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A metric of global maritime supply chain disruptions: The global supply chain stress index - maritime (GSCSI-M)

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ABSTRACT

Global supply chains regularly face widespread disruptions, with events such as the COVID-19 pandemic (2021−22), geopolitical incidents in the Red Sea, and water shortages at the Panama Canal (2023–24) impacting global maritime trade flows and shipping routes. Regardless of the cause, delays or rerouting in critical maritime supply lines have had a global impact. To quantify and assess the magnitude and location of such maritime disruptions, a proposed metric, the Global Supply Chain Stress Index - Maritime (GSCSI-M), has been developed by the World Bank since 2021. The stress metric is derived from AIS (Automatic Identification System) tracking data and calculates the equivalent delayed capacity measured in TEUs (Twenty-foot Equivalent Units), providing insights at the port, country, regional, and global levels. Moreover, the model offers a quantitative perspective on the observed surges in shipping rates during disruptions, based on the assumption that shippers are willing to pay for scarce capacity. The disaggregated data, including port-level details, highlights local bottlenecks and complements the array of tools available to policymakers to address supply chain disruptions. In addition to estimating capacity loss and related costs, this granular information can inform targeted interventions and contingency planning for future events impacting global maritime trade flows.

1. Introduction

In recent years, containerized trade, the backbone of global value chains, has experienced unprecedented disruptions. A confluence of factors has subjected international supply chains to varying stress levels. These include occasional surges in trade demand that exceed available vessel and port capacity, as well as operational disruptions that delay ship and terminal operations. For instance, the COVID-19 pandemic created unforeseen consequences in a far-ranging array of sectors related to maritime supply chains (Verschuur et al., 2022; Notteboom et al., 2021). 2023 witnessed two events that had global ramifications. Firstly, a drought impacted the operation of the locks in the Panama Canal, reducing throughput and restricting the size of vessels able to transit the canal. Later in the year, militant groups carried out attacks in the Red Sea, compelling shipping lines to massively reroute ships servicing the Asia-Europe and Asia-US East Coast trade routes through the Cape of Good Hope. Both events underscore the vulnerability and resilience of global maritime supply chains when facing such disruptions, whether due to natural or anthropogenic factors.

In contrast to typical localized events impacting supply and logistics chains, the recent disruptions have been geographically extensive, long-lasting in duration, and multi-faceted – impacting demand patterns, manufacturing, maritime logistics, port operations, and freight distribution in complex ways (McKinsey Global Institute, 2020). For decades, container shipping networks have dealt with trade imbalances, where surpluses in some regions offset deficits in others (Theofanis and Boile, 2009; Notteboom et al., 2021). This container supply/demand mismatch means that about 20% of container movements are empty repositioning voyages. Shipping lines often cut capacity when disruptions hit through canceled (blank) sailings. However, if demand bounces back rapidly, as was the case during the COVID-19 pandemic, the industry struggles to promptly reassign capacity, leading to bottlenecks (UNCTAD, 2022). Even after restoring capacity, overloaded networks suffering slower operations due to high demand and landside congestion can face perceived capacity shortages, triggering soaring freight rates and container shortages (National Academies of Sciences, Engineering, and Medicine, 2024).

Measuring and understanding the impacts and propagation of supply

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chain disruptions has gained significant attention, especially since the 2021–2022 supply chain crisis. Most efforts in this domain have originated from private sector initiatives, such as those from shipping lines and operators, as well as from maritime research consultancies. The increasing availability of vessel tracking data and schedule information has facilitated these endeavors since this type of information became widely available from 2004, when an IMO regulation mandated Automatic Identification Systems (AIS) on cargo ships (Marine Traffic, 2023). However, economic literature tackling these topics or providing an empirically testable theoretical framework remains limited, with few exceptions (e.g. Bai et al., 2024). A fundamental question as central as the evident connection between freight rates and supply chain disruptions has not been comprehensively addressed in prior literature (Notteboom et al., 2021; Rodrigue, 2024; Tang, 2006).

Indicators quantifying supply chain disruptions generally fall into three broad categories (Table 1): (1) surveys of the sentiment of supply chain professionals, (2) indicators derived from tracking and scheduling data, and (3) meta-indicators combining expert assessments with existing data series. Other noteworthy tools are those visualizing and computing vessel movements at strategic locations within shipping lanes, including the IMF Port Watch,[1] and similar tools made available by maritime consultancies.

All these indicators depict a dimension of supply chain disruptions and measure a specific stress (e.g. volatility in market sentiment, disruptions in shipping schedule reliability and shipping time) at the macro level (global or regional) or along specific trade lanes. A key challenge lies in quantifying the stress levels that global container ports face through a unified metric that can be precisely measured and utilized as a meaningful indicator for multiple scales, from a specific port, a region, to the global.

To fill this gap, the Global Supply Chain Stress Index - Maritime (GSCSI-M) is proposed to capture the specific supply chain disruptions related to delayed container shipping capacity across a large sample of 267 ports. The stress metric belongs to the second category of indicators relying on AIS-derived data. It is inherently port-centric, derived from the monthly analysis of container shipping traffic flows, and can be aggregated from port-level data into regional or global indices. It focuses specifically on container vessels of the Panamax class and larger operating on intercontinental liner services. Feeder loops exhibit, by nature, higher volatility and have not been included in the initial scope. Therefore, the index does not yet fully capture port stress across the entire shipping network, as ports being solely called by ships of lower capacity than Panamax are not included.

The paper is organized as follows: The next section expands the stress index's conceptual framework, including what constitutes maritime supply chain stress. Section 3 explains how the index is constructed from AIS tracking data, while Section 4 describes actual use cases from the global to the port level. Section 5 compares the proposed stress index with selected indicators developed by the private sector or governmental institutions. Finally, Section 6 compares the index with observed patterns of rate hikes during disruptions.

Table 1
Main indicators quantifying supply chain disruptions.

Category	Index
1. Surveys of supply chain professionals	Purchasing Managers' Index and components (HIS Markit, S&P)
2. Tracking, Schedule Data	Schedule reliability[a] (Sea Intelligence) Ocean Timeliness Indicator (OTI)[b] (Flexport)
3. Meta indicators	Global Supply Chain Pressure Index[c] (Federal Reserve of New York) Supply Chain Stability Index[d] (KPMG)

[a] https://www.sea-intelligence.com/services.
[b] https://www.flexport.com/research/understanding-the-ocean-timeliness-indicator/.
[c] https://www.newyorkfed.org/research/policy/gscpi.
[d] https://kpmg.com/us/en/articles/2023/supply-chain-stability-index.html.

2. From disruptions to stress in global maritime supply chains

2.1. Disruption in global maritime supply chains

Disruptions in maritime supply chains originate from natural and anthropogenic causes (Fig. 1). Particularly, they include geophysical disruptions such as earthquakes, extreme weather events such as hurricanes, accidents such as collisions and channel blockages, labor disputes (strikes), economic and financial concerns such as the trade structure and tariffs, information technology failure (cybersecurity), geopolitical events such as conflicts and sanitary crises such as pandemics (UNCTAD, 2022). Each of these events, depending on its location and extent, will create proportional disruptions in maritime supply chains. These disruptions will manifest differently within the shipping network, at the port level, or in the respective hinterlands. For instance, at the port level, berth and yard congestion (through reduced capacity or unavailability) are common manifestations of disruptions.

Due to the nature of maritime supply chains, there are complex propagation and backpropagation mechanisms for disruptions. A divergence exists between the increasingly demanding requirements for punctuality and flexibility in modern supply chains, such as e-commerce fulfillment, and the rigidity inherent in maritime shipping networks optimized for economies of scale through post-Panamax vessels on scheduled services. Shippers and cargo owners often respond to disruptions by increasing inventory holdings and placing additional orders as a buffer, creating a demand-amplifying “bullwhip effect” that propagates backward through supply chains. This surge in demand, driven by actual consumption compounded by precautionary stockpiling, can overload shipping resources, especially the available container equipment pool. Container capacity shortages in the maritime shipping network, at the terminal and in the hinterland became the primary propagation and backpropagation mechanism disrupting maritime logistics networks.

2.2. Disruptions as sources of supply chain stress

If the disruption is significant enough to create a notable deviation from the norm, then a situation of stress is observed, which can be measured. A stress index attempts to quantify deviations from a norm, which is the typical state in which a system operates. The greater the deviation, the more likely the system is to experience stress. However, some level of deviation is often expected due to unforeseen events such as a storm or equipment failure, so only large deviations are considered indicative of stress. Other deviations are variability in regular operations, which is an expected or tolerable deviation. A specific threshold for the standard deviation needs to be defined to determine when a deviation is significant enough to indicate stress.

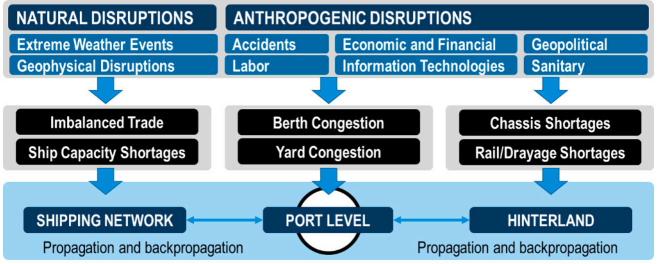

Fig. 1. Disruptions in global maritime supply chains.

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[1] https://portwatch.imf.org/

Therefore, there are chains of causality and impact in port-related distributions, irrespective if they are natural or anthropogenic (Fig. 2). The stress stemming from the declining velocity of container movements initiates a negative feedback loop. As containers spend more time at terminals or inland locations (dwell time) due to capacity constraints, this progressively impairs velocity and fluidity across related transport chain components. Maintaining the same level of service requires deploying additional assets, further exacerbating existing congestion. For instance, if a container yard is congested, it restricts its capacity to handle vessel operations since inbound containers cannot be expeditiously unloaded due to a shortage of yard space. The rising shipping rates are directly the outcome of this declining velocity as users compete for scarce capacity.

