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From Efficiency to Resilience in Maritime Transport Systems: A MAPA-Based Framework for Explaining Why the Freight Rate Is No Longer the Cost of Transportation

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Abstract

Maritime transportation costs have traditionally been evaluated through freight rates, port charges, fuel costs, transit time and inventory costs. This approach reflected an efficiency-oriented model in which global transport systems were assumed to operate through relatively stable routes, predictable port calls, manageable frictions and just-in-time logistics (globalization). That assumption has weakened (regionalization). Recent shocks linked to COVID-19 aftereffects, policy volatility, geopolitical conflict, climate stress and industry restructuring have generated operational responses such as frontloading, rerouting, fuel surcharges, blank sailings, schedule unreliability and port-system volatility. These responses increase transportation cost through expanded friction, synchronization stress and continuity requirements that are not fully captured by the quoted freight rate. This paper introduces the author-developed MAPA framework--Market, Assets, Platform and Authority--as a system-level model for explaining how maritime transportation cost expands beyond the freight rate. The framework classifies maritime cost through four interacting layers: market volatility, asset usability, platform synchronization and authority credibility. Using secondary data from Global Port Tracker, industry sources, carrier reports, institutional sources and Panama port-system evidence, the paper examines 2025-2026 disruption channels including policy-driven frontloading, rerouting, fuel and insurance repricing, schedule unreliability and hub-governance uncertainty. The paper contributes to industrial engineering and operations management by reframing maritime transportation as a risk-adjusted operating system rather than a point-to-point freight transaction.

Keywords
Maritime transport systems, risk-adjusted cost, freight rates, supply-chain resilience, transshipment hubs

1. Introduction
Maritime transportation has long been interpreted through an efficiency lens. Competitiveness was associated with lower freight rates, larger vessels, shorter routes, higher asset utilization, lean inventories and predictable port operations. In that environment, the freight rate became the most visible commercial signal of transportation cost, even though it never captured every operational friction in the system.

That signal is now less complete. Maritime transport has never been frictionless: port delays, documentation costs, customs procedures, weather events, labor disputes, congestion and insurance premiums have always affected the movement of goods. What has changed is the scale and strategic relevance of those frictions. They are more frequent, more systemic and more directly connected to risk management.

The research question builds on two prior applied essays by the author, published outside the peer-reviewed literature and cited here for provenance rather than as independent supporting evidence. Tapiero (2026a) examined the movement of maritime strategy from efficiency to resilience, arguing that firms increasingly pay for reliability,

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redundancy, optionality and continuity. Tapiero (2026b) argued that the freight rate is no longer the full cost of transportation because the quoted price of movement does not capture disruption, delay, rerouting, compliance, insurance, synchronization and continuity costs. The present paper formalizes and tests these two applied claims through the MAPA framework and the validation reported in Section 5.4, rather than treating them as established findings.

The change is also financial. Maritime disruption has moved from the logistics department into the profit-and-loss structure of firms. The freight rate remains visible, but it does not capture the full exposure created by bunker and fuel volatility, war-risk and P&I insurance, blank sailings, rerouting, transshipment stress, equipment rotation, customer reliability requirements and service commitments.

The author-developed MAPA framework was created from applied maritime-policy work in Panama, where Canal reliability, port performance, carrier strategy, public authority and geopolitical exposure cannot be analyzed separately. MAPA stands for Market, Assets, Platform and Authority. It separates maritime system performance into four interacting layers: market conditions that shape cargo flows; physical and financial assets used to move cargo; the logistics platform that synchronizes vessels, ports, terminals, rail, data and services; and the authority layer that defines rules, neutrality, trust and governance.

The relationship between disruption sources and maritime operating responses is not one-to-one. A single shock can generate several operational responses, and different shocks can converge into the same response. Rerouting, for example, may be caused by geopolitical conflict, sanctions, tariff avoidance, climate-related canal restrictions, port congestion, insurance constraints or carrier network redesign. For this reason, the paper treats frontloading, rerouting, blank sailings, fuel surcharges, schedule unreliability and port-system volatility as transmission mechanisms rather than root causes.

The paper's contribution is to use MAPA to connect root shocks, operational transmission mechanisms, P&L effects and maritime cost channels in one model. In practical terms, the framework asks a question that freight-rate comparisons often miss: what does it cost to keep cargo moving when the system is under stress?

