Policy Research Working Paper 10839

A Metric of Global Maritime Supply Chain Disruptions

The Global Supply Chain Stress Index (GSCSI)

Jean-François Arvis
Cordula Rastogi
Jean-Paul Rodrigue
Daria Ulybina

WORLD BANK GROUP
Macroeconomics, Trade and Investment Global Practice
July 2024

Policy Research Working Paper 10839

Abstract

Global supply chains recently faced widespread disruptions. The COVID-19 pandemic caused major disruptions in 2021 and 2022, while in late 2023, geopolitical incidents in the Red Sea and water shortages in the Panama Canal disrupted global shipping routes. Regardless of the cause, delays, or rerouting mean that disruption diffuses at a global scale. To quantify and assess the magnitude of disruptions globally or locally, in 2021, the World Bank developed a proposed metric, the Global Supply Chain Stress Index. The index derives from Automatic Identification System tracking data. It calculates the equivalent stalled ship capacity measured in twenty-foot equivalent units), providing data at the port, country, regional, and global levels. This granular information can inform targeted interventions and contingency planning, improving the resilience of maritime infrastructure and networks. The index explains the observed surges in shipping rates during disruptions, assuming shippers' willingness to pay for scarcer shipping slots. An increase of 1 million twenty-foot equivalent units in global stress pushes the Shanghai Containerized Freight Index up by US$2,300 per twenty-foot equivalent unit.

This paper is a product of the Macroeconomics, Trade and Investment Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at jarvis1@worldbank.org, crastogi@worldbank.org, ecojpr@tamug.edu and dulybina@worldbank.org.

A Metric of Global Maritime Supply Chain Disruptions: The Global Supply Chain Stress Index (GSCSI)

Jean-François Arvis, Cordula Rastogi, Jean-Paul Rodrigue, Daria Ulybina

JEL: F10, F14, L13, R40, R41

Keywords: Maritime Transport, Trade Facilitation and Logistics, Supply chain and logistics

1. Introduction

In recent years, containerized trade, the backbone of global value chains, has experienced unprecedented disruptions. For instance, the COVID-19 pandemic created unforeseen consequences in a far-ranging array of sectors on a global scale, triggering an unprecedented supply chain crisis from late 2020 to mid-2022. Surging trade demand surpassed shipping capacity, itself affected by massive operational disruptions in key ports. In 2023, there were two events of global relevance. First, a severe drought affected the operation of the locks in the Panama Canal, resulting in a reduction in 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, forcing shipping lines to reroute ships servicing the Asia-Europe and Asia-US East Coast trade routes through the Cape of Good Hope.

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. For decades, the container shipping network has operated loop services according to a regular schedule, like passenger rail or air services. Schedule predictability helps deal with trade imbalances, where surpluses in some regions offset deficits in others. This container supply/demand mismatch means that about 20 percent of total container movements are empty repositioning voyages. When disruptions hit, delays in repositioning containers may amplify the effect of ship delays (section 4).

A key challenge lies in quantifying the stress levels global container ports are facing through a unified metric that can be precisely measured and utilized as a meaningful indicator. To fill this gap, the Global Supply Chain Stress Index (GSCSI) is proposed as a measure capturing the delayed container shipping capacity across global maritime ports. This stress metric, which has been published in the World Bank's Trade Watch since late 2021, is inherently port-centric and derived from analyzing container shipping traffic flows. The index is computed monthly 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.

Measuring and understanding the impacts and propagation of supply 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 and publications (e.g., shipping lines and operators, as well as maritime research consultancies), with only a few predating the crisis. The increasing availability of vessel tracking data and schedule information has facilitated these endeavors since this type of information recently became available. However, in contrast, economic literature tackling these topics or providing an empirically testable theoretical framework remains limited, with few exceptions (e.g. Bai, et al. 2024). Notably, a fundamental question as central as the evident connection between freight rates and supply chain disruptions has not been comprehensively covered in prior literature (Notteboom et al., 2021; Rodrigue, 2022).

Indicators quantifying supply chain disruptions generally fall into three broad categories (Table 1): (1) surveys of supply chain professionals, (2) indicators derived from tracking or schedule data, and (3) meta-indicators aggregating existing data series, based on expert knowledge. Other noteworthy tools are those visualizing vessel movements, including the IMF Port Watch and similar tools by maritime consultancies.

Table 1. Indicators Quantifying Supply Chain Disruptions

Surveys of supply chain professionals	Purchasing Managers' Index and components (IHS Markit, S&P), see section 5
Tracking, Schedule Data	**Global Supply Chain Stress Index (GSCSI)** Schedule reliability (Sea Intelligence), see section 5 Ocean Timeliness Indicator[1] (Flexport)
Meta indicators	Global Supply Chain Pressure Index (FED New York), see section 5 Supply Chain Stability Index,[2] KPMG

Source: Authors.

The current working paper informs the underlying methodology and use cases for the GSCSI, which belongs to the second category of indicators. The rest of the working paper is organized as follows: The next section (2) expands the stress index's conceptual framework. Section 3 explains how the index is derived from AIS tracking data, while Section 4 describes real use cases. Section 5 compares the proposed stress index with other indicators developed by the private sector or governmental institutions. Section 6 proposes a rate model in accordance with observed patterns of rate hikes in times of disruptions, and Section 7 concludes.

2. Conceptual Framework and Data Sources

A stress index attempts to quantify deviations from a norm, which is the typical steady 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 expected due to unforeseen events such as a storm or a break in equipment, so only large deviations are considered indicative of stress. Others are a variability in regular operations. A specific threshold for the standard deviation needs to be defined to determine when a deviation is significant enough to indicate stress. Global demand for container shipping has seasonal patterns, with a marked low in February. While disruptions typically have no seasonal patterns, the industry may have more capacity to absorb them in the first quarter of the year.

In this conceptual framework, global container shipping is schematized as a directed network, where the nodes represent ports, and the edges represent the shipping connections between ports used by the shipping lines' loop, or inter-range, services (Figure 1). Under normal circumstances, these loop services are highly predictable, with consistency in:

(i) Lead times: The transit time between the departure port (d) and the subsequent arrival port (a).
(ii) 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 × Transit time

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

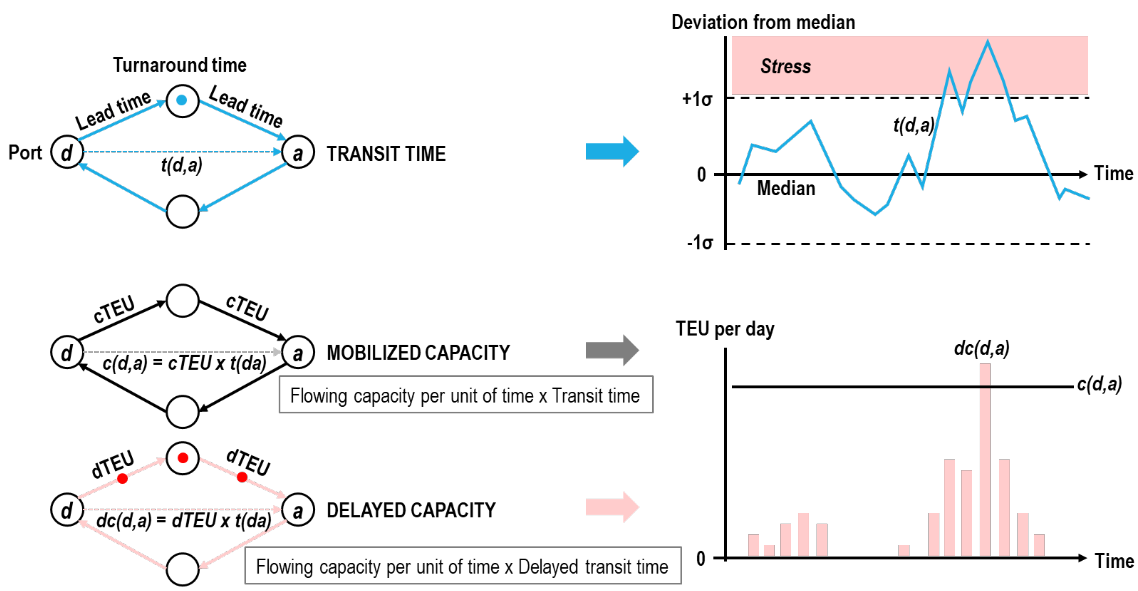
[1] https://www.flexport.com/research/ocean-timeliness-indicator/
[2] https://kpmg.com/us/en/articles/2023/supply-chain-stability-index.html

(i) Delayed arrival event. Ships arriving from earlier ports have to wait at anchorage before berthing.
(ii) 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:

Delayed capacity = Flowing capacity per unit of time × Excess lead time

Figure 1. Concept of the GSCSI



Source: Authors.

