Economic Impacts of Complex Disasters Affecting the Twin Ports of Los Angeles and Long Beach and their Supply Chains

by

Adam Rose, Noah Miller
University of Southern California

Zhenhua Chen
The Ohio State University

Fred Roberts, Andrew Tucci, Latha Vijayagopal
Rutgers University

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Abstract

Seaports are critical infrastructure to economic activity, as part of the marine (maritime) system, and more broadly as part of national and international trade systems via their role as nodes in complex transportation networks. Thus, disruptions to their operation will ripple through regional, national and international economies.

We simulate the economic impacts of a complex seaport disruption consisting of a port-wide labor strike and power outage, and a terrorist attack on a container terminal at the twin ports of Los Angeles and Long Beach. This scenario was developed in collaboration with security personnel at the ports, the U.S. Coast Guard, and other experts. The analysis was performed using a computable general equilibrium (CGE) model of four regions: LA Metro, SF Metro, Rest of California, and Rest of US, as well as Rest of World features. CGE modeling is especially well suited to the problem, as it characterizes the economy as a set of interrelated supply chains in the context of the workings of markets.

The analysis begins with the identification and estimation of major drivers of impacts relating to the disruption of port capacity and the ability to offload imports. We also estimate the impacts of 5 major resilience tactics intended to mute the direct and supply-chain impacts at the LA/LB ports and their direct and indirect customers across regions of the U.S.

The Base Case impacts for the LA Metro region are projected to be more than $4 billion, or 0.373% of its annual GDP in 2023. However, interregional shifts in economic activity to pick up the slack, most notably outside of California, are sizable as well, resulting in a net negative impact of only $300 million for the nation as a whole. We simulate resilience activities at the port in terms of Excess Capacity, Ship-Rerouting and Management Effectiveness, as well as the use of Inventories and Production Recapture among customers down the supply-chain. The resilience tactics are projected to be very effective in reducing negative impacts. Sensitivity tests indicate that our results are robust.

This paper advances the literature in several ways. It is the first study to examine a complex seaport disruption consisting of three overlapping and cascading disruptions. It decomposes results according to more causal factors and resilience tactics than can be found in the current literature. The analysis is performed with further refinements of a state-of-the-art model that is able to capture not only direct impacts but also the supply-chain effects across regions of the U.S. A key refinement is the specification of ship-rerouting internally consistent with CGE model production and trade relationships.

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I. Introduction

Economic disruptions at seaports are becoming more frequent for several reasons. One direct reason is climate change, which can manifest via more intense hurricanes and higher storm surges in the short term, and via sea-level rise in the long term. Another is the prospect of terrorism in the form of chemical, biological, radiologic, or nuclear (CBRN) agents being inserted into shipping containers, which can cause widespread contamination of surrounding cargo and facilities and death and injury to port personnel. Yet another is the continuation of the history of labor unrest, which sporadically results in port shutdowns or slowdowns.

In addition to disruptions directly on-site, off-site events can have disastrous consequences. For example, wildfires can cause power outages, both planned (e.g., to avoid the fires in the first place during especially dry and windy intervals) and unplanned (e.g., from direct fire damage to electric powerplants or transmission systems). With their dependence on sensitive computer equipment, even momentary power interruptions can lead to long disruptions, as equipment is reset and schedules must be revised. Another category of indirect sources is socio-political events, such as the recent Middle East tensions, which have caused major ship-rerouting that increases congestion at some ports, thereby significantly increasing transportation costs and making major shipping accidents more likely.

Not only are such individual disruptions increasing seaport vulnerability, but prospects are increasing that they can be even more disruptive by occurring simultaneously, overlapping somewhat, or occurring sequentially. These *complex* events are likely to have greater negative impacts as a whole than the sum of their individual parts, given negative synergies arising from their interactions in relatively confined locations (Roberts et al., 2022; Egan et al. 2022; Vijagayopal et al. 2022: Tucci et al. 2023).

Seaports are critical infrastructure to economic activity, as part of the marine (maritime) system, and more broadly as part of national and international trade systems via their role as nodes in complex transportation networks (GAO 2021; AAPA 2024). Thus, disruptions to their operation will ripple through regional, national and international economies.

We simulate the regional and national economic impacts of three overlapping and cascading disruptions for the twin ports of Los Angeles and Long Beach, California, the busiest container port system in the United States:

- Labor Strike
- Loss of Electric Power
- Terrorism Incident Affecting Shipping Containers

These disruptions, which define what we call the "West Coast Whammy" (WCW) scenario, were developed in collaboration with security personnel at the Port of LB, the U.S. Coast Guard, the private sector, and other experts. The disruptions are of various durations, and might occur individually, or as part of a larger complex event. Thus, to test for synergies, we simulate the disruptions both individually and simultaneously, and then calculate the difference.

The analysis is performed by applying the Economic Consequence Analysis (ECA) Framework (Rose 2015; Rose et al. 2017), which is a comprehensive, multi-step analytical and empirical process developed at the University of Southern California Center for Risk and Economic Analysis of Threats and Emergencies (CREATE).

The macroeconomic modeling approach is the application of a multi-regional computable general equilibrium (CGE) model known as TERM (Horridge et al. 2012), which is able to estimate the economy-wide impacts of individual and complex disruptions. This model has been utilized successfully in previous analyses of economic disruptions generally (e.g., Wittwer 2017) and of the marine transportation system specifically (e.g., Wei et al. 2020, 2022; Chen et al. 2024).

Data inputs were obtained from a number of sources. Data on qualitative event impacts and resilience tactics were obtained from a project Advisory Board consisting of members with high-level experience in port operations, supply-chain logistics, and seaport protection. This included interviews of Board members on alternative resilience tactics and their potential to reduce negative economic consequences. Data on the commodity value of imports and exports at the Ports of Los Angeles and Long Beach were obtained from the USATrade database. These were combined with the qualitative event impact data to calculate the direct quantitative effects of each event. We supplemented these with additional data on impacts and resilience obtained from a synthesis of the literature. Limitations of these data were tested by a sensitivity analysis.

This paper advances the literature in several ways. It is the first study to examine a complex seaport disruption consisting of three overlapping and cascading disruptions. It decomposes results according to more causal factors and resilience tactics than can be found in the current literature. The analysis is performed with further refinements of a state-of-the-art model that is able to capture not only direct impacts but also the supply-chain effects across regions of the U.S. A key refinement is the specification of ship-rerouting internally consistent with CGE model production and trade relationships.

This paper is organized as follows. Section II provides a brief literature review, and Section III provides background on the Twin Ports of Los Angeles and Long Beach. Section IV details the three events that will be simulated. Section V outlines the methodology for estimating the economic consequences of these events. Section VI introduces resilience tactics. Section VII provides a brief explanation of the TERM model used for the CGE economic analysis Section VIII reports and interprets the results of the analyses. Section IX compares our results to that of other studies and acknowledges its limitations. Section X concludes with policy implications and suggestions for future research.

II. Literature Review

We focus our review to analyses of complex, or multi-hazard, disruptions of ports and marine cargoes. Gou and Lam (2019) developed tools for doing so, but mostly for natural hazards. Gurning and Cahoon (2011) analyze multi-mitigation scenarios for potential maritime disruptions arising from different hazards. These and other analysts (e.g., Lie et al. 2017) have stressed the need for more research on multi-hazard assessments. The reader is referred to Coastal Resilience Center (2016) for examples of nearly 20 predictable and unpredictable threats to the Marine transportation system.

The limited previous work involving complex scenarios has studied a variety of scenarios. Chen et al. (2024) analyze the severe heat and drought on the Mississippi River commercial navigation system during 2022-2023, which disrupted barge traffic and disproportionately affected key commodities, causing a 400% surge in barge rates. Their study analyzes the compound impact of low water levels, and two potential additional sources of supply-chain disturbance -- lock damage and import disruptions. Egan et al. (2022) and Tucci et al. (2023) describe a scenario in which there is a surge in port activity in the Port of New York/New Jersey that coincides with a shortage of trucks, chassis, warehouse space, and some road and bridge repairs. The result is long lines at container terminals and greater than normal congestion. These are exacerbated by a broader scenario that includes a container ship catching fire in the key bottleneck Kill van Kull area, and a cyber-attack on the port terminal when that disruption is winding down.[1]

Some work on the economic costs of port disruptions have revolved around specific disruptions, such as labor stoppages (see also Wendler-Bosco and Nicholson, 2019, for a review). For example, during January 2015, the ports on the US West Coast were closed due to a labor stoppage, with an estimated range of between $1B and $2B a day (counting effect on the GDP regionally and nationally) (Business Wire 2015). Many studies more formally estimate the direct and indirect impacts of port disruptions using a broad set of economic impact models (e.g., input-output models, CGE models, mathematical programming tools, and econometric approaches) and find them to be sizeable (CBO 2006; Park et al. 2008; Pant et al. 2011; Zhang and Lam 2015; Loh and Van Thai 2015; Rose and Wei 2013; Thekdi and Santos 2016; Rose et al. 2018; Wei et al. 2020, 2022). All of them have found the impacts to be sizable from merely singular threats.

Analyses of countermeasures (both pre-event mitigation and post-event resilience) to complex disruptions usually involves some mix of tactics to simple disruptions. Martagan et al. (2009) analyzed rerouting of vessels; Campo et al. (2012) analyzed alternatives for offloading goods to rail transportation or shore-side barges in the case of disruptions to inland waterways; and Jackson (2008) analyzed economic savings of advanced notice of expected flooding. Rose and Wei (2013) and Wei et al. (2020) analyze the applicability of 10 resilience tactics derived from economic production theory (see Rose

[1] Developing complex disruption often builds on prior work to identify "simple" disruptions. Scenarios can benefit from the concept of "failure modes," i.e., "loss of the key functions and capabilities of the supply chain, loss of any such would reduce or remove the ability of the system to perform its mission" (Berle et al. 2011; Rice and Caniato 2003).

2009; Dormady et al. 2023). CISA (2023) provides a recent detailed marine transportation resilience assessment guide covering both pre-event and post-event tactics.[2]

Port operators can implement various measures to speed up the resumption of activities and reduce ship congestion by using excess capacities of undamaged terminals or re-routing ships. Businesses affected by import or export disruptions can initiate a broad range of coping activities, such as use of inventories, conservation, input substitution, diversion of exports for import use, and production rescheduling. However, other than the CREATE researchers (cf. Akakura et al. 2015), very few of the studies adequately factor in all the possible forms of resilience that could mute these losses by using remaining resources more efficiently or by recovering at an accelerated pace. For example, Rose and Wei (2013) and Wei et al. (2020, 2022) have found that the implementation of resilience tactics can reduce business interruption losses (as measured by GDP) by as much as 70%.