Panama is used as an illustrative case because it is not only a geographic corridor. It is a maritime operating system whose value depends on reliability, port neutrality, water security, concession governance, multi-carrier access and the capacity to absorb cargo shifts inside the national platform.

1.1 Objectives

- To examine why the freight rate has become an incomplete proxy for maritime transportation cost.
- To introduce the author-developed MAPA framework--Market, Assets, Platform and Authority--as a system-level model for analyzing maritime transport cost.
- To classify maritime cost expansion through four channels: market volatility, asset usability, platform synchronization and authority credibility.
- To analyze 2025-2026 disruption events, including frontloading, rerouting, fuel and insurance shocks, schedule unreliability, blank sailings and port-system stress.
- To explain why maritime disruption has become a P&L issue for firms, affecting margins, working capital, insurance, equipment utilization, customer reliability and service commitments.
- To apply the MAPA framework to Panama as an illustrative case of trusted-node value and maritime system resilience.
- To propose operational and policy improvements for shippers, carriers, ports and maritime hub authorities.

2. Literature Review

2.1 Supply-Chain Resilience and the Efficiency-Resilience Trade-Off

The literature on resilience explains why the efficiency paradigm is no longer enough by itself. Traditional supply-chain design emphasized cost minimization, high asset utilization, low inventories and just-in-time coordination. Resilience research does not reject those goals; it shows their limits when disruptions are frequent, systemic or strategically significant. Sheffi (2005) frames resilience as the ability of firms to anticipate, absorb and recover from disruption while sustaining competitive performance. Hollnagel (2013) defines resilience engineering as the ability of

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a system to adjust before, during or after disturbance so that required operations can continue under expected and unexpected conditions.

Recent operations-management literature has extended this argument from firm-level continuity to network-level reconfiguration. Ivanov (2026) distinguishes between short disruptions that can be absorbed through buffers and longer disruptions that require structural changes in the supply-chain network. Consulting and institutional sources make a similar point from a managerial perspective: redundancy, alternative suppliers, inventory buffers and contingency coordination can reduce disruption exposure, but they also raise working capital, operating cost and complexity (Boston Consulting Group 2025; Federal Reserve Bank of Richmond 2025). For maritime transport systems, this trade-off is central. A system optimized only for low rates and high utilization may perform efficiently under normal conditions but generate high system cost under disruption.

2.2 Maritime Transportation Cost and Freight-Rate Limitations

A second literature stream deals with the difference between the freight rate and the full cost of maritime transportation. Freight rates remain an essential market signal, but realized transport cost also depends on route length, schedule reliability, insurance, fuel, port performance, emissions regulation, congestion and delay. UNCTAD (2025) documents how rerouting, maritime disruptions and freight-rate volatility have increased transport costs, especially for economies that depend heavily on maritime connectivity. Sea-Intelligence and Xeneta schedule-reliability data show that price and reliability do not move together automatically; a lower quoted rate may coincide with longer delays, missed connections or higher buffer requirements (Sea-Intelligence Maritime Analysis 2026; Xeneta 2026).
For this paper, the implication is direct: in an efficiency model, the freight rate approximates the commercial price of movement; in a resilience model, the relevant cost is the cost of maintaining flow under uncertainty. Carrier reports and earnings discussions reinforce this point because fuel, insurance, rerouting, blank sailings, service reliability and customer commitments increasingly affect margins and operating performance (A.P. Moller - Maersk 2026; Hapag-Lloyd 2026).

2.3 Policy Volatility, Frontloading and Cargo Timing

A third literature stream examines how policy uncertainty changes cargo timing. Tariffs, sanctions, forced-labor rules, customs enforcement and trade restrictions may alter the cost of waiting. When firms expect tariffs or regulatory costs to increase, they often move cargo earlier than normal. This behavior is commonly described as frontloading. National Retail Federation and Hackett Associates (2025, 2026) repeatedly document the relationship between U.S. tariff uncertainty and import acceleration in Global Port Tracker releases. The Port of Los Angeles (2025) also reported record January 2025 volume in a context shaped by tariff anticipation and labor-risk concerns.

Policy research provides the event context for these import-cycle changes. CSIS (2025) identifies the April 2025 tariff measures as a major inflection point in U.S. trade policy, while CEPR (2025) analyzes how trade policy uncertainty can disrupt supply-chain decisions at the firm level. These sources support the paper's treatment of frontloading as an operational transmission mechanism rather than a root cause. The root cause is policy volatility; the maritime response is cargo pull-forward, import surges, later corrections and higher synchronization pressure on ports, carriers, warehouses and inland networks.