The calculation of the GSCSI is derived from an AIS tracking dataset.[3] The dataset includes the full 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 large-scale container ship 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 accurately capture the characteristics of the feeder shipping network.

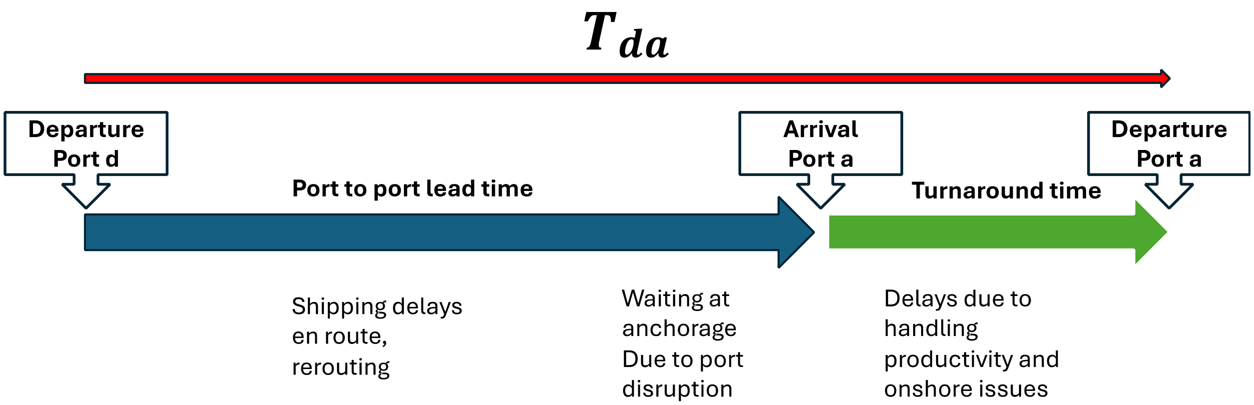
3. The Model

Intermediate Data Frame

[3] Marine Traffic.

The starting point is to take a pair of subsequent port *d*(departure) and *a*(arrival) in a shipping sequence. The time span between departure at *d* and the next departure T(*da*) (or T_{da}) captures most possible disruptions affecting port *a* (Figure 2), whether at *a* or before. These include disruptions *en route* from *a* to *d*, or disruptions at the *a*(arrival) port. Therefore, looking at the lead time statistics of possible inbound connections reveals potential disruptions affecting *a*.

Figure 2. Lead Time Between a Pair of Subsequent Ports



Source: Authors.

For each pair of ports (*d,a*), a dataframe with the following variables was constructed from vessel tracking data:

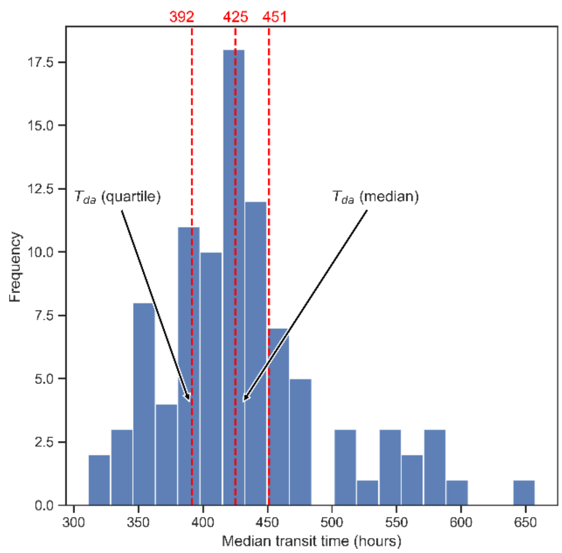
- Period *t* (in practice monthly data from February 2016 until most recent).
- Port arrival *a*.
- Previous port *d*.
- Median shipping time for period *t:* T_{da} *(t).* Using median as opposed to mean avoids problems with outliers (vessels staying in port for noncommercial reasons, such as repairs or crew changes).
- A reference transit time for the edge *(d,a):* T_{da} is representative of normal shipping and port conditions on lane *d* to *a* above which vessels are considered delayed (see below).
- Sum of vessel capacity moving from *a* to *b* for the period C_{da} *(t).*
- The same concept with vessel count N_{da} *(t).*
- Delay for period or transit time above the reference.

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

Estimating Reference Transit Time

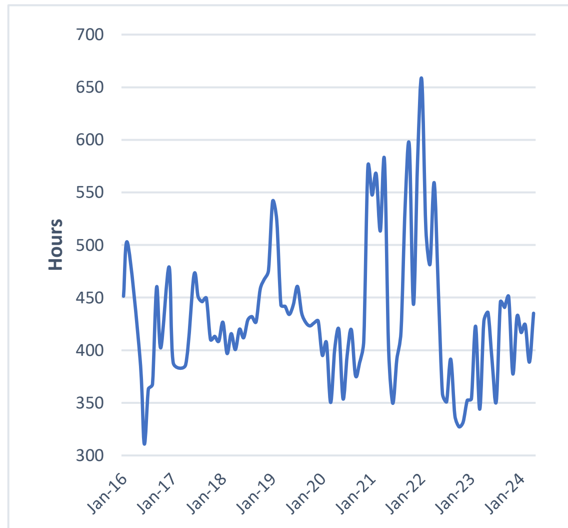
The stress index aims to capture large systemic disruptions. A too small value of the reference transit time (T_{da})) will capture too much noise in the form of small but frequent deviations, such as in a bell curve distribution. Rather, T_{da} should identify outlying lead time on the right side of the distribution of monthly lead time (Figures 3 and 4).

Figure 3. Distribution of monthly median transit time, Port of Shanghai to Port of Long Beach (hours)



Note: 94 records based on 664 voyages for global traffic between Shanghai (CNSHG) and Port of Long Beach (USLGB) between January 2016 and April 2024.

Figure 4. Monthly median transit time (T_{da})) between the ports of Shanghai and Long Beach (hours)



Note: Indicated month corresponds to the timestamp associated with the departure of a vessel from destination port.

Using the mean and standard deviation to identify outliers is not advisable, as these statistics can be skewed by the presence of outliers. Instead, it is preferable to use parameters that are representative of normal or optimal operational conditions.

The model proposed here 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. These tendency and dispersion measures are less influenced by extreme values or outliers.

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 or "stress" 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 true 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 rule for outliers (or 3% probability) gives:

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

Which provides a simple rule to filter episodes of excessive lead time.

Construction of the Index

To identify the disruption by lane as an equivalent trade capacity delayed or stalled (such as moored at port of arrival) at time t, meaning the excess capacity of vessels in the lane compared to the normal:

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

Note that C_{da} *(t)* and Δ_{da} *(t)* must be in the same time unit of hour and capacity received per hour (TEU per hour). Thus, the contribution to the global stress of port a: S_a *(t)* is obtained by summing over all inbound connections *da*, in the unit TEU.

$$S_a(t) = \sum_d S_{da}(t)$$

This definition can be aggregated over ship category by port of arrival, region and globally:

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

Conversely, the contribution of a region or a port to global capacity stress can be directly identified.

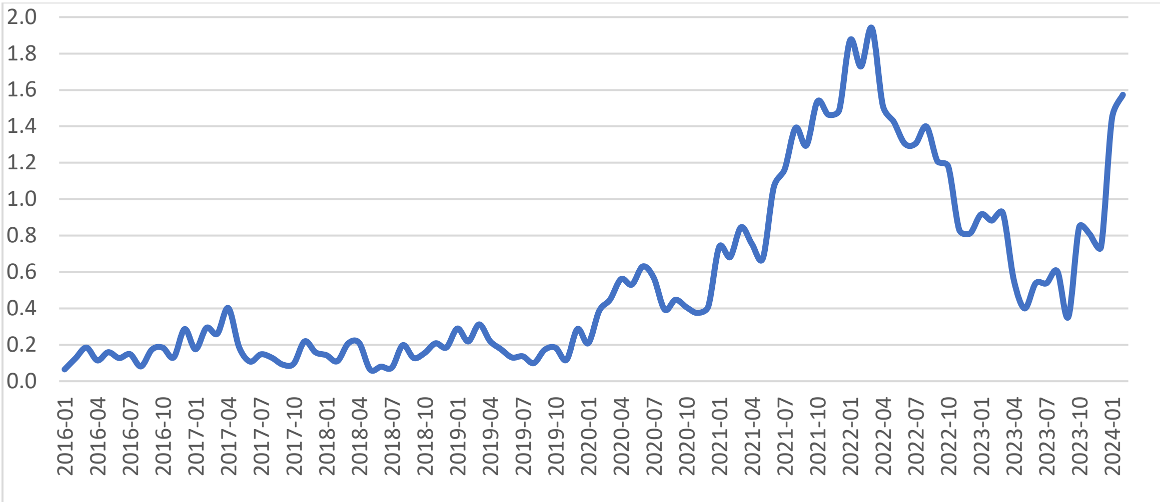
The stress index can also be expressed as an excess delay metric, dividing stress by trade capacity.