One aspect of port reopening after a disruption involves scheduling of waiting vessels based on the value of cargo and the urgency to deliver certain cargos to their final destination. Roberts (2011) formulated that problem and noted that it is both subtle and complex. One needs to consider the number of ships that can be unloaded at a time, the unloading time, the storage time for goods in the port, etc. Even with simplifying assumptions such as setting a uniform duration for unloading all ships, and equal desired arrival times, the problem turns out to be complex, and simple "greedy" algorithms for unloading schedules are not always optimal.[3]

What makes one unloading schedule better than another can be defined by an objective function that considers demand for goods that are not arriving in time. The objective function defines the penalty in terms of quantity demanded, arrival time demanded, and priority. Roberts (2011) discusses a variety of different penalty functions. Weaver et al. (2022) develop a sophisticated model of port disruptions that includes delay penalties resulting from congestion and identification of optimal cargo prioritization and unloading. In other work, Zukhruf et al. (2023) present dynamic programming algorithms for restoring port operations after a disaster that take into account interdependencies to find an efficient approach. Li et al. (2022) present a Markov Decision process procedure to design strategies for modifications in sailing speed, cargo handling rate, and port sequence in response to environmental disruptions, considering the incompleteness and uncertainty of information. Li and Jia (2019) develop a mixed integer linear programming methods to schedule vessel traffic of a seaport to optimize utilization of the navigation channel and anchorage areas. Liu et al. (2021) also use mixed integer linear programming to determine optimal berth allocation and ship scheduling. However, neither of these latter two papers deal specifically with reopening after a disruption.

[2] In a report on the resilience of the Port of New York and New Jersey, Sturgis et al. (2014) point out that "soft" resilience strategies were vital in its recovery after SuperStorm Sandy. Such strategies include planning, people, partnerships and policy that builds 'social capital' through collaboration."

[3] The recovery plan will also be impacted by environmental considerations; labor agreements; continuity of operations planning; planned off-site data processing or emergency operation; supplier/shipper arrangements; and port mutual aid agreements (California Maritime Security Council, 2010).

III. Background on the Ports of Los Angeles/Long Beach

Maritime ports, including the dual ports of Los Angeles and Long Beach, are complex, decentralized systems with many individual actors, each with their own priorities, systems, and procedures. While they compete economically on a routine basis, they will generally cooperate during times of crisis, such as accepting rerouted ships from one another (Port of LA 2024; Port of LB 2024).

Ports and the supply chains they facilitate have some resilience due to cope with routine disruptions, such as equipment breakdowns, weather, and the dynamic nature of any commercial activity. However, the need for speed and efficiency, and the fact that any port is a "chokepoint" with constraints and congestion means that larger disruptions can lead to cascading impacts within and beyond the port environment.

Within a port, efficient operations require careful scheduling of ships, dock availability, equipment, labor, and truck and rail activity needed to move cargo to its next destination. Electrical power and various computer-based systems are key supporting inputs, as is labor. The interruption of any of these inputs for very long soon causes backups, leading to yet more scheduling conflicts and subsequent impacts. If a disruption is regional, rather than confined to a single port terminal or ship, impacts magnify as many independent actors compete for limited resources and must devise ad-hoc procedures to resolve the disruption, individually or in coordination.

Downstream supply chain partners are also affected and may limit the ability of port entities to take effective action. A port terminal can bring in an extra shift of workers to handle a cargo backload, but, if the associated warehouse or rail line is unable or unwilling to make their services available, the cargo will not move.

The twin ports of Los Angeles and Long Beach (LA/LB) are the busiest ports in the US. In 2023, the Port of Los Angeles handled 8.3 million containers (TEUs), 157,000 automobiles and various other cargos with a combined value of $292 billion. Long Beach reported similar volumes for 2023 with a value exceeding $200 billion. Combined, the two ports account for 75% of cargo capacity on the U.S. West Coast and 29% of containerized cargo across all U.S. ports.[4] The five major import categories included light and heavy machinery, motor vehicles, mineral fuels, and recreational equipment. The five major categories of exports were heavy and light machinery, motor vehicles, meat products and fruit (Port of LA 2023; Port of LB 2023).

IV. Complex Threats to the Ports of Los Angeles/Long Beach – WCW Scenario

Our complex disruption scenario consists of the characteristics of an actual labor strike and a potential power outage and a potential terrorist attack. First, the contracts of 22,000 dockworkers at 29 West Coast ports expired without agreement on July 1 (Berger, 2022). Conflicts regarding new contract negotiations caused a labor/management dispute between the International Longshore and Warehouse

[4] Cargo containers are used for a tremendous variety of consumer goods, manufacturing inputs, and food. Although containerized cargo dominates LA/LB port activity, in 2023 the ports handled over 55 million barrels of petroleum products, including crude oil, gasoline, jet fuel, and other refined products. The ports support over 900,000 jobs in the region, and 2.71 million jobs across the United States (Port of Los Angeles 2023; Bennison and McGregor 2022).

Union (ILWU) and terminal operators. This conflict occurs right before peak shipping season (Aug to Oct) (LaRocco, 2022). On July 2, 800 dockworkers go on strike, as current contracts do not prohibit employee-initiated work stoppages. The strike lasted for 5 days (July 2 - July 7), as dockworkers looked to negotiate fair wages and gain assurances that automation would not replace their jobs (Benissan & McGregor, 2022).

To work around the disruptions, importers began diverting cargo first to nearby ports including the Port of Portland, Port of Coos Bay, Port of Tacoma, Port of Seattle, and others nearby. Once those reached near capacity, cargo is later diverted to ports in Houston, Corpus Christi, and New Orleans. This diversion increased congestion and lead times, resulting in ocean shipping spot rates as high as $8,768/40ft container ($5,439 higher than the 5-yr average of $3,329) (Dalheim, 2022). There were 38 container ships at anchor, and crowding and congestion on the waterfront. Container wait times after the strike were as high as 26.5 days. The strike aggravated shortages and increased consumer pricing and is estimated to cost the economy $1.76 billion (LaRocco).

Wildfires have increased in frequency and severity around the world as the number of days with favorable fire conditions (high winds and low relative humidity) has doubled in comparison to conditions in the last four decades (Kaplan, 2021). In our scenario, fires damage transmission lines and substations servicing the Port of LA/LB area on July 12, causing power failure and rendering automation capabilities that might have helped the continuing congestion and backlog less effective. The outage causes 3-days of brownouts, bringing port operations to a standstill as ship-to-shore cranes and automated cranes are crippled and unable to off-load cargo from container vessels during this time (July 12 – 14) (Brown, 2013). Power is restored on a gradual basis, with final port facilities on full power by July 16.

A credible regional security threat leads to MARSEC Level 2 on the West Coast. On the morning of July 18, after two weeks in transit, a ship arrives from an east Asian port to the port of LA/LB. While the terminal is unloading containers off the ship, an explosion goes off from inside one of the containers, killing 3 people, wounding 6 others, and causing severe damage to the surrounding infrastructure (automated cranes) of one of the seven container terminals. The entire port shuts down operations for one full day (July 18) while local police and fire departments, emergency personnel, forensic teams, and FBI officials investigate the cause of the explosion.

Authorities determine that a terrorist organization used a shipping container to smuggle and detonate a bomb in the port of LA/LB. At this point the authorities cannot rule out the potential for additional attacks. The Coast Guard sets MARSEC Level 2 for the ports of LA/LB (at least to selected terminals). This triggers additional security checks (screening) for cargo, which requires additional personnel and leads to further backlogs. With capacity in LA already down by 15% due to the targeted terminal being down for repairs, other terminals struggle to meet the additional MARSEC screening requirements while absorbing the additional cargo load, along with the disruption of numerous law enforcement and emergency response agencies (LaRocco, 2022).

It takes three days (July 19 to July 22) to clear the debris from the terminal and complete basic repairs. The attack is followed by a threat that a number of other similarly rigged containers are on their way into U.S. ports or perhaps have already been offloaded and are awaiting transfer. Port and affiliated workers refuse to work until the government assures some degree of safety. The Coast Guard sets MARSEC Level 2 for the entire west coast, and the Coast Guard, Customs, and other agencies confer on

how to handle the new crisis and develop seamless and effective container screening procedures (Public Policy Institute of California, 2006). The additional screening requirements increases overall shipment costs and causes significant container wait times and berth delays. A one-week shutdown would cause port congestion that would take 26 days to clear and the total estimated damage to the U.S. economy would amount to $16 billion (Public Policy Institute of California, 2006).

Cascading economic impacts of all three components of the complex and narrow would be felt across the country, because West Coast ports, especially LA/LB, handle cargo that is transported overland across most of the country. Moreover, our analysis indicates that ship re-routing supply-change shifts also have widespread geographic effects.

V. Economic Consequence Analysis Process

Below we present methodological refinements of CGE analysis to analyze complex disruptions of seaports. The methodology builds on the CREATE Economic Consequence Analysis (ECA) Framework for disasters in general (Rose et al. 2017; Prager et al. 2018). The framework consists of two sets of advances. First, is the enumeration and decomposition of several drivers of economic consequences of disasters. Second, is the unique role of behavioral responses and resilience. We overcome several methodological challenges in this modeling, especially with regard to isolating consequences of individual drivers, including individual types of behavioral responses and implementation of resilience tactics. This is in part due to the nature of CGE, as well as other types of multi-sector economic models (input-output, social accounting matrices, and sectorally-disaggregated macroeconometric models), which are essentially complexity models because they include extensive interdependencies calculated simultaneously, thus making it difficult to disentangle the economic impacts of the various drivers.

Another challenge is translating disruptions of shipping and ports into variables and parameters that can be accommodated by the structure and nomenclature of the CGE model. This is necessary whether these modeling inputs emanate from sophisticated ship rerouting and cargo prioritization routines (e.g., Roberts 2011; Weaver et al. 2022) or rules of thumb, or whether CGE or other complexity models are used. Thus, our methodology is generalizable to several other types of integrated marine transportation system models.

The economic consequence analysis process involves the following steps:

- Identification of disruptions
- Enumeration of potential impact categories
- Specification of upper and lower bounds for key variables and parameters
- Calculation of direct impacts
- Incorporation of behavioral responses motivated by fear
- Incorporation of resilience actions that can dampen business interruption losses once the disaster strikes
- Translation of direct impacts, including behavioral responses and resilience actions, into user-interface variables for CGE analysis

- Translation of direct impacts and resilience into macroeconomic model drivers
- CGE simulations of individual and complex disruptions varying parameters 500 to 1000 times to generate synthetic data
- Regression analysis of the synthetic data to perform sensitivity tests and to derive estimating equations.[5]

A. Enumeration of Potential Impact Categories

While many studies of disasters tend to focus on *direct* damage and/or business interruption (BI) caused by the disaster, in many cases, the majority of the economic losses stem from the *indirect* (ripple, supply-chain) effects that follow. This is the case for disasters in general (Prager et al. 2018; Zhou and Chen 2020) and especially for cases of seaport disruptions because of the extensive supply-chain impacts (Rose et al. 2018; Wei et al. 2020, 2022).

The three disruptions that comprise the complex event investigated in this paper further drive home this important distinction between direct and indirect losses. In the case of the labor strike and wildfire-induced power loss, there is in fact no direct damage to the port; and the container explosion is quite likely to cause less than $1 million of direct cargo damage. However, by significantly delaying the offloading of cargo from ships – especially in the case of a complex event including all three scenarios – the economic ripple effects can become very large.

Specifically, the main impact of our complex scenario will be short-term commodity shortages and price increases caused by the significant reduction in port capacity. For example, the delay could cause spoilage of fruits and vegetables before being delivered to market, and shortages in stores that may typically only hold a few days of inventories. Producers often rely on critical inputs in their production processes, and a delay in receiving this input could hold up production entirely. For example, following the computer chip shortage during the onset of the COVID-19 pandemic many car manufacturers found their assembly lines held up, which led to revenue losses in excess of $60 billion (Wayland 2021).

