. UNCTAD identifies longer voyages, vessel rerouting, freight-rate volatility, and port disruption as continuing pressures on supply chains [2]. Research on port criticality further shows that highly connected ports may be systemically important even when they are not the largest by volume, so their disruption can affect supply across several sectors [3].

A physical route disruption is not equivalent to an immediate interruption of production. Shipping lines and ports first revise routes, vessel deployment, port calls, and capacity allocation. Firms subsequently confront variations in schedule reliability, arrival time, and transport cost. The disturbance reaches production and delivery only when these service changes exceed the buffering capacity provided by inventory and operational adjustments. Therefore, this study focuses on how maritime disruption is transmitted into the firm-level supply chain and why similar transport disturbances produce different consequences across firms.

1.2 Literature Review and Research Gap

Research on maritime supply chain resilience has concentrated on resilience assessment, risk identification, network structure, and management strategies. The bibliometric review by Li et al. shows that existing research remains dominated by themes at the network and systemic levels [4]. The way that these system-level findings translate into firm-level procurement, inventory, and produc-

tion decisions has received less attention.

Li et al. review maritime disruption management in terms of disruption categories, impacts, and response strategies [5]. Their synthesis covers operational challenges and broader economic and social impacts. This kind of classification provides an overview of the field, but it does not clearly distinguish procurement fulfilment deviation, inventory pressure, and production adjustment as separate stages of firm-level risk transmission.

Dynamic network research provides a further explanation of how disruption develops. Qu et al. show that as product and transport flows adjust, the effects of maritime-network blockage change over time and spread unevenly and nonlinearly across countries and sectors [6]. Although this work captures the dynamic nature of disruption at the network level, the connection between changes in port and liner operations and their subsequent effects on firm-level procurement and production remains insufficiently explained.

Existing research has identified systemic exposure at critical ports and chokepoints, examined liner-network adjustment after disruption, and discussed the buffering role of inventory and alternative sourcing. Nevertheless, these findings remain fragmented across maritime-network research, port operations research, and supply chain resilience literature. As a result, the process through which changes in transport services are translated into procurement fulfilment deviations, inventory pressure, and production adjustment has not been explained from an integrated perspective.

In addition, transport delay, inventory shortage, production interruption, and delivery failure are sometimes presented as a continuous sequence in some studies. In practice, transport disturbance does not necessarily evolve into a production or delivery failure. Some small deviations can be absorbed within logistics and procurement through inventory, planning slack, and alternative resources. Propagation occurs only after these buffers become insufficient.

1.3 Research Objective and Method

This study treats procurement fulfilment deviation as the initial point through which external maritime risk enters the firm. It analyses how this deviation may spread to inventory, production, and delivery, distinguishes localized containment from the ripple effect, and identifies the principal conditions associated with movement between the two states. The study also examines how supply chain resilience capabilities intervene in the transmission process and offers targeted practical strategies to strengthen supply chain resilience.

The study adopts an integrative literature analysis and an inductive reasoning approach. Representative research on maritime disruption, shipping networks, supply chain

ripple effects, and digital resilience is compared in terms of its level of analysis, transmission mechanism, and disruption-containment conditions. The synthesis is used to develop an explanatory account of how maritime route disruption enters firm-level supply chains.

1.4 Innovation points

The main innovation of this study lies in connecting maritime-network disruption with its subsequent consequences at the firm level through an integrated transmission framework. Rather than treating transport disruption and production interruption as a continuous process, the study identifies procurement fulfilment deviation as the point at which changes in maritime services begin to interfere with firm operations. This distinction helps explain why similar transport disturbances can produce different outcomes: some can be contained within procurement and logistics, while others may propagate into production, delivery, and eventually a wider ripple effect. By clarifying how disruption enters and propagates within the firm, the framework further provides a basis for examining how visibility, redundancy, flexibility, and collaboration can intervene in the transmission process and support targeted managerial responses. The study develops a firm-level explanatory framework that links the entry of maritime risk, the conditions governing its propagation, and resilience interventions aimed at containing its operational consequences.

