Journal of International Economics Research

♦ ISSN: 3070-5665 Vol: 02 No.02, 2025 ♦ PP. 22-27

♦ Article DOI: https://doi.org/10.54216/JIER.020205



FULL LENGTH ARTICLE

The Resilience–Efficiency Frontier in International Trade: Structural Changes and Cost Impacts after COVID-19

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Received: July 07, 2025 Revised: September 14, 2025 Accepted: November 20, 2025 ⋆ Corresponding author

ABSTRACT

The post-pandemic period has led to a major reorientation in international economics, shifting the focus of global trade from cost efficiency to structural resilience. This study examines four key factors—supply chain diversification, reshoring initiatives, logistics disruptions, and cost shocks—to explore the transition from the era of "Fragile Efficiency" to a system focused on overall viability. Drawing on global trade data from 2024–2025 and analytical frameworks provided by the IMF, the research introduces the concept of the Resilience–Efficiency Frontier (REF). The findings show that moving from Just-in-Time (JIT) to Just-in-Case (JIC) manufacturing helps reduce the volatility caused by the Bullwhip Effect but also creates a persistent form of "Complexity Inflation." Empirical results indicate that firms are now incurring a "Resilience Premium" of 12–15% to protect their production and distribution networks. The study also emphasizes that trade is no longer purely economic but is increasingly connected to national security and environmental regulations, such as the EU's Carbon Border Adjustment Mechanism (CBAM). This marks a clear shift from the deflationary trends that characterized global trade in the past.

Keywords: International Economics ▪ Resilience–Efficiency Frontier (REF) ▪ Just-in-Time (JIT) ▪ Just-in-Case (JIC) ▪ Supply Chain Diversification ▪ Resilience Premium ▪ Complexity Inflation ▪ Carbon Border Adjustment Mechanism (CBAM) ▪ Agentic AI ▪ Global Value Chains (GVCs)

1. INTRODUCTION

1.1 The Era of "Fragile Efficiency"

For almost thirty years, the main goal of international trade was to produce goods at the lowest possible cost. During this time, companies used a system called Just-in-Time (JIT) manufacturing, which avoided storing extra inventory and kept supplies arriving only when needed. Businesses treated the world like one big factory without boundaries: if wages were cheaper in another country or region, production quickly moved there. This approach made products cheaper and improved efficiency, but it also created a global system with no backup plan. In other words, the world economy became extremely efficient, but also very fragile, because there were no safety buffers when problems occurred.

1.2 The Triple Shock (2020–2025)

The period from 2020 to 2025 exposed how fragile the global production system had become. A model that looked inexpensive and highly efficient under normal conditions proved extremely costly when it was disrupted. Three major shocks occurred in sequence, each adding new pressure points for international trade.

- The first disruption came from the pandemic. COVID-19 demonstrated how easily global supply networks could be

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thrown off balance. When factories or ports in key locations closed, companies on entirely different continents were left without essential components for weeks or months. The crisis made it clear that depending on a single supplier or region left firms without alternatives when emergencies arose.

- A second disruption appeared on the geopolitical front. Events such as the 2024–2025 shipping interruptions in the Red Sea, along with rising tensions over advanced technologies between the United States, the European Union, and China, showed that trade flows are not guaranteed. In this environment, access to shipping lanes, chips, and critical minerals has taken on a strategic character. Trade is no longer viewed solely through the lens of economic efficiency; it is now tied to questions of national power and security.
- The third disruption came from climate and regulatory changes. New environmental rules have altered the cost of moving goods across long distances. Measures like the European Union's Carbon Border Adjustment Mechanism have effectively placed a carbon price on imports, creating financial consequences for emissions-heavy production and transport. Companies that once overlooked environmental factors now face direct regulatory and financial incentives to consider them.

1.3 The Strategic Shift: From JIT to JIC

By 2025, the focus of global business had clearly shifted. Companies were no longer asking, "How cheap can we make it?" Instead, the primary concern became, "How reliable is our supply chain?" The vulnerabilities exposed by the pandemic, geopolitical tensions, and regulatory changes made it clear that extreme cost-cutting and zero-inventory strategies were risky. As a result, many multinational corporations began moving away from the JIT model and adopting a Just-in-Case (JIC) approach.