The GSCSI-M is proposed as a snapshot that measures deviations from the norm for only one segment of the chain, at the intersection between maritime container shipping networks and ports (Fig. 2). The latter is heavily dependent on its hinterland connections to facilitate cargo flows. Port congestion notably impacts the availability of assets like drayage trucks and rail ramps as connections to inland destinations. For instance, a shortage of chassis to haul containers by road can severely limit capacity, as experienced on the United States West Coast during the COVID-19 pandemic. These chassis are also used for container storage at rail yards and distribution facilities (National Academies of Sciences, Engineering, and Medicine, 2024).

3. The GSCSI-M model

3.1. The concept of the GSCSI-M

In this conceptual framework, global container shipping is idealized as a directed network, where the nodes represent ports, and the edges represent the movement of vessels sequentially between the nodes/ports. (Fig. 3). Container shipping tends to operate on scheduled routes, where a shipping lane consists of a handful of vessels continuously running through the loop and adhering to a fixed timetable of port visits. By design, the scheduled rotations system offers predictability, reliability, and efficiency in moving goods over large distances. Under normal circumstances (i.e., in the absence of disruptions), the movements (port calls) of container ships are organized as inter-range loops, which are highly predictable and consistent in:

- Lead times: The transit time between the departure port (d) and the subsequent arrival port (a).
- Turnaround times: The time spent at each port, especially for loading and unloading operations.

Network data at a given time is therefore characterized by the moving trade capacity (expressed in TEUs) between ports, as well as the consistent transit times, which tend to be relatively stable within the same ship class. Therefore, the mobilized trade capacity (flowing capacity) on a given connection can be calculated as:

Mobilized trade capacity $=$ Flowing capacity per unit of time $\times$ Transit time.

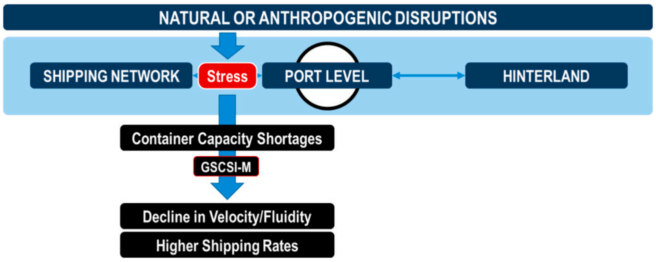

Fig. 2. The GSCSI-M at the intersection of ports and maritime shipping.

However, operational disruptions, such as congestion around the destination port, can lead to:

- Delayed arrival event. Ships arriving from earlier ports have to wait at anchorage before berthing.
- Delayed departure event. The time required to service the ship is longer than normal.

To analyze supply chain disruptions, one can look at the statistics of the transit time from the departure of the previous port to the departure of the current port, which includes both the lead time and the port turnaround time. Episodes of stress are identified as outliers where the transit time exceeds the "normal" range. These stress episodes imply an increase in the required ship capacity for the same amount of trade, and the corresponding additional or stalled capacity can be calculated as:

$$\text{Delayed capacity} = \text{Flowing capacity per unit of time} \times \text{Excess lead time}$$

The calculation of the GSCSI-M is derived from an AIS tracking dataset from Marine Traffic.[2] The dataset includes the entire sequence of port calls (arrival and departure) for all container ships, along with information about their capacity and size category. The current analysis focuses on global trade, considering only ships of Panamax size or larger, as this containership traffic forms the backbone of global value chains. The same analytical approach could also be applied to feeder shipping activities, but would require a different dataset. Feeder shipping, by its nature, tends to exhibit more volatility compared to the main global trade routes, with less frequent services and more variability in lead times. Therefore, a separate data set would need to be produced to capture the characteristics of the feeder shipping network accurately.

3.2. Measuring lead time and capacity deployment

The starting point is to take a pair of subsequent port d (departure) and a (arrival) in a shipping sequence (general lead time) that involves a port-to-port lead time and a port turnaround time. The time span between departure at d and the next departure T_{da} captures most of the possible disruptions affecting port a (Fig. 4), whether within the port or beforehand. These include disruptions *en route* from d to a, or disruptions at the arrival port (a). Therefore, looking at the aggregate of these lead time statistics of possible inbound connections for port-to-port and turnaround times reveals potential disruptions affecting port a.

These disruptions are related to a deployed capacity C_{da} in terms of the sum of TEUs and the number of ships N_{da}, which is a single ship for an observation, but involves several observations over a time period.

3.3. Intermediate matrix

For each pair of ports (departure port d and arrival port a), a matrix $\Delta_{da}(t)$ was constructed for a monthly period:

$$\Delta_{da}(t) = \begin{cases} T_{da}(t) - rT_{da} & \text{if } T_{da}(t) \geq rT_{da} \\ 0 & \text{if } T_{da}(t) < rT_{da} \end{cases}$$

It includes the following variables from vessel tracking data:

- Period t (monthly data from February 2016 until April 2024). This period is judged to be significantly long enough to provide data allowing the calculation of a reference lead time despite potential stress episodes.
- Median shipping time for period t ($T_{da}(t)$).
- A reference transit time for the edge (d,a) (rT_{da}) is representative of normal shipping and port conditions on that lane above which vessels are considered delayed.

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[2] https://www.marinetraffic.com/

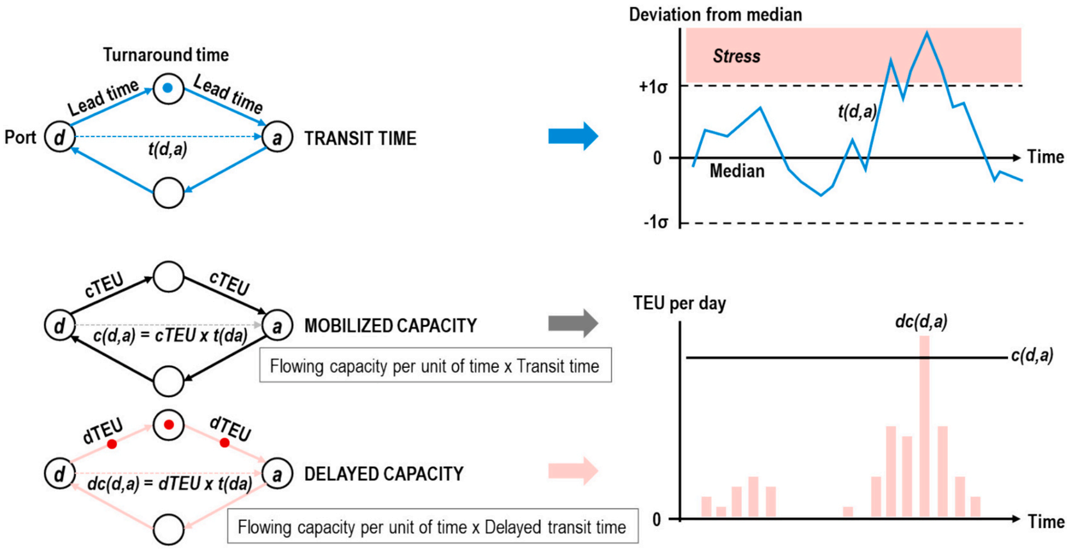

Fig. 3. Concept of the GSCSI-M.

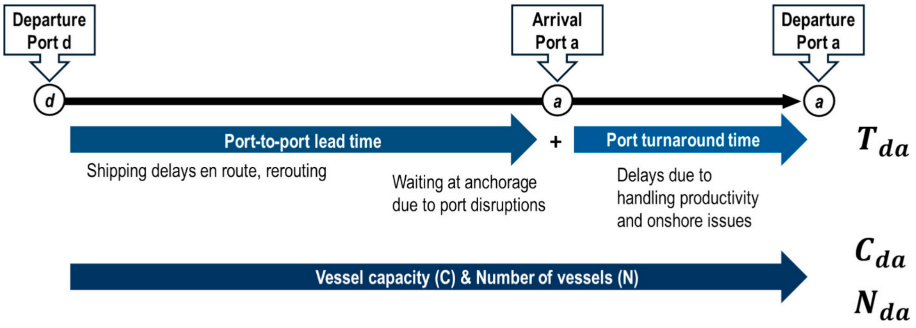

Fig. 4. Lead time and capacity deployment between a pair of subsequent ports.

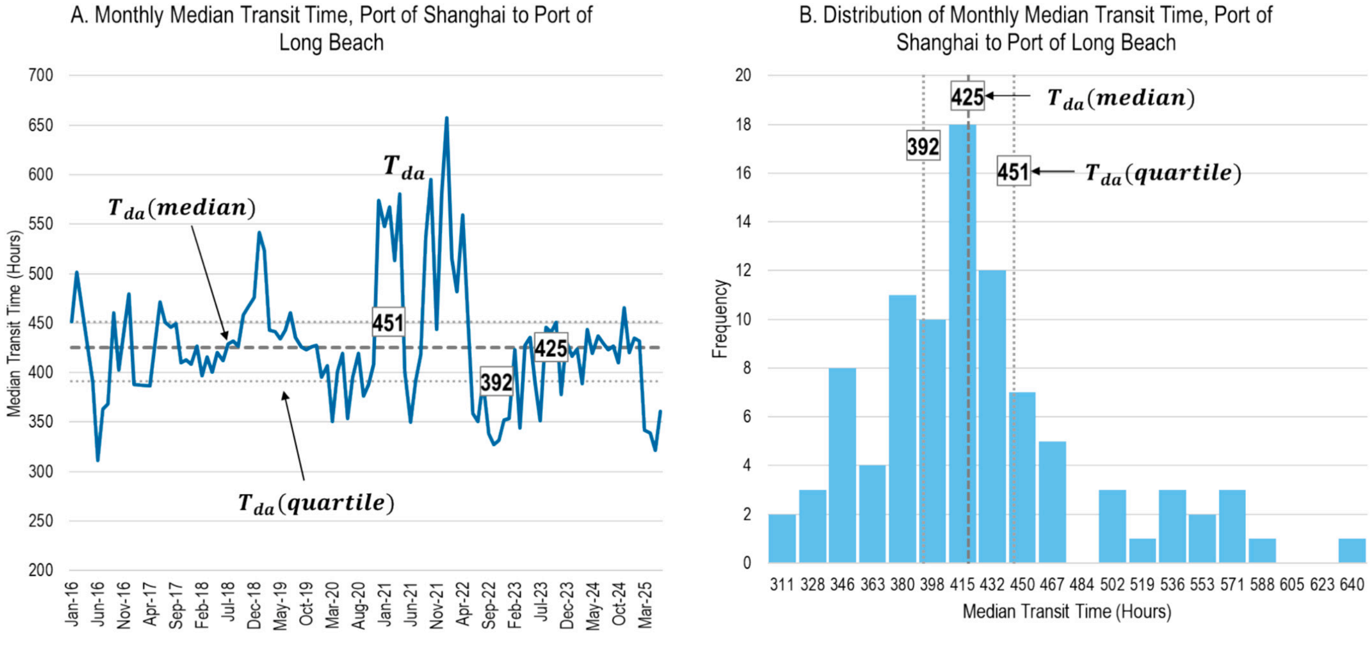

Fig. 5. Monthly median transit time, port of shanghai to port of long beach.

