EVALUATING THE ROLE OF RESILIENCE IN REDUCING ECONOMIC LOSSES FROM DISASTERS: A MULTI-REGIONAL ANALYSIS OF A SEAPORT DISRUPTION*

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Abstract

Models to estimate economic impacts of disasters have recently been augmented to include resilience. However, most research to date has incorporated only a limited set of resilience tactics and has not estimated their individual effect on reducing losses. We present a comprehensive framework for decomposing the effects of a broad set of post-disaster resilience tactics. Our methodological innovation is illustrated by adapting the TERM Multi-Regional CGE Model in the case of a seaport disruption, distinguishing inherent resilience working through the price system from primarily adaptive resilience tactics to cope with input shortages. We also overcome a path-dependency problem in the modeling process.

Keywords: Economic Consequence Analysis, Resilience to Disasters, Decomposition Analysis, Port Disruptions, Spatial Reallocation of Resources

1. Introduction

Numerous studies have estimated the regional and national economic impacts of disasters. More recently such studies have been enhanced to include more unique considerations as part of broader economic consequence analysis. For example, in recent years, analysts have noted that, while it is too late to prevent most of the property damage once the disaster strikes, affected entities do not react passively but rather engage in various actions to reduce the flow losses in terms of gross domestic product (GDP) and employment. These actions are increasingly referred to as resilience tactics, or ways to reduce business interruption by utilizing remaining resources more efficiently and recovering at an accelerated pace (see, e.g., Rose and Liao, 2005; Resurreccion and Santos, 2012; Rose et al., 2017; Graveline and Gremont, 2017; Xie et al., 2018). These tactics are applicable at either the microeconomic, mesoeconomic (market or industry), and macroeconomic levels. Studies of actual and hypothetical events have indicated that resilience can significantly reduce the economic losses from disasters (see, e.g., Rose et al., 2009; Kajitani and Tatano, 2009; Prager et al., 2018), and hence studies that omit these considerations are likely to overestimate disaster consequences.

Ports play a vital role in a nation's economic well-being. They represent the major portal for its material exchanges with the rest of the world and, in some cases, with other regions within its own borders. As a critical node of the nation's supply-chain, a disruption of a major port can reverberate throughout the entire economy. Inputs for intermediate and final consumption cannot be delivered, thereby causing production interruptions down the supply chain and to end-users. Also, exports for other markets are blocked, thus causing an ensuing disruption of production up the supply chain as exporters cancel their orders for inputs. An increasing number of port disruptions have taken place in recent years, caused by such incidents as labor disputes, natural disasters, technological accidents, and ports are also considered prime targets for terrorist attacks (Rose and Wei, 2013; Rose et al., 2018).

A modeling approach that can estimate the economic consequences of disasters, including the effect of various resilience tactics, is a multi-regional computable general equilibrium (CGE) model. This approach is especially pertinent to seaport disruptions because of the likelihood of the geographic spread of economic impacts, since most commodities transacted through ports are not used as inputs or consumed by final users in the port region but elsewhere. Hence, it is especially important to have a model capable of analyzing spatial allocation of the direct imports and exports and the spatial reallocation of the economic activity of direct users of the commodities up and down the supply chain.

Previous CGE analyses of port disruptions, including those of the authors, have focused on the influence of various *adaptive* resilience tactics and have ironically downplayed the role of *inherent* resilience tactics, those that exist naturally in the operation of businesses, markets and regional economies, and are intrinsic in a CGE model. These include substitution away from disrupted inputs, importing inputs from regions not directly disrupted, and otherwise shifting the location of economic activity across regions through physical moves of facilities or use of excess capacity in branch facilities or loss of production opportunities by companies within the disaster area to their competitors in other regions. These tactics have the ability to reduce business interruption substantially as well. While these tactics are automatically included in the economic consequence analysis, it is still important to determine their effectiveness for the sake of accurate estimation and for the analysis of the optimal mix of strategies among the sets of pre-event mitigation, inherent resilience, and adaptive resilience.