There are two main underlying reasons why cargo would be delayed. First is a full port shutdown. This would occur in the case of a walk-off labor strike, electric power loss, and the initial response to a container explosion and possible extended terrorist threat. Second is a reduction in port capacity despite the port remaining open or re-opening. This would occur in the case of a partial labor strike, the recovery period following the power loss in which electricity is slowly/intermittently restored, and in the destruction of port facilities from the container explosion, as well as the additional time required to conduct heightened security checks in the aftermath of the attack.

In our Base Case scenario, the walk-off labor strike lasts 5 days, the wildfire-induced power loss lasts 3 days, and the initial shutdown following the container explosion lasts 5 days for the terminal that

[5] This "reduced form" process was used to develop the Economic Consequence Analysis Tool (ECAT), a decision-support software tool for rapid estimation of impacts of several types of disasters (Rose et al. 2017; see also a subsequent specialized application to radiologic/nuclear threats in the development of GRAD-ECAT by Dixon et al. 2018). The research contained in this paper represents a major stage in the development of a more specialized tool known as the Marine Consequence Analysis Tool (MCAT) (see also, Egan et al. 2022). The last two steps above will be the focus of a follow-on paper.

suffered the explosion, and 3 days for the rest of the terminals in the ports.[6] Following these initial shutdowns, port activity is restored immediately (in the case of the labor strike ending), or slowly over time (in the case of the container explosion) – as described previously in the scenario description, as well as in Table 2 in the following subsection.

B. Specification of the Base Case and Upper and Lower Bounds for key variables and parameters

Importantly, a 10-day shutdown does not mean that a few ships are delayed for 10 days – rather, a backlog of ships would begin to form during those 10 days, which would only start being addressed once the port re-opened and ships began being serviced again (Port Technology International 2024).

To translate the full and partial port closures into offloading delays we first derive an empirical estimate of average excess capacity inherent to port operations. By comparing the offloading capacity during the twin ports' busiest month in 2023 with the average offloading capacity for the same year, we find that, *on average*, the ports have the capacity to offload about 9.92% more cargo per day than what arrives at the port.[7] We assume a linear relationship between length of shutdown (full or partial) and time to clear the backlog, which reflects a first-order Taylor approximation of this potentially non-linear relationship.[8]

After calculating the implied delay length caused by the disruptions – either individually or as a complex event – we apply commodity delay cost functions adapted from Weaver et al. (2022) to estimate the implied impact of the delay on the price or available quantity of each of seven overarching commodity categories.[9] These categories comprise: perishables (short term), perishables (long term), just-in-time (JIT) production inputs, consumer durables, producer durables, raw materials, and non-durable goods. Figure 1 illustrates the combined delay cost function for the Ports of LA/LB, value weighted by 2023 imports.[10]

[6] In recent years, ILWU workers at the ports have not engaged in a walk-off strike but rather have engaged in prolonged partial strikes during contract negotiations. In such cases, however, rather than an unexpected and transitory shock to LA/LB port capacity, this disruption would represent a "new normal" for the maritime supply chain, and actors all along the supply chain would adjust to a new equilibrium. As this represents a wholly different modelling exercise than the short-run scenarios considered in this paper, we defer its analysis to future research.

[7] We calculated this using data on monetary value of imports, rather than TEU quantity, based on the assumption that this would be the metric that importers and port operators optimize for when making business decisions. Note that constructing the same measure of excess capacity using total TEU throughput, the estimate of average excess capacity is very similar, at 10.29%.

[8] In our Base Case, we assume an annualized average excess capacity but examine the effects increasing or decreasing excess capacity in later sensitivity analyses.

[9] Notably, the Weaver et al. (2022) delay cost functions are in turn based on work by Hummels and Schaur (2013) and Minor (2013), who estimate the time-cost of additional days spent in shipping for different commodity types.

[10] As seen in Figure 1, some commodities follow a non-linear delay cost, such as perishables and just-in-time (JIT) input commodities used by the importing firms in their production processes. The prices of other commodities, such as raw materials (e.g., ore, lumber) are less affected by delays as they are typically less critical and do not spoil. Notably, the aggregate delay cost function presented in Figure 1 excludes the use of inventories to offset delays – a form of inherent resilience – to present a "no resilience" baseline (see further details below).

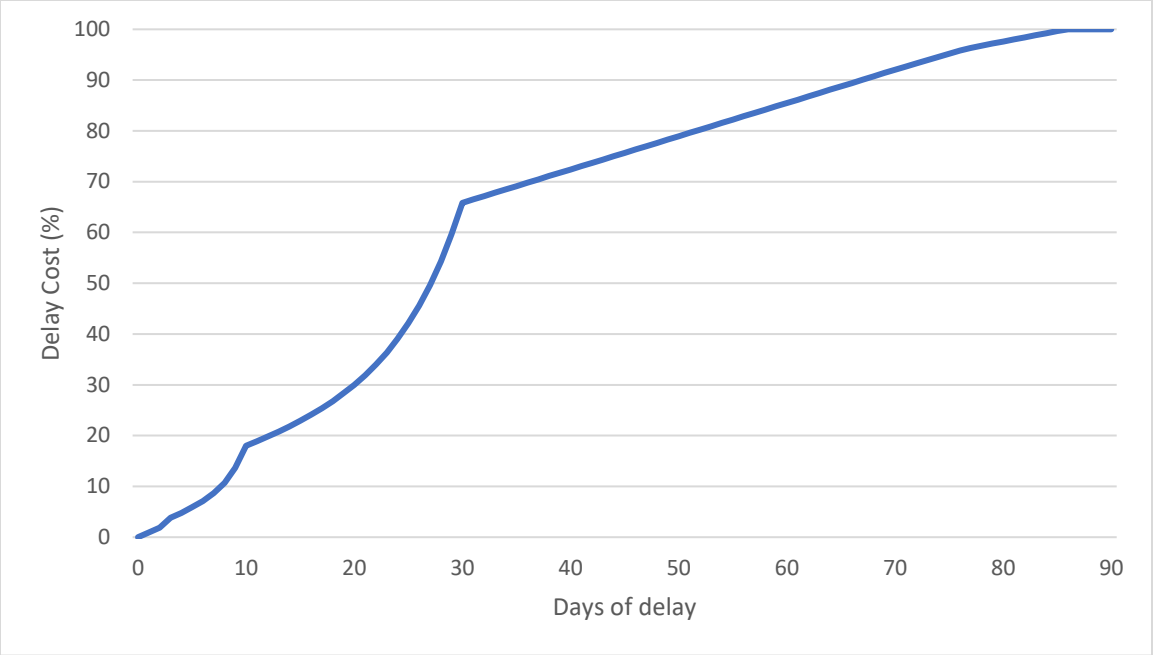


Figure 1. Shipping Delay Costs as a Function of Time

In addition to a Base Case scenario, for each disruption we consider a range of potential impacts, which we characterize in Table 1 as Lower and Upper Bounds. We consulted the literature, various subject matter experts (SMEs), and reviewed similar historic incidents to arrive at the durations for these cases. The Base Case disruption parameter values were chosen to reflect a "most likely" scenario. The Lower Bound values were chosen based on the lowest values that were still of an economically meaningful length.[11] The Upper Bound is not based on historically observed values alone because we note the trend of seaport disruptions increasing in severity over the years. Thus, the bounds are not symmetric around the Base, but rather have much stronger differentials between the Base and Upper Bound with regard to such parameter values as disruption duration and recovery for some of the threats. Our CGE (TERM) model database comprises four regions and 97 economic sectors. The regions are defined as the LA Metro Region (encompassing Los Angeles, Orange, and Riverside Counties), SF Metro Region (including Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma Counties), Rest of California, and Rest of the U.S.

[11] For example, some "labor strikes" at the ports have been as short as 8 minutes and 46 second (Sweeney, 2020) or a targeted a specific ship (SF Star 2014), or ships (Littlejohn 2022), based on origin.

Table 1. Timing and Impact of Events on Port Closure and Capacity Reduction

	Lower Bound	Base Case	Upper Bound
Panel A. Immediate aftermath (days of 100% closure)			
Labor Strike	1	5	14
Wildfire Power Outage	1	3	5
MARSEC Incident (affected terminal)	3	5	14
MARSEC Incident (rest of port)	2	3	10
Panel B. Recovery period (days of reduced capacity)			
Labor Strike (Partial/Prolonged)	182.5	273.75	365
Wildfire Power Outage	1	2	6
MARSEC Incident (affected terminal – crane repairs)	365	547.5	730
MARSEC Incident (all terminals – MARSEC 2)	4	10	40
MARSEC Incident (all terminals – return to normal - MARSEC 1, but lingering worker avoidance)	7	14	60
Panel C. Reduction in capacity during recovery period (%)			
Labor Strike Prolonged	10	15	33
Wildfire Power Outage	50	50	50
MARSEC Incident (affected terminal – crane repairs)	8	10	15
MARSEC Incident (all terminals – MARSEC 2)	33	50	66
MARSEC Incident (all terminals – return to normal - MARSEC 1, but lingering worker avoidance)	5	10	20

C. Translation of impacts and resilience into macroeconomic model drivers

The translation of direct impacts into macroeconomic drivers involves multiple steps but is logically straightforward. First, we take the implied number of days of delay faced by ships arriving on each day of the considered disruption scenario. To find the delay faced by each ship, we apply the following algorithm:

1. Assume ships are serviced in the order they arrive.[12]
2. Assume that each ship carries the same basket of commodities that reflect the value-weighted average of annual imports to the Ports of Los Angeles and Long Beach.[13]
3. Assume an annualized average arrival rate for ships into the ports.[14]
4. Assume that for each day of full operation the ports have an inherent excess capacity of 9.92%, i.e., they can offload 9.92% more cargo than would arrive on an average day without disruption.[15]
5. For each ship, estimate the days of delay until cargo is offloaded, based on the original arrival date, the days of full or partial shutdown caused by the event, and the implied offloading rate at the ports given the disruption(s).
6. For each ship, apply the delay cost functions described previously to the value of the cargo based on their realized delay.
7. Sum the delay costs estimated in (6) across all ships. Note that for perishable goods we take this aggregate delay cost as an estimate of the quantity lost due to spoilage, while for non-perishable commodities we take this as a direct price shock.[16]

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[12] Note, however, that because container ships will typically carry a mix of products, prioritizing *cargo* is more complicated than prioritizing *ships*. Furthermore, ships are only able to "jump the queue" in a small number of situations: 1) US Flag ships serving US ports; 2) military cargo;(3) special categories defined by government bodies in response to emergencies – i.e., PPE during the initial stages of the COVID pandemic; and 4) if the vessel pays the port to do so. The first three situations are outside the scope of our analysis, which focuses on a general port disruption without direct government intervention to facilitate the re-prioritization of certain commodities. The fourth situation occurs so rarely as to not have available data on the types of cargo that such paying ships may carry compared to the average cargo basket. Without data on the difference between the cargo baskets in paying versus non-paying ships, the net economic impacts of re-arranging ships in the queue is zero.

[13] This simplifying assumption abstracts from the fact that, in reality, different ships would carry different sets of commodities. However, this assumption is not unreasonable, because the timing, length, and severity of the events examined are plausibly independent of any specific timing of shipment that different commodities may face, and because over a sufficiently long disruption period the cargo carried by affected ships, in aggregate, would converge in expectation to the representative basket of commodities.

[14] Notably, changes in the arrival rate, i.e., seasonally, is mathematically equivalent to changes in the port's "inherent excess capacity," which is addressed in point #4.