Note: 108 monthly records based on 664 trips between Shanghai (CNSHG) and Port of Long Beach (USLGB) between January 2016 and June 2025. The indicated month corresponds to the timestamp associated with the departure of a vessel from the destination port.

There are as many of these matrices as there are port pairs. Each matrix tries to capture the delay for a stated period above the reference lead time.

3.4. Estimating reference transit time

The stress index aims to capture large systemic disruptions. A small value of the reference transit time (rT_{da}) may run the risk of having the index capture too much noise in the form of small but frequent deviations. Rather, rT_{da} should discard outlying lead time on the right side of the distribution of monthly lead time, since any observation below $T_{da}(t)$ is not considered a disruption. To illustrate this issue, Fig. 3 depicts the distribution of monthly median transit times between the Port of Shanghai and the Port of Long Beach. Monthly median transit times between the two ports have substantially fluctuated (Fig. 5.A), particularly in 2021 and 2022 during the post-pandemic surge. This surge created outliers that are clearly visible on the right side of the distribution in Fig. 5.B, which results in an average transit time of 432 h as opposed to a median of 425 h over the 2016–2025 period.

Therefore, using median shipping time instead of mean shipping time avoids distortions created by outliers, including vessels staying in port for noncommercial reasons, such as repairs or crew changes. Instead, it is preferable to use parameters that are representative of normal or optimal operational conditions. The proposed model utilizes the median transit time T_{da} (*median*) and the lower quartile transit time T_{da} (*quartile*) as the reference points for defining normal operating ranges. Extreme values or outliers have less influence on these tendency and dispersion measures.

By focusing on the median and lower quartile transit times, the model can establish thresholds that capture the typical, expected operational performance without being unduly impacted by atypical events already registered in the transit timetables. This approach provides a more robust method for identifying supply chain stress or disruption episodes, as deviations from these left-skewed reference points are more likely to indicate actual operational disturbances.

For a Gaussian (or normal) distribution of monthly lead time median and first quartile link to the standard deviation as:

$$\sigma \approx \frac{3}{2}\left(T_{da}(median) - T_{da}(quartile)\right)$$

A two-sigma (standard deviations) rule for outliers (5% probability of occurrence) gives:

$$T_{da} = T_{da}(median) + 2^{*}\sigma \approx 3^{*}T_{da}(median) - 2^{*}T_{da}(quartile)$$

This provides a simple rule for filtering episodes of excessive lead time out of reference lead time.

3.5. Construction of the GSCSI-M

To identify the level of disruption (stress) by lane as an equivalent TEU capacity delayed or stalled (such as anchored at the port of arrival) at time t, $S_{da}(t)$, the deployed vessel capacity in that lane is compared to the normal:

$$S_{da}(t) = C_{da}(t)^{*}\Delta_{da}(t)$$

If $\Delta_{da}(t)$ is zero, then the lead time is within reference, implying that there is no observed stress for this lane, which means a value of zero. If it is above the reference, then the deployed capacity on that lane, $C_{da}(t)$ is multiplied by the delayed lead time. $C_{da}(t)$ and $\Delta_{da}(t)$ must be in the same time unit of hour and capacity delayed per hour (TEU per hour). Therefore, the contribution of a port to global stress in TEU $S_{da}(t)$ is obtained by summing over all its inbound connections:

$$S_a(t) = \sum\nolimits_{d} S_{da}(t)$$

This port-level stress, composed of 267 observations (ports), can be aggregated by ship category, by port of arrival, by region, and globally:

$$S_{Region\ A}(t) = \sum\nolimits_{port\ b \in Region\ A} S_b(t)$$

Conversely, the contribution of a region or a port to global capacity stress can be directly identified. The stress index can also be expressed as an excess delay metric, dividing stress by trade capacity:

$$Delay_a(t) = \frac{S_a(t)}{C_a(t)} = \frac{\sum_d C_{da}(t)^{*}\Delta_{da}(t)}{\sum_d C_{da}(t)}$$

4. Findings and applications of the index

By converting the supply chain disruptions into their impact on trade capacity, the GSCSI-M offers a tangible representation of the scale of the global supply chain challenges faced. Having TEU figures for delayed capacity allows for estimates of trade and supply chain impacts, particularly for supply chains vulnerable to high inventory levels in transit, relying on consistent flows. These figures can be multiplied by cargo value figures per TEU to provide estimates of economic impacts. This supply chain stress metric can be a valuable tool for tracking, analyzing, and contextualizing the significant operational disruptions that have reverberated through global maritime and logistics networks in recent years. It underlines that shipping lines and terminal operators must contend with notable unpredictability, in addition to more predictable seasonal and economic cycles (World Bank, 2010).

4.1. Global level GSCSI-M

The primary use of the GSCSI is to inform global trends, but it is based on the summation of the stress levels of all 267 ports being monitored. Applying the analytical approach to global shipping data from 2016 to 2025 yields a global supply chain stress metric consistent with the general understanding and knowledge of past events (Fig. 6). Globally, the GSCSI-M has risen consistently from early 2020 to March 2022, as expressed in terms of trade capacity (measured in TEUs). This indicates considerable stress across the global supply chain over this period, which was subsiding in 2023 but surged again at the end of the same year. The quantitative GSCSI-M metric provides a data-driven measure that captures the severity and persistence of the supply chain stress observed during this time frame.

The consistent upward trend in the GSCSI-M aligns with the widespread supply chain disruptions and congestion issues that have been widely documented and experienced globally since the onset of the COVID-19 pandemic in 2020 (e.g. Millefiori et al., 2021; Notteboom et al., 2021). It underlines that over the 2021–22 period, two trends unfolded. First, containerized trade rebounded rapidly from the initial pandemic drop, overshooting pre-pandemic levels by late 2020. This surge was driven by a shift in consumer spending toward goods needed to accommodate sudden changes in lifestyles (e.g., work-from-home) in developed countries (North America and Europe). Second, while the shipping industry aimed to meet growing demand, supply was hampered by pandemic-induced port capacity restrictions (notably in Asia) and operational constraints at other ports that caused multi-week vessel queues.

The GSCSI-M reflects effectively these disruptions globally and at the port level. By mid-2021, severe berth and yard congestion had become prevalent among the world's major container ports (Fig. 7), exacerbating the availability of containers and straining shipping lines' capacity to move containerized cargo. This widespread congestion resulted from delays concentrating on a limited number of key international gateway ports.

In August 2021, 25 ports out of the 267 monitored, primarily located in China and on the West Coast of the United States, accounted for 85.7% of the delayed trade capacity. Moreover, just ten ports, including Shanghai, Yantian, Los Angeles/Long Beach, Savannah, and Ningbo,

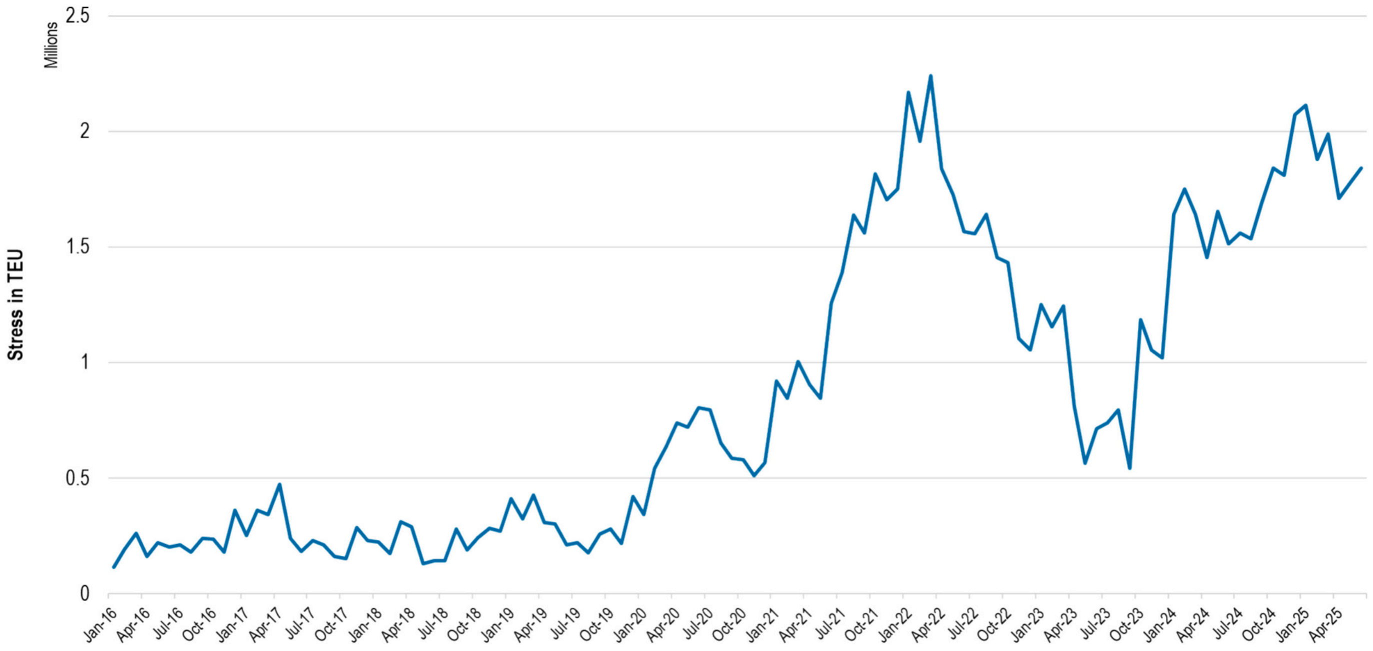

Fig. 6. Monthly global supply chain stress index - maritime (MTEU), Jan 2016 to Jun 2025.