This paper develops and applies a comprehensive analytical framework for analyzing the various aspects of the economic consequences of and resilience to seaport disruptions. We adapt the TERM (The Enormous Regional Model) Multi-Regional CGE Model to illustrate the usefulness of the framework. Through a decomposition analysis, the paper is the first to compare the resilience tactics intrinsic in a CGE model with a set of other resilience tactics that requires more explicit actions and supplemental modeling adjustments. The analysis also resolves a path-dependency issue associated with the sequencing of the inclusion of various resilience tactics.

This paper fills several important gaps in the literature on economic consequence and resilience analysis in general and with respect to seaport disruptions. For example, most studies to date have only examined a select few types of resilience tactics, such as ship-rerouting, diversion of exports for domestic use, and conservation of scarce inputs (CBO, 2006; Park et al., 2008; Rose and Wei, 2013). However, they used models, such as input-output and econometric analysis, that were unable to estimate the effects of the key inherent resilience tactics. Even studies that have utilized CGE models have neglected to estimate the effectiveness of these inherent tactics and have instead focused on more adaptive resilience tactics (see, e.g., Horridge et al., 2005; Rose et al., 2016; Wei et al., 2016; Rose et al., 2017). This literature on seaport disruptions is representative of the literature on economic consequence analysis and resilience in general (Rose et al., 2017).

The rest of this paper is arranged as follows. Section 2 identifies the research gap that we fill by reviewing the relevant literature. Section 3 introduces the basic considerations of economic resilience and the set of supplier-side and customer-side resilience tactics relevant to port disruptions. Section 4 describes the approach to formally integrate resilience analysis into CGE modeling. Section 5 introduces the TERM multi-regional CGE Model. Section 6 presents the simulation scenario and the overall analysis approach. Section 7 presents the simulation results. Section 8 summarizes the paper and offers conclusions.

2. Literature Review

In this section we summarize the contributions of the literature on modeling the regional economic impacts of disasters in general and to ports in particular (see Table 1 for a summary of these studies). An et al. (2004) evaluated 19 regional economic impact models (REIMs) capable of evaluating the performance of regional economies subject to disaster damage to infrastructure. The evaluation was based on 11 criteria, including policy relevance, spatial dimension, industry disaggregation, integration of models across disciplines, dynamic analysis, degree of endogeneity of key variables (including prices, technology change and travel behavior), transferability between regions and countries, operationality, accessibility, and updatability. The study concluded that although none of the models evaluated fully meet all criteria, the multi-regional linear programming model developed by Rose et al. (1997) and the Southern California Regional Planning Model (Version 2) SCPM2, a multi-regional input-output (I-O) model, (Cho et al., 2001) meet the largest number of criteria, as both models implicitly included resilience in the form of locational shifts of economic activity.

Okuyama (2007) performed an evaluation of the most widely used models for economic impact analysis of disasters, including I-O, social accounting matrices, CGE, and econometric models. The author's criteria included the time dimension, areal extent, and built-in countermeasures (some of which are comparable to what we refer to as "resilience"). These measures, or tactics, included changes in consumption behavior (such as donating goods to the damaged area and reducing discretionary purchases) and input substitution.

Haddad and Teixiera (2015) developed a Spatial Computable General Equilibrium (SCGE) Model to analyze the economic impacts of flood scenarios in Sao Paulo, Brazil. Geographic Information System (GIS) was used to delineate the inundation areas, as well as to identify the number and type of firms in the flood zones. These translate into direct impact estimates, which were in turn used as input to the CGE model. However, this study did not include any analysis of economic resilience beyond input substitution.