2. Maritime Disruption and Initial Transmission to Firm-Level Operations

2.1 Disruption Typologies and Risk Characteristics

Maritime route disruptions differ in how they alter transport services. Geopolitical conflict and navigation security threats may force carriers to reroute with little certainty about how long the disruption will last. Capacity restrictions caused by drought or canal controls are more observable and predictable and develop more gradually. Port congestion or equipment failure may begin within a single operational area. Their initial impact may be local, yet the close links among cargo handling, yard operations, transshipment, and inland transport can cause the disturbance to spread beyond the original node.

The geographical scope of disruption also changes the firm's alternative options. A local port failure may be mitigated via alternative ports or a revised inland transport arrangement. Disruption at a major maritime chokepoint can affect multiple shipping routes simultaneously and trigger capacity reallocation across wide areas. Verschuur et al. show that the consequences of chokepoint disruption

depend jointly on trade dependence, rerouting feasibility, and disruption duration [7].

The purpose of distinguishing among disruption types is to identify how different events change transport conditions. Event persistence, the number of affected nodes, and residual capacity on alternative routes provide important external conditions for subsequent transmission.

2.2 Procurement Fulfilment Deviation as the Firm-Level Entry Point

A maritime route disruption does not act directly on production. When a route, canal, or port becomes abnormal, carriers and logistics service providers normally revise routing, vessel deployment, and port calls to maintain transport services. Yap and Yang showed that the Red Sea crisis changed liner-service and port-call structures [8].

Following transport adjustment, firms experience changes in timeliness, fulfilment reliability, and service availability. Rerouting and port substitution extend the actual transport cycle and cause arrival dates to deviate from procurement plans. Schedule revisions, skipped calls, and altered transshipment sequences reduce delivery stability. A fixed and predictable delay may be incorporated into planning, whereas repeated revisions to the estimated time of arrival are more difficult to accommodate within inventory and production schedules. Longer voyages and capacity reallocation may also reduce available vessel space and increase freight, insurance, and transshipment costs.

Firm-level operational disruptions arise when transport variations disrupt established procurement arrangements. A procurement fulfilment deviation occurs when actual delivery conditions, including arrival time, quantity, cost, or reliability, no longer correspond to the firm's purchasing and production plans.

Procurement fulfilment deviations are not merely equivalent to transport delays. Transport delay describes the status of cargo movement. Procurement fulfilment deviation indicates that changes in transport conditions are beginning to interfere with the firm's purchasing and operating plan. It represents the point at which external maritime risk enters firm-level operations.

The magnitude of the deviation can vary among firms exposed to the same maritime event. Firms with bookings, long-term carrier agreements, or longer procurement cycles may experience a smaller immediate effect. Firms that depend on fixed weekly services, a single port, or just-in-time replenishment are more likely to experience significant deviation. As shown in Figure 1, procurement fulfilment deviation represents the point at which maritime disruption enters firm-level operations and may either be locally contained or propagate through inventory, production, and delivery.