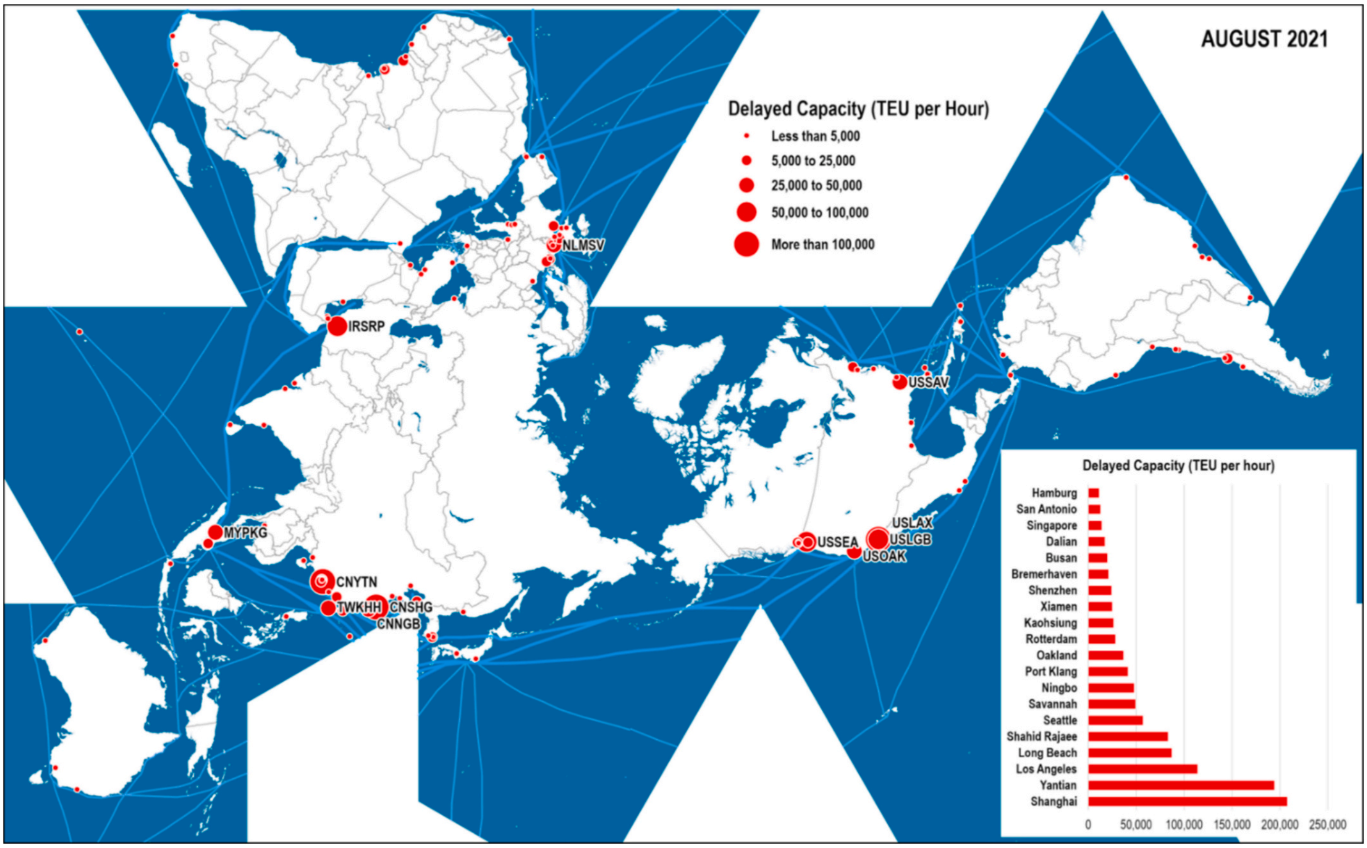

Fig. 7. Containership delayed capacity at port, August 2021 (in TEU per hour).

were responsible for 65.4% of the delayed capacity, underscoring the excessive concentration of these disruptions. Several container yards were operating at or near full capacity, slowing the processing of ships that could not be unloaded until sufficient yard storage space became available. According to UNCTAD, ships spent about 20% more time in ports during that period because of the lack of capacity.

These delays subsequently rippled through shipping networks as vessels awaiting service at anchorage removed capacity from the system. This resulted in additional container shortages and surging freight rates. For supply chains, an acute bullwhip effect materialized as growing delivery uncertainties prompted inventory building, which in turn contributed to a surge in overall demand and further capacity constraints.

Focusing on North America (Fig. 8) also reveals an uneven distribution of the disruptions, underlining that the highest disruptions are related to ports having a notable import function for Asian supply chains. For instance, while Los Angeles and Long Beach accounted jointly for 30% of the North American container traffic (including Mexico), they accounted for 54.5% of the delayed capacity. Oakland and Savannah, having strong Asian connectivity, were also ports with a high share of delayed capacity.

Consequently, reliability and timeliness in global logistics plummeted to unprecedented lows. The proportion of container ships arriving on time, within an 8-h window, fell from a typical 75% pre-mid-2020 to just 35% in early 2021. This dramatic drop in on-time performance underscores the significant erosion of predictability affecting global logistics networks designed around scheduled services.

4.2. Regional level GSCSI-M

The index can be assembled according to regional constructs that can help depict specific events. These constructs can be a maritime range (e.g., US West Coast), an ocean, a sea, or a bottleneck (e.g., Strait of Malacca), underlining a geographical commonality linked with disruption (Fig. 9). This regionalism in disruptions is apparent in the volatility of the China Sea (Yellow Sea, East China Sea, and South China Sea), which is mainly attributed to seasonal typhoons. The East and West Coasts of North America are characterized by a high level of stability, with a clear impact of the supply chain crisis of 2021–22. Afterward, the system resumed its stable state, but with more volatility, including the port strike on the East Coast in October 2024.

Examining the impacts of the Red Sea Crisis on selected maritime regions is illustrative, particularly on the Red Sea, and on the East and West Mediterranean (Fig. 10). Beginning in November 2023, attacks by armed groups in Yemen on merchant vessels in the southern Red Sea jeopardized the key Asia-Europe maritime route through the Suez Canal. Major carriers rerouted vessels around the Cape of Good Hope to circumvent the Red Sea, adding 3000–3500 nautical miles (5500 to 6500 km) and 7–10 days to a typical Asia-Europe voyage. This massive rerouting had a more severe impact on container shipping than on bulk trades. Although the port-centric stress index does not directly measure the impacts of rerouting, it appears to capture implications on capacity stress well, as evidenced by 1.42 million TEUs of additional capacity absorbed into longer routings by late 2024 (Fig. 6).

Compared with the post-COVID surge of 2021–2022 (Fig. 6), the disruption pattern as of October 2024 was radically different. While the concentration level of the delayed capacity was lower, the top 10 still accounted for 48.2% of the delayed capacity, and 25 ports accounted for 72.4%. The most disrupted ports were along the East Asia – Suez – Europe route, with transshipment hubs such as Singapore, Colombo, Port Said, Algeciras, and Tanger Med particularly impacted. Major European gateways for the Asian trade, such as Rotterdam, Piraeus, Felixstowe, and Hamburg, were experiencing significant delays in capacity. The effects of the ILA port strike of early October on the US East Coast were also apparent. An outlier concerns the Pacific Coast of Mexico, with Lazaro Cardenas and Manzanillo, due to increasing trade volumes from Asia and port capacity constraints. This trend has also affected the port of Cartagena, a major Caribbean transshipment hub.