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

4. Findings and Applications of the Index

The application of this analytical approach to global shipping data from 2016 to 2024 yields a global supply chain stress metric consistent with the general understanding and expert knowledge of current and past events. Globally, the GSCSI has risen consistently from early 2020 to March 2022, as expressed in terms of trade capacity (measured in TEUs, Figure 5). This indicates a considerable level of stress across the global supply chain over this period. The index went up in late 2023 in response to the Red Sea crisis.

Figure 5. Global Supply Chain Stress Index (MTEU) January 2016- February 2024 (Monthly)



Source: World Bank.

By converting the supply chain disruptions into their impact on trade capacity, the GSCSI offers a tangible representation of the scale of the global supply chain challenges faced over the 2020-2022 period and beyond. This supply chain stress metric can serve as 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 a notable unpredictable variability, in addition to more predictable seasonal and economic cycles.

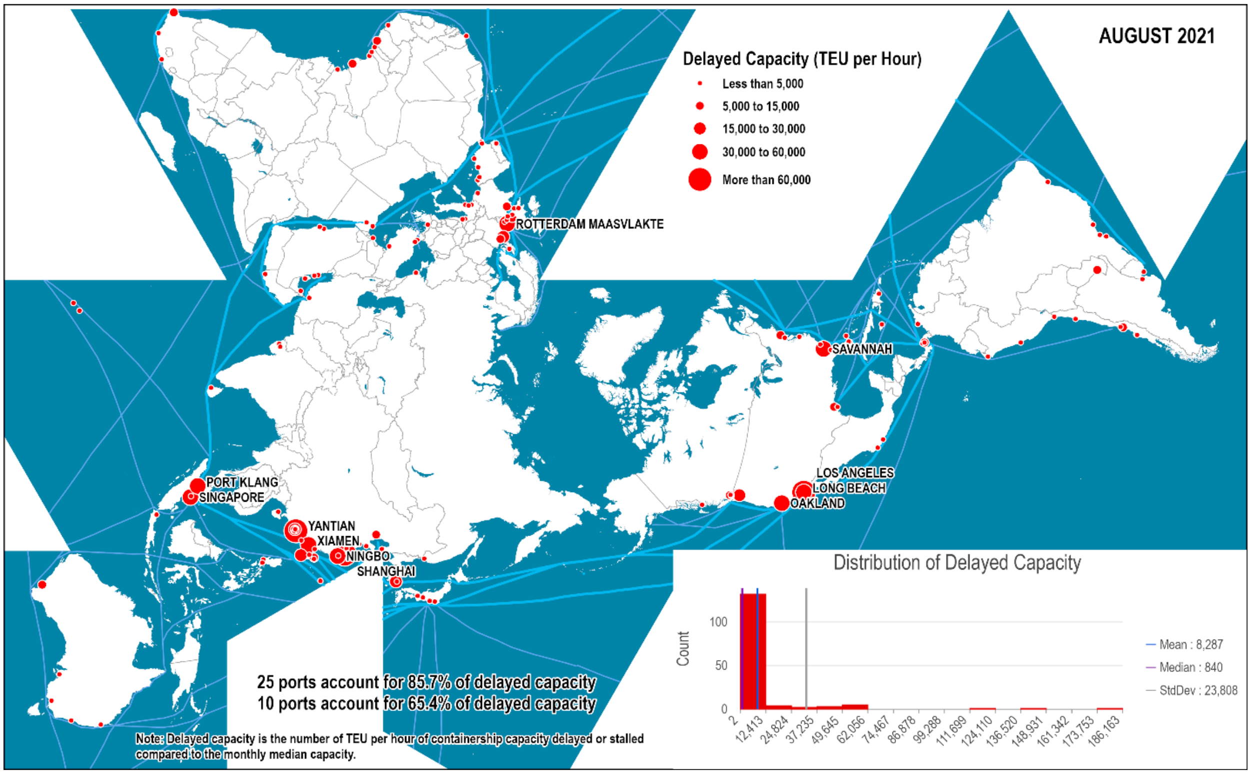
The COVID-19 Pandemic and the 2021-22 Supply Chain Disruption

The 2021-22 supply chain crisis resulted from two trends: 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 high-income countries. While the shipping industry aimed to meet growing demand, supply was hampered by pandemic-induced port closure (notably in Asia), and operational constraints at other ports that caused multi-week vessel queues (especially on the US West Coast).

By mid-2021, severe pier and yard congestion had become prevalent among the world's major port gateways (Map 1), 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.

Ship delays were amplified in the first half of 2021 by repositioning containers to where they were needed for exports (notably East Asia). At the start of the pandemic, shipping lines often cut capacity through canceled (blank) sailings. When demand bounced back rapidly, the industry struggles to promptly reassign capacity, and reposition containers, leading to bottlenecks. 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.

Map 1. Delayed capacity at World’s Major Port Gateways (August 2021)



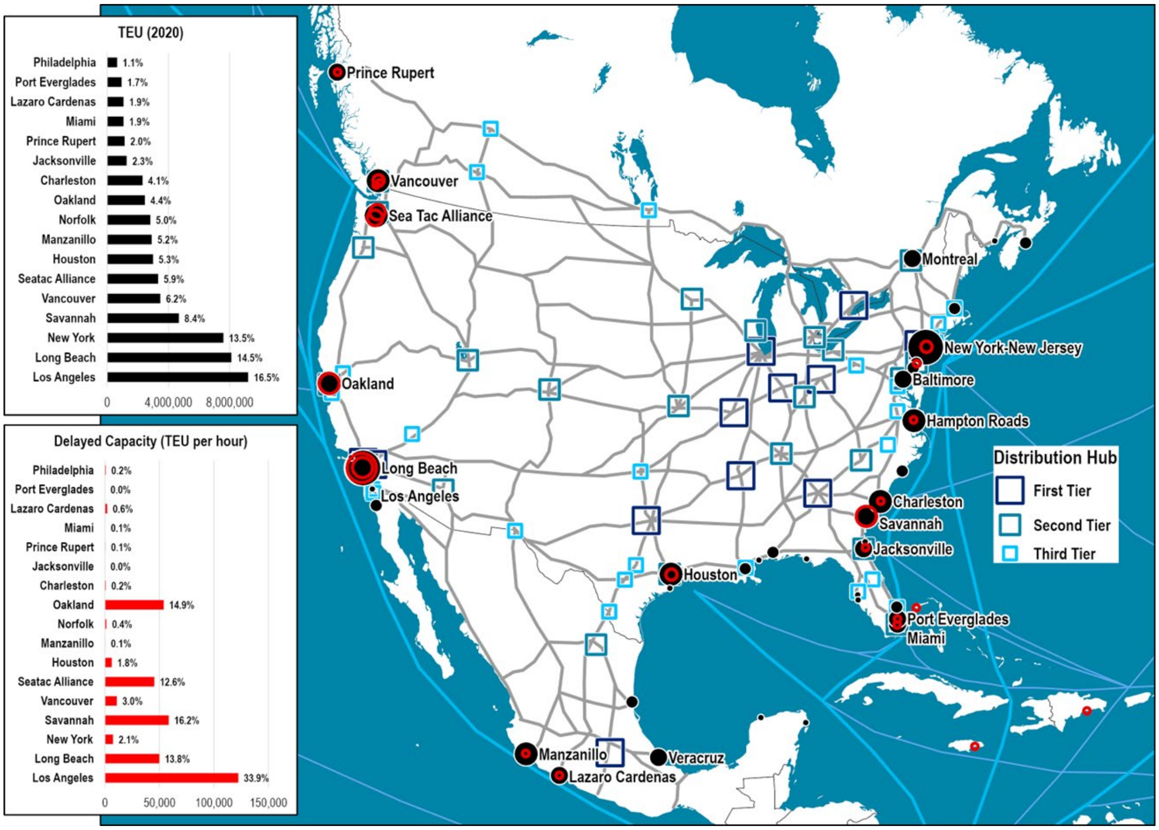
Source: Authors.

