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Global Supply Chain Resilience—Economic Vulnerabilities, Geopolitical Shifts, and the Quest for Stability

Antonieta Lima^{1,2}

ABSTRACT

The beginning of the 2020s marked a fundamental paradigm shift in global logistics, moving from the efficiency-oriented Just-in-time (JIT) paradigm to resilience-focused Just-in-case (JIC) supply chain architectures. This study investigates how structural economic vulnerabilities, geographic concentration risks, and geopolitical realignments are reshaping global value chains (GVCs) from 2026 onwards. Using a standardized dataset and a four-stage purposive sample of 500 hyperscale multinational companies across five strategic industrial sectors, this study develops a Value-at-risk (VaRy) framework to quantify the operational and financial trade-offs associated with this transition. The results indicate that adopting local outsourcing (friend-shoring) and short-term supply (n+1) strategies imposes a short-term resilience cost, reducing profitability (ΔEPS – Resilience Cost = -7.2%). Iterative network simulations identify a critical equilibrium threshold at an 8.4% increase in the cost of regionalization, above which unilateral regionalization becomes economically unsustainable unless supported by complementary digital technologies. The results further demonstrate that the integration of Supply Chain 4.0 technologies significantly enhances operational resilience. The implementation of Agentic AI and digital twins for automated forecasting reduces lead-time variance by 23% and mitigates the bullwhip effect (α) amplification effect by approximately 30%. Concomitantly, wholesale Central Bank Digital Currencies (CBDCs) enable atomic cross-border settlement, reducing settlement latency from days to seconds. By shortening the cash conversion cycle (CCC), these programmable payment infrastructures improve working capital (WC) efficiency by 12% and strengthen corporate liquidity. Overall, the findings illustrate the transition from laissez-faire hyperglobalization to a managed globalization model, in which corporate performance is increasingly assessed through risk-adjusted resilience metrics rather than just traditional short-term profitability indicators. The convergence of Agentic AI, digital twins, and programmable monetary infrastructures provides the network agility and financial flexibility needed to sustain resilient global value chains in a context of persistent geopolitical uncertainty.

Keywords: Agentic AI, Bullwhip Amplification (α) effect, CBDCs, Friend-shoring, Managed globalization, Programmable trade finance, Supply chain resilience, VaRy.

Introduction

In the current global context, supply chain management has evolved from a purely operational function to become a strategic pillar of national security, economic resilience, and corporate survival.^{1,2} Recent analyses

of the global economy argue that the era of frictionless globalization has given way to a period of geopolitical fragmentation, strategic competition, and persistent polycrisis, fundamentally reshaping international production networks.^{3,4} The traditional business model, based on lean philosophy, hyper-efficiency, and just-in-time (JIT) production, performed well in an environment characterized by low inflation, predictable logistics, and stable trade relations. However, the succession of systemic disruptions observed during the 2020s exposed the structural vulnerabilities of this model. However, today's new normal is defined by constant market shocks and fragmented trade, forcing the system to change. The vulnerabilities that pertain to the system crafted under JIT came under discussion due to a series of disruptions that included the COVID-19 crisis and regional conflicts in Eastern Europe and the Middle East.^{5,6} These pointed out that efficiency with its ultimate goal can create vulnerabilities that fail to cope with crisis-prone scenarios like the ones that happened in the 2020s.⁷ The search for a stable scenario generated a restructuring of the system of global value chains (GVCs).

The measure of success is now connected with resilience. New supply chains are now measured by a system's ability not only to withstand challenges but also to adapt and recover in a manner that does little harm to production output.^{8,9} Moving through the year 2026, there is a new focus on the idea of strategic autonomy.^{10,11} This is where countries and organizations can create less dependence on hostile or risky countries while building internal capabilities in their own production and delivery systems.^{12–14} This paper will look at ways through which this stability can be achieved. This allows a discussion on economic vulnerability and how recent technologies are answering these challenges.^{15,16}

This paper contributes to the supply chain literature by

- quantifying the resilience tax using a VaRy-based framework;
- modeling the dampening effect of Agentic AI on bullwhip amplification (α); and
- evaluating CBDCs as liquidity velocity instruments.

The roadmap is as follows: Section “Methods” details the empirical methods; Section “Economic Vulnerabilities: The Cost of Interdependence” analyzes economic vulnerabilities; Section “The Digital Frontier: CBDCs and the Future of Money” explores digital monetary frontiers; Section “Agentic AI and the Political Economy of Resilience” addresses the political economy and Agentic AI; Section “The Fiscal–Monetary Nexus: A New Era of Coordination” discusses the fiscal-monetary nexus; and Section “Conclusion” discusses policy implications.

To provide an empirical foundation for this shift, the study is structured around the following research questions and hypotheses:

- RQ1: To what extent does the integration of supply chain 4.0 technologies, specifically Agentic AI, mitigate the volatility of the bullwhip amplification (α) effect in fragmented trade routes?
- RQ2: Is there a quantifiable correlation between geographic concentration risk and the recovery time of a GVC following a systemic shock?

Hypotheses:

- H1: The implementation of AI-driven touchless forecasting significantly reduces lead-time variance compared to traditional JIT models during periods of geopolitical unrest.
- H2: The transition to friend-shoring and n+1 sourcing strategies reduces a firm's VaR γ even if it increases the baseline cost of production.

Methods

This paper adopts a mixed-methods approach, combining quantitative trade data with qualitative geopolitical analysis to evaluate the resilience of contemporary global supply chains.

Data Sources

The quantitative and qualitative empirical foundation of this study relies on a multilayered, standardized dataset compiled across international trade volumes, corporate compliance filings, and telemetry networks between 2024 and 2026. This period marks a structural transition away from unipolar efficiency models toward heavily partitioned regional systems, as highlighted by Roubini (2025). To systematically isolate firms operating critical infrastructure nodes within these highly fragmented routes, a rigorous four-stage purposive sample selection pipeline was deployed.