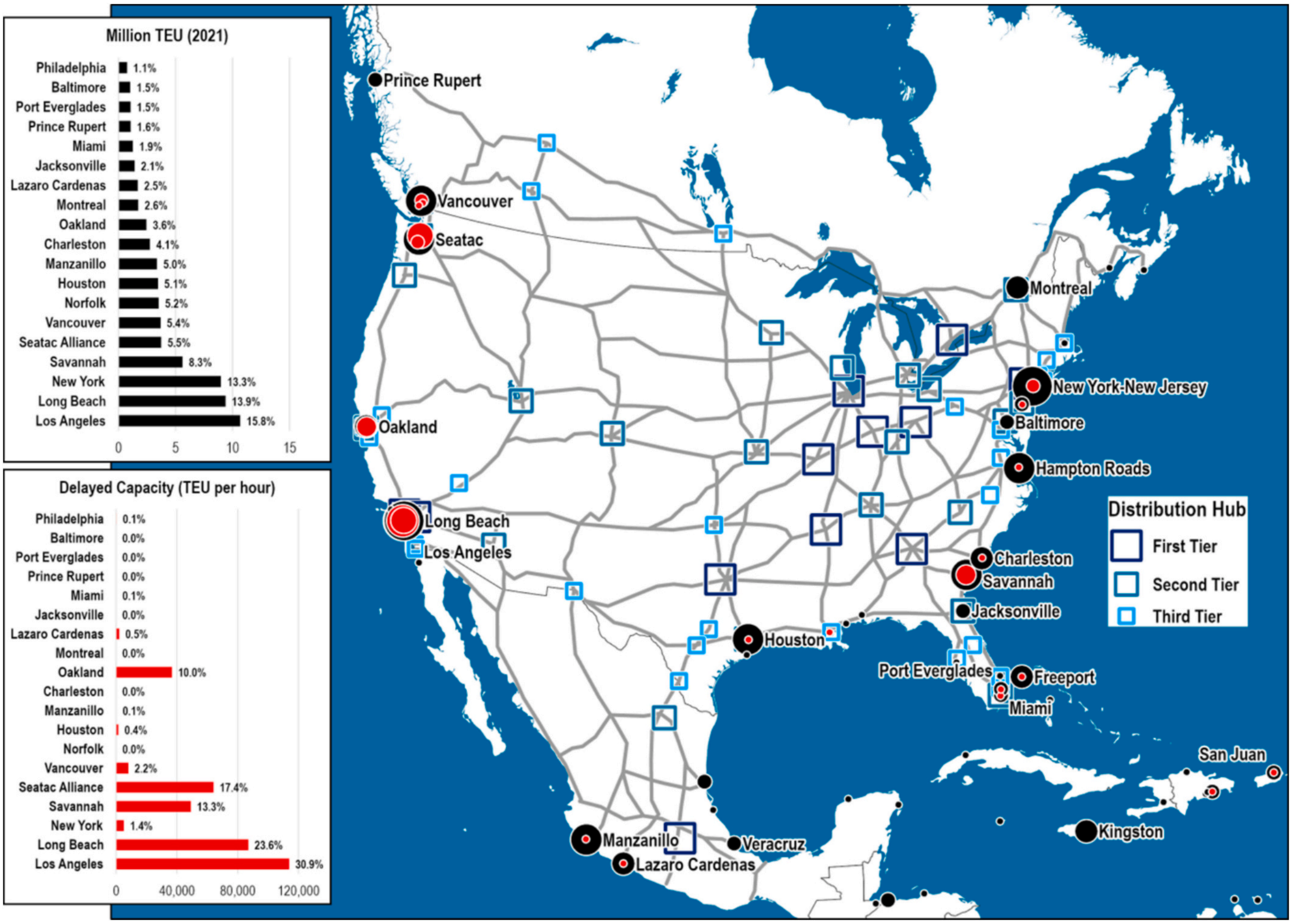

Fig. 8. Port activity and containership delayed capacity at North American Ports, August 2021.

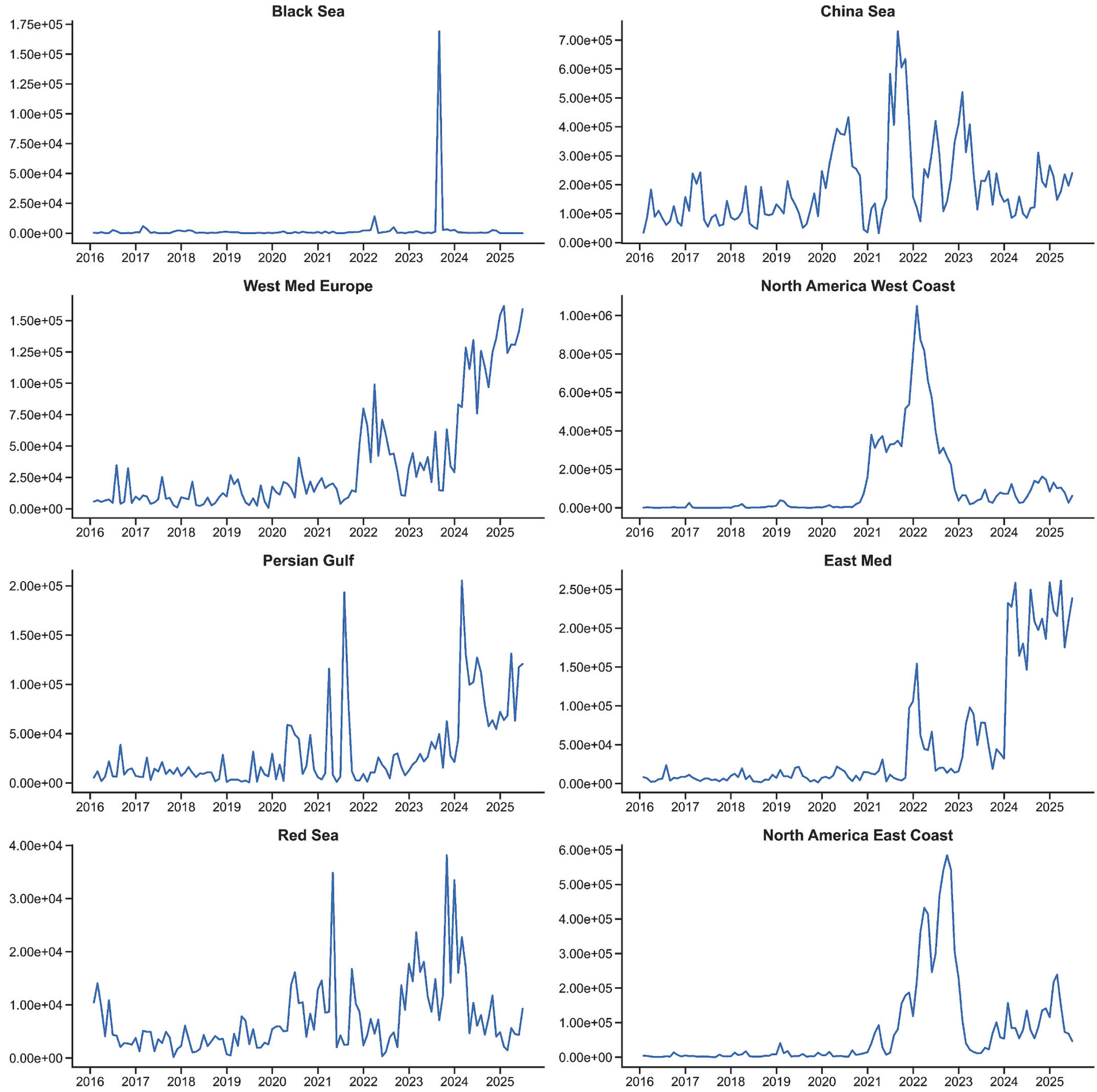

Fig. 9. Global supply chain stress index – maritime (TEUs) for selected maritime regions.

4.3. Port level GSCSI-M

At the other end of the spectrum, port-level stress data highlights local issues potentially amenable to policy interventions since port congestion severely challenges schedule reliability for maritime supply chains (Fig. 11). Aside from the 2021–22 period impacting most gateway ports, individual ports tend to experience short-lived stress episodes. The Port of Long Beach experienced two periods of stress during the pandemic-induced crisis: first, when ports were affected by lockdown and staff availability, then a longer period from the end of 2021, when the pressure from demand challenged handling throughput. In comparison, a port such as Durban in South Africa experienced bursts of stress prior to the pandemic, which may be related to known systemic in-country infrastructure management issues, including a major cyberattack in 2021. Then, in 2024, the Cape of Good Hope diversion from the Red Sea crisis created a stress surge because of the sharp increase in traffic as shipping lines changed several of the Asia-Europe routes and where Durban suddenly became a new port of call. For Ningbo, the sharp stress experienced in September 2022 is attributed to Category 1 Typhoon Muifa, which forced the closure of the port. In 2022, the port of Hamburg was impacted by disruptions caused by low water levels on the Elbe, forcing ships to reduce capacity, and by labor disputes that disrupted terminal operations.

Transshipment hubs such as Singapore and Tanjung Pelepas exhibit similar erratic stress patterns compared to gateway ports serving as final vessel destinations or departures and were impacted in a similar fashion by the Red Sea crisis. The 2024 stress surge is related to the readjustment of trade routes, namely the Cape Route deviation, which incited an

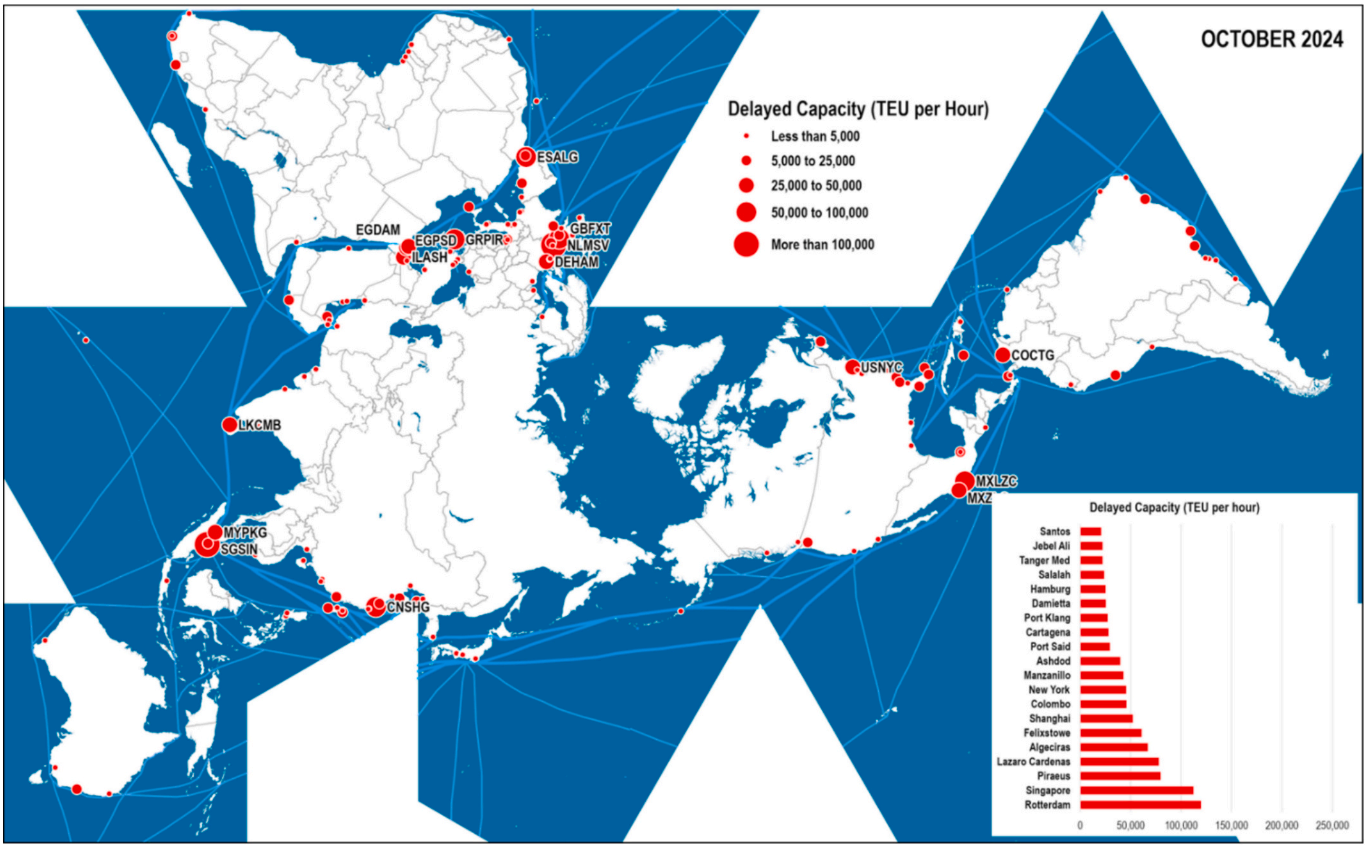

Fig. 10. Containership delayed capacity at Port, October 2024 (in TEU per hour).