Table 1. Comparison of Studies on Regional Economic Impact Modeling of Disasters

Study	Disruption Event/Scenario	Type of Model	Geographic Impacts	Resilience Inclusion	Limitation
Rose et al. (1997)	Electricity lifeline disruptions caused by a magnitude 7.5 earthquake simulation on the New Madrid Fault	I-O and linear programming models	Shelby County, Tennessee	Conservation; back-up power sources	Linearity; Limited number of resilience tactics
Cho et al. (2001)	Hypothetical magnitude 7.1 earthquake in LA	Multi-regional I-O model plus Garin-Lowry spatial model	Five-county Los Angeles metropolitan region	Inherent redundancy of the road and highway system; locational shifts of economic activity	Inherent limitations of I-O models; Limited number of resilience tactics
Haddad and Teixiera (2015)	Flood scenarios	Spatial CGE Model	Sao Paulo, Brazil	Input substitution	Limited number of resilience tactics; No separate estimate of the effects of input substitution on losses
Park et al. (2007)	Terrorist attacks on three major US ports: LA/LB, Houston, and NY/NJ	Demand-driven NIEMO	U.S. economy	none	Inherent limitations of I-O models; no resilience
Park et al. (2008)	2002 shutdown of the LA/LB ports	Multilevel linear regression model	U.S. economy	Direct impact is mitigated via substitutions over time, by transportation mode and by port	Limited number of resilience tactics
Oosterhaven and Bouwmeester (2016)	Trade and production disruptions in a hypothetical economy	Interregional I-O model in a non-linear programming (NLP) framework	Hypothetical open economy	Import substitution for domestic production and export diversion for domestic use.	Fixed production coefficients and fixed industry market shares; Limited number of resilience tactics
Tobben (2017)	Heavy flooding events in 2013 in Eastern and Southern Germany	Interregional NLP model	16 German states	Spatial substitution of economic activities	Limited number of resilience tactics
Horridge et al. (2005)	Australian drought of 2002-03	TERM CGE Model	Australian economy and 18 regions most affected by the drought	No explanation of intrinsic features of the model representing various types of resilience; briefly mentioned adjustments reflecting adaptive input & import substitution	Limited number of resilience tactics
Dixon et al. (2012)	Drought events in Australia	Dynamic TERM-H2O CGE Model	Australia	Inherent resilience captured by the TERM Model—input substitution, import substitution, and regional production shifts (IIR), specifically substitution between irrigable and non-irrigable land	No separate estimate of the effects of IIR on losses; no consideration of other types of resilience
Wittwer and Griffith (2012)	Prolonged Drought	Dynamic TERM-H2O CGE Model	Southern Murray-Darling Basin in Australia	IIR; dynamic model that includes both short-run and long-run regional impacts; excess capacity	No separate estimate of the effects of IIR or excess capacity on losses
Rose and Wei (2013)	90-day port shutdown at Port Arthur and Port of Beaumont	Supply-driven and demand-driven I-O models	Port MSA and U.S. as a whole	Import ship diversion & overland rerouting Strategic Petroleum Reserve Inventories Export diversion Conservation Production rescheduling	Inherent limitations of I-O models; No evaluation of the IIR inherent resilience
Rose et al. (2018)	90-day disruption of petroleum trade Port of Beaumont and Port Arthur	Supply-driven and demand-driven I-O models	Port MSA and U.S. as a whole	Ship re-routing Strategic Petroleum Reserve Inventories Export diversion Relocation of refining activities Production rescheduling	Inherent limitations of I-O models; No evaluation of the IIR inherent resilience

Park et al. (2007) applied the interregional National Interindustry Economic Model, (NIEMO), to analyze the impacts of terrorist attacks on three major US ports (Los Angeles/Long Beach (LA/LB), Houston, and New York/New Jersey). This model encompasses all 50 states of the U.S. and is capable to estimate the indirect impacts of a port shutdown in one state on all others. However, the only indirect impacts examined pertained to losses stemming from a curtailment of exports. On the import-side, only the direct effects of the import disruption were included in the total loss estimates, thereby understating the impacts from this stream of curtailed activity. At the same time, there is an over-estimation in the study because it does not include most forms of resilience. Park et al. (2008) also estimated the economic impacts of the 11-day labor strike shutdown at the LA/LB ports in 2002, though the analysis covered the ensuing 4-month adjustment period as well. They supplemented NIEMO with a multi-level linear regression model to estimate direct (final demand) losses and also included variables to reflect port and other transportation mode substitutions in the regression analysis. However, they did not separately estimate the effects of resilience on losses.

Oosterhaven and Bouwmeester (2016) extend an interregional input-output model in a non-linear programming (NLP) framework to examine the impacts of disasters in general and apply the model to the case of the destruction of interregional transportation infrastructure in particular. The model includes both backward and forward linkages in the interregional system. It is intended for short-run applications, and thus reasonably assumes that input substitution is limited or non-existent. The NLP algorithm optimizes the response to the disruption across regions by intrinsic substitution of imports where domestic production is lacking and the diversion of potential exports for domestic use. However, these two tactics are not separately analyzed nor is the combination of them analyzed as resilience tactics in relation to a case of rigid trade coefficients. Such a test, however, is performed by Tobben (2017) with a more standard interregional I-O model in an application to flood losses in Germany.