[15] While at first glance almost 10% excess capacity may seem high, recall that much of port operations reflects capital investments (land, gantry cranes, warehousing, etc.) which port operators may optimize to meet demand during peak shipping season, and which are fixed in the short-run. This infrastructure would thus be more than what is required during off-peak times of the year. Nevertheless, in our later robustness checks we examine the impact of increasing or reducing this channel of excess capacity.

[16] We do not include direct or supply-chain impacts of *export* disruption in our analysis because their production has already occurred, so there is no upstream impact. Furthermore, their producers will still be paid, either by foreign purchasers or by insurance companies, so there are no income effects.

8. Scale to an annualized impact by weighting the quantity and price shocks by the value of affected cargo relative to the total cargo value.[17]

There is unlikely to be any direct cargo damage from the labor strike or the power loss events – other than potential spoilage already captured by the delay cost functions. And, while there is likely to be some direct cargo destruction due to the container explosion, it is expected to be minimal compared to the delay costs and is thus omitted from the calculation.[18]

Notably, not all imports into the Los Angeles region arrive via the ports. Thus, to calculate the regional price and quantity shocks for integrating into the CGE modelling simulation, we scale the delay impacts for each commodity imported via the ports to the total commodity imports to the region (i.e., those that may arrive via truck, rail, or air). Specifically, for each commodity, we take the annual import value via the ports, and divide by the total annual import value from all transportation modes to arrive at a scaling factor. We then multiply the delay costs calculated above for each commodity by their respective scaling factor. That is, for each imported commodity c, we define the scaling factor, c_f*:*

$$c_f = \frac{c_p}{c_t}$$

where c_p is the imported value of commodity c via the ports, and c_t is the total imported value of the commodity in the Los Angeles Metro region.

In numerical terms, using a simple example, consider a commodity in which the LA Metro region imports $1,000,000 (2023 dollars) annually, with the value of annual imports via the ports equal to $250,000. Consider also that the delay cost function implies a 50% increase in the import price for the commodity. We would thus calculate the price shock to the LA Metro region due to the port disruption as:

$$p_{shock} = 1.5\left(\frac{250{,}000}{1{,}000{,}000}\right) + 1\left(\frac{750{,}000}{1{,}000{,}000}\right) = 1.5(.25) + 1(.75) = 1.125 = 12.5\%\ increase$$

In other words, the average price increase for imports of this commodity into the LA Metro region would receive an initial (partial equilibrium) shock of 12.5% – though the CGE model may converge to a lower price after substitution, or possibly even a higher price after other general equilibrium effects come into play.

[17] We use the 2023 customs value of all imported (exported) cargo at the ports of Los Angeles and Long Beach for this scaling. For example, the combined worth of imported and exported cargo was $365 billion for 2023. If the total affected value was $73 billion, we would scale the quantity and price shocks by 1/5th to reflect the annual average impact of the disruption – as the TERM model, like most CGE models, is based on a 1-year timescale.

[18] As a quick back of the envelope calculation: The ports handle roughly $365 billion in cargo per year, or $1 billion per day. There are 13 terminals total across both ports that handle containers. For simplicity assuming that each terminal handles the same amount of cargo value, and that all cargo value is containerized (an overestimate), each container terminal handles $77 million in value per day. Each terminal has between two to six berths, averaging roughly three, such that each berth handles approximately $25 million in value per day. But an explosion of one container is not going to destroy all cargo at the berth, only a - likely small - subset. Thus, in terms of actual cargo destruction, there is likely to be low single-digit millions of dollars in losses, if not less.

D. Accounting for behavioral effects

The container explosion incident is likely to cause behavioral responses among many dock-workers, including a reluctance or outright refusal to return to work until safety can be guaranteed – often termed "avoidance behavior" in the literature (see, e.g., Giesecke et al. 2012; Rose 2022). This can take place even after the Coast Guard and other government agencies have ended any formal security requirements and given an "all-clear" sign. A case in point is dockworkers' response to the COVID-19 outbreak. The San Francisco Chronicle (2020) reported that "Some dockworkers at the Port of Oakland are threatening to refuse work at a terminal that they say isn't properly sanitizing equipment and facilities for employees. The move could halt logistics operations and further strain the global supply chain amid the coronavirus outbreak."

Such behavioral effects are unlikely to be observed following the labor strike or power loss scenario, as neither poses a threat to health or life safety. We estimate the extent to which port workers will stay away out of concern for their personal safety and examine the economic impact of this behavioral response by estimating the Base Case complex event with and without such avoidance behavior.

E. Comparing complex events with individual events

To investigate any potential synergies (positive or negative) in a complex event scenario, we need to construct a baseline for comparison of a similar set of events that would preclude synergies. To that end, we start with each individual scenario within the complex event – labor strike, wildfire-induced power loss, and container explosion – and estimate their economic impacts via the TERM CGE Model as if the scenarios had occurred as standalone events. We then take the set of three distinct economic impacts and sum them to approximate the combined impact of all three events, exclusive of any synergies.

We next compare this sum to our prior complex event result which reflects the simultaneous occurrence of all three events.[19] The difference between the "simultaneous" solution and the "summation" solution sets of estimates provides us with an estimate of the synergies. Intuitively, for example, consider the case where the labor strike happened in February, the power loss happened in June, and the terrorist attack happened in November. For each of the three shocks, the disruption would have been completely resolved well before the next one occurred, and thus there would realistically be no synergistic impacts between events.

By comparison, in the complex event scenario, all three disruptions happen in quick succession, leading to potential synergies in their respective impacts. For example, ships waiting in a queue due to the initial labor strike disruption may be further delayed due to the power loss and terrorist attack.

Examples of positive synergies from complex disruptions are rare, though we do not discount that they may exist, e.g., greater improvisation in adaptive resilience tactics discussed below, given learning from

[19] We use the term simultaneous broadly here to refer to a group of events that appear in close proximity (e.g., back to-back) and that are modeled together, but do not necessarily overlap in timing.

the previous event.[20] However, there is no evidence on which to base a quantitative analysis of such a phenomenon, so it is beyond the scope of this paper.

F. Sensitivity analysis and generalization of disruption impacts

Sensitivity analysis is performed in two ways. First, we simulate the Lower and Upper Bounds based on the parameter values in Table 1 to compare them to the Base Case. We also examine the time-path of some major inputs into the CGE model, the main one being the disruption of landed imports into the Ports of LA/LB.

Specifically, we estimate the economic impacts of disruption lengths ranging between 3- and 30-days, in 3-day increments. In each case, we consider the scenario where the ports are fully shut down for the given disruption length and follow the same methodology as in our Base Case for determining the inputs into the TERM Model. These time paths are displayed in Figure 2, which indicates that the effect of disruption length on Imports Landed is initially non-linear across all sub-regions but becomes approximately linear after about the 9th day of full shutdown. This is primarily due to the functional forms of the underlying delay costs, in which time-sensitive goods, such as perishables and JIT production inputs, follow a steep nonlinear slope, while other commodities follow a piece-wise linear, or relatively shallow nonlinear path.[21] Panel A presents the full set of results, while Panel B excludes LA from the figure to more clearly depict the impacts in the other regions and nationally.

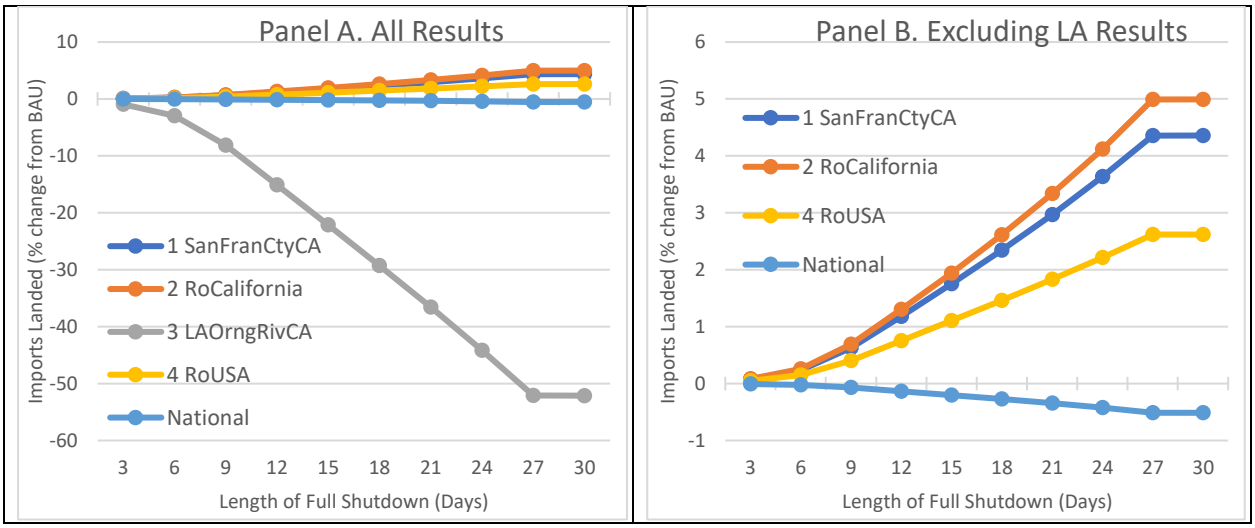


Figure 2. Impacts of a Full Port Shutdown on Landed Imports – 3 to 30 Days

[20] Another example of where the "simultaneous" solution for overlapping advances would yield lower estimates than the simple summation is not actually synergies, but related to the issue of double-counting. For example, if the port is closed for a strike, and a power outage occurs at the same time, there is no additional lost "production" from the individual disruption that is estimated to have the lesser of negative impacts because these impacts would be redundant.

[21] Note that all values are un-weighted, i.e., a one percent change in at the National level would be much greater, in absolute terms, than a one percent change for LA Metro. Results in Panel A include values for each sub-region and the National total, while the results in Panel B exclude the LA Metro results in order to present a clearer image of the ripple effects throughout US.

VI. Resilience Analysis

A. Background

Resilience is usually broadly defined as the ability to mitigate, absorb, respond to, recover from, and adapt to future disasters (Executive Office of the President 2014; DHS 2024). In this paper, we focus on recovery aspects after the disruption has begun despite attempts to mitigate it and beyond any cushioning/absorption of the shocks. Moreover, we focus on efficient recovery, which, following Rose (2009, 2017), Rose and Dormady (2018) and Dormady et al. (2022), we refer to as *economic resilience.*[22]

We begin by acknowledging that resilience is a process, whereby some resilience capacity already exists in the economy and can be enhanced in advance of the disruption, but the actual implementation doesn't take place until the disaster strikes. Property damage can typically not be reduced at this stage, but our focus is on losses related to business interruption (BI) in any case.

Note the following distinctions:

Static Economic Resilience refers to the efficient use of remaining resources to maintain as much function as possible to reduce BI losses before any repair and reconstruction.

Dynamic Economic Resilience refers to efficient use of resources for repair and recovery to restore and maintain function to reduce BI losses.

We also make the following distinction:

Inherent Resilience, which is of 2 types:

-- *intrinsic* refers to resilience capacity already present in the economy (ability to substitute one input for another, excess capacity).

-- *pre-positioning* refers to building up resilience capacity, which has time for implementation once the disruption begins (holding inventories, emergency management drills)

Adaptive Resilience refers to improvisation after the disruption occurs, which can reduce losses (finding new substitutes or suppliers, technological change)

Note also that resilience applies on both the supply and demand sides. The former refers to the port activity that allows cargo to move efficiently from ships to direct and indirect (supply-chain) customers.[23] Demand-side resilience refers to direct customers to which the commodities are shipped and used as intermediate inputs and all of the downstream businesses and supply chain that can be disrupted, as well as government and household customers.