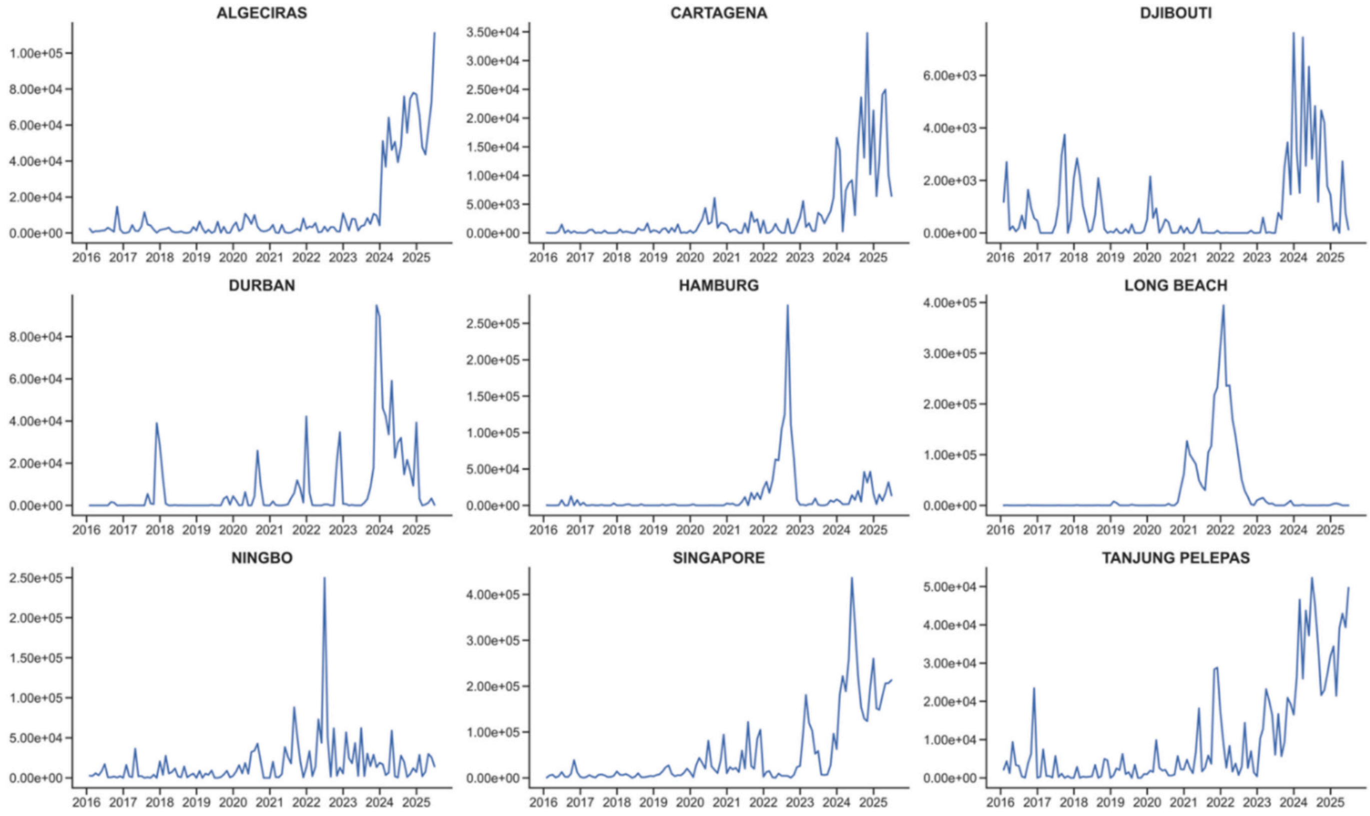

Fig. 11. Global supply chain stress index – maritime (TEUs) for selected container ports, 2016–2025.

additional use of transshipment hubs in Southeast Asia (Singapore), South Africa (Durban), and the Western Mediterranean (Algeciras). A few selected known instances of local port congestion can also be identified using the stress index at the port level. Therefore, port-level stress data can serve as valuable complementary information and provide insights alongside other established indicators and data on port and/or logistics performance, such as the World Bank's Container Port Performance Index (CPPI: World Bank, 2025a) and the Logistics Performance Index (LPI; World Bank, 2023).

5. The GSCSI-M and other indexes

At least three other indicators aim to measure and quantify supply chain disruptions: the Purchasing Manager's Index, the Schedule Reliability Index, and the Global Supply Chain Pressure Index. The section will explore the fundamental similarities and dissimilarities between these indices and the GSCSI-M.

5.1. Purchasing manager's index (PMI)

The Purchasing Managers' Index USA (PMI) from Standard & Poor (IHS Markit) derives from multi-dimensional sentiment surveys of US manufacturing supply chain executives. It is widely recognized for its relevance in forecasting short-term economic trends, as it is forward-looking since current purchases and decisions will become cargo flows in the subsequent months. It is a diffusion index that reflects the general direction of the growth or decline in manufacturing, reflecting the confidence of supply chain managers concerning current and future demand. Thus, a high PMI-USA could be associated with a high stress index in American ports since a larger inventory is acquired and in transit because of positive market conditions, which may result in port congestion if the surges are substantial. Further, the PMI is a forward-looking index, while the GSCSI-M is a current index, implying a lagging effect between the two. A forward three-month adjustment (a reasonable lead time for international orders) was made on the PMI-USA, which was cross-referenced against the corresponding GSCSI-M for the US East and West Coasts. A correlation of 0.477 is observed, indicating a good level of association between expectations of additional deliveries by US supply chain managers and US port stress (Fig. 12). A change in expectations of additional deliveries by US supply chain managers is associated with a change in port stress on the East and West Coasts.

5.2. Sea intelligence schedule reliability index

Sea-Intelligence consultancy[3] publishes a Schedule Reliability Index benchmarking carrier's on-time performance within one day of scheduled arrival. Despite being available at the global and shipping line levels, this metric unsurprisingly strongly negatively correlates with the Stress Index ($R^2 = -0.745$), as both leverage the same underlying vessel movement data (Fig. 13). As schedule reliability declines, delayed capacity increases proportionally. However, the Stress Index is port-centric and scalable, while the reliability measure focuses on services, trade lanes, and carriers, implying a high complementarity.

5.3. Global supply chain pressure index

The Federal Reserve Bank of New York's Global Supply Chain Pressure Index[4] (GSCPI) is a meta-indicator that integrates several existing series to compound into supply chain disruption indicators. Global transportation costs are measured by employing data from the Baltic Dry Index (BDI; Baltic Exchange, 2024) and the Harpex Index,[5] as well as airfreight cost indices from the U.S. Bureau of Labor Statistics. The GSCPI also uses PMI supply chain-related components. The index is normalized, so zero represents the historical average, while negative values are representative of a low-pressure situation, and positive values express elevated levels of pressure.

The Pressure and Stress indices are moderately correlated with each other ($R^2 = 0.278$) and reflect the major turmoil, but the latter is more granular regarding containerized shipping (Fig. 14). Conversely, the GSCPI's US-centric composition may explain its relative insensitivity to the Red Sea crisis compared to the Stress Index, visible through their divergence beginning in late 2023. Another explanation is that an event such as the Red Sea crisis did not create major disruptions in supply chains in general, outside of increasing lead times that are eventually mitigated. Therefore, the GSCSI-M and the GSCPI are complementary indices that mainly measure different disruptive effects.

6. Stress and rates: competing for scarce capacity

6.1. Conceptual framework of stress and rate formation

Historical freight rate patterns suggest two market regimes (Table 2). Under normal conditions, shipping capacity accommodates shipper demand (Talley and Ng, 2013). Complex price mechanisms exist, which have, in some regions, replaced systems such as freight rate conferences, where prices were fixed. The industry structure is concentrated within six major carriers that provide the bulk of the capacity for global container shipping. The existing global operational alliance system, accepted by regulatory authorities, allows carriers to consolidate and optimize vessel utilization with partners while alliance members remain commercially independent (Ghorbani et al., 2022).

The complexity of the shipping business and its capital intensiveness limit the number of entrants, impacting the competitive environment with oligopolistic behavior. However, in a normal regime and without price collusion, lines are price takers, and rates correspond to the marginal price considering the imbalance in demand (full containers) across directions. The conventional wisdom in the industry is that shipping lines cannot easily recover their investment, except for the period of tensions when rates spike.

In times of capacity tensions, shippers compete for scarce remaining slots on vessels, becoming rate-takers rather than setters. This is especially true for shippers not engaged in longer-term contracts. Willingness-to-pay dynamics emerge, hinging on freight's ad valorem markup over product value. Lower value goods suffer more acute increases proportional to cargo value, potentially leading to supply chain disruptions. This first manifests for export cargoes out of origin regions (e.g., China) before affecting import legs.