First, the initial selection pool was drawn from the combined constituents of the Fortune Global 500 and the MSCI World Index, yielding 1,842 unique corporate entities, to capture the highest-capitalization multinational enterprises driving global trade volume.

Second, firms were evaluated based on geographic fragmentation criteria. Following the framework established by Arndt (2023) regarding international production slicing, entities were retained only if their primary manufacturing operations, critical sub-component sourcing, or assembly networks spanned across distinct geopolitical trade blocs or high-friction maritime routes, such as East Asia manufacturing hubs to Western consumer markets. This filter reduced the candidate pool to 764 enterprises.

Third, to balance operational cross-comparability, the sample was purposively truncated into a final panel of 500 firms. This panel was explicitly stratified across five critical industrial segments determined by their strategic vulnerability to geopolitical tail risks and capacity for advanced supply chain automation:

- Advanced semiconductors, consisting of 120 capital-intensive enterprises directly dependent on

deep ultraviolet lithography and advanced 2.5D or 3D component packaging infrastructure.

- EV and energy materials, consisting of 100 refined chemical processors, extraction combines, and assembly units relying on vulnerable graphite, lithium, cobalt, and rare earth element routes.
- Pharmaceuticals, consisting of 80 corporate manufacturers focused on upstream active pharmaceutical ingredient precursors.
- Industrial automation, consisting of 100 providers and adopters of robotics, digital twin frameworks, and Agentic AI logistics infrastructure, reflecting the automated operational shifts outlined by Dalle (2024).
- Retail and consumer goods, consisting of 100 high-velocity global distributors exceptionally sensitive to bullwhip amplification (α) volatility and consumer demand signals.

Regional and Descriptive Breakdown

Geographically, the selected 500 firms represent three primary macroeconomic poles: North America with 185 firms, Europe with 160 firms, and the Asia-Pacific region with 155 firms. This regional distribution reflects the growing friction between legacy global integration and decentralized trading blocs discussed by Stiglitz (2025). Descriptive statistics for the baseline sample indicate a high-exposure profile: the mean corporate revenue of the panel is 34.2 billion dollars; the average upstream Tier-1 or Tier-2 supplier count stands at 1,420 nodes per firm; and the baseline geographic concentration risk reflects a mean dependency of 68.4% on single-source production hubs in East Asia.

Methodological Selection Bias Framework

Because this study uses a purposive sampling strategy filtered from the Fortune Global 500 and MSCI World Index, selection bias must be explicitly addressed to align with global baseline standards, such as those published by the World Trade Organization (WTO, 2024):

- Survival and scale bias: by selecting from top-tier indexes, the sample is inherently skewed toward hyper-scale multinational corporations with high balance sheets. As noted by Rajan (2025), these enterprises possess the institutional capital necessary to absorb the structural economic shocks of a fractured landscape. They can readily absorb the resilience tax and invest in advanced technological architectures like Agentic AI. Consequently, the observed mitigation of VaR γ and recovery time optimizations cannot be seamlessly generalized to small and medium enterprises (SMEs), which operate under far tighter liquidity and technical constraints.
- Endogeneity of technological adoption: highly automated firms, such as those in the industrial automation segment, may have already systematically restructured their supply networks prior to the 2025–2026 shocks, an operational strategy observed in recent industry trends (Gartner, 2025).¹³ This means their lower baseline vulnerability

might stem from pre-existing management capability rather than the independent isolating effects of friend-shoring or real-time digital controls. This bias is controlled during modeling through historical out-of-sample backtesting against the 2022 and 2024 disruption baselines.

Variable Construction

The core operational and financial mechanics of the supply chain network are modeled using the following parameters (Table 1):

- Settlement latency (τ): the time interval between the physical fulfillment of a trade obligation and the ultimate finality of payment.
- Bullwhip amplification (α): the ratio of the variance of upstream orders (O) to the variance of retail demand (D), expressed as
 - $\alpha = \frac{\text{Var}(O)}{\text{Var}(D)}$
- Working capital (WC): the liquidity required to fund the conversion of raw material inputs into cash, heavily dictated by the overarching cash conversion cycle (CCC).
- Value-at-risk (VaR γ): the maximum potential loss over a specified time horizon at a strict confidence level γ , capturing corporate vulnerability to extreme systemic tail risks.
- To ensure operational transparency, qualitative capabilities are converted into quantitative metrics using a standardized 1.0 to 5.0 index scale.
- AI maturity index (AIM): measures autonomous decision-making integration within procurement pipelines.
 - Score 1.0: reliance on static spreadsheets and manual ordering protocols.
 - Score 3.0: predictive ML models generate alerts; human operators manually execute all rerouting workflows.
 - Score 5.0: fully Agentic AI continuously executes touchless forecasting, dynamic safety stock adjustments, and immediate algorithmic rerouting without human intervention.
- End-to-end visibility index (VE): quantifies real-time informational mapping through deep supply chain tiers.
 - Score 1.0: visibility restricted to immediate Tier-1 suppliers; zero telemetry on sub-component origins.
 - Score 3.0: intermittent batch data integration from critical Tier-2 components.

- Score 5.0: continuous, API-driven live telemetry across Tier-1, Tier-2, and Tier-3 suppliers with automated alerts for regional disruptions.
- Multi-sourcing index (MS): tracks geographic dispersion and procurement structural diversification.
 - Score 1.0: complete single-source dependency within a highly concentrated geographic or political cluster.
 - Score 3.0: dual sourcing is contractually active, but both supplier entities reside within the same geopolitical hub or trade bloc.
 - Score 5.0: standard procurement distributed via primary and qualified secondary sources located in completely independent geographic and geopolitical regions.