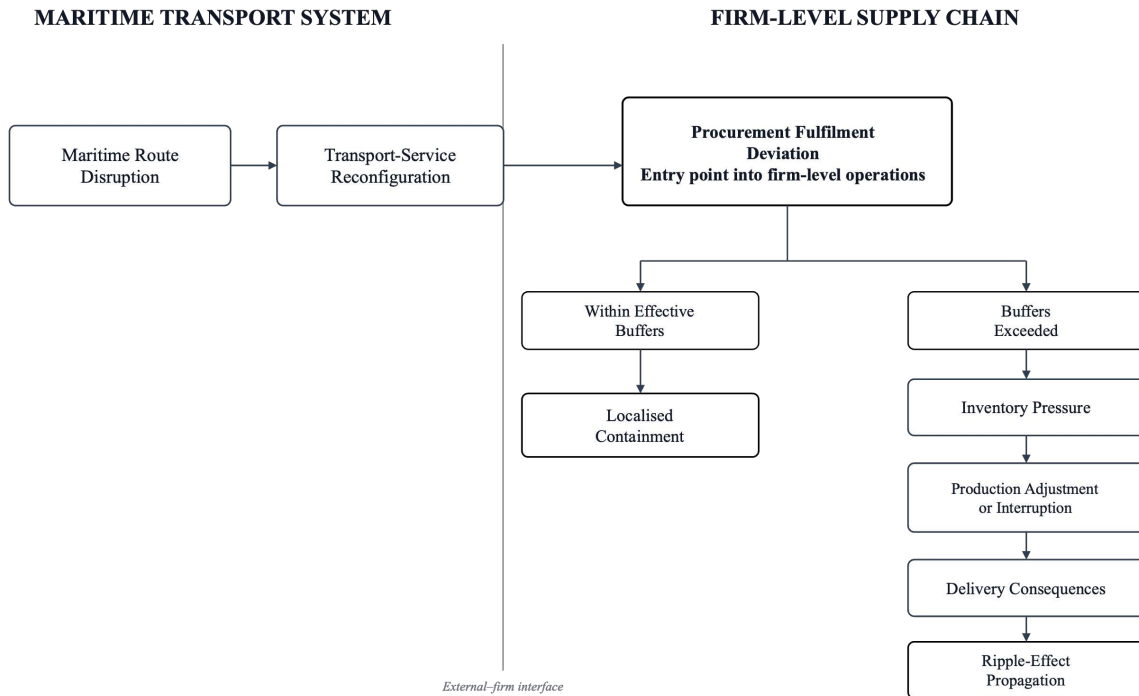


Fig. 1 Conceptual framework of maritime disruption transmission and ripple-effect propagation

3. Risk Transmission Mechanisms and the Role of Supply Chain Resilience

3.1 Internal Transmission to Inventory, Production, and Delivery

A procurement fulfilment deviation does not immediately result in production interruption. Firms typically draw on on-hand inventory and unaffected in-transit materials to bridge the supply gap between scheduled and actual arrivals. Continued transmission depends on the relationship between the persistence of the deviation and the buffers available to the firm.

When the inventory of a critical material covers the delay, production can continue. The firm may incur higher transport expenditure, inventory carrying costs, and managerial workload, but the main consequences remain within procurement and logistics.

As the delay persists, inventory coverage declines gradually. The firm may need to use alternative suppliers, substitute materials, or emergency transport. If these measures become effective before critical inventory is depleted, the disturbance can remain confined. If alternatives are restricted by cost, technology, or capacity, procurement deviation then becomes an inventory shortage and a production-scheduling problem.

Firms may prioritize the production of products for which materials are available or which make a larger contribu-

tion to revenue. By contrast, orders that depend heavily on the missing input may be postponed. Continued shortage may reduce output, suspend part of a production line, and eventually cause order delays, contractual penalties, and reduced customer service.

3.2 Localized Containment and Its Boundaries

Localized containment describes a situation in which an initial disruption has created additional cost or operational deviation, but its effects remain within the original node or a limited number of activities. The concept is consistent with ripple-effect research, in which supplier disruption propagates downstream when it cannot be localized [9].

In a maritime context, localized containment does not mean an absence of loss. The firm still needs to pay higher freight rates, carry additional inventory costs, and devote more managerial time to the event while core production and major customer deliveries remain materially unaffected. The central issue is whether sufficient time and resources are available to complete the adjustment before the transport deviation crosses the production boundary.

Buffers operate along temporal (inventory coverage, delivery windows), structural (alternative suppliers, ports, routes), and decisional (timely risk information, cross-functional coordination) dimensions. These buffers are neither independent nor unlimited. Safety stock declines as disruption persists. A potential alternative supplier may depend on the same port and shipping corridor

as the original supplier. Early warning can extend the decision period, but cannot create additional vessel space or terminal capacity that is unavailable in the market.

Localized containment is therefore a conditional state rather than an automatic consequence of holding inventory or identifying an alternative supplier. Its effectiveness depends on disruption duration, the risk independence of buffer resources, the speed with which alternatives can be activated, and the availability of external market capacity.