The JIC strategy emphasizes preparedness over minimalism. Companies now maintain extra inventory, or "safety stocks," to avoid shortages when disruptions occur. They are also diversifying suppliers and relocating some production closer to key markets—a practice known as reshoring or nearshoring. For example, electronics firms are moving factories from distant regions back to domestic or nearby locations to reduce dependency on long shipping routes. Managing this new approach introduces more complexity. To handle it, firms are increasingly relying on advanced AI systems capable of autonomous decision-making. These systems can monitor inventory levels, predict potential supply bottlenecks, reroute shipments, and adjust production schedules in real time. By anticipating problems before they escalate, companies can maintain continuous operations even during unexpected disruptions.

The shift from JIT to JIC also reflects a broader change in corporate strategy. Reliability, resilience, and flexibility have become as important as cost efficiency. Firms are willing to accept slightly higher production costs—sometimes referred to as a "resilience premium"—because a supply chain that can withstand shocks is ultimately more valuable than one that is simply cheap. In this new era, technology, strategic planning, and risk management are tightly intertwined, creating supply networks that are both smarter and more robust than before.

1.4 Comparative Analysis of Trade Eras

To better understand how global trade has evolved, Table 1 highlights the key differences between the traditional Efficiency Era and the modern Resilience Era. While the Efficiency Era focused on minimizing costs through JIT production, the Resilience Era emphasizes reliability, risk management, and adaptability. The table summarizes the main changes across logistics, supplier networks, factory locations, technology, trade policies, and the resulting impact on consumer pricing.

Interpretation

The comparison between these periods highlights a clear change in how global trade is understood and managed. Before 2020, most governments and companies believed that the best trade system was the one that kept costs as low as possible. This thinking produced supply chains with very little spare inventory, production concentrated in a few low-cost locations, and heavy reliance on offshoring.

By contrast, the situation in 2025 looks very different. A series of disruptions revealed how fragile these highly efficient systems actually were. As a result, many firms are now willing to accept higher operating costs in exchange for more stability. This shift has led to the rise of safety stock, multiple supplier networks, and the movement of factories closer to end consumers. In short, resilience has become just as important as efficiency in the design of today's global supply chains.

2. THEORETICAL BACKGROUND

2.1 The Traditional Model: Efficiency as the Only Variable

For much of the late 20th century, international trade theory focused heavily on cost efficiency as the driving force behind global production networks. Production philosophies such as JIT emerged from the Toyota Production System (Ohno, 1988), emphasizing the elimination of excess inventory and streamlined processes. In the economics literature of the 1990s and early 2000s, deeper market integration and specialization were expected to lower overall costs and improve welfare (Krugman, 1991; Helpman & Krugman, 1985; Melitz, 2003). Within this framework, inventory was often viewed as unused capital, and geographic distance appeared to matter mainly as a transportation cost (Hummels, 2007). Many models indirectly assumed that global markets would function smoothly and remain open, a belief reflected in the growth of uneven, cross-border supply chains (Bernard et al., 2003; Eaton & Kortum, 2002).

2.2 Operational Efficiency and Competitive Advantage

Alongside economic theories, business and operations scholars focused on how companies could work faster and waste less. Studies showed that systems like JIT helped firms use their resources better, shorten production times, and boost overall output (Womack et al., 1990; Schonberger, 1982; Shah & Ward, 2003). Total Quality Management encouraged companies to reduce errors and unnecessary steps in pro-

Table 1. Structural Evolution of Global Trade (2019 vs. 2025)