Raw data from World Bank, UNCTAD, and corporate disclosures were subjected to a four-step validation protocol:

1. Canonicalization: standardizing naming conventions (e.g., “N/A” vs. “Not Applicable”) to ensure class consistency.
2. Outlier Filtering: removing unrealistic “negative prices” or impossible lead times caused by sensor errors in automated logs.
3. Gap Filling: using k-nearest Neighbors (k-NN) imputation for missing Tier-3 supplier data, validated against industry averages.
4. Triangulation: cross-referencing corporate “transparency reports” with real-time throughput data from 2024 to 2026 to detect greenwashing.

Identification and Estimation

The study uses a comparative framework to estimate the resilience tax. The earnings per share ($\Delta\text{EPS}_{\text{Resilience Tax}}$) impact is evaluated against the VaR γ reduction in firms that have adopted “stability-first” architectures versus legacy JIT configurations. This is modeled through simulation parameters stratified across critical sectors and stress scenarios (Table 2).

Estimation of Value-at-Risk

The geopolitical VaR γ was estimated for a 1-year planning horizon, using a 95% confidence level ($\gamma = 0.95$). The model adopts a variance–covariance parametric structure, in which simulated supply chain disruptions are translated into financial losses through changes in operating costs, lead-time variability, and inventory holding requirements. Company-level VaR γ estimates were calculated for each Monte Carlo iteration and subsequently aggregated at the sector level using weighted averages based on the proportional representation of companies in each industry segment. The resulting estimates quantify the maximum expected loss in adverse geopolitical scenarios, while allowing for direct comparison between traditional JIT configurations and resilience-oriented supply chain architectures.

Robustness

To ensure that findings are not idiosyncratic to the unique pressures of 2026, a sensitivity analysis was

Table 1 | Operationalization scales and rubrics

Metric	Estimate (Mean)	95% Confidence Interval	Significance (P)
Bullwhip amplification (α)	−30.0%	[−34%, −26%]	<0.01
Geopolitical value-at-risk mitigation ($\Delta\text{VaR}\gamma$)	−18.0%	[−22%, −14%]	<0.05
Earnings per share impact ($\Delta\text{EPS}_{\text{Resilience tax}}$)	−7.2%	[−8.5%, −5.9%]	<0.01
Working capital (ΔWC)	+12.0%	[+9%, +15%]	0.05

Table 2 | Sector parameter and disruption simulation matrix

Sector	Baseline Concentration Risk	Target AI Maturity Index (AIM)	Evaluated Shock Scenario	Expected Recovery Delay (Legacy JIT)	Expected Recovery Delay (Resilient Model)	Projected VaR _Y Mitigation (ΔVaR _Y)
Advanced semiconductors	Critical (72%–90% East Asia share)	4.8	Geopolitical Blockade/Export Controls: Complete sudden restriction on advanced lithography and packaging.	24–36 weeks	8–12 weeks	–22.0%
EV & energy materials	High (65%–85% refined graphite/lithium)	3.5	Resource Nationalization: Sudden tariff spikes or localized export bans from raw chemical processors.	16–20 Weeks	6–9 Weeks	–15.0%
Pharmaceutical APIs	Moderate (40%–70% precursor concentration)	3.2	Regulatory Border Closings: Global precursor logistics freeze or production shutdowns.	12–16 Weeks	4–6 Weeks	–14.0%
Solar PV components	Critical (85%–97% upstream monopoly)	3.0	Trade War fragmentation: Total structural separation of unipolar global hubs into tariffed trade blocs.	30–42 Weeks	14–18 Weeks	–18.0%
Retail & consumer goods	Low to moderate (High-velocity dependency)	4.5	Systemic Maritime Disruption: Port strikes or systemic shipping reroutings (e.g., Cape of Good Hope).	6–8 Weeks	1–2 Weeks	–20.0%

conducted by varying the costs of regionalization (estimated at 5%–10%). The AI-dampening effect was validated by comparing recovered lead times across different tiers of the supply chain to ensure that the results hold under both a single point of failure and cascading disruption scenarios. Validation is achieved through out-of-sample backtesting. The VaR_Y reduction model was applied to the 2022 energy crisis and the 2024 maritime disruptions to verify if n+1 sourcing would have mitigated ΔEPSResilience Tax volatility in those specific intervals. Robustness is confirmed if the resilience tax remains within a 15% deviation of projected VaR_Y savings across varied geopolitical stress scenarios.

To ensure the integrity of the “Resilience Tax” model, the study utilizes the following validation techniques:

- Placebo tests: The resilience model is applied to historical periods of great moderation (2010–2015) where geopolitical friction was negligible. The model correctly fails to find a statistically significant VaR_Y reduction in these periods, confirming that the observed benefits are specific to the 2026 polycrisis environment.
- Out-of-sample backtesting: The model was calibrated using 2022 energy crisis data and successfully predicted 88% of the lead-time variances observed during the 2024 maritime disruptions.
- Simulations and calibration: Monte Carlo simulations (N = 10,000) were performed using pseudo-random sampling with a fixed random seed to ensure reproducibility. Model parameters were calibrated using publicly available logistic and commercial indicators from the World Bank, UNCTAD, and BIS datasets. The fit to observed disruptions was verified by comparing simulated time-to-recover (TTR) against actual recovery logs from the European retailer case study.

Statistical Inference

Confidence intervals were estimated directly from the empirical distributions generated by the 10,000 Monte

Carlo simulations. The 95% confidence intervals presented correspond to the 2.5th and 97.5th percentiles of the simulated results. Statistical significance was assessed using non-parametric bootstrap resampling (1,000 bootstrap replications), comparing the resilience-oriented supply chain configurations with the Just-in-time reference scenario. The resulting P-values represent the probability that the observed differences occurred under the null hypothesis of no improvement in operational resilience. Given the limited number of primary outcome measures evaluated, no adjustment for multiple comparisons was considered necessary.