The TERM (Multi-Regional CGE) Model, which we apply in this paper, has been used to analyze the national and regional impacts of disasters. The first application was by the Model's developers (Horridge et al., 2005) and examined the impacts of the Australian drought of 2002-03, which transmitted its effects primarily through agricultural productivity decreases. The authors did not explain intrinsic features of the model represent various types of resilience. However, they do briefly mention adjustments that reflect adaptive input and import substitution resilience tactics, which will be defined in the following section, but they did not separately estimate their effects on losses. Additional aspects of resilience have been incorporated into TERM for application to more recent droughts through explicit modeling of substitution between irrigable and non-irrigable land and between land in general, labor and capital (Dixon et al., 2012) and in a dynamic version that includes excess capacity (Wittwer and Griffith, 2012).

Rose and Wei (2013) developed a refined I-O methodology to estimate the effects of a wide range of resilience tactics on the economic consequences stemming from a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas. The resilience tactics examined are ship re-routing, export diversion, conservation, use of inventories, and production recapture. The authors found that when the potential of several major resilience tactics is taken into account, the initial total regional economic loss of $13 billion can be reduced by over two-thirds. Production recapture and ship re-routing were found to be the most effective resilience tactics. A study by Rose et al. (2018) focusing on petroleum trade found those two tactics, along with crude petroleum storage, to be major offsets to the BI losses. However, neither study explicitly estimated the effects of resilience intrinsic to CGE models relating to input substitution, import substitution, and regional production shifts (IIR).

In light of the limitations of the literature, our study introduces a novel approach to estimate the economic consequence of and resilience to natural hazards using both regional and national I-O models and a multi-regional CGE model. For the first time, the impacts of IIR resilience are analyzed and differentiated. Since several U.S. counties/regions are involved, and are competitive and interconnected by various transportation networks, the CGE model is multi-regional in order to trace and capture these interdependencies across space. In addition, we use a CGE model so as to be able to capture not only direct effects but also general equilibrium effects stemming from economic interdependence. Such an interdependence is captured not just through quantities of goods and services supplied and demanded along sectoral supply chains, but also to determine how price changes affect them within and across regions. We also explain the process of enhancing and implementing a number of other resilience tactics intended to reduce the BI impacts and how these tactics are separately evaluated and compared to IIR resilience.

3. Basic Considerations of Economic Resilience

In the past few years, many analyses of the impacts of disasters in the U.S. have highlighted the "resilience" of the economy (see, e.g., Boettke et al., 2007; Chernick, 2005; Flynn, 2008; Rose et al., 2009). Resilience is often used to explain why regional or national economies do not decline as much as might be expected after disasters, or why they recover more quickly than predicted. The concept has received increasing emphasis for more than a decade, with progress on its definition stemming from the work of Tierney (1997), Bruneau et al. (2003), Chang and Shinozuka (2004), and Rose (2004, 2017). Various disciplines and definitions seem to be evenly split between those that define resilience broadly to include attributes that contribute to pre-event disaster resistance, and those who prefer to reserve the terms for actions undertaken after a disaster begins that are intended to reduce losses. In this study, we exclude pre-event actions that fall into the broad category of mitigation, though we do include pre-event actions that enhance resilience capacities that are implemented after the event as disused below.

A. Defining Economic Resilience

Although there are many definitions of resilience, Rose (2009, 2017), Cutter (2017) and others have found more commonalities than differences. We offer the following general definitions of resilience, which capture the essence of the concept, and then follow them with definitions that capture the essence of economic considerations. Following Rose (2004, 2017), we distinguish two major categories:

- In general, Static Resilience refers to the ability of the system to maintain a high level of functioning when shocked (Holling, 1973). *Static Economic Resilience* is the efficient use of remaining resources at a given point in time. It refers to the core economic concept of coping with resource scarcity, which is exacerbated under disaster conditions.
- In general, Dynamic Resilience refers to the ability and speed of the system to recover (Pimm, 1984). *Dynamic Economic Resilience* is the efficient use of resources over time for investment in repair and reconstruction. Investment is a time-related phenomenon—the act of setting aside resources that could potentially be used for current consumption in order to re-establish productivity in the future. Static Economic Resilience does not completely restore damaged capacity and is therefore not likely to lead to complete recovery.