Feature	The "Efficiency" Era (Pre-2020)	The "Resilience" Era (2025)	Economic Consequence
Logistics Philosophy	Just-in-Time (JIT): zero waste; minimal stock.	Just-in-Case (JIC): high buffers; "safety stock."	Higher warehouse costs; fewer shortages.
Supplier Network	Single-source: concentrated in one low-cost hub.	Multi-sourced: diversified across 3+ friendly nations.	Reduced risk of total system shutdown.
Factory Location	Offshoring: chasing the lowest labor wages.	Friend-shoring: prioritizing political allies and neighbors.	Higher production costs; better security.
Primary Tech Tool	Basic spreadsheets and ERP systems.	Agentic AI: autonomous logistics "control towers."	High technology investment; 24/7 visibility.
Trade Policy	Globalization and tariff reduction.	De-risking: carbon taxes and technology export bans.	Trade is now a branch of national security.
Consumer Pricing	Deflationary: prices fell as trade grew.	The Resilience Premium: structural price hikes.	12–15% increase in final goods prices.

duction (Deming, 1986; Juran, 1988). In these discussions, keeping extra inventory or backup suppliers was mostly seen as a waste of money (Christopher & Towill, 2000). Because of this mindset, most risk planning in business focused on expected delays rather than large-scale disruptions that could shut down entire supply chains.

2.3 Emergence of Global Value Chains

Production across borders grew rapidly, with companies breaking their operations into different stages and placing each where it was most efficient or cost-effective (Gereffi & Korzeniewicz, 1994; Gereffi, Humphrey, & Sturgeon, 2005). Parts and materials for a single product often crossed international borders multiple times before final assembly (Hummels, Ishii, & Yi, 2001). Global value chains (GVCs) also enabled firms to access specialized labor markets and raw materials in different countries, increasing flexibility and competitiveness (Bair, 2005). However, this fragmentation created hidden vulnerabilities. Disruptions in one region could quickly ripple across the entire chain, as seen in natural disasters, port shutdowns, or political crises (Craighead et al., 2007). At this stage, most experts still believed that supply chain risks could be managed through careful planning and coordination rather than by changing the overall structure (Gereffi et al., 2005).

Over time, GVCs became central not only to manufacturing but also to the service sector, including software, logistics, and finance, demonstrating that international production networks are a structural feature of the modern economy rather than a temporary trend (Baldwin, 2016). The global spread of production increased efficiency and lowered consumer prices, but it also made firms more sensitive to geopolitical events and supply chain shocks, highlighting the need for strategies that balance efficiency with resilience (Evenett, 2019).

2.4 Early Recognition of Risk in Trade

For many years, global trade strategies focused almost entirely on efficiency, aiming to cut costs and streamline operations. However, a growing group of researchers began to notice that this focus often left companies exposed to unexpected shocks (Tang, 2006; Sheffi, 2001). They argued that flexibility, backup suppliers, and small inventory buffers could act as insurance, helping firms navigate disruptions such as port closures, sudden demand spikes, or supplier failures (Tang, 2006; Sheffi, 2001). Some studies highlighted that ignoring rare but serious events—like natural disasters, political unrest, or strikes—could lead to cascading failures across the entire supply chain (Chopra & Sodhi, 2004; Blackhurst et al., 2008). The research also emphasized a critical trade-off: adding redundancy and safeguards increases costs, but without them, a single disruption could be far more expensive than the saved efficiency (Craighead et al., 2007).

These early insights paved the way for later work on resilience and supply chain viability. Researchers suggested that the goal should not only be to recover quickly after a disruption but to maintain core operations even under stress (Ivanov, 2021; Ponomarov & Holcomb, 2009). Initially, mainstream economic models largely ignored these ideas because they assumed that markets and supply chains were stable and predictable (Chopra & Sodhi, 2004; Sheffi, 2007). Today, this early recognition of risk is seen as a turning point. It showed that a purely efficiency-driven approach could backfire and introduced the idea that companies might willingly pay extra—what practitioners now call a "resilience premium"—to keep operations running smoothly during crises (Sheffi, 2021; Ivanov, 2021). Essentially, these studies remind us that there is no free lunch in global trade: safety and stability come at a cost, but without them, the risks are far greater.

2.5 Supply Chain Resilience: Conceptual Development

In recent years, resilience has become central to supply chain thinking. At first, resilience was described as the ability of a system to recover after a disruption (Christopher & Peck, 2004). The concept also includes the ability of resilient supply chains to anticipate problems, adapt quickly, and reorganize operations when shocks occur (Ponomarov & Holcomb, 2009; Wieland & Wallenburg, 2012). The concept of viability suggests that it is not enough for a supply chain to bounce back after a problem; it must be able to continue functioning during the disruption itself (Ivanov, 2021). This idea shifted the focus from reactive strategies to proactive system design.