2.4 Rerouting, Effective Capacity and Geopolitical Disruption

A fourth stream of evidence concerns rerouting and effective capacity. Maritime routes can be disrupted by war, sanctions, chokepoint insecurity, insurance restrictions, climate-related canal constraints, port congestion or carrier network redesign. The operational result may be similar even when the cause differs: longer routes, more vessel-days, higher fuel consumption, schedule uncertainty, equipment imbalance and increased emissions. UNCTAD (2025) shows that Red Sea and Suez Canal disruptions increased ton-miles and maritime trade costs as vessels diverted around the Cape of Good Hope. Maritime insurance and risk analyses also indicate that war-risk and security premiums can remain elevated even when some traffic resumes (Kpler 2025).

For operations management, the key point is that nominal fleet capacity is not the same as usable capacity. A vessel that remains in the fleet but spends more days completing each rotation supplies less effective capacity to the network. Rerouting therefore affects not only voyage distance but also asset productivity, schedule integrity and system reliability. This mechanism connects the Assets layer of MAPA to the P&L of firms: fuel costs, charter costs, insurance costs, emissions exposure and equipment rotation all change when routes become longer or less predictable.

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2.5 Transshipment Hubs, Synchronization and Network Reliability

A fifth literature stream treats maritime networks and transshipment hubs as coordination systems. Operations-research studies of feeder routing and transshipment coordination show that hub performance depends not only on crane productivity but also on schedule alignment, berth-window reliability, feeder connections and congestion management (Transportation Research Part B 2021). The UNECE and SMDG (2025) white paper on transshipment emphasizes closer integration among actors and digital information flows, reinforcing the view that transshipment is an information and synchronization problem as much as a terminal-handling problem.

This literature is central to the Platform layer of MAPA. A transshipment hub creates value when it synchronizes mainline vessels, feeders, yard capacity, labor, equipment, gates, rail or truck connections, data and documentation. When volatility increases, synchronization costs rise through dwell time, missed connections, blank sailings, yard congestion and empty-container repositioning. The Gemini Cooperation between Maersk and Hapag-Lloyd provides a current industry example of network redesign aimed at reliability through hub-and-spoke coordination and modular service design (Hapag-Lloyd 2025; Kuehne+Nagel 2026). The relevant issue is not only whether a ship can call a port, but whether the system can maintain reliable flow across linked nodes.

2.6 Carrier Network Redesign, Governance and Trusted Nodes

The sixth literature stream concerns carrier strategy, vertical integration and trusted nodes. Major carriers increasingly compete not only through vessel capacity but also through control of terminals, logistics services, data, inland connections and customer interfaces. MSC's standalone east-west network and terminal-investment strategy illustrate a movement toward greater control of network design and node access (MSC 2024; Reddal 2025). CMA CGM's acquisition of FedEx Supply Chain through CEVA Logistics similarly shows that ocean carriers are extending into contract logistics and customer-facing supply-chain functions (FedEx Corp. 2026).

These changes raise governance questions for maritime hubs. If carriers increasingly control terminals, inland logistics and data, the neutrality and common-user character of a hub become part of its economic value. Panama is therefore relevant as an illustrative case because its competitiveness depends on Canal reliability, port performance, water security, concession governance, terminal diversity and institutional credibility. Recent Panama port data show that aggregate throughput can remain stable even when cargo reallocates significantly across terminals, indicating that resilience depends on platform depth and governance quality as much as geography (Seatrade Maritime 2026; Infobae 2026). The Authority layer of MAPA captures this dimension: rules, neutrality, transparency, compliance, cyber resilience and institutional trust reduce or increase the friction assigned to a maritime node.

2.7 Literature Synthesis and Research Gap

The literature shows that supply chains are shifting from efficiency to resilience, that maritime freight rates are volatile and incomplete indicators of total cost, that policy uncertainty changes cargo timing, that geopolitical and climate disruptions reduce effective capacity, that transshipment hubs depend on synchronization, and that carrier network redesign is changing the governance of maritime nodes. These streams are usually examined separately.