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Rose, 2004; Tierney, 2007; Cutter, 2016). Inherent resilience refers to resilience capacity that is either already built into the system or that can be incorporated in advance of the disruption by enhancing resilience capacity though "pre-positioning". Examples include the ship rerouting, other transport mode shifts, and geographic production shifts, all stimulated by the workings of the market system in providing price signals for decision about redirecting scarce resources. Adaptive resilience is exemplified by undertaking conservation that was not previously thought possible, changing technology, or devising new government post-disaster assistance programs. The focus of economic resilience is not on property damage, which has already taken place at the onset of the disruption, but rather the reduction in the loss of the *flow of goods and services* emanating from the damage to or cessation of operation of the port's *capital stock*. The former is often measured in terms of the reduction in the level of production at the micro level or by GDP at the macro level, and is typically referred to as business interruption, or BI. Note that BI just begins at the point when the disaster strikes, but continues until the system has recovered (Rose, 2017).

In order to evaluate the effects of resilience, the next step is to translate these definitions into something that can be measured. Following Rose (2004, 2017), for static resilience, the metric is the amount of BI prevented by the implementation of a given resilience tactic or set of tactics comprising a resilience strategy divided by the maximum potential BI from the disaster if the tactic were not implemented. Several studies have measured resilience using this and related metrics (see, Rose et al. 2009; Rose and Wei, 2013; Xie et al., 2014).

B. Resilience Tactics for Port Regions

Port resilience is a special case of economic resilience (Rose and Wei, 2013). In the context of a port shutdown or disruption, *static* economic resilience relates to the operation of the port and the activities of both its direct customers (importers and exporters) and businesses upstream and downstream along the supply chain of these direct customers. It refers to how ports and businesses can utilize remaining resources effectively to maintain functioning to the extent that they can. Supplier-side resilience is concerned with delivering outputs to customers, and, in the context of a port disruption, it refers to maintaining functionality at the port. (The various resilience tactics ports undertake to accelerate the speed of recovery of port operations through investment in restoring port capacity come under the heading of *dynamic* economic resilience, and are not analyzed here.) On the customer-side, businesses that are affected by the import or export disruptions could initiate a broad range of coping activities. These actions are taken not only by importers and exporters, but also by others that are indirectly affected by the port disruptions throughout the economy-wide supply chain. Our analysis focuses on *static* economic resilience on both the customer-side and supplier-side.

Expanding on Rose and Wei (2013) and Rose et al. (2018), we define the various supplier-side and customer-side resilience options relating to port disruptions below.

Supplier-Side Resilience Options

1. *Excess capacity*. Utilization of unused capacity at undamaged terminals of the port to unload or load cargo that was originally handled in other terminals that experience facility downtime.

2. *Cargo prioritization*. Altering schedules for unloading or loading based on the characteristics or value of the cargo (e.g., giving perishable items a higher priority or identifying key commodities needed to minimize supply-chain losses or to accelerate recovery).

3. *Ship re-routing*. Sending ships to other ports. This requires an assessment of alternative locations, ship and cargo type, and transportation costs, the extent to which some cargo can eventually be re-routed to the disrupted port area through land surface or sub-surface (pipeline) transportation.

4. *Export diversion for import use*. Sequestering goods that were intended for export to substitute for lack of availability of imports or domestically-produced goods that require imported inputs. Care needs to be taken, however, to ensure that the goods diverted from export are adequate replacements for those goods that are in short supply.

5. *Effective management*. Improvements in decision-making and expertise that enhance functionality. Much of it refers to improvisation, but some relates to established port-level emergency-management plans to share information and facilitate communications and coordination of stakeholders after the incident; and to effectively allocate manpower and other resources to expedite debris removal, repair, and reconstruction.

6. *Production recapture (Rescheduling)*. Working extra shifts or over-time to clear up the backlog of vessels after the port facilities resume operation after the disruption. This option is usually only

viable for short-run disruptions, for which most ships will wait for the re-open of the port in the harbor, rather than re-rout to other ports.