In August 2021, 25 ports, primarily located in China and on the West Coast of the United States, accounted for 86 percent of the delayed trade capacity. Moreover, the sources of disruption were concentrated. Just ten ports, including Shanghai, Yantian, Los Angeles/Long Beach, Savannah, and Ningbo, were responsible for 65 percent of the delayed capacity measured by the GSCSI, underscoring the excessive concentration of these disruptions. In the United States, 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.

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.

A focus on North America (Map 2) 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 percent of the North American container traffic (including Mexico), they accounted for 48 percent of the delayed capacity. Oakland and Savannah, having a strong Asian connectivity, were also ports with a high share of delayed capacity.

Map 2. Port Activity and Containership Delayed Capacity in TEU per Hour at Port North America (August 2021)



Consequently, reliability and timeliness in global logistics plummeted to unprecedented modern lows (Figure 4). The proportion of container ships arriving on time, within an 8-hour window, fell from a typical 75 percent pre-mid-2020, to just 35 percent in early 2021. This dramatic drop in on-time performance underscores the significant erosion of predictability affecting global logistics networks designed around scheduled services.

The Red Sea Crisis

Beginning in November 2023, attacks by armed groups in Yemen on merchant vessels in the southern Red Sea jeopardized the key maritime route through the Suez Canal. To circumvent the Red Sea, major carriers rerouted vessels around the Cape of Good Hope, adding 3,000- 3,500 nautical miles (5,500 to 6,500 km) and 7-10 days to a typical Europe-Asia voyage. This massive rerouting impacted container shipping more severely than 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 its latest elevation reflecting over 700,000 TEUs of additional capacity absorbed into longer routings (Figure 5).

Port-Level Stress

The Stress Index's primary use is to inform global trends. At the other end of the spectrum, port-level stress data highlights local issues potentially amenable to policy interventions. Aside from the 2021-22 period impacting most gateway ports, individual ports tend to experience short-lived stress episodes. Port congestion severely challenges schedule reliability for maritime supply chains. The examples provided in Annex 2 illustrate the stress pattern. The Port of Long Beach, in California, 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 first. 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.

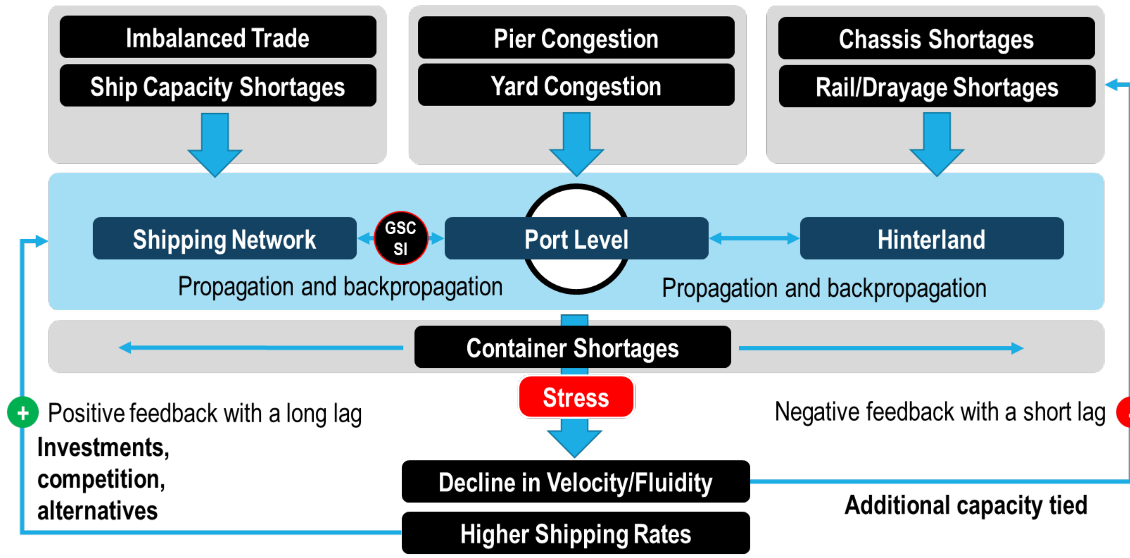
Transshipment hubs such as Algeciras, Singapore, and Tanjung Pelepas appear to exhibit similar erratic fluctuations in their stress patterns compared to gateway ports serving as final vessel destinations or departures. Therefore, port-level stress data can serve as valuable complementary information and provide insights alongside other established indicators and data on port and/or logistics performance (like the World Bank's Container Port Performance Index (CPPI) and the Logistics Performance Index (LPI)).

A port is heavily dependent on its hinterland connections to facilitate cargo flows. Port congestion has notable impacts on the availability of assets like drayage trucks and rail ramps as connections to inland destinations. 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 for example. These chassis are also utilized for container storage at some rail yards and distribution facilities.

There exists a divergence between the increasingly demanding punctuality and flexibility of modern supply chains, such as e-commerce fulfillment, and the rigidity inherent to maritime shipping networks optimized for economies of scale through post-Panamax vessels. Shippers and cargo owners often respond 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 availability and shortages became the primary propagation and backpropagation mechanism disrupting maritime logistics networks. In this context, containers were spending 20 percent more dwell time immobilized within the logistics system on vessels, chassis, and container yards.

The stress stemming from the declining velocity of container movements initiates a negative feedback loop that occurs with a short time lag (Figure 6). As containers spend more dwell time at terminals or inland locations due to lack of capacity, it progressively impairs velocity and fluidity across all components of the transport chain. Maintaining the same level of service necessitates deploying additional assets, which only further exacerbates prevailing congestion. For instance, if a container yard is congested, it restricts the terminal's capacity to handle vessel operations since inbound containers cannot be expeditiously unloaded due to a shortage of yard space. As could be seen during the COVID-19 pandemic, localized disruptions near major ports can create significant cargo backups in the hinterland.

Figure 6. Disruptions in Global Maritime Supply Chains and the GSCSI



Source: Authors.

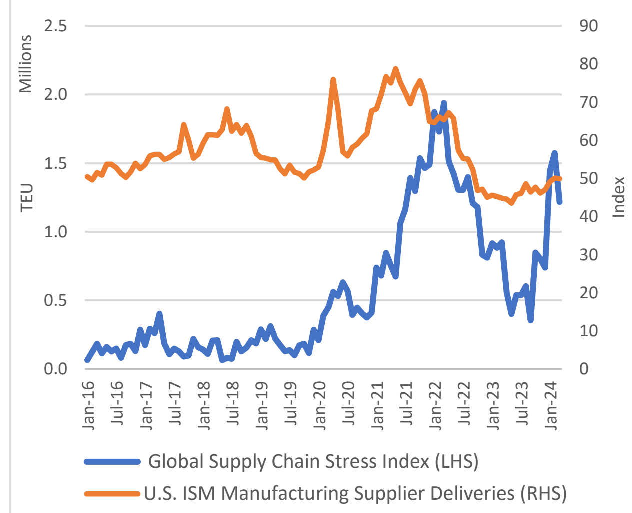
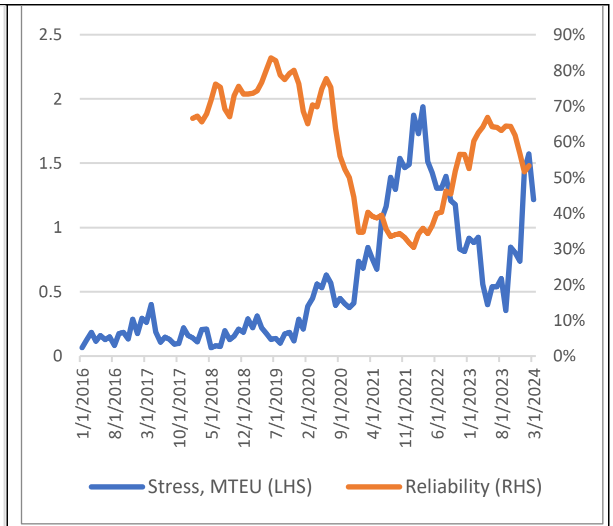
5. The GSCSI and Other Indexes

Several established or recent indicators aim to measure and quantify supply chain disruptions from a different standpoint.