3.3 Ripple Effect Propagation and Network Amplification

A ripple effect begins when transport disturbance exceeds internal buffers and subsequently affects production, delivery, or additional supply chain nodes. It is not simply an outcome of longer transport delay. It results from the interaction of external disruption, firm structure, and network capacity.

Disruption duration is an important determinant of propagation. A short delay may be absorbed by inventory, whereas prolonged rerouting and repeated schedule changes progressively consume temporal buffers. High concentration among suppliers, ports, and routes also reduces the number of alternatives available to the firm. Even if firms set up a second supplier, both suppliers may be affected by the same port, route, or regional disruption. The capacity and capability of alternatives further affect containment. A substitute port may lack sufficient handling, yard, or inland capacity. Product characteristics, cost, and market capacity restrict rail and air transport. If many firms move towards the same alternative node, the resource that was expected to absorb the disturbance may itself become saturated, triggering secondary transport disruptions.

Using a system dynamics model, Zhang et al. show that disruption in one part of a multimodal terminal can propagate through operational dependencies among terminal subsystems, producing delay and cargo accumulation [10]. For firms, operational problems may already have developed within port and intermodal activities before their effects are reflected in procurement and delivery.

Similar responses by multiple firms can place further pressure on the transport network. When firms bring purchases forward or compete for limited vessel space at the same time, demand surges over a short period. The resulting shift towards alternative routes and ports may overload the capacity intended to absorb the original disruption, creating secondary transport disruptions. This situation may ultimately produce wider network spillovers.

3.4 The Intervening Role of Supply Chain Resilience Capabilities

Ponomarov and Holcomb define supply chain resilience as an adaptive capability that enables a supply chain to

prepare for unexpected events, respond to disruptions, and recover to an original or improved state [11]. This conceptualization frames supply chain resilience as a continuous process covering preparation, response and recovery phases, instead of merely equating resilience with the speed of restoring regular operations.

Lau et al. observed that maritime transport resilience research covers ports, shipping firms, freight systems, and transport networks [12]. At the firm level, visibility, redundancy, flexibility, and collaboration should not be treated as separate resources. Together, they influence whether disruption can be contained.

3.4.1 Visibility and risk recognition

Following a route disruption, firms are often unable to determine when cargo will arrive or whether available inventory can cover the delay. Visibility reduces the interval between risk recognition and managerial decision by connecting supplier dispatch, in-transit movement, port conditions, estimated arrival, and inventory information. Its value depends on whether information is timely, accurate, and linked to procurement and production data. Vessel location alone cannot capture delays arising from port waiting, transshipment, or inland transport. Visibility provides a basis for decision-making but does not directly create inventory, capacity, or alternative supply.

3.4.2 The buffering role of redundancy

Redundancy provides time and resources for absorbing short-term procurement fulfilment deviations through safety stock, alternative suppliers, and emergency production capacity. Thus, it can delay the transmission of disruption into production.

Its effectiveness depends not only on resource quantity but also on coverage duration and risk independence. Several suppliers provide limited protection when they rely on the same port or route. Redundancy also increases inventory and resource-maintenance costs, so it is critical to make a differentiated configuration according to material criticality, substitution difficulty, and potential production loss.

3.4.3 Flexibility and adaptive operational adjustment

Flexibility is the ability to adjust suppliers, ports, routes, transport modes, materials, and production arrangements in response to disruption. It also allows the firm to modify its operating path as redundant resources decline rather than wait for the original transport service to recover.

Flexibility should not be measured by the number of alternatives. Alternative suppliers may require qualification, backup ports may lack customs or inland connections, and production resequencing may be constrained by equipment and product requirements. Effective flexibility requires prior verification of activation time, cost, and implementation conditions.

3.4.4 Collaboration and cross-organizational coordina-

tion

Firms can adjust their inventories and production plans, but cannot independently control supplier delivery, liner capacity, or port capability. When internal buffers are insufficient, coordination with suppliers, freight forwarders, carriers, and customers becomes necessary.

Effective collaboration depends less on communication frequency than on the exchange of decision-relevant information and the clarification of responsibility and cost allocation. Information sharing may focus on expected arrival, critical material gaps, available capacity, and order priority. Collaboration supports both early risk assessment and the timely implementation of alternative arrangements.