Customer-Side Resilience Options

1. *Use of inventories*. Stockpiling critical inputs for the production of goods and services by firms. Note that the cost of inventories is not the actual value of the goods themselves, but simply the carrying costs; the goods themselves are simply replacement for the ordinary supplies.
2. *Conservation*. Finding ways to utilize less of disrupted imported goods in production processes that are disrupted by the curtailment of imports directly, as well as conserving critical inputs whose production is curtailed indirectly.
3. *Input substitution*. Utilizing similar goods in the production process to those whose production has been disrupted (again both directly and indirectly).
4. *Import substitution*. Bringing in goods and services in short supply from outside the region through transportation means other than water transportation.
5. *Production relocation.* Shifting production to branch plants or losing production opportunities to competitors in other locations.
6. *Production recapture (Rescheduling)*. Making up lost production by working extra shifts or over time after the port re-opens and the supply of critical inputs resumes. This is a viable option for short-run disruptions, where customers are less likely to have cancelled orders.
7. *Technological change.* Improvising the way goods are produced in order to maintain functionality, including imparting additional flexibility into production systems both before and after the disaster.

Note that input substitution, import substitution, and production relocation (IIR) listed above are inherent aspects of CGE models and thus estimated automatically.

4. Modeling Overview of Resilience to Port Disruption into a Multi-Regional CGE Model

Most resilience tactics can be connected to an expanded set of production function input variables and parameters (Rose and Liao, 2005; Dormady et al., 2018). Others need to be applied in an ad hoc manner, such as loosening input constraints or adjusting output. Note that, although there are several examples of formal incorporation of resilience tactics into CGE modeling on the customer-side, these resilience options have not yet been simulated in CGE models on the supplier-side to any significant extent. However, many of the methodologies are similar to those on the customer-side that will be presented below. In Appendix A, we present in details the major categories of resilience tactics on both supplier-side (port-side) and customer-side, the applicability of the tactics to factors of production in port and business operations, and the methods for incorporating them into the CGE models.

Figure 1 displays the major linkages in tracing port disruptions, beginning with direct economic impacts through short-run and long-run impacts across five analytical time stages of a disaster scenario (using Tsunami as an example). The scenario begins with the Tsunami Event, which first translates into a risk of a port shutdown, cargo damage, and isolated terminal downtime for extended periods of time. Various supplier-side resilience tactics that can facilitate a more speedy recovery of the commodity flows at the ports are shown in the blue rounded-edge boxes. At the macroeconomic level, port disruptions lead to intermediate production inputs and final goods shortfalls, and reduction in final demand associated with reduction in exports. Relevant customer-side resilience tactics that can be utilized by the businesses requiring the imported commodities as inputs, as well as by final users, to mitigate their potential losses from port disruptions are depicted in orange rounded-edge boxes. The total impacts involve the general equilibrium impacts stemming from the direct impacts that ripple through the entire supply chain, taking interdependencies and resource constraints into consideration.