Suppliers' Delivery Times from the Purchasing Manager's Index (PMI)

The suppliers' delivery time index captures the extent of supply chain delays across developed and emerging markets. It is available from IHS Markit's (Standards & Poor) PMI business surveys. The PMI and its components are commercially available monthly and are widely recognized for their relevance to forecasting short-term economic trends. PMI is a multi-dimensional sentiment survey that captures short terms industry trends, experienced by supply chain executives. PMI's supplier delivery time captures the time that it takes for suppliers to provide inputs to their factories in comparison with previous month. The values of supplier delivery times index for United States exhibit only a loose correlation with the Stress Index (Figure 7). A high PMI could be associated with a high stress index since stress implies shipping delays. However, the supplier delivery times available are specific to United States and thus do not incorporate the sentiment of managers from other countries. Furthermore, this PMI's component assesses the delays in the overall delivery process, while the Stress index focuses on its the maritime component.

Figure 7. PMI Supplier delivery time (USA) and Stress Index (MTEU), 2016-2024	Figure 8. Schedule Reliability (%) and Stress Index (MTEU), 2016-2024

	
Source: S&P and World Bank Note: The PMI suppliers' delivery time survey question takes 3 positions: faster/slower/same delivery time compared to last month. The index is the percentage of respondents reporting improvement plus 0.5 the percentage responding a stable trend, hence an above 50 values report an increase in the Supplier Delivery time.	Source: Sea Intelligence and the World Bank. Note: Schedule reliability is a measure of the actual on-time performance of individual vessel arrivals in ports around the world.[4]

Sea Intelligence Schedule Reliability Index

Sea-Intelligence consultancy[5] publishes a Schedule Reliability Index benchmarking carrier on-time performance within an 8-hour window. Despite being available globally and by shipping line, this metric unsurprisingly correlates with the Stress Index, as both leverage the same underlying vessel movement data. However, the Stress Index is port-centric and scalable, while the reliability measure focuses on services, trade lanes, and carriers.

Global Supply Chain Pressure Index

The Federal Reserve Bank of New York's Global Supply Chain Pressure Index[6] (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) and the Harpex index,[7]

---

[4] Each month, Sea-Intelligence measures schedule reliability across more than 11,000 vessel arrivals on average, in more than 270 ports, which is the underlying data for the monthly global on-time performance, as well as the individual carrier, trade lane and service on-time performance. The trade lane and service schedule reliability are based on a two-month rolling averages. In other words, February trade lane on-time performance is based on the average on-time performance of vessel arrivals in both January and February. The definition of "on-time" has in accordance with the widely used calendar-day definition been settled as arrival within plus or minus 1 calendar day from the proforma schedule.

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

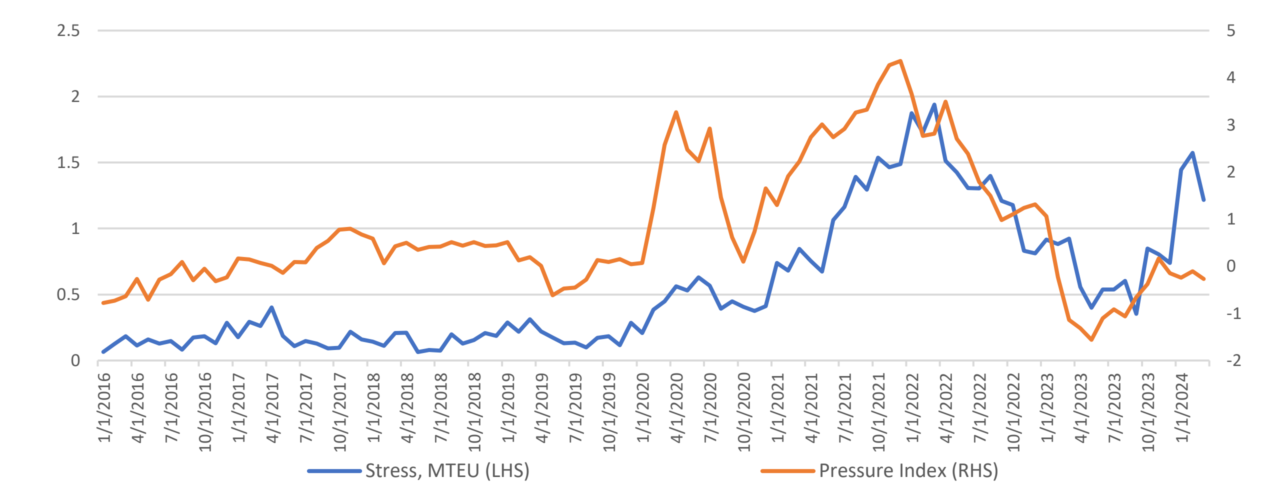
[6] https://www.newyorkfed.org/research/policy/gscpi#/overview

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

as well as airfreight cost indices from the U.S. Bureau of Labor Statistics. The GSCPI also uses supply chain-related components from the PMI. The index is normalized, so zero represents the historical average, while negative values are representative of a very low stress situation and positive values express a level of stress.

The Pressure and Stress indices reflect major events, but the latter is more granular regarding containerized shipping specifically. Conversely, the GSCPI US-centric composition may explain its relative insensitivity to the Red Sea crisis as compared to the Stress Index.

Figure 9. Global Supply Chain Pressure Index and Stress Index (MTEU), 2016-2024



Source: Federal Reserve Bank of New York and the World Bank.

6. Stress and Rates: Competing for Scarce Capacity

Convergence between GSCSI and Freight Rates

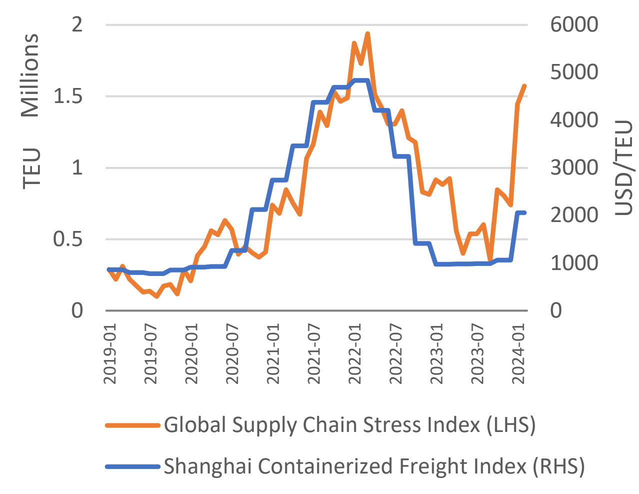
The striking parallelism between global stress and freight rate trends, while expected, merits further elaboration (Figures 10 and 11). It should be noted that prevailing freight rate indices reflect *spot* rates, imperfectly capturing the actual shipping costs faced by large trade volumes under annual 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.

The following factors help explain the boom/bust rate cycles:

1. Freight demand exhibits low rate elasticity, as freight cost represents a relatively small share of the landed price at destinations. The Free On Board (FOB) value of the content of a 40-foot container of manufactured goods from China ranges from USD 50,000 to several million. An increase in spot freight rates amounts to an ad valorem markup of only a few percent of the cargo value. Even at elevated 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), implying that sectors such as furniture have less elasticity than others such as office machines.

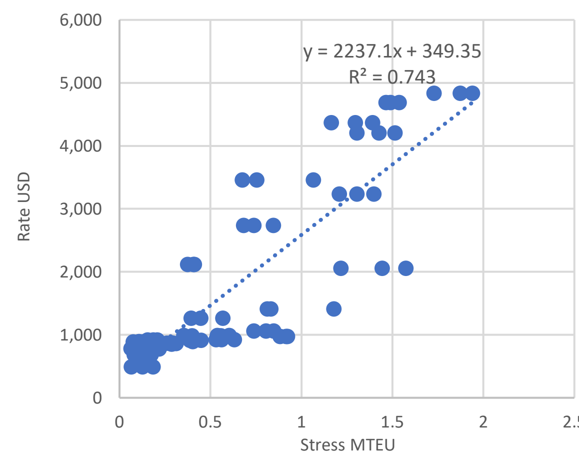
2. Investments in shipping capacity occur across long cycles. Carriers must carefully anticipate demand to avoid costly overcapacity yet still meet upswings. Therefore, capacity-to-demand adjustments are imperfect. The 2021-22 combination of booming demand and congestion-induced capacity losses was unforeseeable and sparked a surge in orders for new (large) container vessels to be delivered in 2023-24 amid slowing demand.