Looking at the interactions between the shipping markets, the following factors help explain the boom/bust rate cycles (e.g. Stopford, 2009):

1. Freight demand exhibits low price elasticity, as freight cost represents a relatively small share of the landed price at destinations. The average Freight On Board (FOB) value of the content of a 40-ft container of manufactured goods from China ranges from USD 50,000 to close to USD 1 million, depending on the product type. An increase in spot freight rates amounts to an ad valorem markup of only a few percent of the cargo value. Even with periods of high rates, shippers willingly pay premiums to expedite deliveries and cut lead time. However, there are notable variations by commodity sector (standard international trade classification (SITC) categories),

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[3] https://www.sea-intelligence.com

[4] https://www.newyorkfed.org/research/policy/gscpi#/overview

[5] https://www.harperpetersen.com/harpex This index reports chartering rate for container shipping.

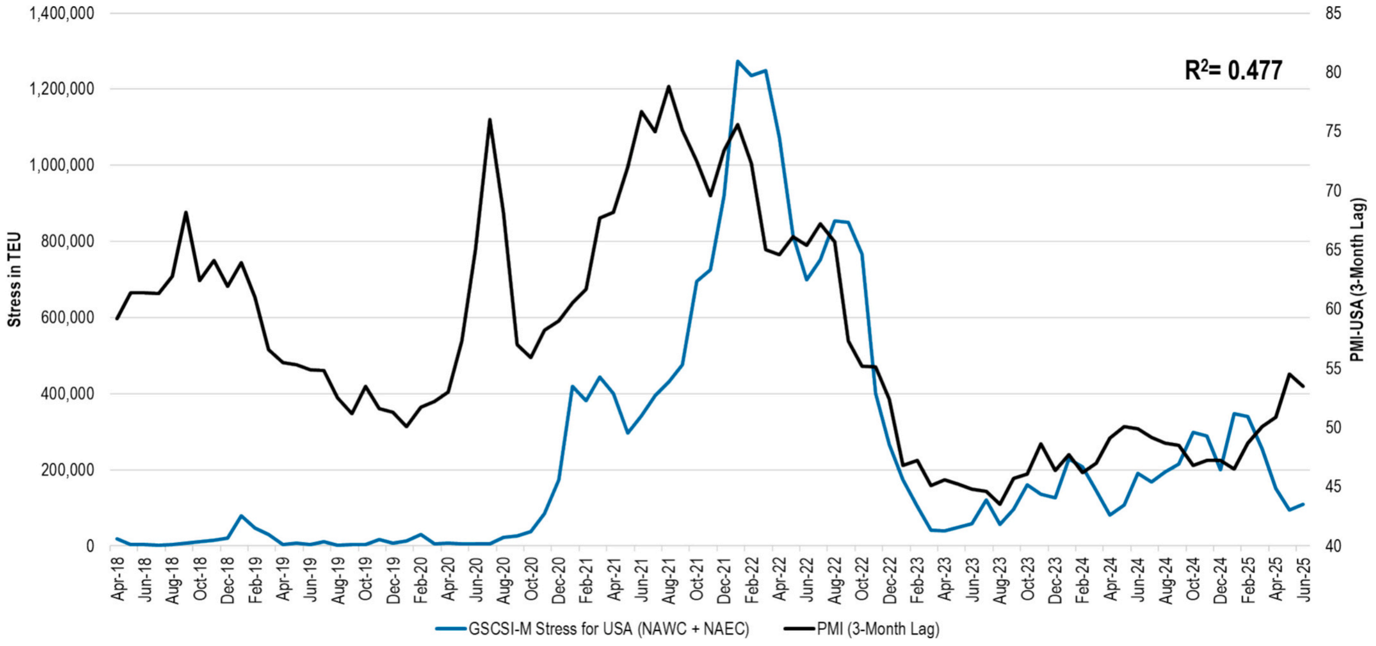

Fig. 12. PMI supplier delivery time (3 months lag) (USA) and USA stress (NAWC+NAEC) index, 2018–2025.
Note: The PMI suppliers' delivery time survey question takes three positions: faster/slower/same delivery time compared to last month. The index is calculated as the percentage of respondents reporting improvement, plus 0.5 of the percentage responding to a stable trend. Values above 50 report an increase in the Supplier Delivery time.

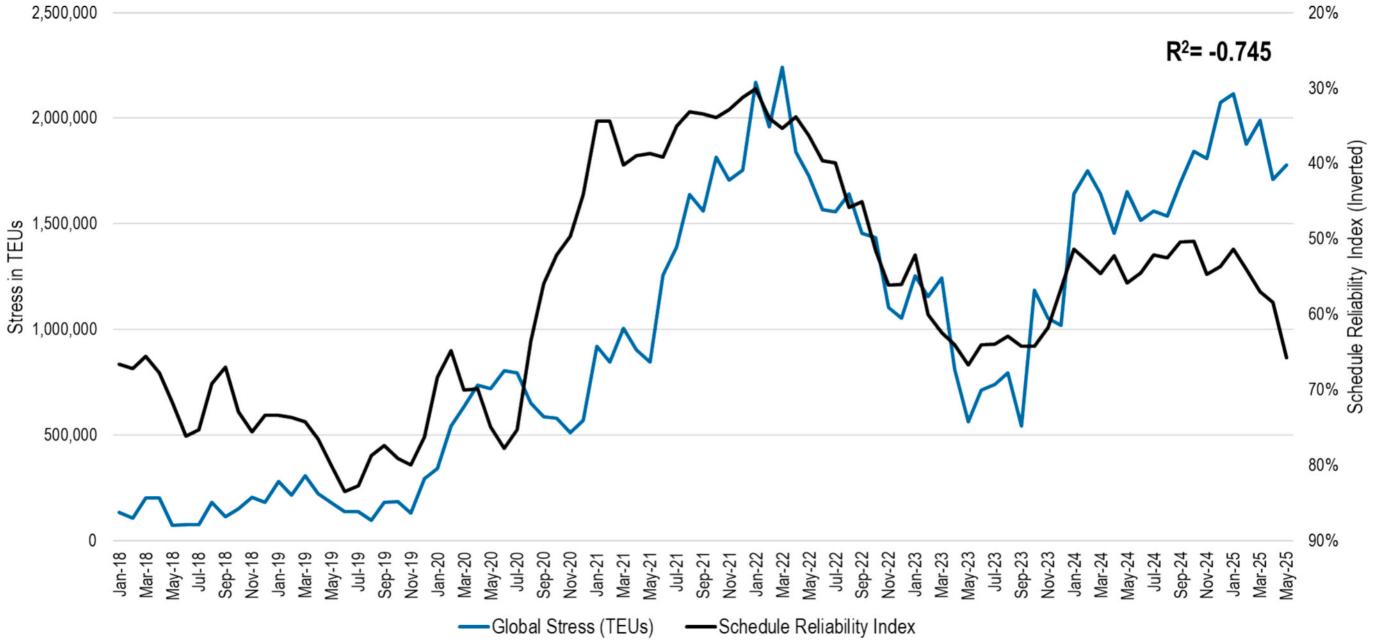

Fig. 13. Schedule reliability and stress index, 2018–2025.
Note: Schedule reliability measures the actual on-time performance of individual vessel arrivals in ports worldwide. The scale has been inverted.

implying that sectors such as furniture have less elasticity than others, such as office machines.

2. Investments in shipping capacity occur across long cycles (De et al., 2011). Carriers must carefully anticipate demand to avoid costly overcapacity while still meeting cyclical surges in demand. Therefore, capacity-to-demand adjustments are imperfect and often involve a lagging effect. The 2021–22 combination of booming demand and congestion-induced capacity losses was unforeseeable and sparked a surge in orders for new (large) container vessels that were delivered in 2023–24 amid slowing demand.

6.2. *Convergence between GSCSI and freight rates*

The striking parallelism between global stress and freight rate trends, as illustrated by the Shanghai Container Freight Index (SCFI[6]), underlines the rate formation mechanisms previously discussed (Fig. 15). The high correlation between container shipping rates and the GSCSI ($R^2 = 0.719$) underlines that rate spikes are closely associated with

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[6] Shanghai Shipping Exchange (https://en.sse.net.cn/)

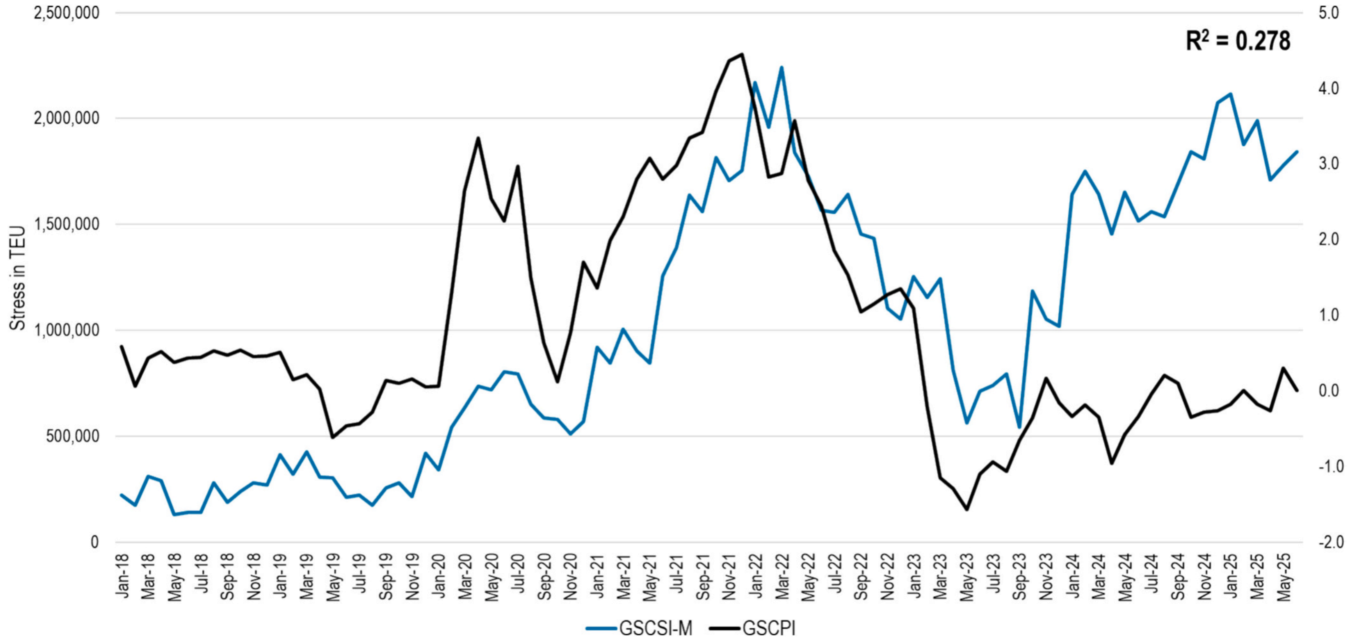

Fig. 14. Global supply chain pressure index and stress index (MTEU), 2018–2025.