3.4.5 Synergistic operation of resilience capabilities

The four resilience capabilities do not constitute a strictly linear sequence. They form an interdependent system of intervention. Their effectiveness depends on whether these capabilities are connected around the same disruption state and whether the firm can move from risk recognition and shock absorption to operational adjustment and external coordination before internal buffers are exhausted. The quality of this connection ultimately influences whether procurement fulfilment deviation remains within logistics and procurement or propagates into production, delivery, and additional supply chain nodes.

4. Managerial Implications and Resilience Strategies

The following strategies correspond to the main points of intervention identified in the transmission mechanism:

exposure concentration, buffer availability, information delay, alternative activation, and cross-organizational coordination.

4.1 Risk-Oriented Material Classification and Dependency Mapping

Traditional ABC classification relies mainly on purchasing expenditure or annual usage value. This approach may underestimate the value of inexpensive components with limited substitutability and a substantial effect on production continuity. In the context of maritime route disruption, classification should also consider production criticality, substitution difficulty, total replenishment lead time, and the concentration of supply and transport routes. Class A, B, and C materials differ in production criticality, substitutability, and replenishment conditions, as summarized in Table 1.

Material classification should be combined with supply chain dependency identification. Firms need to examine the practical relationships among materials, suppliers, loading ports, shipping routes, discharge ports, and production lines to determine whether different supply chains overlap at critical nodes. Supplier numbers alone do not demonstrate genuine diversification, because several suppliers may rely on the same port, corridor, or discharge node.

ABC classification identifies the consequences of material shortage, while dependency identification assesses whether several materials may be affected by the same disruption. Together, they reveal supply structures that appear diversified but remain operationally concentrated and provide the basis for subsequent resource allocation.

Table 1. Risk-Oriented Material Classification Framework

Class	Classification basis	Required dependency assessment
A	High production criticality, low substitutability, or long replenishment lead time	Detailed mapping of suppliers, loading ports, shipping routes, and discharge ports
B	Moderate operational impact and partial substitutability	Review of shared ports, routes, and major transport bottlenecks
C	Limited immediate production impact and broad market availability	Periodic monitoring of market-wide shortages and route concentration

4.2 Differentiated Allocation of Resilience Resources

Following material classification and dependency identification, firms should allocate inventory, sourcing, and transport resources according to risk level rather than applying the same buffering standard to all materials. Class A items may justify targeted safety stock and pre-validated alternative sourcing, port, and emergency

transport arrangements. Class B items can rely on flexible replenishment and production adjustment to limit inventory cost. Class C items may remain under lean inventory control, supported by periodic review of broader market conditions.

Alternative arrangements have operational value only after prior verification. Firms need to assess transit time, available capacity, port and customs conditions, product

restrictions, and activation cost. A sea-to-air option may be appropriate for high-value, low-weight materials with substantial production-stoppage costs. Large-volume materials may be divided across shipments or ports to reduce the likelihood of simultaneous delay.

4.3 Supply Chain Digital Twin for Visibility and Scenario-Based Decisions

The main difficulty is not merely a lack of data. Data are distributed across suppliers, carriers, ports, freight forwarders, and internal enterprise systems. These data differ in format, update cycle, and definition. Surucu-Balci et al. found that blockchain- and cloud-based platforms can improve information processing and sharing, although implementation remains constrained by technical compatibility, data governance, and stakeholder-related barriers [13]. The practical task is therefore to connect dispersed data to specific materials, orders, and production requirements.

A supply chain digital twin can build this connection. It links purchase orders and inventory records with transport information such as AIS positions, port congestion, and liner schedules. Ivanov's framework presents a supply chain digital twin as a socio-technical system rather than merely a visual interface [14]. In a maritime disruption, the model can be used to assess arrival times, estimate inventory coverage, and identify which delayed orders are most likely to affect production. Its value becomes clearer when managers need to compare feasible responses. Potential trade-offs may exist between different operational practices, and digital twin technology can clarify these trade-offs and support the identification of preferable solutions.