Figure 10. Coevolution of Global Stress (MTEU) and Freight Rates (USD/TEU), 2019-2024



Source: The World Bank, Shanghai Shipping Exchange (https://en.sse.net.cn/). The Shanghai Containerized index is a weighted average of Chinese Shipping rates (per TEU) across global destinations.

Figure 11: Shanghai Freight Index and Stress



Source: The World Bank, Shanghai Shipping Exchange (https://en.sse.net.cn/).

Figure 12. Baltic Dry Index, 1985-2024

Source: Baltic Exchange, the Baltic Dry Index is a global average of observed rates over a series of major routes.

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 the Baltic Dry Index (Figure 12). This historical pattern suggests that shipping rates have a “low normal” state, interrupted by bursts of high rates when capacity cannot match demand surges.

Conceptual Framework of Stress and Rate Formation

Historical freight rate patterns suggest two market regimes: Under “normal” conditions, shipping capacity accommodates shipper demand. 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 with six major carriers providing the bulk of the capacity in 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.

The nature of the business and investment size limits the number of entrants impacting the competitive environment in oligopolistic behavior. However, in a normal regime and in the absence of 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 recover their investment but for the period of tensions when rate spikes happen. Classical models of price formation such as Bertrand’s apply to this regime.

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 shapes the markets: price formation à la Ramsey-Boiteux-Dessus hinging on freight’s ad valorem markup over product value. Lower value goods suffer more acute increases proportional to cargo value. This first manifests for export loads out of origin regions (e.g., China) before affecting import legs.

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	Ramsey-Boiteux
Source: Authors.		

Empirical Connection of Stress and Rate

Quantitative rate-setting models remain an underexplored topic. Rate impacts happen at varying stress thresholds depending on demand levels. The 2021-22 period saw the conjunction of high demand (pandemic-induced consumer demand for goods) with disruptions. The Red Sea crisis (starting November 2023), while increasing stress, faced a comparatively weaker demand backdrop.

One complication in this model is that the impact of capacity stress on the market depends on the number of vessels available. The 2021-22 episode caught the industry at the bottom of an investment cycle, where few vessels were available to compensate for the lack of velocity in shipping due to port delays. Since then, more vessels have been put in circulation and the disruptions in the Red Sea happened with more capacity slack than in 2021-22, hence the apparent reduced impact on rates.

Therefore, the connection between rates and stress is non-linear such as:

$$Rateindex \simeq baseline\ rate + \alpha * Ramp(Stress - Slack)$$

Where Slack represents the reserve capacity of the industry at the time of the disruption. $Ramp(x) = x\ if\ x \geq 0, else\ 0$ Hence rates increase above this threshold of maximum capacity absorption. The Scattered data points (Figure 12), illustrate that in this regime the relationship is linear.

$$\Delta Rateindex\ (USD) \simeq 2300 * \Delta Stress\ (Million\ TEU)$$

The capacity slack prior to a disruption is expected to change slowly over time unlike disruption and stress index, which see fast changes. Unfortunately, there is no good proxy for this threshold: slack is expectedly higher in 2024 than in 2020 due to ship delivered since. The empirical analysis will try explaining the slope α of the connection between stress and rate.

Annex 3 provides a model by which shippers' willingness to pay depends, inversely, on the value of their goods per container. According to this model, stress, and rate changes are proportional.

$$\Delta Rateindex\ (USD) \simeq \frac{Typical\ goods\ value\ per\ TEU}{Moving\ capacity\ (M\ TEU)} * \Delta Stress\ (Million\ TEU)$$

Typical value of a container is computed as an average mean across commodities, hence representative of lower end values.

With the moving capacity for vessels during the period of interest being 18MTEU, the typical value of goods implied by the observed connection is about **40,000 USD per TEU**. This value is indeed at the lower end of the value per TEU statistics (Annex 4). Therefore, capacity constraints and willingness to pay may explain the very high-rate bursts observed in recent periods of disruptions.

7. Conclusion

The pandemic-induced crisis and other disruptions from 2020 onward significantly impacted shipping capacity and freight rates. While many regions experienced disruptions in their supply chains, the proposed metric and stress index effectively capture relative maritime supply chain disruptions despite their simplicity. Beyond measuring global trends, localized stress signals highlight chokepoints warranting a level of policy interventions. This framework could be extended to other scales (e.g., feeder loops or domestic shipping) and supply chains, where visibility data exists. Systematically producing the Stress Index, including disaggregated data at the regional or port level, could automatically inform productivity and capacity bottlenecks, flagging needs for infrastructure or operational improvements. Port productivity benchmarks like the World Bank's CPPI, or dwell time made available in the World Bank's Logistics Performance Index (2023) could be complemented with recurrent localized stress series, with 'bursts' flagging port investment needs or operational constraints. This would require a partnership between AIS data providers and an international organization.

The connection between rate spikes and disruptions warrants deeper investigation across sectors, regions, and transport modes (bulk shipping or other modes, e.g., air cargo). The primary takeaway from the proposed framework is that market mechanisms explain the observed significant increases in rates. The latter should not be immediately interpreted as a sign of monopolistic behavior.

Mitigating maritime supply chain disruptions requires multi-faceted support:

1. Enhancing port-hinterland infrastructure resilience including IT systems, contingency planning for infrastructure services and customs, and other initiatives (as outlined in existing toolkits by the World Bank and others (World Bank, 2003)).
2. Increasing end-to-end shipment visibility through real-time tracking to empower shippers and supply chain actors to make agile decisions. Visibility solutions are generally led by the private sector, but public-private collaboration unlocking data-sharing (e.g., API to port community system or customs) could facilitate visibility solution development.
3. Ensuring more flexibility in the utilization of available capacity is crucial for mitigating impacts during periods of supply chain stress. Systems that facilitate capacity sharing across operators can yield substantial benefits, including positive benefits for end consumers. This principle extends to the alliance framework in global container shipping, which most industry experts see as having played a constructive role in the recent crisis. However, the European Commission's stated intent[8] to re-examine exemptions granted to shipping alliances under competition policy may mean that new forms of operational collaboration may be required in the future.

[8] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4742

References and resources

Akinci, Ozge, Gianluca Benigno, Ruth Cesar Heymann, Julian di Giovanni, Jan J.J. Groen, Lawrence Lin, and Adam I. Noble. 2022. “The Global Supply Side of Inflationary Pressures.” Liberty Street Economics, FRB New York, https://libertystreeteconomics.newyorkfed.org/2022/01/the-global-supply-side-of-inflationary-pressures/

Arslanalp, S.; R. Koepke ; J. Verschuur. 2021. “Tracking Trade from Space: An Application to Pacific Island Countries”, IMF Working Paper No. 2021/225 (August 2021) https://www.imf.org/en/Publications/WP/Issues/2021/08/20/Tracking-Trade-from-Space-An-Application-to-Pacific-Island-Countries-464345

Baltic Exchange. 2024. "BDI Baltic Exchange Dry Index"; London, United Kingdom Retrieved from Trading Economics: https://tradingeconomics.com/commodity/baltic Accessed: May 2, 2024

Flexport Research. 2024. "Ocean Timeliness Indicator", January 8, 2024 https://www.flexport.com/research/ocean-timeliness-indicator/ Accessed: April 25, 2024

KPMG LLP and Association for Supply Chain Management (ASCM). 2022. "The KPMG Supply Chain Stability Index" 2022 https://kpmg.com/us/en/articles/2023/supply-chain-stability-index.html Accessed: April 25, 2024

Marine Traffic. 2023. MarineTraffic: Global Ship Tracking Intelligence. https://www.marinetraffic.com/en/ais/home/

Notteboom, T., A. Pallis and J-P Rodrigue (2021) “Disruptions and Resilience in Global Container Shipping and Ports: The COVID-19 Pandemic vs the 2008-2009 Financial Crisis”, Maritime Economics and Logistics. https://doi.org/10.1057/s41278-020-00180-5.

Rodrigue, J-P. 2020. “The Geography of Transport Systems”, Fifth Edition, London: Routledge. 456 pages. ISBN: 978-0-367-36463-2. https://doi.org/10.4324/9780429346323.