Table 2
Shippers' Willingness to pay: mechanism, rate formation and theoretical reference.

Regime	Unstressed normal	Stress and rate bursts
Mechanism	Shipping capacity supply clears demand	Shippers are competing for shipping slots
Rate formation	Oligopolistic competition: Marginal price	Shippers' willingness to pay
Theoretical reference	Bertrand Competition	Ramsey-Boiteux Pricing

surges in delayed capacity. It should be noted that prevailing freight rate indices reflect *spot* rates, imperfectly capturing the actual shipping costs faced by large trade volumes under annual contracts negotiated between carriers and major shippers. They may imperfectly represent the actual shipping cost of trade, as spot rates correspond to rates paid by ad-hoc shippers competing for remaining slots, which can be limited. As such, they dynamically reflect real-time supply/demand tension in terms of their marginal cost.

While unprecedented for containerized shipping, freight rate spikes have periodically occurred in other shipping segments like dry bulk prior to the 2008 financial crisis, when soaring commodity demand over a multi-year span quintupled shipping rates. This historical pattern suggests that shipping rates have a “low normal” state, interrupted by bursts of high rates when capacity cannot match demand surges. The

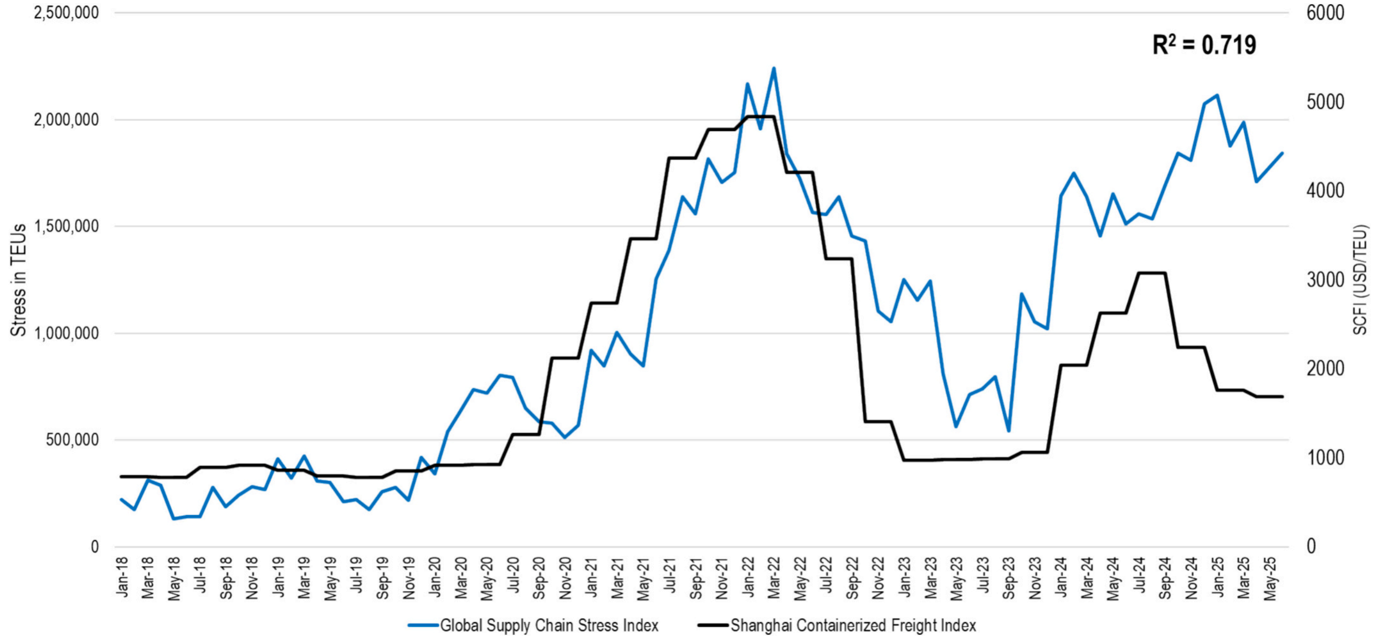

Fig. 15. Shanghai Container Freight Index (SCFI; Monthly) and Stress Index, 2018–2025. Source: Shanghai Shipping Exchange, 2024.
Note: The Shanghai Containerized Index is a weighted average of Chinese Shipping rates (per TEU) across global destinations.

GSCPI-M reflects this behavior well, as it is closely associated with container freight rates.

7. Conclusion

The pandemic-induced and other operational disruptions from 2020 onward significantly impacted shipping capacity and freight rates to levels not previously experienced. These disruptions incited the development of an array of metrics to capture their scale, scope, and impacts, for which the GSCSI-M provides a perspective. While many regions experienced disruptions in their supply chains, the proposed metric and stress index effectively captured relative maritime disruptions despite their simplicity. Beyond measuring global trends, localized stress signals highlight chokepoints that may warrant policy intervention. This framework could be extended to other scales (e.g., feeder loops or domestic shipping) and supply chains, where visibility data exists. Port productivity benchmarks, such as the World Bank's CPPI, could be complemented by recurrent localized stress surges that flag port investment needs or operational constraints (World Bank, 2025b).

Comparing the GSCSI-M with other related indices reveals relevant associations, particularly with the schedule reliability and freight rates, which are single-variable maritime indices (Table 3). It underlines that high port stress, low schedule reliability, and rate spikes are interrelated. A lower level of association is observed with meta-indices (multi-variables) such as PMI and GSCPI, where port stress is only one component impacting supply chains. This high association with single-variable maritime indices and lower association with generic multivariable supply chain indices is encouraging, as it indicates that the GSCSI-M is in line with well-known maritime indicators, while offering a unique and complementary perspective for supply chain indicators.

Table 3
Association between the GSCSI-M and selected supply chain indexes, 2018–2025.

Index	Correlation	Association
Purchasing Manager's Index (PMI) - USA Delivery Time	0.477	Change in expectations of additional deliveries by supply chain managers associated with port stress at the regional (US) level.
Sea Intelligence Schedule Reliability Index	−0.745	Strong direct and inversely proportional association with schedule reliability. Higher port stress levels reflect disruptions in schedule reliability.
Global Supply Chain Pressure Index (GSCPI)	0.278	Port stress is a limited but significant component of a meta supply chain disruption indicator.
Shanghai Container Freight Index (SCFI)	0.719	Strong direct association between port stress and the related decline in capacity, which directly impacts container shipping rates.

The connection between rate spikes and disruptions warrants deeper investigation across sectors, regions, and transport modes (bulk shipping or other modes such as air cargo). The primary takeaway from the proposed framework is that significant rate increases can be attributed to market mechanisms, particularly the decline in the velocity of freight, which the GSCSI-M captures through estimated volumes of delayed capacity. These should not be immediately interpreted as signs of monopolistic behavior, but as market mechanisms change during surges, where the willingness of shippers to pay for available scarce capacity becomes the key driver. Further, while the GSCSI-M has been associated with the variability of other indexes used in the shipping industry, it can be further tested in terms of its elasticity by controlling for variables such as energy and commodity prices, exchange rates across major currencies, freight rates, and demand drivers (e.g. growth in port throughput). The GSCSI-M was assessed through a specific threshold level (quartile), but it is not clear which actual threshold level results in rate spikes, which are likely to be associated with geographical variability in market conditions. It is also worth considering to what extent port-level stress is mitigated or magnified by connectivity, as illustrated by UNCTAD's Liner Shipping Connectivity Index (UNCTAD, 2024). While it can be assumed that high levels of connectivity provide resilience against disruptions, it is unclear whether this connectivity can be an amplifying factor under specific circumstances, such as a disruption at the hub.

Based on the observed behavior of the GSCSI-M and what it measures, maritime supply chain disruptions can be mitigated through the following. (1) For gateway ports, enhancing port-hinterland infrastructure resilience includes IT systems and contingency planning for infrastructure services and customs. (2) Increasing end-to-end shipment visibility through real-time tracking to allow shippers and supply chain actors to make agile decisions. (3) Ensuring more flexibility in the utilization of available capacity is crucial to mitigating impacts during periods of supply chain stress. Systems facilitating capacity sharing across networks can yield substantial benefits, including positive spillover effects for shippers. This principle extends to the alliance framework in global container shipping, which played a constructive role in the recent crises by more effectively managing existing capacity.

Looking ahead, integrating gateway and hinterland metrics like dwell time made available in the World Bank's Logistics Performance Index (2023) would further enrich disruption monitoring. More granular rate information across trade lanes beyond the main East-West routes also remains a data gap. This gap is further underlined by the fact that the GSCSI-M focuses only on Panamax containerships and above, leaving the feeder market and its smaller ports unaccounted for. The GSCSI-M underlines that while it is a component metric of supply chain disruptions, it focuses on a specific part of the chain, the maritime segment, as measured at container ports. This leaves the door open for additional components that could be developed with a similar methodological framework, including yard dwell time, gate dwell time, and hinterland congestion.

CRediT authorship contribution statement

Jean-François Arvis: Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Jean-Paul Rodrigue:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Daria Ulybina:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Cordula Rastogi:** Supervision, Conceptualization.

Data availability

Data will be made available on request.

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