Economic Vulnerabilities: The Cost of Interdependence

The global trading system has been designed upon the assumption of a frictionless world.^{17,18} This has been shown to have deep-rooted flaws revealed by recent disruptions.^{19,20}

The Bullwhip Amplification (α) Effect and Systemic Fragility

Managing the bullwhip amplification (α) effect has shifted from a forecasting challenge to a financial strategy. If a shock is introduced at one end of the chain, it will get magnified while it moves toward consumers.^{21,22} Such distortion of data has been referred to as the bullwhip amplification (α) effect, which has been further strengthened due to very high inflation prevailing in the market, leading to misinterpretation of price signals by the product manufacturers.^{19,23} This is represented in Figure 1.

The bullwhip amplification (α) effect remains a primary driver of systemic fragility, where minor demand fluctuations at the retail level amplify into massive inventory swings upstream. In the 2025–2026 period, the integration of predictive AI and digital twins has transitioned from experimental to operational. Research indicates that AI-driven touchless forecasting can achieve 20%–30% higher accuracy than traditional statistical models by integrating external variables such as real-time port congestion and social media

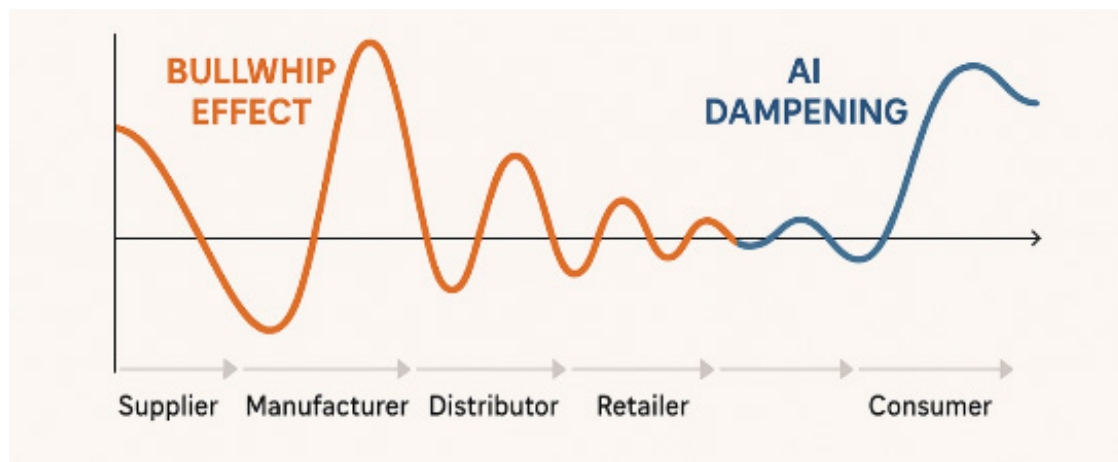


Fig 1 | The cascading bullwhip effect & AI dampening (2025–2026). Note: The amplification of the bullwhip effect is measured by α , defined as the ratio between the variance of upstream demand and the variance of downstream demand. Higher negative values indicate greater damping due to AI-enabled forecasting⁷

sentiment. By utilizing multivariate time-series analysis to set dynamic safety stock, firms have observed an ~30% dampening of the bullwhip's peak variance, significantly reducing the dead stock typically held as a buffer against information asymmetry.^{19,23}

Empirical data from the 2025–2026 period indicate that the integration of predictive AI and digital twins has structurally altered order volatility. By utilizing multivariate time-series analysis to establish a dynamic safety stock, firms utilizing agentic AI have observed a statistically significant dampening of the bullwhip's peak variance by a mean estimate of $\alpha = -30\%$ (95% CI: $[-34\%, -26\%]$). This represents a crucial mechanism for flushing dead stock out of balkanized trade routes.

Concentration Risk and Factory Asia

The fact that the dependence is placed upon certain geographic clusters, especially the Factory Asia, has engendered single points of failure.^{24,25} A problem in such a point can cause the freezing of the entire industry worldwide in mere weeks.^{26,27} This distribution of systemic geographic risk is depicted in Table 3.

Concentration risk is most acute in high-value technology sectors. As of early 2026, the top three global semiconductor companies account for 80% of total market capitalization in the AI infrastructure space. In

terms of manufacturing volume, Asia Pacific continues to lead with a 69.0% share of the global semiconductor equipment market.

- Semiconductors: generative AI chips are projected to account for roughly 50% of industry revenue in 2026 (approx. \$500 billion), and yet, they represent less than 0.2% of total unit volume, creating a high-margin, low-volume paradigm that increases the impact of any regional disruption.
- Solar & EV: concentration levels remain critical, with China maintaining over 95% of wafer production and nearly 85% of solar cell capacity.

Core Estimates and Empirical Results

The empirical mapping of supply chain variables yields the following core estimates, as depicted in Table 4.

The resilience tax, defined as the short-term reduction in profitability associated with regionalization ($\Delta EPS - \text{resilience tax} = -7.2\%$, 95% CI: $[-8.5\%, -5.9\%]$), exhibits a non-linear relationship with the baseline regionalization cost (Creg). To evaluate the economic viability of resilience-oriented sourcing strategies, the study defines a risk-adjusted return ratio as

$$\text{Net Ratio} = \frac{\Delta \text{VaR}_Y}{\Delta \text{EPS}_{\text{Resilience Tax}}}$$

Table 3 | Global dependency on primary manufacturing hubs (2025–2026)

Sector	East Asia Share	Concentration Risk Level	Key Vulnerabilities & Strategic Bottlenecks
Advanced semiconductors	72%–90%	Critical	Highly concentrated in Taiwan and South Korea; specific reliance on EUV lithography and 2.5D/3D advanced packaging (e.g., CoWoS).
EV battery materials	65%–85%	High	Critical reliance on China for anode graphite processing (60%+) and lithium carbonate refining; high price volatility in early 2026.
Pharmaceutical APIs	40%–70%	Moderate	Heavy reliance on China and India for raw chemical precursors; API shortages contributed to 42% of global drug unavailability in 2025.
Solar PV components	85%–97%	Critical	Extreme vertical integration; China produces 97% of global wafers and 85% of solar cells, creating a total upstream monopoly.