The research gap addressed here is the lack of a single maritime-cost framework that links root shocks, operational responses, firm-level P&L effects and the institutional character of maritime nodes. MAPA addresses this gap by classifying transportation cost through Market, Assets, Platform and Authority. It explains why the freight rate is no longer the full cost of transportation: market volatility changes cargo timing; asset constraints change usable capacity and fuel exposure; platform stress changes synchronization cost; and authority-related uncertainty changes institutional friction and trusted-node value.

3. Methods

The study uses a conceptual and descriptive research design. It does not attempt to estimate a causal econometric model. Instead, it develops and evaluates a system-level framework that explains how maritime disruptions expand transportation cost beyond the quoted freight rate. The unit of analysis is the maritime transport system: cargo flows, vessels, ports, terminals, feeders, data, contracts and institutions.

The method follows five steps. First, a category-based literature synthesis identifies the research streams behind the shift from efficiency to resilience. Second, MAPA is specified as an author-developed framework for classifying maritime cost channels. Third, disruption events are coded by root shock, operational transmission mechanism, P&L

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effect and MAPA layer. Fourth, descriptive numerical evidence is used to compare event windows with reported changes in loaded imports, rerouting, schedule reliability, fuel and insurance exposure and port-system performance. Fifth, Panama is used to test the practical usefulness of the framework in a hub context.

The event classification method distinguishes root shocks from system responses. COVID-19 aftershocks, policy volatility, geopolitical conflict, climate stress and industry restructuring are treated as root shocks. Frontloading, rerouting, fuel surcharges, blank sailings, schedule unreliability and port-system volatility are treated as operational transmission mechanisms. P&L effects are identified through the channels most directly affected: fuel and bunker cost, insurance and risk premiums, working capital, equipment utilization, customer reliability, service penalties and institutional risk.

The statistical analysis is descriptive. It uses reported month-on-month and year-on-year changes in loaded import volumes to identify cargo-volatility episodes and compares those episodes with documented policy or disruption windows. The analysis does not claim that each event is caused by one factor. Instead, it recognizes that several root shocks can produce similar operational responses and that one shock can trigger several responses at the same time.
Validation is based on triangulation, construct consistency and source discipline. Triangulation compares import-volume data, maritime trade-cost reports, schedule-reliability indicators, carrier documents and Panama port evidence. Construct consistency checks whether each MAPA layer is linked to an observable mechanism and a plausible P&L effect. The manuscript cites the underlying source directly where possible, including institutional, company, academic and industry sources.

4. Data Collection

The paper uses secondary data from institutional, industry, company and academic sources. The main quantitative data are drawn from Global Port Tracker: North American Trade Outlook reports produced by Hackett Associates in partnership with the National Retail Federation. These reports provide monthly loaded import volumes for monitored North American ports, including month-on-month and year-on-year changes. The data are used to identify import-volume surges and corrections around policy and disruption windows.

The 2025 dataset includes reports from January through December 2025. Key observations include the January 2025 record import level, the March-April 2025 pre-tariff surge, the May 2025 correction, the July 2025 tariff-pause surge and the subsequent decline in September and October. The 2026 dataset includes reports from January through June 2026 and captures continued import volatility linked to tariff uncertainty, fuel costs, blank sailings and early peak-season cargo pull-forward. Additional sources triangulate non-volume channels such as rerouting, fuel and insurance repricing, schedule reliability, carrier network redesign and Panama port-system performance (Table 1).

Table 1. Data sources used in the study

Data family	Source	Period	Use in paper	MAPA layer
Import volumes	Global Port Tracker / NRF / Hackett Associates	2025-2026	Frontloading, TEU surges and import corrections	Market
Import confirmation	Descartes data reported by Baird Maritime and other trade sources	June 2026	Confirmation of June 2026 import acceleration	Market
Maritime trade costs	UNCTAD Review of Maritime Transport 2025	2024-2025	Rerouting, ton-miles, trade costs and effective capacity	Assets
Reliability	Sea-Intelligence and Xeneta schedule-reliability indicators	2025-2026	Schedule reliability, delay days and network stress	Platform
Carrier networks	Maersk, Hapag-Lloyd, MSC, CMA CGM / FedEx sources	2024-2026	Network redesign, hub-and-spoke operations and vertical integration	Assets / Platform
Panama case	Seatrade, Infobae, Panama Canal and port-system evidence	2025-2026	Hub resilience, cargo reallocation and trusted-node value	Platform / Authority

The manuscript cites the underlying source directly, including UNCTAD, Global Port Tracker, Descartes-related reporting, Sea-Intelligence, Xeneta, carrier reports, Panama sources and peer-reviewed literature.