These studies underline a basic point: there is no free lunch. Maintaining a resilient supply chain requires investment—more planning, more resources, and often more advanced technologies—to manage added complexity and ensure operations keep running smoothly during crises (Sheffi, 2021; Ivanov, 2021). This helps explain why many firms are now willing to accept higher costs, sometimes referred to as a "resilience premium," to safeguard their supply networks. Re-

silience is no longer optional; it has become a strategic necessity in a world of unpredictable shocks, whether from pandemics, geopolitical conflicts, or natural disasters (Ivanov, 2021; Christopher & Peck, 2004).

2.6 Network Complexity and Diminishing Returns

As companies try to make their supply chains more resilient, they often run into a new challenge: complexity. Adding extra suppliers, multiple sourcing, or backup facilities can protect against disruptions, but it also creates more work for managers and teams responsible for coordination (Craighead et al., 2007; Tang & Musa, 2011).

Beyond a certain point, adding more layers of redundancy does not improve outcomes as much as expected. This phenomenon, called complexity inflation, occurs when the costs of managing a highly diversified network—such as monitoring multiple suppliers, keeping track of inventories, or handling logistics across different countries—start to outweigh the benefits (Chopra, 2020; Ivanov & Dolgui, 2020). Building resilience is therefore not just a matter of adding more suppliers or warehouses. Firms must also invest in advanced planning tools, decision-making systems, and skilled managers to handle the added complexity. Without these, the network can become so complicated that the risk of errors, miscommunication, or delays actually increases. Resilience comes with a trade-off: the safer a supply chain becomes, the more effort, coordination, and cost it requires to keep it running smoothly (Ivanov & Dolgui, 2020; Chopra, 2020).

2.7 Sustainability, Technology, and the Modern Supply Chain

In today's global trade, resilience is shaped not just by economics, but also by environmental and technological factors. Climate policies, carbon pricing, and regulations like the European Union's Carbon Border Adjustment Mechanism (CBAM) influence where and how companies produce goods (Aldy & Pizer, 2021; Nordhaus, 2015; Cosbey et al., 2019). These regulations have made sustainability a core consideration for supply chain design, as companies must now balance cost efficiency with environmental responsibility.

At the same time, technological advancements are transforming how firms manage complexity and risk. Tools such as data analytics, digital twins, and AI-based forecasting allow companies to predict disruptions, optimize routes, and manage inventory in real time (Waller & Fawcett, 2013; Choi et al., 2018). Recent research highlights agentic AI systems that can autonomously reroute shipments or adjust production schedules when a shock occurs, directly linking technology to resilience outcomes (Ivanov & Sokolov, 2020; Queiroz et al., 2020).

Together, environmental and technological factors have shifted the modern supply chain from a purely cost-driven system to one that must simultaneously address sustainability, risk, and operational intelligence. Firms that fail to integrate these considerations risk higher costs, regulatory penalties, and operational disruptions, while those that embrace them can achieve a more robust and responsive supply network (Ivanov & Sokolov, 2020; Aldy & Pizer, 2021). Building on the evolving concepts of resilience, complexity, and technological adaptation in global supply chains, artificial intelligence (AI) now emerges as a transformative tool that not only optimizes operational efficiency but also reshapes innovation management, enabling firms to anticipate disruptions, make data-driven decisions, and integrate advanced digital capabilities into strategic processes (Khalid et al., 2023).

3. OBJECTIVES OF THE STUDY

The main aim of this research is to examine how global trade has shifted from a focus on minimal cost to a system that prioritizes resilience and stability. The specific objectives are:

- **Map the Resilience–Efficiency Frontier (REF):** Identify the balance point where cost-saving strategies like JIT are outweighed by the need for JIC safety buffers.
- **Analyze the Triple Shock (2020–2025):** Study how the pandemic, geopolitical disruptions, and environmental regulations such as CBAM permanently reshaped global trade systems.
- **Quantify the Resilience Premium:** Determine the reasons behind the 12–15% increase in final product costs due to friend-shoring, inventory redundancy, and supply chain diversification.
- **Assess AI in Supply Chain Management:** Examine how advanced agentic AI systems ("control towers") help companies manage network complexity, predict disruptions, and maintain operational continuity.