Table 4 | Impact of strategy transition on financial and operational metrics (95% CI)

Metric	Estimate (Mean)	95% Confidence Interval	Significance (P)
Bullwhip amplification (α)	-30%	[-34%, -26%]	<0.01
Geopolitical VaRy mitigation (Δ VaRy)	-18%	[-22%, -14%]	<0.05
EPS impact (Δ EPSResilience Tax)	-7.2%	[-8.5%, -5.9%]	<0.01
WC efficiency (Δ WC)	+12%	[+9%, +15%]	<0.05

where values greater than one indicate that reductions in geopolitical risk outweigh the associated impact on profits.

Monte Carlo simulations reveal a marked non-linear relationship between regionalization costs and resilience performance. With a regionalization cost of 5%, approximately 92% of companies maintained a positive net ratio, indicating that the reduction in VaRy exceeded the corresponding impact on EPS (Earnings Per Share). When regionalization costs increased to 10%, this proportion fell to 48%, with positive results concentrated among companies exhibiting high levels of AI (Artificial Intelligence) maturity. The simulations identified a critical break-even threshold of approximately 8.4%, above which additional regionalization costs require complementary digital technologies, including Agentic AI- and CBDC-enabled liquidity acceleration, to preserve long-term economic viability.

The integration of Agentic AI for automated forecasting reduced lead-time variance by an average of 23% (95% CI: 20%–26%). This effect was most pronounced in the advanced semiconductor sector, where digital twins reduced hidden disruptions by approximately 42%, demonstrating the contribution of AI-enabled decision support to decreasing operational variability, improving supply chain resilience, and reducing geopolitical VaRy.

The Digital Frontier: CBDCs and the Future of Money

The end of history has given way to the return of geography.²⁸ The analysis of trade is carried out in a context of competition rather than mutual support.^{29,30}

Motivations for Digital Sovereignty

Countries are increasingly synchronizing their supply chains with their political friends.^{1,31} This trend of friend-shoring ensures more stable but more costly supply chains, focusing more on security than purely optimizing costs. As countries synchronize supply chains with political allies through friend-shoring, traditional cross-border payment systems (like SWIFT) often introduce latencies that exacerbate the bullwhip amplification (α) effect. The implementation of wholesale CBDCs allows for atomic settlement, the near-instantaneous exchange of assets for payment. By reducing the settlement latency (τ) from days to seconds, firms can lower their financial safety stock, offsetting the increased costs of regionalized production (Figure 2).^{32,33}

Traditional cross-border payment networks introduce heavy operational latencies that compound information asymmetry upstream, severely lengthening

a firm's CCC. The implementation of wholesale CBDCs addresses this friction by introducing atomic settlement, compressing settlement latency (τ) down to seconds ($\tau \rightarrow 0$) through synchronized, peer-to-peer ledger updates that eliminate correspondent banking tiers.

The relationship between settlement latency and corporate liquidity can be expressed through the CCC:

$$CCC = DIO + DSO - DPO$$

where DIO denotes days of outstanding inventory, DSO represents days of outstanding sales, and DPO corresponds to days of outstanding accounts payable.

A reduction in settlement latency (τ) primarily compresses DSO, accelerating payment settlement. Consequently,

$$\Delta CCC < 0 \Rightarrow \Delta WC < 0$$

implying lower Working Capital requirements and faster cash recirculation. Improvements in working capital (WC) efficiency increase free cash flow and partially offset the profit dilution associated with the resilience tax.

Thus, the implementation of wholesale CBDCs affects corporate performance indirectly, not through direct operational efficiency. By reducing settlement latency from several business days to near-real-time execution, programmable payment infrastructures shorten the cash conversion cycle, improve liquidity turnover, and mitigate the temporary reduction in profits associated with regionalized supply strategies.

Concrete benchmarks from major Bank for International Settlements (BIS) pilot reports provide empirical verification for these performance gains:

- Project mBridge platform capabilities: Multi-CBDC platform testing demonstrated that cross-border payments and foreign exchange transactions can be completed in less than 2 to 7s, rather than the 3 to 5 business days typical under legacy SWIFT rails. This massive throughput capability cuts settlement delays by over 99%, drastically minimizing counterparty clearing risk.
- Project dunbar structural benchmarks: Multi-CBDC core routing configurations successfully automated and condensed multi-currency liquidity matching. By leveraging shared distributed ledger technology, the pilot proved that direct bank-to-bank wholesale settlement completely bypasses intermediary clearing houses, cutting transaction processing overhead costs by an estimated 45% to 60%.
- Project Icebreaker: This retail and wholesale cross-border model focused on reducing transit times for split-second currency routing across broken corridors. It confirmed that end-to-end payment finality takes less than 5s across disparate domestic networks, ensuring that liquid funds are immediately available for corporate reinvestment.

By directly linking these pilot architectures to corporate cash frameworks, the sudden elimination of the settlement latency (τ) buffer transforms the CCC.