We analyze several resilience tactics, divided into supplier and customer categories. The former pertains to ports and shipping companies. The customer side pertains to direct users of imported commodities as

[22] Post-disruption adaptation, so as to be less vulnerable to future disruptions and be able to rebound more effectively in the future, is beyond the scope of this paper.

[23] Note that we abstract from many idiosyncrasies of Port operations in these generic characterizations. However, we do address major aspects of Port operations that have a bearing on resilience.

intermediate inputs into production and direct consumption and investment, or as intermediate inputs along the downstream supply-chain.

A major challenge is to separately estimate resilience tactics that are "intrinsic" in CGE analysis, i.e., automatically calculated as a group within the basic CGE model. The research advances the work of Wei et al. (2020), which was able to isolate the sum effect of intrinsic resilience responses of input substitution, import substitution, and interregional production shifts as a group from other individual resilience tactics. Below we explain how we are able to isolate aspects of ship rerouting.
In the case of resilience tactics, we would adjust the delay cost functions on a case-by-case basis. This includes adjusting the length of delay, or % change in capacity resulting from the implementation of the resilience tactic in some cases, and then applying the delay cost functions for these new sets of values to adjust the CGE input parameters. For other resilience tactics, we use established methods from our previous research (see e.g., Rose et al. 2017; Wei et al. 2020, 2022).

B. Incorporating Resilience on the Port Side

There are several forms of intrinsic resilience that the TERM model automatically accounts for in estimating the general equilibrium economic impacts of the port disruption. While most forms of intrinsic resilience would be similar across other studies, such as input substitution or regional shifts in production, one key form of intrinsic resilience to our analysis is ship re-routing.

1. Ship Re-routing – In response to a prolonged port slow-down, or complete shut-down, ships may choose to re-route to alternative ports to offload (or load) their cargo. For example, if the price of imports increases in one region – such as Los Angeles – other US regions in the model will begin importing more goods directly to avoid these higher prices. While these other regions would not necessarily pay higher prices for the import goods, they would pay higher prices for the *transportation* of those goods, as demand for shipments increases.[24] The TERM Model, however, is not able to correctly reduce the initial delay cost associated with the ship-rerouting reductions in congestion. More explicitly, these resilience responses take two forms:

a. An intrinsic substitution of domestic production for the reduction in imports. Here we are careful to distinguish cargo delays from import reduction (the latter is limited to cases of cargo damage, as in the spoilage of perishables).
b. An intrinsic substitution of imports geographically from one port region to another. This is a separate effect, though difficult to disentangle, from an increase in imports to other regions stemming from those regions' increase in economic activity to pick up some of the slack from the LA region.[25]

[24] Depending on the contract, importers or the ports themselves may also face penalties for the late delivery of goods. These penalties, however, are likely to be minor in relation to the other effects and may also be covered by insurance in any case, so we omit them from consideration in the analysis.

[25] The decreased imports to LA/LB will exceed the increased imports to all other regions because of the increased costs of transportation and production in general causing a move away from the original (unique least-cost) equilibrium. This assumes domestic production of disrupted commodities is available at sufficient scale, and could be obtained within the expected duration of the disruption. However, we point out that the disruptions we are modeling are not large enough to violate this assumption because: 1) they are of a relatively short duration, 2) ship

Note that (a) is unrelated to ship-rerouting and is instead capturing a response to higher import prices. In (b), however, the response is capturing the shift in imports from one port to another in terms of the *avoided* delay costs (though these shifts are accompanied by increased intermodal transportation costs). Still, it is not capturing the *reduction* in delay costs that results from shifting imports from LA/LB to other ports, which would reduce congestion at LA/LB and thus also reduce the delays faced by ships that did not re-route.

Specifically, the TERM model itself is insensitive to the mechanism through which these delay costs are generated, and thus does not account for the fact that if imports are re-routed to other regions this would reduce the load on the LA/LB ports, thereby reducing the queue and decreasing delay costs on disrupted goods. We develop a "convergence algorithm" (see Appendix) to better estimate the impact of ship rerouting.

Notably, not all affected ships would reroute to other ports. For example, ships already at port would remain there, and ships that are already enroute to LA/LB may continue to go there if they expect the delay to be shorter than the added time and cost to re-route. Importantly, arriving at port and offloading cargo is only part of the consideration to re-route. Shipping companies would also need to consider the potential for added time from intermodal transportation to the destination for their cargo. Consider a simplified example in which all cargo on a ship was ultimately headed for Los Angeles itself. If a ship re-routed to a Gulf Coast port, it would not only need to consider the added ocean travel time to the new port, but also the additional intermodal travel time and cost to ship its cargo back to Los Angeles via truck or train. With this in mind, our estimate of ship re-routing obtained via the convergence algorithm, approximately 3.3% of annual imports, appears to be in-line with what might be expected.

2. Inventories – The ports themselves don't really "hold inventories" of the goods that pass through them, except for the small amounts waiting to be loaded onto trucks or trains.[26]

2. Excess Capacity. Our Base Case analysis uses the difference between shipping inflow to the twin ports of LA and LB during the busiest month of the year versus the average month of the year. We take this difference as an estimate of the average inherent excess capacity at the ports. To estimate the economic impact of increasing or decreasing excess capacity, we instead compare the busiest month of the year with the average of the three next busiest months (effectively decreasing the estimated level of excess capacity) and the average of the three least busy months of the year (effectively increasing the estimated level of excess capacity).[27]

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rerouting and other resilience tactics significantly reduce the disruption, and 3) inventories of domestic substitutes are available.

[26] The inventories that apply here are items like spare parts, etc. for port operations, and again are only relevant to the MARSEC incident. However, seaports hold only very limited spare parts for their equipment on site, so we don't explicitly model them.

[27] Note that choosing two or four months, instead of three, does not significantly change the level of calculated inherent excess capacity. The three least busy months for LA/LB, on average, between 2020 and 2023 were February, April, and June, while the three busiest months were August, September, and May.

3. Management Effectiveness. This refers to various managerial and organizational capabilities and activities that can reduce losses once the disruption begins. It includes the implementation of advance preparation through emergency drills and cross-training of workers before the disruption in its inherent form, and organizational changes and minor technological fixes in its adaptive form. Based on input from SMEs, we assume this is 10% for the Base Case, and 5% and 15% or the bound.

4. Adaptive resilience (cargo re-prioritization) – As discussed earlier in the methodology section, we do not consider this tactic here, as it would only be put into effect for events that required government intervention (e.g., as in the case of ships carrying medical supplies, including PPE during COVID).

5. Export Diversion: We do not consider this resilience tactic, as it is unlikely to take place for a short-term disruption, export goods are often in perfect substitutes for ports, this tactic and requires a decision at a very high level of government. Even though our disruptions are severe, they are unlikely to meet the standard needed for application of this tactic, which will likely only be in effect for severe long-term events such as wars.

6. Conservation: The potential for conserving on disrupted imports in the production process is very limited for short durations, so we omit this tactic.

7. Resource Isolation: This tactic refers to separating an aspect of business operations from dependence on a critical input. This could be applicable to the power outage caused by wildfires. However, there is very limited backup generation in terms of portable generators microgrids at the Ports of LA/LB.

8. Input Substitution: This is applicable to cases where inputs to port operations are disrupted/damaged, and thus to the MARSEC incident. Examples here are the substitution of labor for equipment when offloading cargo or the substitution of equipment for labor in screening containers. However, because of labor union restrictions, it is reasonable to omit this resilience tactic.

9. Management Effectiveness: We incorporate this tactic based on lower bound, mid-level, upper bound values and(5%, 10%, 15%, respectively) provided by input from our SMEs.

10. Technological Change: We incorporate this tactic in tandem with Management Effectiveness, also based on three parameter values (5%, 10%, 15%) provided by input from the SMEs.

11. Resource Pooling: This is not an option for a disruption that affects the twin ports, as no other major ports are nearby with which to pool resources.

12. Production recapture: This would apply to working overtime and/or extra shifts to offload the backlog of cargo.[28] This resilience tactic is not commodity specific, except for the tension between perishables and non-perishables, in contrast to the customer-side analysis below.

[28] We note that longshoremen may not be willing to work overtime (or may be restricted from doing so by their union contracts) and that shippers may not be willing to pay the overtime premiums. We are also aware that these limitations also apply to employees at warehouses handling the extra cargo. These factors are factored into the conservative production recapture factors used in this study.

C. Incorporating Resilience on the Customer-Side Resilience:

1. Inventories: When shipments of new goods are delayed, businesses and households may be able to use their existing inventories as a stop-gap. To the extent that these inventories can be drawn down, they could significantly reduce the economic impact of short port disruptions. Longer disruptions, however, would likely see the effectiveness of this resilience tactic wane, as inventories would not be sufficient to outlast the delay of new shipments.

The original delay cost functions adapted from Weaver et al. (2022) implicitly included the use of inventories. To recover an estimate of the effectiveness of this inherent resilience tactic we need to first estimate the economic impacts of the scenario without inventories.[29] To this end, we first adjust the delay cost functions to remove any effects of inventories, which had otherwise reduced the costs associated with delays. Later, when estimating the effectiveness of resilience, we apply the original delay cost functions that had accounted for inventories

Our Base Case analysis assumes zero inventories in the absence of resilience. While this is perhaps an overly strict assumption, it serves two purposes. First is to highlight the potential economic impact of continued market shifts towards just-in-time (JIT) supply chain management in the face of supply chain disruptions. Second, to provide a baseline against which we can compare the economic impacts when including inventories.

While our Base Case estimates used a set of adjusted delay cost functions that removed any inventories, to estimate the effectiveness of this resilience tactic, we adopt the original delay cost functions directly from Weaver at al. (2022), which include the use of inventories. For the scenarios with resilience we use the 50/100/150% of inventories as the basis for the lower- mid- and upper-level sensitivity tests.

Note the delay cost functions are piecewise with a single kink on the day that inventories run out, such that the function has a lower slope when inventories can be used, and a steeper slope once inventories have run out. By adjusting the timing of the kink, we can impose any level of inventories. For example, if typical inventory holdings for a given sector are 8 days, then we would set the kink in the delay cost function to occur on day 4/8/12 corresponding to 50/100/150% of typical inventory levels.[30]

2. Conservation: Again, we do not consider this tactic because of its limited potential for short duration disruptions

3. Input Substitution: Its estimation is intrinsic to CGE modeling, and cannot readily be calculated separately. Moreover, it is likely to be extremely limited in the short term.

[29] Admittedly, it is unlikely that businesses would not hold any inventories whatsoever except in specific cases of JIT logistics, a strategy that is in declining use in an era of supply-change shortages. That said, in order to not under-value the benefits of this inherent resilience tactic, we compare against a baseline of zero inventories.

[30] In terms of direct vs supply chain customers, for direct customers, this would be via the shifted (and kinked) delay cost functions – the higher the inventory level, the lower the cost function (for the same length of delay). For downstream supply chain customers, we use an ad hoc adjustment to the CGE drivers/output results based on input from subject matter experts.

4. Import Substitution: This pertains to the substitution of a domestically supplied counterpart of the disrupted foreign-produced input. It is also intrinsic to CGE modeling.

5. Production Recapture: Sector-specific Recapture Factors (Rose and Wei, 2013; Wei et al., 2020) are applied as scalar adjustment factors after the model has been run for the "without resilience" cases.