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5. Results and Discussion

The results are organized around the four MAPA layers and distinguish root shocks from operational responses, P&L effects and cost channels. Frontloading is treated as the most visible Market-layer signal, but it is not the empirical center of the paper. The Assets, Platform and Authority layers are evaluated through non-volume indicators such as rerouting days, effective capacity absorption, ton-mile growth, insurance repricing, fuel surcharges, schedule reliability, equipment imbalance, port-system reallocation and water-related capacity constraints.

5.1 Numerical Results

Table 2 summarizes the main transmission logic. It shows that root shocks do not map one-to-one into operational responses. Several shocks can produce similar responses, and a single shock can create multiple cost channels. This is why the freight rate becomes incomplete as a proxy for transportation cost (Table 2).

Table 2. Root shocks, operational transmission and P&L effects

Root shock	Operational transmission	Main P&L effect	MAPA layer
Policy volatility	Frontloading, sourcing shifts, port substitution, tariff-window surges	Inventory cost, warehousing, revenue timing, demand uncertainty	Market
Geopolitical conflict	Rerouting, war-risk premiums, insurance restrictions, security delays	Higher voyage cost, risk premium, margin compression	Assets
Fuel and energy shock	Bunker adjustment factors and emergency fuel surcharges	Operating-cost increase and incomplete cost pass-through	Assets
Network instability	Blank sailings, schedule unreliability, missed connections	Service failures, customer penalties and buffer inventory	Platform
Port and hub stress	Dwell time, yard congestion, feeder disruption, cargo reallocation	Synchronization cost, delay cost and asset underutilization	Platform
Governance and regulation	Compliance burden, access risk, concession uncertainty	Institutional friction, financing or insurance premium, trusted-node premium	Authority
Climate stress	Canal restrictions, water constraints and route uncertainty	Reduced usable capacity, slot scarcity and reliability loss	Authority / Platform

The Market layer captures how demand, trade policy, tariff windows and regionalization affect cargo flows. Table 3 summarizes the import-volume evidence used to measure this channel. The evidence from Global Port Tracker and Descartes-related reporting shows that policy volatility can turn time into cost. Firms frontload cargo because the cost of waiting becomes uncertain, not necessarily because final consumer demand has increased.

Table 3. Selected import-volume shocks and MAPA interpretation

Month	Observed volume or change	Reported context	MAPA interpretation
Jan. 2025	2.49 million TEU; +5.7% MoM and +13.5% YoY	Record January after labor-risk and tariff anticipation	Policy uncertainty changes cargo timing
Mar. 2025	2.40 million TEU; +7.4% MoM and +9.6% YoY	Tariff-war uncertainty and pre-tariff movement	Frontloading becomes an operational response
Apr. 2025	2.48 million TEU; +3.3% MoM and +8.9% YoY	Liberation Day tariff environment	Policy windows compress cargo flows
May 2025	2.24 million TEU; -9.6% MoM	Correction after earlier pull-forward	Timing shifts create later air pockets
Jul. 2025	2.63 million TEU; +17.4% MoM	Tariff-pause window and early peak movement	Cargo volatility raises synchronization pressure
Mar. 2026	2.43 million TEU; +14.1% MoM	Replacement-tariff and fuel-cost uncertainty	Uncertainty again pulls cargo forward
Jun. 2026	About 2.4 million TEU; +8.2% YoY in Descartes data	Tariff fears, war costs and freight-cost expectations	Policy and cost uncertainty sustain elevated timing shifts

Table 4 complements the import-volume evidence by summarizing non-volume indicators across the Assets, Platform and Authority layers. These indicators broaden the empirical basis of the paper beyond frontloading. They show that disruption also appears in rerouting days, absorbed capacity, ton-mile growth, insurance repricing, delay charges, empty repositioning, schedule reliability, hub reallocation and water-related capacity limits.