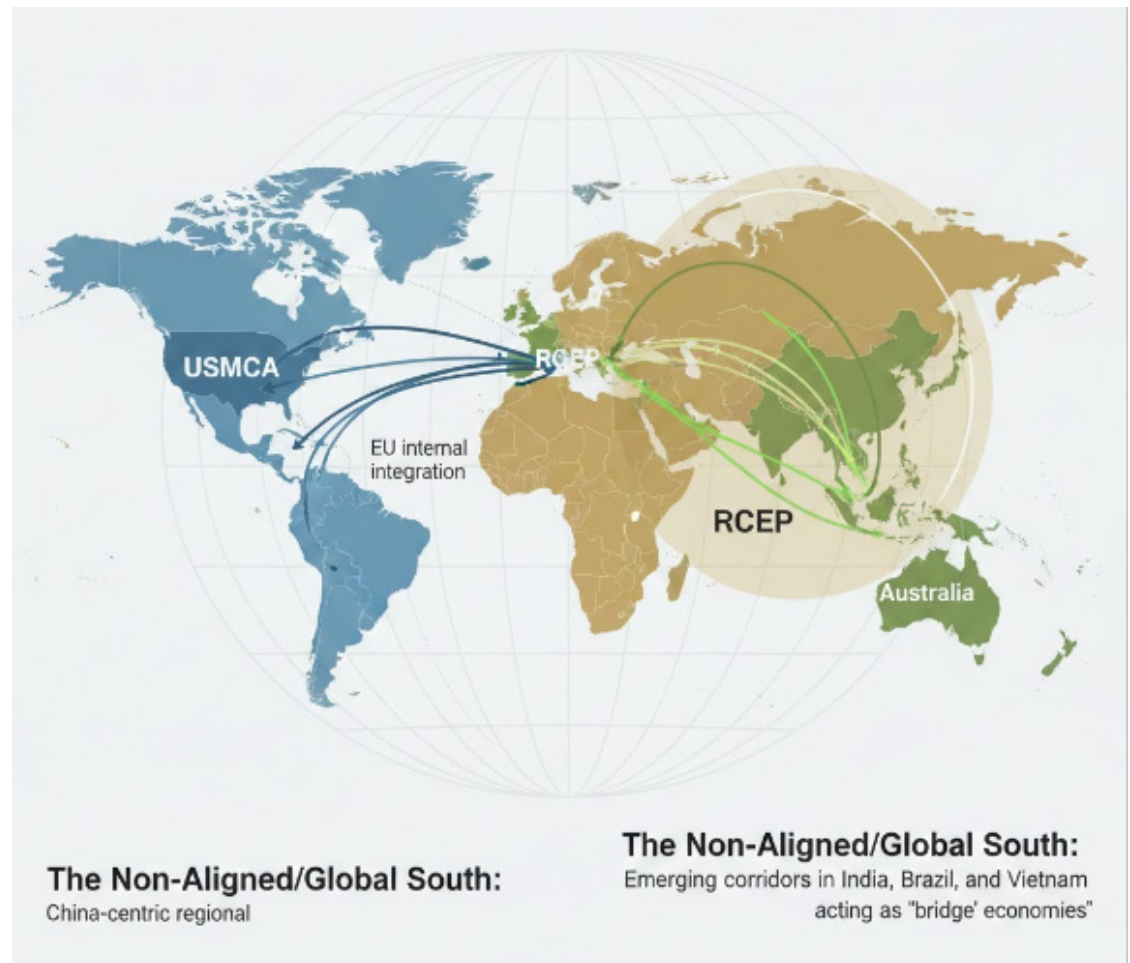


Fig 2 | The evolving trade map (2026)—Visualizing the shift from a unipolar global web to a fragmented three-hub model. Note: The figure illustrates the evolution of global production networks toward regionalized trade corridors, driven by geopolitical fragmentation and supply strategies geared toward resilience

Freeing trapped cash-in-transit allows corporations to safely downsize their precautionary financial safety stock. This optimization offers a structural counterweight to the resilience tax, accelerating the recirculation of liquidity throughout the supply chain. Instead of directly increasing accounting profitability, CBDC-enabled settlement improves corporate financial flexibility through lower working capital requirements, greater cash availability, and more robust free cash flow generation.

Risks to Financial Intermediation and Stability

The race for what is now called critical minerals like lithium, cobalt, and rare earths has inaugurated a new age of export control and state interventionism.^{12,34} The management of raw materials is the new economic lever of statecraft. In response, programmable money via CBDCs enables Smart Contracts that release payments only upon the verification of physical milestones (e.g., a shipment clearing a specific port). This creates a trustless resilience mechanism in high-risk corridors, ensuring that geopolitical friction does not lead to a total cessation of trade credit.^{30,35,36}

Agentic AI and the Political Economy of Resilience

In order to counter these risks, companies have increasingly turned their focus toward supply chain 4.0.^{37–39}

The Rime Horizon Mismatch

Businesses can also execute “what-if” scenarios for port strikes, hurricanes, or border closings by simulating their existing supply chain infrastructure on a virtual platform.^{40,41} In 2026, Agentic AI—autonomous systems that allow for rerouting of shipments without human interaction—is already cutting recovery time by 60% or more.⁴²

A major European retailer responded to persistent maritime disruptions affecting Red Sea and Cape of Good Hope routes by implementing a digital twin integrated with Agentic AI decision-support systems. The platform continuously evaluated over 1,000 alternative logistics scenarios, incorporating vessel availability, port congestion, customs delays, and multimodal transport options across maritime and rail corridors. This approach aligns with recent advancements in digital twins and agentic AI for supply chain disruption management and operational resilience.^{22,40,41,43}

Table 5 | Comparison of a traditional linear model versus a circular model in sustainability

Metric	Linear Model (Traditional)	Circular Model (Resilient)
Sourcing	Global raw materials	Local recycled inputs
Volatility exposure	High (susceptible to global price spikes)	Low (stable domestic supply)
Logistics risk	High (reliant on long-haul sea freight)	Low (streamlined reverse logistics)
Sustainability	Low (high carbon footprint)	High (net zero alignment)

Prior to implementation, the retailer faced substantial variability in lead time due to frequent route deviations and unpredictable shipping schedules. After implementation, lead-time variation decreased by approximately 23%, while average safety stock levels were reduced without compromising product availability. Service levels remained above 97%, despite the increased transport distances imposed by regional disruptions. These results are consistent with previous studies reporting that AI-enabled forecasting, digital twins, and intelligent logistics systems improve supply chain visibility, reduce uncertainty, and enhance operational performance under disruptive conditions.^{7,22,23,43}

The reported performance indicators are derived from the calibrated simulation framework described in Section “Methods” and are intended to illustrate the operational resilience mechanisms enabled by AI, rather than to disclose confidential company-specific operational data.