Several other customer-side resilience tactics, analogous to port-side tactics, are not applicable here, primarily because of the short duration of the disruptions being modeled. These include: Technological Change, Relocation, Resource Isolation, Management Effectiveness, and Resource Pooling. And again, Inherent Input Substitution, Inherent Import Substitution, and Interregional Production Shifting are intrinsically estimated in the CGE model. The adaptive versions of these resilience tactics are not applicable because of the short duration of the disruptions as well.

VI. Term CGE Model

To assess the economic impacts of hazard scenarios and the effectiveness of economic resilience strategies, we employ the TERM (The Enormous Regional Model) CGE (Computable General Equilibrium) model (Horridge 2012; Wittwer 2017). This advanced modeling tool is ideal for analyzing the economic consequences of disasters, especially those affecting the marine transportation system, as it depicts the economy as a network of interlinked supply chains that respond to market prices and resource constraints (Rose et al. 2017; Chen and Rose 2018; Wei et al. 2020).

CGE models stand out among economy-wide modeling approaches due to their ability to integrate the strengths of various model types while overcoming their weaknesses. They maintain the detailed input accounting, extensive multi-sectoral analysis, and interdependency found in input-output (I-O) models. However, unlike I-O models, CGE models incorporate behavioral responses, allow for input and import substitution, and account for resource constraints (Rose 1995).

The structure of the TERM model aligns with that of other CGE models (Horridge 2012). In this framework, regional producers minimize production costs by employing a mix of intermediate and primary factor inputs, organized through a Constant Elasticity of Substitution (CES) nesting structure. At the top level, output is produced by combining a composite of primary factors with a composite of intermediate inputs. The primary factor composite includes capital, land, and labor, with labor further disaggregated by skill type using CES functions. Similarly, the composite intermediate input is made up of various commodities sourced from different regions, also modeled using CES functions. In each region, a representative household maximizes utility by selecting optimal bundles of goods, guided by preferences and budget constraints. The simulations conducted using the TERM model were based on a short-run closure rule, in which wages were treated as exogenous, while employment levels adjusted endogenously.

VIII. WCW Results

A. Basic Results (without Resilience)

The results of the Base Case simulations for all three disruption types for the U.S. as whole and four of its sub-regions (LA, SF, Rest of California, Rest of US) are presented in Table 2. The relatively small $298 million (0.002%) projected decline in overall annual U.S. GDP obscures the complexities of regional shifts illustrated in this and other columns of the table and the decomposition of disruptions presented in Table 3 below.

The combined disruptions are projected to decrease GDP in the LA Metro Area by nearly $5.747 billion (or 0.373%) and to decrease the GDP in Rest of California (excluding the San Francisco Metro Area) by only $464 million (0.043%). At the macro-level, these negative impacts are offset very slightly by a $6.4 million (0.007%) increase in San Francisco Metro GDP but primarily by a very large positive impact on the Rest of the US of $5.857 billion (0.024%). The net impact on U.S. GDP is a negative $419 million.

The large negative impact on LA Metro is caused by a combination of decreased imports and the region's increased GDP Price Index (GDPPI) of 0.208% and a much larger increase in its Consumer Price Index (CPI) of 0.478%, which make production inputs and consumer goods more expensive. Ensuing supply-chain production declines and price increases are the reasons for the much smaller Rest of California.

On the other hand, San Francisco Metro is also projected to face higher prices, but this dampening effect on GDP is more than offset, primarily by increases in imports and regional production to replace the lost production in LA Metro and the Rest of California. Similar effects are even stronger in the Rest of US, where the increase in imports and production much more than offsets the dampening price increase effect. Note, however, that in addition to the large differences in the distribution of impacts across regions, even within each of these net positively impacted regions the distributional effects would likely be unequal, as some individuals and businesses gain from increased job opportunities and income, while everyone is negatively affected by the increased prices of goods and services.

The results for each of the three standalone disruptions (Strike, Power Outage, MARSEC Incident) across the five geographic areas are presented in Table 3. The table also presents two totals. The fourth row presents the simple summation of the three disruptions as if they took place fully independently. The last row of the table, however, presents the results of simulating them as a combined complex event, mirroring the results in Table 2. Importantly, this does not reflect a temporally simultaneous analysis, i.e., as if the three disruptions happened all at the same time, but it does represent the sequential nature of the disruptions and picks up some interdependencies (synergies). These pertain primarily to the backup of ships at the LA/LB ports, which is cumulative due to the next disruption beginning before the previous one has fully subsided. The prolonged wait times increase the quantity of imports disrupted and their direct and indirect transportation costs. It thereby raises producer and consumer prices much more than if a given event had been fully resolved before the next one began.

The negative impacts on GDP are much smaller for LA Metro for the Summation Total than for the Combined Total (compare -0.146% with -0.373%). The former reflects less ship rerouting to San Francisco Metro and Rest of US, resulting in the impact on San Francisco GDP being negative for all three threats, in contrast to the overall positive impact on that region's GDP in the Combined simulation. The

GDP impacts on Rest of US are positive for all three disruption types, but their Summation Total is only one quarter as large as the Combined Total.

The divergence in GDP impacts between the two totals is largest for Rest of the US (4-fold), in contrast to the ratio for the Rest of California (only 2-fold). For San Francisco Metro, the interesting result is not so much the ratio of the 2 totals but rather the reversal in sign between the two, reflecting a lower level of ship rerouting to that region because the Ports of LA/LB experience lower congestion costs when the disruptions are not sequential.[31] Interestingly, the negative impact on National level GDP is greater for the Summation Total (-0.0025) than the Combined Total (-0.0020) by 25%. This is due in great part to the sign reversal of the GDP impacts in San Francisco Metro.

When comparing the relative impacts of the three disruptions, the Labor Strike is projected to result in the greatest GDP loss for the Nation (-$307 million, or -0.0011%), while the MARSEC Incident is projected to have the largest negative impact of the three on the GDP of LA Metro (-$586 million, or - 0.085%).

Notably, the impacts of the 3 disruptions on San Francisco Metro are surprisingly uniform (-0.001%), as are the impacts for Rest of US, except for the MARSEC incident, which is quadruple the size of the other two disruptions. In contrast, the Rest of California is expected to experience a much lower negative impact from the Power Outage disruption compared to the other two.

B. Sensitivity Analyses

Tables 4 presents the results of the Sensitivity Tests described in Table 1 for a Lower Bound (LB) and an Upper Bound (UB) case in comparison to our Base Case (BC).

The overall effects on U.S. GDP are very similar for the LB and BC cases (-0.0015 and -0.0020), respectively, which translate into National losses of $420 million and $559 million, respectively. However, the comparison of results between the UB and BC cases is quite dramatic, with the -0.0277% projected decline in GDP being about a 14-fold increase over the BC and amounting to a projected GDP decline of $7.57 billion. The negative impact on the LA Metro economy is nearly 6 times as great as in the BC. Another important result for the UB is that all 3 other sub-national regions are impacted positively, meaning they are all picking up the slack in port and other economic activity in LA Metro. The increase in San Francisco Metro GDP amounts to several hundred million dollars.

Figure 3 displays the results of a sensitivity analysis in which we simulate 10 separate full-port shutdowns to the LA/LB ports, ranging from 3 to 30 days in 3-day increments in terms of percentage change in GDP. Note that all values are un-weighted, i.e., a one percent change in GDP at the National level would be much greater, in absolute terms, than a one percent change for LA Metro. Results in

[31] More specifically, ship re-routing (leading to relocation of production) incurs a discrete cost on the shipper (producer). Thus, when the delay at the originally intended destination port is expected to be short, the re-routing cost is much more likely to dominate the cost of simply enduring the delay i.e., for short disruptions to LA/LB, far fewer ships will opt to re-route. In such cases, the SF Metro economy is still affected by the, albeit lower, price increases and production disruptions caused by the delay at LA/LB, but now without the added economic activity that would occur with ship re-routing and ensuing temporary production shifts.

Panel A (left-hand side) of each figure include values for each sub-region and the National total, while the results in Panel B (right-hand side) exclude the LA Metro in order to present a clearer image of the trends nationally and in each of the other three sub-regions.

Recall from Figure 2 of Section IV, which examined the effect of disruption length on Imports Landed, and thus serves as the basis for Figure B, that the impacts were initially non-linear across all sub-regions but become approximately linear after about the 9th day of full shutdown. This is likely due to the functional forms of the underlying delay costs, in which time-sensitive goods, such as perishables and JIT production inputs, follow a steep nonlinear slope, while other commodities follow a piece-wise linear, or relatively shallow nonlinear path. When looking at Figure B, however, note that the effects maintain a non-linear shape throughout most of the time-steps, especially for LA Metro and SF Metro. The latter result is particularly interesting, as it is the only sub-region that does not follow a monotonic function. Aside from the slight irregularity in the GDP impacts for SF Metro corresponding to short-term (< 9 day) disruptions, the pattern of impacts appears intuitive and consistent across disruption lengths, with negatively impacted regions (LA Metro, Rest of California) increasingly negatively impacted with longer disruption lengths, while the opposite holds true for the positively affected regions (SF Metro and Rest of US).

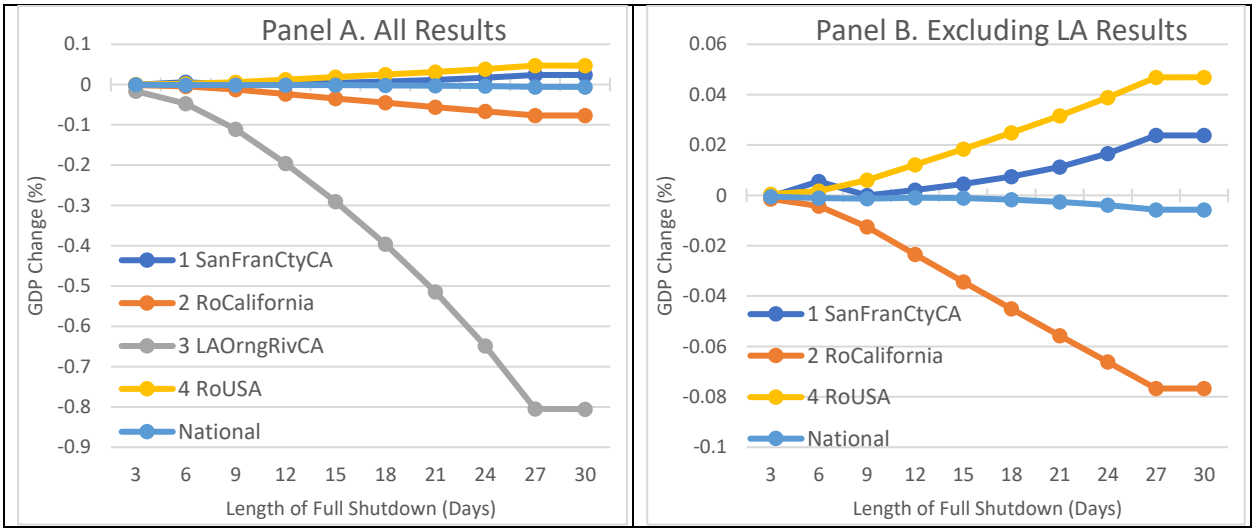


Figure 3. Total Economic Impacts of a Full Port Shutdown on GDP – 0 to 30 days

Table 4 also presents the results of simulating Avoidance Behavior in relation to the Base Case associated with broader fears of the terrorist attack of the shipping container (MARSEC Incident). The results are qualitatively as expected for all the regions. The percentage change in GDP impact on LA Metro is -0.424, or about 14% higher than for the Base Case, thus having a much lower increased impact than does the UB. This results from higher rerouting to San Francisco Metro and a very slightly higher positive impact on its GDP. Impacts on Rest of California are slightly more negative than the BC, and the impacts on Rest of US increase by less than 10%; however, this small increase in such a large region leads to an overall decline in national impacts in comparison to the BC.