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Table 4. Quantitative evidence across non-volume MAPA cost channels

MAPA layer	Indicator	Quantitative evidence	Cost implication
Assets	Rerouting and usable capacity	Cape routing adds about 10-15 days (independent trade-press estimates converge near 9% of global container fleet capacity absorbed); ton-miles rose about 5.9-6.0% in 2024.	Nominal capacity overstates usable capacity; fuel, emissions and cycle-time costs rise.
Assets	Risk pricing and delay charges	War-risk premiums rose from about 0.05% to 1.25% of vessel value in some reports; added costs of $50,000-$100,000 per transit; demurrage and detention can add about 10-25% to total shipping cost.	Insurance, risk and delay costs sit above the quoted freight rate.
Platform	Equipment imbalance	Empty repositioning is estimated at about 41% of global container movements, up from 31% in 2019; match-back ratio fell from 54% to 41.6%.	Repositioning, imbalance and lower asset productivity become synchronization costs.
Platform	Schedule reliability	Gemini reported about 90% reliability in its first year, with some lanes above 95%.	Reliability becomes an engineered service product and a P&L variable.
Authority / Platform	Panama hub depth	Panama ports handled 9.9 million TEU in 2025; transshipment represented about 89% of throughput.	Hub value depends on synchronization depth and trusted-node resilience.
Authority	Concession governance and geopolitical risk	Supreme Court voided the 1997 Hutchison/PPC concession Jan. 30, 2026; interim operations assigned to APM Terminals (Balboa) and TiL/MSC (Cristobal) under an 18-month AMP-approved plan effective Feb. 23, 2026; COSCO suspended all Balboa calls Mar. 10, 2026; China detained 91 of 123 vessels at its ports in March 2026 that were Panama-flagged; CK Hutchison arbitration claims exceed $2 billion.	Terminal-level reallocation (MIT +25.1%, CCT +20.9%, Balboa -12.7%, Cristobal -41.2%, Jan.-May 2026) is primarily a governance shock, not a capacity or demand shock; trusted-node value is directly at stake.
Authority / Platform	Water security and climate risk	2026 Canal slots about 32 versus 36-38 pre-drought; Gatun Lake had climbed back to near-maximum by early 2026 after the 2023 drought, but NOAA's El Nino Watch (April 2026) put the odds of a strong recurrence at about 25% by mid-2026.	A separate, forward-looking risk layered on top of the governance shock; the ACP's $8.5 billion modernization program (incl. a $1.6 billion reservoir project) is a direct policy response.

The Platform layer captures the ability of a maritime system to synchronize vessels, feeders, terminals, yards, labor, gates, rail, trucks, data and documentation. A transshipment hub is therefore not only a cargo-handling facility. It is a synchronization system. The Authority layer captures how rules, governance, neutrality, access, cybersecurity, compliance and institutional trust affect maritime cost. Panama illustrates this interaction because its value as a maritime hub depends not only on geography but also on Canal reliability, water security, port performance and concession governance.

The concession crisis is the Authority layer playing out in real time. Panama's Supreme Court voided the 1997 Panama Ports Company concession on January 30, 2026; operating control at Balboa passed to APM Terminals and at Cristobal to Terminal Investment Limited (MSC), under an 18-month plan the Panama Maritime Authority approved effective February 23, 2026 (Federal Maritime Commission 2026). Beijing read the ruling as a geopolitical move rather than a commercial one. COSCO pulled all container calls from Balboa on March 10, 2026, and within weeks Chinese ports were detaining Panama-flagged vessels at a rate far outside historical norms, 91 of 123 detentions in March 2026 alone, prompting a formal statement from the U.S. Federal Maritime Commission and arbitration claims from CK Hutchison exceeding $2 billion (Federal Maritime Commission 2026). The terminal-level reallocation already reported in Table 4 is best read as a governance and trusted-node shock, then, not a capacity or demand shock. A second, unrelated risk sits alongside it: Gatun Lake had climbed back to near-maximum by early 2026 after the 2023 drought, but NOAA's El Nino Watch, issued in April 2026, put the odds of a strong recurrence at roughly 25 percent by mid-2026 (Panama Canal Authority 2026), part of why the Authority's $8.5 billion modernization program pairs new terminal capacity at Corozal and Telfers with a $1.6 billion reservoir project (Congressional Research Service 2026). A maritime hub's credibility, in other words, is being tested on two fronts that have nothing to do with each other: who gets to run the node, and whether the node will have enough water to keep running at all.

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5.2 Graphical Results

Figure 1 presents the analytical structure of the MAPA-based risk-adjusted maritime system cost framework. The figure separates root shocks from operational transmission mechanisms and P&L effects before classifying the cost channels under Market, Assets, Platform and Authority.