The supply chain digital twin still faces practical limitations. Le and Fan note that data integration, model maintenance, interoperability, and organizational acceptance remain practical challenges [15]. A digital model cannot remove the physical limits of vessel space, terminal capacity, or qualified supply. The model should therefore support managerial judgement rather than replace it.

Developing a sophisticated supply chain digital twin system requires substantial time and resources. Firms can first standardize material and order identifiers, align inventory definitions, and improve estimated-arrival data for critical materials and high-risk routes. With improvements in data quality and model accuracy, supply chain digital twins can be deployed for broader risk visibility development and operational decision-making.

4.4 Trigger-Based Coordination Mechanisms

Firms should establish a response mechanism that is not based on a single fixed delay threshold, but instead considers several factors, including expected delay, inventory coverage, material criticality, and risks to production and delivery. As long as the expected delay can still be

absorbed by existing buffers, the firm can continue monitoring transport conditions and updating relevant data without activating costly alternatives. Once the available buffers are no longer sufficient, procurement, logistics, and production should coordinate their actions and adjust sourcing, transport, or production arrangements. When the response extends beyond the firm, coordination should be based on clear information and clearly assigned responsibilities to prevent inconsistent messages and competition for resources from further amplifying the disruption. The purpose of this mechanism is not to activate every response as early as possible, but to prevent further risk transmission and amplification while keeping response costs within a reasonable range.

4.5 Post-Event Learning and Parameter Updating

After a disruption, firms should compare early warnings with realized outcomes. Relevant evidence includes arrival-time error, actual inventory coverage, activation time for alternatives, additional cost, production loss, and delivery variation.

The results should inform ABC classifications, inventory parameters, supplier assessment, and digital-twin assumptions. The mechanisms of disruption are not identical across events. Post-event learning should improve the ability to distinguish among risk types, identify transmission boundaries, and adjust resource allocation, rather than create a single permanent contingency plan.

5. Conclusion

The effects of maritime route disruption do not move directly from a blocked route to the production line. Disruption first alters transport conditions, creating procurement fulfilment deviations. Whether these deviations propagate into inventory, production, and delivery depends on the adequacy of the firm's buffers and adjustment capabilities. When inventory, planning slack, alternative supply, and decision speed are sufficient, the main consequences remain within procurement and logistics, and the disturbance is locally contained. When disruption persists beyond internal buffers, alternatives lack risk independence, and residual capacity in the external transport network is insufficient, the disturbance enters production and delivery and may develop into a ripple effect.

Visibility, redundancy, flexibility, and collaboration jointly shape transmission outcomes. Visibility creates decision time, redundancy provides absorption capacity, flexibility supports operational adjustment, and collaboration extends the resources available beyond the firm. Supply chain resilience should therefore not be equated with a general increase in inventory. It requires differentiated allocation of four supply chain resilience capabilities based

on material criticality, dependency structure, and the state of disruption transmission.

In practice, firms should first use risk-oriented ABC classification to identify materials that are both critical to production and exposed to shared suppliers, ports, or routes, which helps them develop tailored inventory policies instead of applying the same buffer to every item. As disruption conditions change, a supply chain digital twin can help managers assess current risks and compare feasible responses. As available buffers decline, a trigger-based mechanism can guide the shift from monitoring to internal adjustment or cross-organizational coordination.

Although the framework clarifies how maritime disruption enters and propagates through firm-level supply chains, it remains conceptual and has not been validated with firm-level operational data. This limits the ability to quantify how disruption conditions interact with available buffers and to identify the boundary between localized containment and wider ripple-effect propagation. The applicability of the framework across different industries and supply structures also requires further examination, as firms may differ in their dependence on maritime transport and their capacity to absorb disruption. Future research could integrate firm-level order, inventory, production, and delivery data with AIS, port-congestion, and transport-service information to validate and refine the framework. This empirical validation would also make it possible to quantify the transmission boundary between localized containment and ripple-effect propagation, examine how this boundary shifts under different disruption conditions, and assess how resilience interventions may influence further risk propagation.

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