Table 2. Base Case LA/LB Import Disruption Economic Impacts – Without Resilience (quantity and price shocks combined for all 3 disruptions)

Macro Variable	LA Metro	SF Metro	RoCalifornia	RoUS	National
Real GDP (millions of 2023$)	-4,084.5	41.9	- 330.1	4,073.2	-297.6
Real GDP (% change)	-0.373	0.007	-0.043	0.024	-0.002
ExpVol (% change)	-0.391	-0.380	-0.412	-0.380	-0.382
ImpVolUsed (% change)	-4.713	0.025	-1.158	0.059	-0.250
ImpsLanded (% change)	-27.822	2.222	2.472	1.390	-0.256
GDPPI (% change)	0.208	0.200	0.262	0.213	0.215
CPI (% change)	0.478	0.200	0.280	0.203	0.221
ImpsLandedPI (% change)	5.436	n.a.	n.a	n.a.	0.282

Table 3. Base Case Decomposition of Disruption Economic Impacts (percent change in Annual GDP)

Disruption	LA Metro	SF Metro	RoCalifornia	RoUS	National
Strike	-0.036	-0.001	-0.008	0.001	-0.0011
Power Outage	-0.025	-0.001	-0.002	0.001	-0.0008
MARSEC Incident	-0.085	-0.001	-0.009	0.004	-0.0006
Complex Event Summation	-0.146	-0.003	-0.019	0.006	-0.0025
Complex Event Combined	-0.373	0.007	-0.043	0.024	-0.0020

Table 4. Base Case Sensitivity Analyses of Economic Impacts (percent change in Annual GDP)

Disruption	LA Metro	SF Metro	RoCalifornia	RoUS	National
Lower Bound	-0.069	-0.001	-0.007	0.003	-0.0015
Base Case	-0.373	0.007	-0.043	0.024	-0.0020
Upper Bound	-2.158	0.087	0.057	0.099	-0.0277
Avoidance Behavior	-0.424	0.008	-0.048	0.026	-0.0019

C. Results with Resilience

The results for simulations of Resilience Tactics are presented in Table 5. The first two tactics are Excess Capacity on the port side and Inventories on the customer side, which are modeled by reducing delay times for ships arriving at the ports in the case of excess capacity or reducing delay costs (via a shift of the delay cost function) in the case of inventories.[32]

Excess Capacity – Recall from earlier discussion that (port-side) excess capacity, while a resilience tactic, is inherent to the ports' operations. Thus, even in the "Without Resilience" Base Case, we simulate impacts using the annual average excess capacity – which we calculated to be 9.92% for 2023. In the first set of resilience analyses we examine the effects of increasing or decreasing this level of excess capacity, e.g., due to the ports having previously invested in more capacity, or simply due to the disruptions occurring during busier (lower-bound excess capacity) or slower (upper-bound excess capacity) times of the year. The former is calculated using the average of the three busiest shipping months, while the latter is calculated using the average of the three slowest shipping months.

A low level of Excess Capacity at the ports would more than double the negative impact on LA Metro, while a high-level of this resilience tactic would cut the negative impacts by more than half. The results for other regions follow suit in terms of relative improvements (the high-level of excess capacity has the strongest influence of any of the tactics in terms of being able to reduce GDP losses for LA Metro). The results for the Nation are relatively symmetric as well, with a low level of excess capacity increasing negative GDP impacts on the US Economy 7-fold, and a high level of this tactic decreasing the negative impact 7-fold.

Inventories – In the second set of resilience analyses we examine the effects of (consumer side) inventories. Recall that, to provide a better baseline, in the "without resilience" Base Case, we exclude the use of any inventories.[33] For the "with resilience" Base Case, as a middle ground estimate we assume 100% of typical inventory holdings for each commodity type, fixed across all sectors.[34] Note that the inventory effects are *in addition* to the baseline level of excess capacity, which is included in all

[32] Specifically, changes in excess capacity at the ports affect how quickly arriving ships can be offloaded and their goods delivered, thus reducing delay costs. On the other hand, changes in customer-side inventory holdings affects the functional form of the delay cost functions themselves, as the delay costs implied by the cost functions are lower while inventories are available but become more impactful once they are exhausted. As discussed previously, on average, the ports of LA/LB operate with an inherent excess capacity of approximately 10%, though this is as low as just under 3% during the busiest seasons of year, and as high as almost 23% during the slowest seasons. With regards to customer-side inventories, recall that our Base Case (Without Resilience) assumes zero inventories in order to provide a clear basis against which to compare the impact of this resilience tactic. For our "With Resilience" analyses, we assume a base case of 100% of typical inventory holdings, adopted from the original Weaver et al. (2022) delay cost functions, but also examine the effects of reducing or increasing inventory holdings by 50%.

[33] Note that we do not consider inventory holdings to be intrinsic to business operations in the same way as excess capacity, because inventories are short-run inputs into production/final sales that are consumed, and which can be marginally increased or decreased with little friction. Port-side excess capacity comes from long-run capital investments such as land, gantry cranes, warehousing, etc. which cannot be as easily adjusted as inventories.

[34] Recall that the seven commodity types are: short-term perishables, long-term perishables, JIT inputs, raw materials, consumer durables, producer durables, and non-durables. Following Weaver et al. (2022), we allow the level of inventories to vary based on commodity rather than on sector.

analyses due to its inherent nature. Results for the simulation of Inventories indicates a strong ability to reduce the negative impacts on LA Metro and Rest of California, and an even stronger positive impact on the other regions and the Nation. Even the lowest level of inventories simulated as 50% of normal which results in a slightly less than 10% decrease in negative GDP impacts for LA Metro (compare -0.373% with -0.338%) and for Rest of California. The two other regions that typically experience increased GDP have this impact reduced, and the overall impact on the National economy is -0.0012, or approximately 20% lower than had there been no Management Effectiveness. Overall, the results are not very sensitive to variations in this resilience tactic.

Production Recapture -- The effect of the 4 basic resilience tactics is presented in Row 2 grouping of Table 5 for the Mid-Level. The combination of these tactics is able to reduce negative impacts on LA Metro in relation to the Base Case (Row I) by almost half (from -0.373% to -0.1959%). Not surprisingly the positive impacts on San Francisco Metro are also cut in half. The impacts on the Rest of California are reduced by 37%. However, the resilience tactics increase the positive impact on Rest of US six-fold and turn the national impacts positive. The reason is primarily the availability of inventories (excluded from the Base Case), which are less expensive than imports of the same commodity, primarily due to lower transportation costs—note the positive impact for the Nation in II is approximately the same as the projected impact after the implementation of inventories alone and Row 1.

The Production Recapture resilience tactic is modeled separately from the set presented in Row 2 Lower Bound, Mid-Level and Upper Bound values. Note that recapture estimation is based on sectoral recapture factors refined from FEMA's hazard loss estimation software—HAZUS (FEMA, 2024). It has been used in prior port studies by the research team (Rose and Wei 2013, Rose et al. 2018; Wei et al. 2020, 2022). These are simply multiplicative factors applied to reducing potential output losses (after the other resilience tactics are taken into account). As in previous studies, the recapture factors are adjusted downward by 50% initially for the Mid-Level to account for implementation obstacles. The Lower Bound values are 25% and the Upper Bound values are 75% of the original recapture factors. Hence, the numerical results of application of these scalars is symmetric.

The average recapture factor is in the range of 45 to 50% for each of the regions of our analysis, and the Mid-Level results reflect this. For example, the Mid-Level Production Recapture results reduce losses for LA Metro from -0.1959 to -0.098. The combination of all 5 resilience tactics reduces the Base Case for LA Metro from a GDP impact of -0.373% to -0.098, or by 73.7%. The Lower Bound recapture factors would reduce the Base Case losses by 65%. Similar percentage reductions in impacts are projected for all the other regions and the Nation, whether positive or negative

In terms of dollars of GDP, these Mid-Level results including all 5 resilience tactics translate to a $1.509 billion loss for LA Metro and a $145.1 million loss for Rest of California. However, this is more than offset by a very small GDP gain for SF Metro of $15.4 million and a very sizable GDP gain of $1.781 billion for Rest of US. The total leads to a positive $144.2 million GDP gain for the U.S. economy, though this is only .0005 of 1% of the baseline level. Again, this positive outcome for the Nation as a whole is primarily due to the role of Inventories as a resilience tactic.

We note a limitation of the analysis that is likely to lead to an overall negative impact on U.S. GDP, though to a very small level. The TERM Model includes trade with the rest of the world but not all of the feedback effects of shocks like the ones we have simulated. For example, it is likely that some of the gap in production in LA Metro and Rest of California will not be made up entirely by production in the U.S.,

but by production in other countries and shipped to ports other than LA/LB (see further discussion of limitations of our analysis in the following section). Still, the overall results of our analysis indicate significant resilience potential of the U.S. economy in relation to even complex (compound and cascading) disruptions of seaport activity.

Table 5. Table 5. Net Impacts of the WCW Scenario with Resilience

Resilience Tactic	LA Metro	SF Metro	RoCalifornia	RoUS	National
1. Base Case (includes intrinsic resilience)	-0.373	0.007	-0.043	0.024	-0.0015
Excess Capacity -- Port (low – 2.63%)	-0.946	0.015	-0.084	0.059	-0.0105
Excess Capacity – Port (mid – 9.92%)*	-0.373	0.007	-0.043	0.024	-0.0015
Excess Capacity -- Port (high – 22.94%)	-0.180	0.003	-0.022	0.012	-0.0002
Inventories -- Customers (low – 50%)	-0.319	0.005	-0.040	0.022	-0.0002
Inventories – Customers (mid – 100%)	-0.282	0.005	-0.038	0.020	0.0009
Inventories – Customers (high – 150%)	-0.229	0.003	-0.033	0.017	0.0011
Ship Rerouting – Port (low – 2.99%)	-0.2946	0.0052	-0.0345	0.0189	-0.0009
Ship Rerouting – Port (mid – 3.32%)	-0.2879	0.0051	-0.0338	0.0186	-0.0008
Ship Rerouting – Port (high – 5.16%)	-0.2565	0.0046	-0.0303	0.0167	-0.0006
Management Effectiveness – Port (low -- 5%)	-0.356	0.001	-0.041	0.023	-0.0014
Management Effectiveness – Port (mid -- 10%)	-0.338	0.006	-0.039	0.022	-0.0012
Management Effectiveness – Port (high --15%)	-0.321	0.001	-0.037	0.021	-0.0011
2. All Resilience Tactics (Simultaneous without Recapture - Mid-Level Case)	-0.1959	0.0034	-0.0269	0.0146	0.0010
3. All Resilience Tactics (Simultaneous with Recapture)					
3a. Recapture – Customers (low – 25%)	-0.1469	0.0026	-0.0202	0.0110	0.0008
3b. Recapture – Customers (mid – 50%)	-0.0980	0.0017	-0.0135	0.0073	0.0005
3c. Recapture – Customers (high—75%)	-0.0490	0.0009	-0.0067	0.0037	0.0003
4. GDP impacts for the Mid-Level All Resilience Tactics (millions of 2023 dollars)	-1,070.4	10.9	-102.9	1,263.4	102.3

*****Some Excess Capacity is inherent to port operations, which we calculated to be approximately 9.92% on average for 2023. We thus take this value as the mid-level for this resilience analysis, which therefore mirrors the Base Case "Without Resilience" results from Table X.