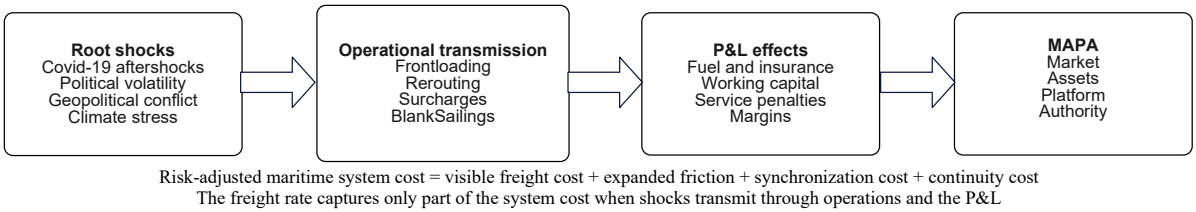
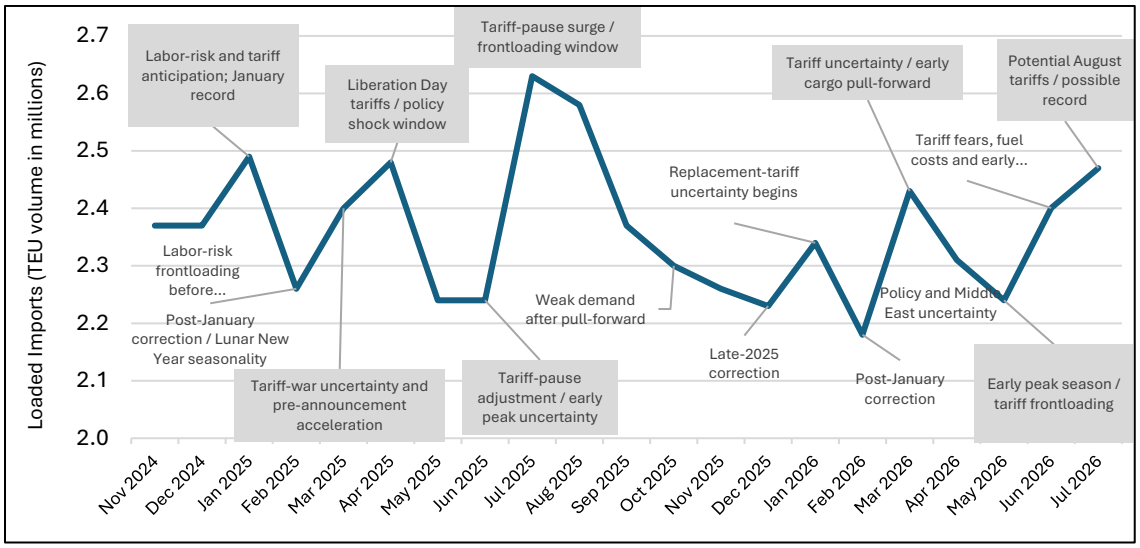


Figure 1. MAPA-based risk-adjusted maritime system cost framework

Figure 2 shows selected monthly loaded import observations from late 2024 through June 2026. The pattern illustrates that import volumes do not move smoothly when policy and disruption windows change. Surges and corrections are consistent with cargo pull-forward, early peak-season behavior and later air pockets.



Source: Hackett Associates/National Retail Association Global Port Tracker.

Figure 2. Monthly loaded imports and disruption windows, 2024-2026

Figure 2 and Table 3 illustrate the Market layer by showing how policy and disruption windows change cargo timing. Table 4 broadens the evidence to the Assets, Platform and Authority layers. Together, the evidence shows that risk-adjusted transportation cost emerges through rerouting, capacity absorption, fuel and insurance repricing, schedule reliability, equipment imbalance, governance and trusted-node performance.

5.3 Proposed Improvements

The proposed improvements are organized under MAPA. The objective is to move decision-making from freight-rate comparison toward risk-adjusted system-cost evaluation (Table 5).