Sea-Intelligence, "Press Release: Schedule reliability improves M/M in February 2024" (April 2024), Global Liner Performance (GLP) report https://www.sea-intelligence.com/press-room/254-schedule-reliability-drops-again-in-january-2024

Shanghai Shipping Exchange. 2024. "Shanghai Containerized Freight Index" https://en.sse.net.cn/indices/scfinew.jsp, Accessed: April 25, 2024

S&P Global and Institute for Supply Management (ISM), 2024. US Composite Purchasing Managers’ Index (PMI) Retrieved on April 25, 2024 from https://tradingeconomics.com/united-states/composite-pmi

S&P Global & Global eProcure (GEP). 2024. "Global Supply Chain Volatility Index" https://www.gep.com/newsroom/demand-at-asian-factories-rises-at-strongest-rate-in-over-2-years-improving-near-term-growth-outlook-for-manufacturing-worldwide-gep-global-supply-chain-volatility-index , Accessed April 25, 2024

UNCTAD. 2024. “Liner Shipping Connectivity Index (LSCI)”, Geneva Switzerland, March 2024, https://unctadstat.unctad.org/datacentre/dataviewer/shared-report/8df8f52c-de5e-4090-84ea-5d428b94011f

Verschuur, J., Koks, E.E. & Hall, J.W. 2022. “Ports’ criticality in international trade and global supply-chains”. Nat Commun 13, 4351 (2022). https://doi.org/10.1038/s41467-022-32070-0

World Bank. 2020-2024. Trade Watch series (May 2020 - First Quarter 2024) (English). Washington, D.C. : World Bank Group. https://www.worldbank.org/en/topic/trade/brief/trade-watch

World Bank. 2023. "Connecting to Compete 2023: Trade Logistics in an Uncertain Global Economy - The Logistics Performance Index and its Indicators" (English). The International Bank for Reconstruction and Development/The World Bank, Washington, DC (2023) https://lpi.worldbank.org/

World Bank. 2022. "The Container Port Performance Index 2022: A Comparable Assessment of Performance Based on Vessel Time in Port" (English). Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/099051723134019182/P1758330d05f3607f09690076fedcf4e71a

World Bank. 2021. "The Container Port Performance Index 2021: A Comparable Assessment of Container Port Performance" (English). Container Port Performance Index Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/099125006072255739/P1758330dccd270a70b31e0619fee32eb41

World Bank. 2007. Port Reform Toolkit. Washington, DC: World Bank. World Bank. 2010. "Trade and Transport Facilitation Assessment: A Practical Toolkit for Country Implementation." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/2490

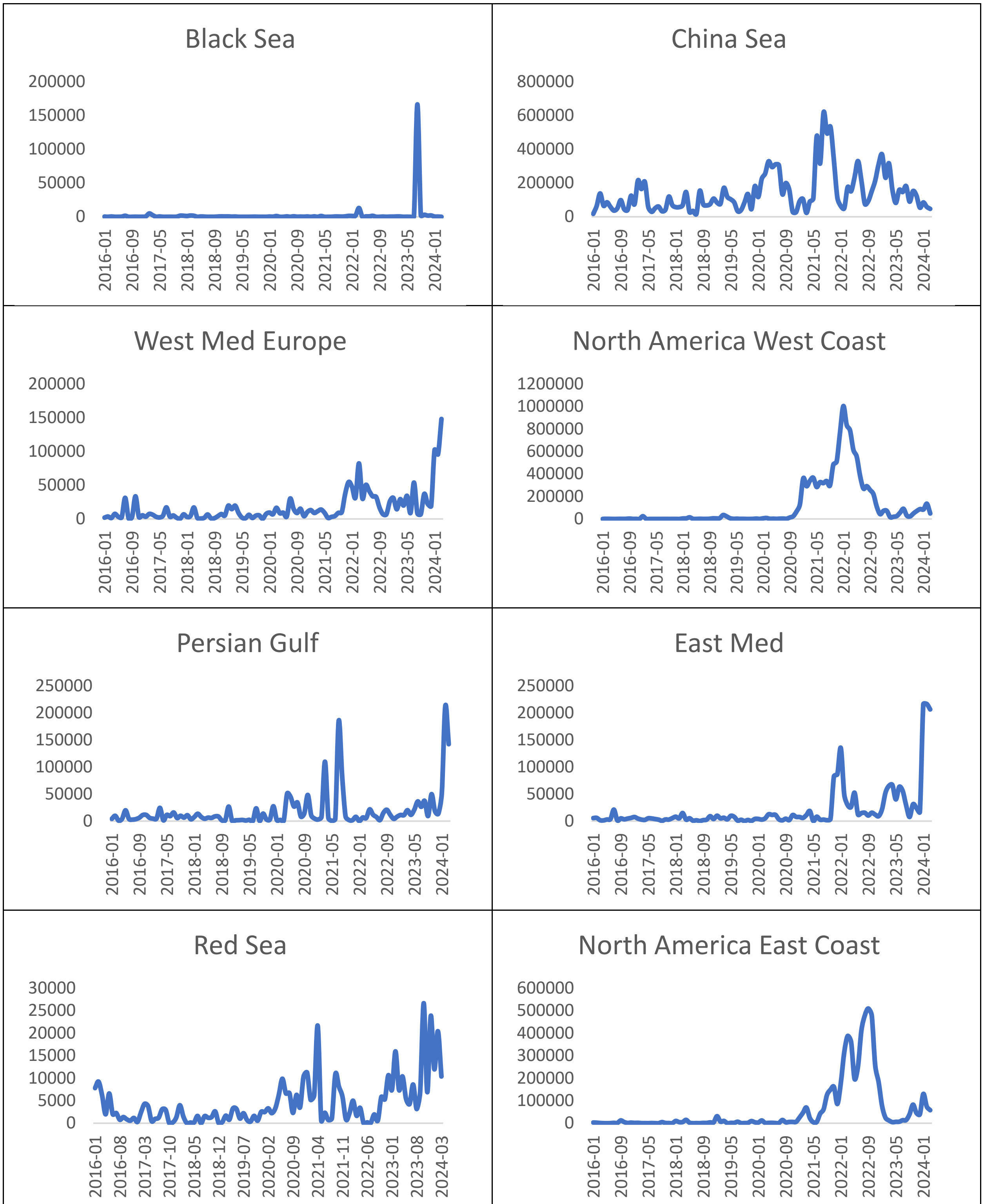
World Bank. 2003. Port Reform Toolkit. Washington, DC: World Bank. https://elibrary.worldbank.org/doi/epdf/10.1596/0-8213-5046-3

Bai, Xiwen; Jesús Fernández-Villaverde, Yiliang Li, and Francesco Zanetti, 2024. "The Causal Effects of Global Supply Chain Disruptions on Macroeconomic Outcomes: Evidence and Theory" (NBER Working Paper 32098), https://www.nber.org/system/files/working_papers/w32098/w32098.pdf