IX. Discussion

We have simulated the economic impacts of a complex seaport disruption consisting of a labor strike, power outage, and terrorist attack on a cargo container at the twin ports of Los Angeles and Long Beach (LA/LB). The analysis was performed using a CGE model of four regions: LA Metro, SF Metro, Rest of California, and Rest of US. The analysis began with the identification and estimation of major drivers of impacts relating to the disruption of port capacity and the ability to offload imports. We also estimated the impacts of 5 major resilience tactics intended to mute the direct and supply-chain impacts at the LA/LB ports and their direct and indirect customers across regions of the US.

The Base Case (BC) impacts before considering resilience were relatively large, on the order of more than $4 billion for the LA Metro region, or 0.373% of its annual GDP in 2023. However, shifts in economic activity to pick up the slack, most notably outside of California, were sizable as well, resulting in a net negative impact of only $300 million for the nation as a whole. The terrorist incident had the largest impact on LA Metro, though the labor strike had the largest net impact on the US economy. The negative impacts of the sequential occurrence of the three disruptions was more than twice as great than if we summed the impacts of each disruption happening in isolation because of the cumulative back-up of ships in the offloading queue.

We performed various sensitivity tests on the results and found that behavioral responses in relation to the terrorist attack, manifesting themselves in workers avoiding the ports for an extended period, could increase the negative impacts in LA Metro by another 13%. We also performed sensitivity tests on the key parameters of disruption duration and reduced port capacity. The results did not alter the outcomes of regional and national impacts qualitatively, except for San Francisco Metro, but they did indicate the results are highly sensitive to duration of disruptions. The Lower Bound (LB) case resulted in projected GDP impacts of less than 20% of the BC, and the Upper Bound impacts were more than six times greater than the BC.

We also simulated resilience activities at the port in terms of Excess Capacity, Ship-Rerouting and Management Effectiveness, as well as the use of Inventories and Production Recapture among customers down the supply-chain. The resilience tactics are projected to exert a very powerful effect to the extent of reducing negative GDP impacts for LA Metro for example, by 72%.

The results are based in part on a key methodological advance in the estimation of ship-rerouting. We have developed a straightforward algorithm for quickly estimating the extent of ship rerouting that is internally consistent within the TERM Model, without the need to rely on estimating and integrating complex network models or other approaches that are external to the CGE framework. By itself, the CGE model will intrinsically account for some aspects of ship-rerouting, e.g., via re-allocation of economic activity to unaffected regions and interregional trade shifts along with commensurate increases in imports to these regions. The model will not, however, reduce the initial congestion impact in the affected region(s) that would occur with ship-rerouting. Our approach addresses this missed component by iteratively updating the reduction in congestion at the affected ports based on model-reported changes in imports to unaffected regions until the CGE results converge to a new equilibrium.

With regard to excess capacity, we have emphasized the special contexts of port operations, wherein many aspects of their production function are fixed in the medium- to long-term (e.g., terminals, gantry cranes, warehousing). Thus, to the extent that ports optimize for busier seasons, these fixed capital

assets represent potential *inherent* excess capacity in the face of short-term disruptions, especially ones that may occur during less busy times of year. The increased resilience from this inherent tactic should thus be considered a co-benefit when ports are considering the optimal level of investment in these long-term fixed assets.

Overall, our results are consistent with findings in studies of various types of disruptions of these and other ports, both without and with resilience, by the research team (see Rose et al. 2018; Wei et al. 2020, 2022), as well as by other researchers (e.g., Park et al. 2008; Zhang and Lam 2015). All of the studies have found ports and their host economies significantly vulnerable, resilience tactics to be relatively effective, and major interregional shifts in economic activity to offset the disruption in the target region significantly.

We acknowledge several limitations of our analysis. First, is the fact that CGE modeling typically results in a relatively rapid return to equilibrium (though at an otherwise lower level of employment than before the disruption). This causes an underestimation of negative impacts. Also, the unit of analysis in the model is the sector, so that this obscures the potential wide range of impacts on individual firms, including some going out of business or relocating to other regions permanently.

Also, we were not able to separate all of the impacts of Resilience because some are intrinsic in the CGE model. This does not affect the total impacts, but just means we have not fully attributed some of the offsetting responses to disruptions in the BC to the 5 explicit resilience tactics simulated. We have also not simulated all possible resilience tactics categories, which number nearly a dozen identified by Rose (2017) and Dormady et al. (2022). However, some of these resilience tactics are not applicable to the threats we modeled, and others are likely to have a negligible impact.

X. Conclusion

Our analysis indicates that the economic vulnerability of seaports to disruptions can be sizable and is exacerbated greatly for complex cases (i.e., disruptions happening sequentially or simultaneously and having widespread cascading effects). At the same time, we have shown that various types of resilience can significantly reduce negative impacts. Sensitivity tests indicated that the results are robust.

We have shown how these impacts can be modeled within a CGE framework, which is especially suitable because it characterizes the economy as a set of interrelated supply chains. Our methodology is applicable to a broader set of disruption types than have been analyzed here. Also, although we have performed a limited analysis of ship-rerouting, our methodology is sufficiently general to accommodate the results of more sophisticated analyses of this resilience tactic and others.

As to future research, more work is needed on the distribution of impacts, both within economic sectors among firms of different types, and across socioeconomic groups. Also, more research is needed to separate out the effects of intrinsic resilience. Accuracy of the resilience analysis is important for both private and public sector decision-makers, as it identifies those tactics that can be most effective in reducing economic losses from seaport disruptions.

Appendix 1. Input Data Construction Steps

1. Map HS 4-digit commodity codes to TERM sectors using a concordance table.
2. Map HS 2-digit commodity codes to 7 overarching commodities from Weaver et al. (2022).
3. Assign Port of LA/LB import and export values (HS 4-digit level, obtained from USATrade) to TERM sectors using map from (1).
4. Assign each observation from (3) a delay cost function using map from (2).
5. Separately for imports and exports, for each TERM sector, create the value-weighted average delay cost function of all nested HS 4digit commodities mapped to that TERM sector.
    a. For example, each TERM sector nests multiple HS 4digit commodities, which may be mapped to distinct delay cost functions.
    b. To calculate the correct delay cost function at the TERM sector level, we first create a weight for each HS 4digit commodity within each TERM sector equal to the value of that commodity divided by the value of the entire sector. This is done separately for both exports and imports.
    c. We then multiply each HS 4-digit commodity's matched delay cost function by this weight and sum all delay cost functions within each TERM sector to arrive at the sectoral delay cost function.
    d. Represented mathematically: $F_s = \sum_{h \in s} \frac{value_h}{\sum_{h \in s} value_h} f_h$
    e. Where F_s is the delay cost function for TERM sector s, f_h is the delay cost function for HS 4-digit commodity h, and $value_h$ is the total import (export) value for commodity h.
6. Note that not all TERM sectors are represented in the USATrade data, as not all sectors include commodities, and for these sectors we assign a constant delay cost of zero. In other words, for these sectors, the *direct* impact of a disruption at the port would be zero, although there are likely to be indirect impacts, i.e., ripple effects, on these sectors due to the disruption.
7. Note also that a small fraction of imports and exports are not mapped to TERM sectors (e.g., imports of repaired exports, duty free items for museum loan, etc.); however, these represent a small fraction of the total imports and exports that pass through the Ports of LA/LB, so they are omitted.
8. Delay functions are operationalized in the datafile as both the percentage increased cost (or percentage of lost cargo due to spoilage in the case of perishables), and total value affected, for each day of delay ranging from 1 to 90 days.

Appendix 2. Details of Estimating the Effect of Ship Rerouting

A. Overview

The following sub-sections explain how the TERM Model handles ship rerouting intrinsically and proposes adjustments to the modelling approach to separately estimate this resilience tactic. The second channel by which The TERM Model handles price shocks is through an intrinsic substitution of imports from one geographic location to another, i.e., shifting comparatively expensive LA imports, which were subject to a delay cost, to comparatively less expensive delivered imports into other regions which would not be subject to as much of a delay cost (only the fuel and labor cost differentials of rerouting). The CGE Model intrinsically adjusts all transportation margins (both on the direct import side and for the intermodal transportation margins that happen within the U.S. after the imports have landed), so this approximates the added costs of rerouting.

Thus, the TERM Model is intrinsically accounting for part of ship rerouting (decreasing imports in the directly affected region and having imports increased in directly unaffected regions, as well as adjusting the transportation margins accordingly). However, because we are calculating the direct price and quantity shocks separately from the TERM model, following the incorporation of the adapted delay cost functions from Weaver et al. (2022) into TERM, the Model does not account for how reductions in imports landed at LA would reduce the delay costs themselves and is not able to endogenously reduce the price and quantity shocks accordingly.

For our Base Case, intended to exclude the effects of resilience, we therefore must accept the result that some types of resilience are intrinsically calculated by the model.[35] However, we are able to estimate the effectiveness of the second part of ship rerouting -- the actual reduction in delay costs.

B. Iterative algorithm for determining the amount of ship rerouting at LA/LB

We take the percent increase in imports landed, weighted by the total value of regional imports relative to LA/LB's import value, in all regions aside from LA Metro from the Base Case CGE analysis results as an initial approximation of the percentage of ship-rerouting that occurs from the LA ports.[36] We then use this approximation of ship-rerouting to re-calculate the initial delay cost parameters and re-run the CGE

[35] This is a limitation of our study, but we point out that separately estimating the impacts of this type of intrinsic resilience has not been performed by anyone else to our knowledge. Intrinsically calculating some resilience means that our Base Case results are likely biased downward because they include some intrinsic resilience, and the estimates of the impact of ship rerouting is also biased downward, since part of the tactic is intrinsically included in the Base Case.

[36] We scale down the imports landed in the "Rest of the US" region by 50%, which includes predominantly the East Coast and Gulf Coast, to account for the fact that while imports may be increasing here, to counteract the delay at LA/LB, many of these imports are likely to simply fall under "import substitution" and not be explicitly re-routed ships that were originally destined for LA/LB. A search of the literature did not yield any estimates of the appropriate level for this scaling factor. Thus, we opted for the middle-ground estimate of 50% in our analysis. While this is an ad hoc approach we note that even in the absence of any scaling factor, the level of ship rerouting would be only about 6%, rather than our estimated 3.36%.

analysis with these new parameters. The percentage reduction in imports landed in LA for this second set of results is lower than in the original run, as the imposed delay costs are lower. We then iteratively repeat these steps, each time using the newly estimated percentage increase in value-weighted imports landed in all regions aside from LA Metro as an approximation of ship-rerouting to re-calculate initial delay costs. We consider the model's estimate of ship-rerouting as having converged once the difference in ship-rerouting between iterations is less than 0.05%.[37]

[37] To provide an example: in our Base Case, the value-weighted increase in imports landed at regions aside from LA Metro was 5.16%. The next iteration reduced this to 2.99%, with the following iteration increasing to 3.41%. The next iteration reduced this to 3.32%, with the final iteration increasing to 3.36%.

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