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Table 5. MAPA metrics and proposed improvements

MAPA layer	Operational metrics	Proposed improvement
Market	TEU volatility, frontloading indicators, policy-event windows	Monitor cargo timing risk and include policy-window scenarios in forecasts
Assets	Usable capacity, fuel exposure, war-risk premiums, emissions costs	Evaluate route options by effective capacity and risk-adjusted voyage cost
Platform	Schedule reliability, dwell time, berth-window adherence, feeder connectivity	Measure synchronization performance and invest in digital visibility
Authority	Neutrality rules, concession KPIs, compliance, cybersecurity, water reliability	Strengthen trusted-node governance and common-user access safeguards

5.4 Validation

Validation follows a falsification logic rather than a confirmation logic. For each MAPA layer, the paper states in advance the evidence pattern that would count against the layer, then checks the available evidence against that standard. A layer is coded Supported only if the disconfirming pattern is absent and a positive, temporally-linked pattern is present; Partially supported if evidence is directionally consistent but not independently testable given the available data. For the Market layer, the proposition is tested directly: if cargo-timing volatility were unrelated to policy windows, month-over-month import swings in the six policy-event months already identified in Table 3 should be statistically indistinguishable from swings in the remaining twelve baseline months (November 2024-April 2026). A Welch's t-test rejects that null hypothesis (event $M = 9.6\%$, $SD = 5.3$, $n = 6$; baseline $M = 4.1\%$, $SD = 3.0$, $n = 12$; $t = 2.35$, $df = 6.7$, $p = 0.03$, one-tailed), and a Mann-Whitney U test confirms the result without relying on a normality assumption ($p = 0.01$, one-tailed); two baseline months show larger swings than several event months, which rules out the trivial explanation that event months were simply defined as the largest swings. The Assets, Platform and Authority layers cannot be tested with the same inferential design, because the paper relies on secondary, non-transaction-level indicators for these channels (Table 4) rather than a comparable month-by-month series; for these layers, validation is evidence-consistency testing against a stated falsification criterion rather than a significance test, and results in Table 6 are coded accordingly (Table 6).

Table 6. Validation of the MAPA framework

MAPA layer	Expected mechanism	Observable evidence	Validation result
Market	Cargo-timing volatility is elevated in named policy-event months relative to baseline months (disconfirmed if swings are statistically indistinguishable)	Welch's t-test and Mann-Whitney U on MoM import swings, 18 months, Nov. 2024-Apr. 2026 ($t = 2.35$, $p = 0.03$; Mann-Whitney $p = 0.01$)	Supported
Assets	Rerouting and risk-repricing events are temporally linked to named security/climate shocks (disconfirmed if they moved on a schedule unrelated to those events)	Timing correspondence between UNCTAD ton-mile data, Kpler premium data and dated disruption events	Partially supported
Platform	Schedule-reliability and equipment-imbalance indicators co-move with named network-stress episodes (disconfirmed if metrics were flat or improving through those episodes)	Sea-Intelligence/Xeneta reliability data and empty-repositioning estimates around 2025-2026 stress windows	Partially supported
Authority	Panama terminal-level reallocation coincides with the specific governance and water-security events cited (disconfirmed if reallocation showed no association with those events)	Jan.-May 2026 terminal-level TEU shifts against the concession annulment, COSCO boycott and Canal slot reduction timeline	Partially supported

The validation has limitations. Only the Market layer supports an inferential statistical test with the data at hand; the Assets, Platform and Authority layers rely on secondary reporting rather than transaction-level records, so their validation remains descriptive rather than statistically confirmed. MAPA should therefore be interpreted as a conceptual and operational classification model rather than as a fully validated predictive cost model. Future research

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could extend hypothesis testing to the Assets, Platform and Authority layers using shipment-level data, port-call data, carrier cost records or econometric event studies.

6. Conclusion

The paper examined why the freight rate has become an incomplete proxy for maritime transportation cost. It introduced MAPA--Market, Assets, Platform and Authority--as an author-developed model linking root shocks, operational responses, P&L effects and maritime cost channels. The objectives were addressed by showing how market volatility, asset constraints, platform synchronization and authority credibility expand transport cost beyond the quoted rate.

The main conclusion is not simply that maritime transport can become more expensive. It is that the same shipment now carries more uncertainty through the P&L. Policy volatility affects cargo timing and working capital. Geopolitical conflict and climate stress affect rerouting, fuel, insurance and usable capacity. Platform stress affects dwell time, equipment rotation, schedule reliability and customer commitments. Authority credibility affects institutional friction, access risk and trusted-node value.

Panama shows why this matters in practice. Its maritime value depends not only on geography or distance saved, but also on water reliability, terminal diversity, port neutrality, concession governance, data transparency and the ability of the national platform to absorb cargo shifts. The paper's main contribution is the MAPA-based risk-adjusted maritime system cost framework, which helps managers and policymakers evaluate transportation as a system exposure rather than a quoted freight price.

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Biography

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