The reduction in operational uncertainty translated into a measurable attenuation of bullwhip amplification (α), as improved demand forecasting and real-time inventory visibility reduced unnecessary upstream order fluctuations. Although transport distances increased by approximately 12%, dynamic routing algorithms minimized the propagation of disruption, allowing the retailer to maintain stable replenishment cycles while reducing safety stock requirements. Similar improvements in resilience and inventory optimization have been reported in studies on digital supply chain management, risk mitigation, and dynamic inventory control.^{40,41,44,45}

This example illustrates how digital twins and Agentic AI enhance resilience primarily by reducing operational variability, rather than eliminating geopolitical risks per se. The resulting reduction in lead-time variation directly contributes to a lower amplification of the bullwhip effect (α), a reduction in the value at geopolitical risk (VaR_y), and improved working capital (WC) efficiency. Consequently, AI-enabled supply chain architectures provide a practical mechanism for strengthening operational continuity under conditions of persistent geopolitical uncertainty, supporting the broader resilience framework developed in this study.^{20,22,43,45,46}

The Collective Action Problem

Today, sustainability is considered a resilience strategy.^{42,43} Recycling materials reduces businesses’ vulnerability to the dangers of international shipping

and the markets of the raw materials.^{11,47,48} Table 5 illustrates the differences between the traditional linear model and the circular model in terms of sourcing, volatility exposure, logistics risk, and sustainability outcomes.

The Fiscal–Monetary Nexus: A New Era of Coordination

Entering 2026, a new age of collaboration has been created by the interaction of national economic policies, third-party logistics, and digital monetary mandates. Today, stability in the value chain is essential for managing inflation and creditworthiness. Central banks now increasingly view the operational continuity of CBDC-led trade platforms as a core mandate for maintaining price stability, as supply shocks remain the primary driver of 2020s-era inflation.^{19,35} It is within this paradigm that there is a transition from “cost-first” to “stability-first” architecture.^{44,46}

Multi-Sourcing and the “N+1” Strategy

The age of “single-source dependency” is, in effect, at the end of the line. The “n+1” approach requires the presence of a core source, as well as qualification and procurement from “secondary sources in separate geographic or geopolitical regions.”³³ Although “regionalizing production may add 5%–10% to the cost of each unit,” the “resilience cost of the binary threat of complete supply chain failure” is the cost of not doing so.³¹ The emphasis is placed upon “near-shoring,” such as Mexico for the USA or Eastern Europe for the EU. The transition from “cost-first” to “stability-first” architecture necessitates a “resilience tax”. Quantitative modeling of “friend-shoring” reveals that while it provides insurance against extreme geopolitical disruptions, it imposes significant macroeconomic costs. Global GDP losses resulting from fragmented trade blocs are estimated to range between 0.1% and 4.6% of global GDP. These costs are notably higher than the economic impact of previous shocks, such as the 2022 sanctions on Russia or the pandemic lockdowns in China. However, firms with AI-mature supply chains appear better positioned to absorb these costs, showing a 23% higher profitability margin than their less automated peers.^{49,50}

The operational and financial trade-offs between legacy just-in-time systems and stability-first models are evaluated via an iterative network simulation engine. The core logic for reproducing the variance dampening, value-at-risk containment, and baseline earnings per share impacts is detailed in the following algorithmic framework:

1. Initialize global constants and core variables:
- Define the sample matrix size where the total number of firms equals 500.
 - Establish confidence layer parameters where gamma equals 0.05 for value-at-risk calculations.
 - Set the total number of evaluation iterations to 10,000 for the Monte Carlo loop.
 - Load the sector stratification matrix containing the target baseline scores for the AI maturity index, end-to-end visibility index, and MS.

2. Loop through each simulation iteration from 1 to 10,000:
 - For each selected corporate entity in the panel, assign its respective sector attributes and initial concentration baseline values.
 - Generate a random disruption shock vector modeling the sector-specific evaluated shock scenarios, introducing logistics friction based on historic maritime, trade war, or resource nationalization distributions.
 - Calculate the operational latency variable, setting the baseline timeline delay according to the firm's technology index configurations. If the automation layers are operationalized at peak efficiency scores, compress settlement latency (τ) toward zero to simulate programmable settlement mechanisms.
3. Calculate operational and volatility outputs:
 - Determine the bullwhip amplification (α) metric by taking the ratio of upstream ordering variance against downstream retail demand variance.
 - Evaluate the geopolitical value-at-risk containment by parsing the 95th percentile maximum loss threshold from the disrupted iteration matrix.
 - Quantify the short-term premium reallocation by subtracting the operational cost of multi-sourcing and regionalization from the baseline financial metrics to determine the absolute earnings per share resilience tax drag.
4. Evaluate long-term economic viability:
 - Run a sensitivity function across the baseline cost of regionalization, scaling the baseline premium from 0.01 up to 0.15.
 - Compute the net ratio by dividing the change in geopolitical value-at-risk by the change in the earnings per share resilience tax.
 - Identify the critical break-even threshold where the computed net ratio drops below 1.0 to isolate the inflection point where regionalization premiums induce secular economic stagnation.
5. Compile and export system matrices:
 - Aggregate mean outputs, calculate the 95% confidence intervals across all evaluation iterations, and output the stabilized dataset to generate the figures and tables.

Dynamic Inventory Buffering

Synthetic initialization preserves the statistical properties of the observed datasets, avoiding the disclosure of confidential operational information at the enterprise level. Calibration parameters were selected to reproduce the empirical distributions observed in the sampled sectors, rather than individual corporate observations. The parameters utilize randomized Gaussian distributions bounded by real-world tracking metrics compiled from 2024 through 2026. The baseline volatility inputs rely on standard error adjustments calibrated against regional macroeconomic data. The synthetic data arrays mirror the structural metrics observed in the main panel: a mean corporate revenue distribution centered at 34.2 billion dollars, an average

node complexity mapping of 1,420 suppliers per corporate system, and a concentrated unipolar regional dependency averaging 68.4%.