4. RESULTS AND FINDINGS

- **The 12–15% Resilience Premium:** Prices for goods have risen permanently by 12–15%. This is because companies moved from JIT (no extra stock) to JIC (keeping extra stock) to ensure they never run out of products.
- **The Complexity Inflation Trap:** Having many suppliers reduces risk but makes management harder. This creates "complexity inflation," where the high cost of coordinating different nations and partners can eventually outweigh the safety benefits.
- **Trade as National Security:** After the "Triple Shock" (pandemic, Red Sea disruptions, and geopolitics), trade is about more than money. Getting chips, minerals, and safe shipping routes is now a matter of national power and safety.
- **Regulatory Reshaping via CBAM:** New rules like the EU's CBAM put a price on carbon. This ends the era of "chasing the lowest wage" and forces companies to produce goods closer to home (nearshoring) to avoid environmental taxes.
- **Agentic AI as a Viability Tool:** Agentic AI "control towers" help handle complex supply chains. These systems help firms see problems early and keep working even during major global disruptions.

5. CONCLUSION

The period from 2020 to 2025 marks the end of the "Fragile Efficiency" era, which focused almost entirely on minimizing costs. While JIT manufacturing and borderless offshoring were effective in reducing prices, they left global supply

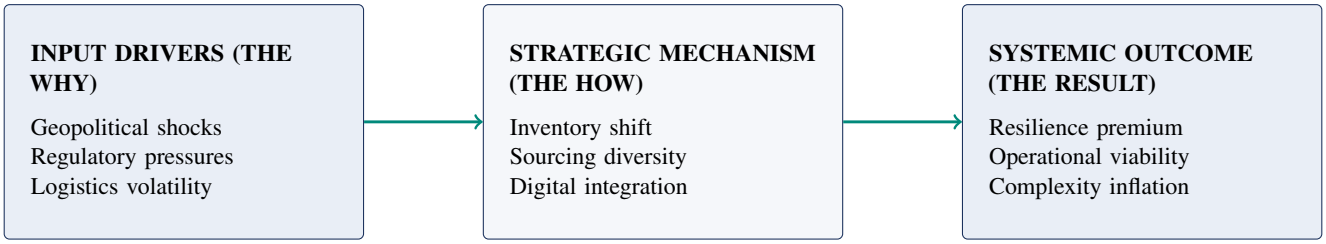


Figure 1. The integrated trade resilience framework (ITRF): drivers, mechanisms, and outcomes.

Source: Developed by the author, adapted from the theories of Krugman (1991), Sheffi (2001), and Ivanov (2021).

chains highly vulnerable because of the absence of safety buffers. The "Triple Shock"—comprising the COVID-19 pandemic, geopolitical crises in the Red Sea, and climate regulations like the EU's Carbon Border Adjustment Mechanism (CBAM)—exposed the inherent fragility of a purely efficiency-driven system. In response, the global economy has shifted toward prioritizing reliability and preparedness over the lowest possible price.

The adoption of JIC strategies has introduced a permanent "Resilience Premium," raising final goods costs by 12–15%, reflecting the capital required to maintain safety stocks and regionalize production through friend-shoring. However, diversification also brings administrative and coordination challenges, giving rise to "Complexity Inflation." To address this, agentic AI "control towers" have become essential tools, enabling firms to predict bottlenecks, optimize logistics, and maintain continuity in real time. Today, international trade is no longer solely an economic activity but is deeply intertwined with national security and environmental sustainability. Policies like CBAM have effectively shifted production closer to end consumers, ending the era of chasing the lowest wages. Although the Resilience Era comes with higher costs, it establishes a stronger and more adaptive global economic foundation, where the Resilience–Efficiency Frontier emphasizes the importance of strategic alignment and technological intelligence in navigating an increasingly unpredictable world.

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