List of acronyms

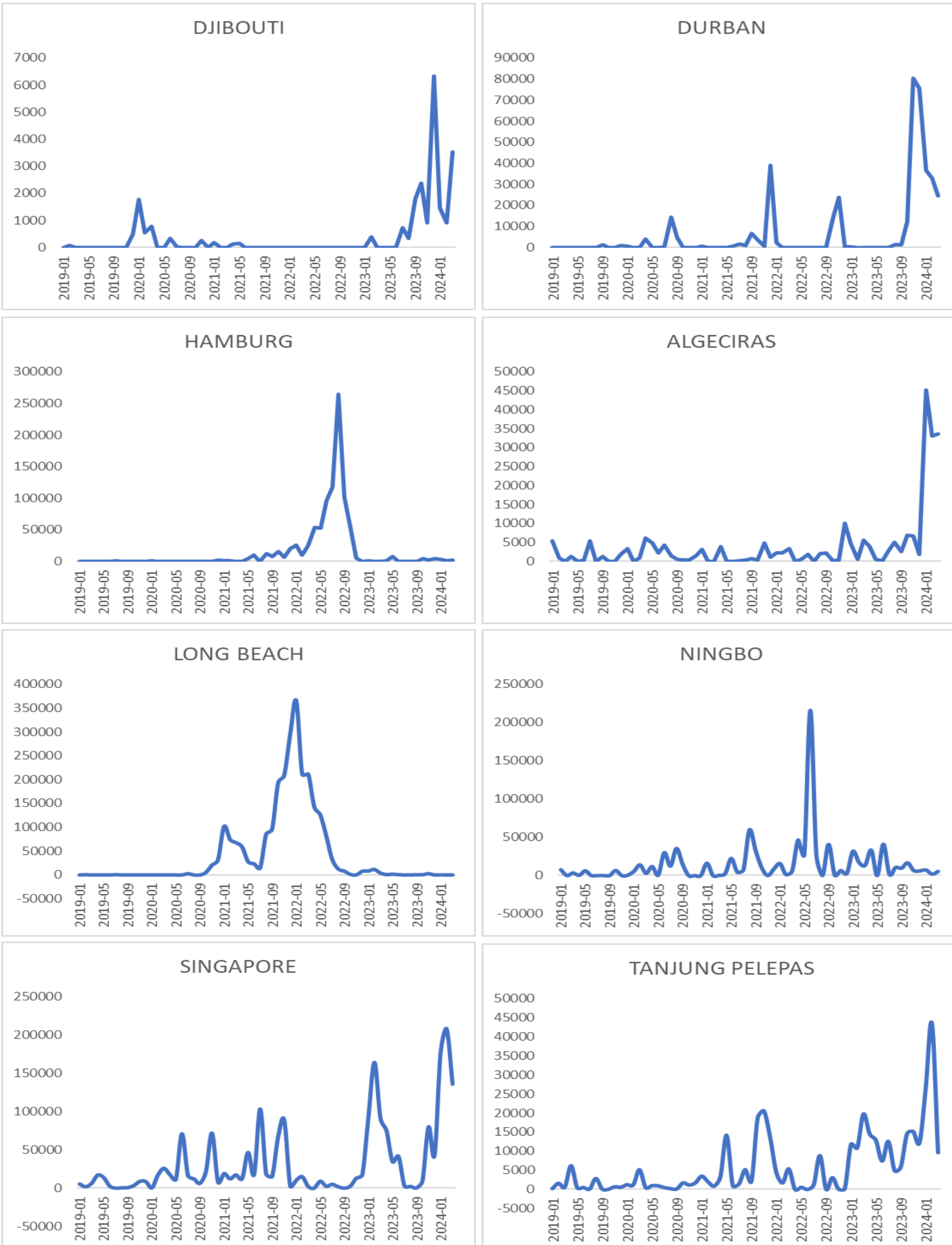
AIS	Automatic Identification System
API	Application Programming Interface
BDI	Baltic Dry Index
CES	Constant Elasticity of Substitution
CPPI	Container Port Performance Index
FOB	Free on Board
GSCPI	Global Supply Chain Pressure Index (FED New York)
GSCSI	Global Supply Chain Stress Index
IT	Information Technology
LPI	Logistics Performance Index
MDST	MDS Transmodal
PMI	Purchasing Managers' Index (IHS Markit (S & P))
SITC	Standard International Trade Classification
TEU/MTEU	Twenty-foot Equivalent Units / 1 million Twenty-foot Equivalent Units
UNLOCODE	United Nations Code for Trade and Transport Locations
USD	United States Dollar

Annex 1: Global Supply Chain Stress index for selected maritime regions (in TEUs)



Source: World Bank.

Annex 2: Global Supply Chain Stress Index (TEUs) for selected seaports, 2019-2024



Source: World Bank.

Annex 3: A preliminary model: How stress quantitatively relate to rates in times of crisis

When capacity constraints cause a "willingness-to-pay" (Ramsey-Boiteux) market regime, the impacts on cargo flows are linked to the intrinsic value of the cargo carried. Lower-value bulky commodity products, such as furniture, are relatively more impacted by freight rate hikes and are more susceptible to severe trade disruptions resulting from reduced capacity. Conversely, higher value per container merchandise, like pharmaceutical products, exhibit resilience, with shippers demonstrating a willingness to absorb higher freight rates to ensure uninterrupted supply chains.

The following models apply by route *r* and product *k.*

Key parameters for product *k* include:

- $\mathrm{Value_k}$, the FOB value per container for product *k*,
- C_{rk} the share of global available shipping capacity *C* used for product *k* on route *r* (before rate increase)
- α_k the **supply** elasticity for product *k.* This elasticity is not Armington's constant elasticity of substitution (a large number) but an indication of how much ad valorem rise in freight costs a trader is willing to absorb. Unfortunately, unlike CES or elasticity to distance, this number is not measured in current trade research. However, intuitively, it should be less than one.

Consider the spot TEU freight rate P_r over normal reference P_{0r}, in the absence of capacity constraint on route (long term marginal price). The increase in ad valorem freight cost for product *k* experienced when shipping on route r is:

$$\frac{P_r - P_{0r}}{\mathrm{Value_k}}$$

The price increase $P_r - P_{0r}$ over the FOB price triggers a reduction in volume of *k* and a reduction of freight demand for product *k*

$$\Delta C_{rk} = -\alpha_k \ \frac{(P_r - P_{0r})}{\mathrm{Value_k}} C_{rk}$$

In an efficient market, the price induced reduction will compensate for the physical capacity constraints or stress S, yielding by summing over all products and routes:

$$S = -\sum_{k,r} \Delta\, C_{rk} \ = \sum_{kr} \frac{\alpha_k}{\mathrm{Value_k}} C_{rk} * (P_r - P_{0r})$$

The rate index such at the Shanghai index averages price increases over routes.

$$Rateindex = \sum_r \frac{C_r}{C} * (P\_r - P\_or)⟧$$

where $C_r = \sum_k C_{rk}$ is the capacity for route *r*

and $C = \sum_{rk} C_{rk}$ is the global capacity.

Averaging over routes, the model yields an approximate linear relationship between stress and freight rate index.

$$Rateindex = Rateindex_0 + \frac{KS}{C}$$

With

- $C = \sum_{kr} C_{rk}$ is total available ship capacity.
- $K = \left(\sum_k \frac{\alpha_k}{\mathrm{Value_k}} * \ \ c_k\right)^{-1}$
- $c_k = \frac{\sum_{\mathrm{r}} C_{rk}}{C}$ is the share of total capacity allocated to product k

Hence K is the harmonic mean of $\frac{\mathrm{Value}_k}{\alpha_k}$. K represents a value per container. It means that:

Rate index increase= (representative value per container) X (share of fleet idled by disruption)

Since values per TEU are in the tens of thousands of dollars or more, this simple rule explains that shipper's competition for shipping slots may explain the burst observed.

The harmonic mean is lower than the arithmetic mean. Therefore, K is more representative of products with low FOB value or high elasticity, which conforms to intuition.

Empirical implementation

Value per container is taken from MDST World Cargo database (commercial source). Values are estimated at SITC 2 digits as median and quartiles of observation along share of the commodity in containerized trade. (Annex 3).

Ship global capacity entering the stress calculation is about 18 MTEU, taken from the fleet of ships in Marine Traffic, used in the estimate of the Stress index.

The empirical value of K is K=2,300*18=41,400 USD.

Harmonic mean of value per container is estimated at 25,500 USD. The lower value implies an average elasticity of supply across products of 0.6 to match the value of *K.*

Annex 4: Value per TEU at STIC 2 digits (median observed value)

Product (SITC)	**USD**		**Product (SITC)**	**USD**
Live animals	47,394		Plastics in primary forms	34,798
Meat & meat preparations	30,625		Plastics in non-primary forms	82,455
Dairy products & eggs	33,225		Other chemicals	74,007
Fish & fish preparations	35,403		Leather & manufactures	56,019
Cereals & cereal preparations	10,870		Rubber manufactures	17,012
Vegetables & fruit	20,146		Cork & wood manufactures	9,441
Sugar & sugar preparations	23,046		Paper & paperboard	22,984
Tea/coffee/cocoa/spices	29,800		Textiles & made-up articles	36,633
Animal Feeding stuffs	20,933		Mineral manufactures	29,143
Miscellaneous Food Products	26,032		Iron & steel	45,940
Beverages	31,240		Nonferrous metals	125,516
Tobacco & tobacco manufactures	41,245		Metal manufactures - other	45,831
Hides/skins/furs - raw	10,526		Power generating machinery	93,009
Oilseeds and oleaginous fruits	10,967		Specialized machinery	74,989
Crude rubber	20,333		Metalworking machinery	90,225
Cork & wood	7,178		General industrial machinery	130,064
Pulp & wastepaper	13,049		Office machines & adp	210,078
Textile fibers	7,351		Telecom & recording equipment	193,155
Animal oils & fats	19,020		Electrical machinery	93,828
Fixed vegetable fats and oils	21,795		Sanitary/plumbing/heating/lighting	22,755
Other animal & vegetable	17,857		Furniture	24,749
Organic chemicals	68,917		Travel goods & handbags	37,538
Inorganic chemicals	42,898		Clothing & accessories	138,951
Dyeing/tanning/coloring materials	77,134		Footwear	84,885
Medicinal/pharmaceutical products	875,391		Professional, scientific instruments.	125,350
Essential oils/cleansing/toilet	115,930		Photographic/optical/watches	77,754
Manufactured fertilizers	20,512		Miscellaneous Manufactures	40,768

Source: MDS Transmodal World Cargo Database and World Bank.