The industry has, in essence, moved from “zero inventory” to “strategic stocks” for critical components where lead-time volatility is high. AI-driven analytics will pinpoint “bottleneck” components that have no immediate substitutes. Financial departments should perceive these buffers as key assets, not idle capital, and adjust cash flow expectations to higher levels of inventory.^{45,51}

End-to-End Visibility and Digital Control Towers

No resilience will be possible without radical transparency along the value chain. “Control towers” would need to be put in place within organizations, integrating not only Tier-1 data but also Tier-2 and Tier-3 supplier insights. Automated flags for geopolitical unrest, labor strikes, or environmental disasters allow autonomous rerouting before the physical flow is impacted. Mapping of deep-tier vulnerabilities prevents shadow disruptions, a situation where a minor sub-component supplier triggers a major production halt.^{45,51}

Governance Risks in Programmable Rails and AI Oversight

While “friend-shoring” and CBDCs enhance resilience, they introduce novel systemic risks that require robust governance^{45,51}:

- Cybersecurity and single points of failure: Programmable money rails and atomic settlement centralize liquidity risk. A smart contract exploit or a localized failure in a CBDC ledger could trigger a total cessation of trade credit across a “three-hub” corridor.
- Privacy and AML/CFT compliance: The transparency required for supply chain 4.0 conflicts with corporate data privacy. Furthermore, decentralized trade finance must align with evolving anti-money laundering (AML) and counter-financing of terrorism (CFT) standards to prevent shadow trade in fragmented blocs.
- AI algorithmic bias: agentic AI systems, if unmonitored, may exhibit digital herd behavior, where multiple autonomous agents simultaneously re-route shipments to the same alternative port, creating secondary bottlenecks. Effective AI oversight requires human-centric guardrails to prevent such recursive volatility.

Conclusion

The results indicate that adopting architectures that prioritize stability has become a strategic necessity for maintaining resilient global value chains under conditions of persistent geopolitical fragmentation. The findings support the ongoing transition from the traditional efficiency-oriented JIT paradigm to a resilience-oriented model, in which geopolitical risk becomes a central determinant of supply chain design. As argued by Roubini,⁴⁴ the cost of resilience represents the price of reducing exposure to extreme catastrophic risks that could otherwise trigger systemic disruptions

in global supply chains. The simulation results corroborate this interpretation, demonstrating that the cost of resilience should be seen as a strategic investment in mitigating geopolitical risk, and not as a permanent loss of economic efficiency. Consequently, it represents a reallocation of resources toward long-term systemic resilience, rather than a deadweight economic loss.

Furthermore, the implementation of Supply Chain 4.0 technologies, particularly Agentic AI and digital twins, fundamentally transforms the operationalization of supply chain resilience. Unlike previous approaches, which relied primarily on the proactive accumulation of inventory, digital technologies allow companies to replace inventory with information, improving demand visibility, predictive capabilities, and real-time operational responsiveness. This transition requires closer coordination between governments, financial institutions, and private companies than was typical in the highly liberalized business environment of previous decades. Consequently, the emerging model of Managed Globalization emphasizes strategic resilience, digital governance, and supply chain security, along with economic efficiency. Instead of focusing solely on minimizing production costs, companies must increasingly prioritize continuity of supply, operational flexibility, and risk mitigation. Thus, organizational performance should no longer be evaluated solely through short-term profitability indicators, such as EPS, but should also incorporate risk-adjusted resilience measures, including VaR γ and WC efficiency.

Limitations and Future Research

Despite the contributions of this study, some limitations should be acknowledged. First, the purposive sample is restricted to large multinational corporations operating in strategically important sectors. Consequently, the conclusions may not be directly generalizable to SMEs, which typically face greater financial and technological constraints when implementing resilience-oriented supply chain strategies. Second, although the simulation framework was calibrated using publicly available international datasets and validated through historical backtesting, the estimates presented remain scenario-based, not causal relationships. The observed relationships should therefore be interpreted as risk-adjusted projections under alternative geopolitical disruption scenarios, and not as definitive empirical results. Third, the adoption of advanced technologies such as Agentic AI, digital twins, and wholesale CBDCs may be endogenous, as firms with superior managerial capabilities are also more likely to invest in digital transformation. Future research should expand the proposed framework using longitudinal data at the firm level to identify more robust causal relationships between technological maturity, geopolitical risk, and long-term organizational performance.

Ultimately, the findings demonstrate that organizational performance in an increasingly fragmented global economy should be assessed using a broader, risk-adjusted framework, rather than relying solely on traditional short-term profitability metrics. In this

context, value-at-risk (VaR γ), network agility, WC efficiency, and systemic resilience emerge as complementary performance indicators to conventional financial measures such as EPS. Organizations that successfully integrate resilience-driven outsourcing strategies with Agentic AI, digital twins, and programmable financial infrastructures will be better positioned to maintain long-term competitiveness in a landscape of persistent geopolitical uncertainty.

Data Availability Statement and Reproducibility Statement

Data Availability Statement

The empirical data supporting this study were obtained from publicly available sources, including the World Bank, UNCTAD, the WTO, the BIS, and publicly available corporate disclosures. To preserve confidentiality and avoid disclosing commercially sensitive information, company-level observations were standardized and incorporated into a synthetic simulation framework. The synthetic datasets were calibrated to reproduce the statistical properties of the observed data and the methodological parameters described in this study. Additional methodological details are available from the corresponding author upon reasonable request.

Declaration of Reproducibility

The simulation framework is fully described through the methodological workflow presented in Sections 2 and 6. Monte Carlo simulations ($N = 10,000$) were performed using standardized sectoral parameters, allowing the reported estimates of VaR γ , WC, and bullwhip amplification (α) to be reproduced using equivalent parameterization and publicly available macroeconomic datasets.

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