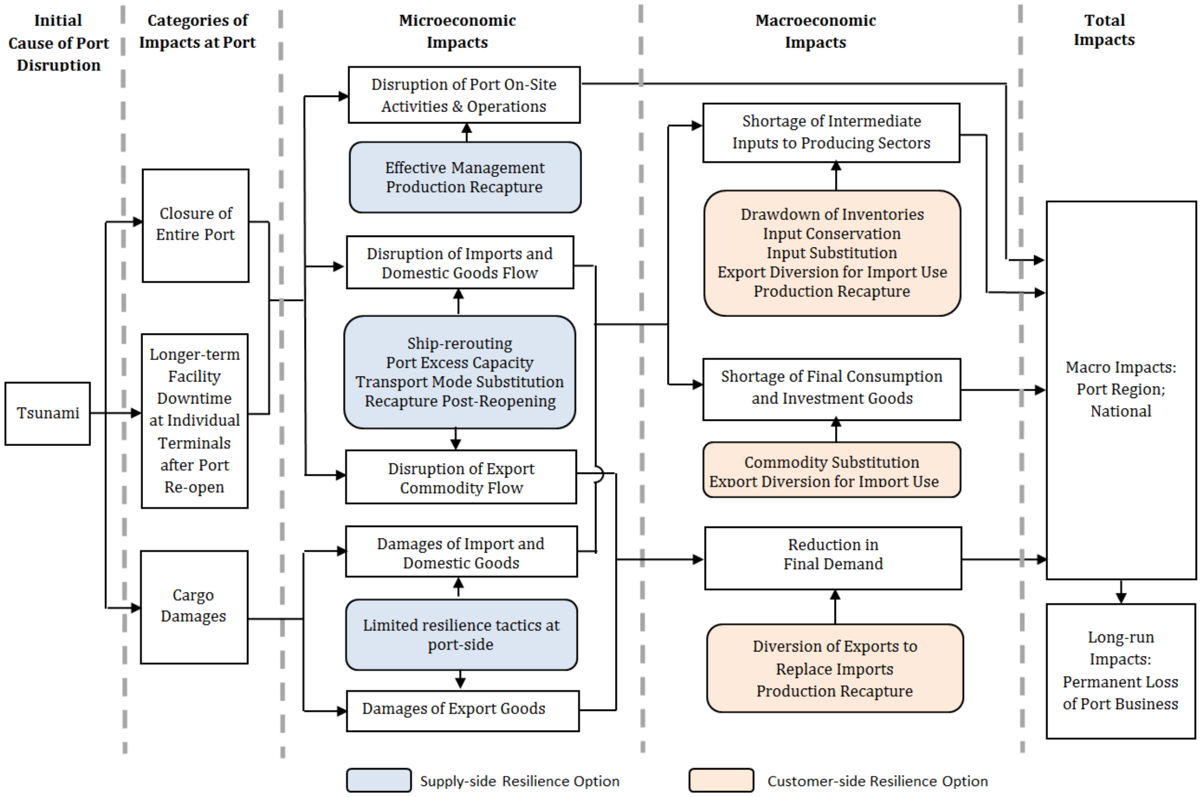

Figure 1. Analytical Framework of Estimating Total Economic Impacts of a Port Disruption with Implementation of Resilience Tactics

5. Model Framework

A. Overview

A major innovation of our study is the decomposition of the effectiveness of a full set of resilience strategies that can reduce business interruption losses from a disaster. Previous studies have not separated out the effects of major forms of inherent resilience stemming from the price system's ability to efficiently reallocate resources through input, import, and locational substitution (i.e., the three major categories of inherent resilience captured by the CGE model to be discussed further in more detail below) from adaptive resilience and other forms of inherent resilience. In this study, we separate this first set of inherent resilience tactics from the second set, including some additional inherent resilience tactics, such as excess capacity and normal inventory levels, plus adaptive tactics, such as ship rerouting, conservation, and production recapture.

The simulations and decompositions of resilience tactics are complicated by a path-dependency issue. If we simply run the CGE simulation with the first set of tactics (automatically taken into account by the workings of the model) and then add the second set on top of this in the subsequent simulations (i.e., running each individual resilience case in the TERM Model), this would yield misleading results, since the second set of resilience tactics would have a smaller base of (remaining) BI losses to which to be applied (since the first set of tactics will be automatically integrated in each simulation of the second set of tactics in the TERM Model). The analogous problem arises if we simulate the second set of resilience tactics initially and then simulate the first set on top of them. Hence, to avoid the path-dependency problem, we run each of the two sets of tactics separately and independently with respect to the Base Case (no resilience) to decompose their separate effectiveness in reducing losses. We simulate the first set as a group because of the difficulty of separating input, import and locational substitution.[1] However, we simulate the second group one at a time in a comparative static mode.

Also, if we add the separate resilience impacts of the two groups of tactics, we would be over-estimating the combined effect due to overlaps and duplications. Hence, we combine all of the resilience tactics in one complete CGE simulation to estimate the total effectiveness of resilience.

We invoke a short-cut in our calculations for the second set of resilience tactics. We first run each tactic in the second set separately in the CGE Model. We then use the proportions of loss reduction from these comparative static analyses with the CGE Model and apply these proportions to Base Case BI loss levels from the I-O model. If we applied them in an I-O simulation, we would overestimate the indirect effects because of linearity of the model.[2]

[1] We could perform this decomposition if the TERM Model were more flexible. However, it is not possible for us to set input or import (Armington) elasticities to zero. Also, this would require running the model for each sub-region separately, so as to stifle the inter-regional relocation of economic activity.

[2] Of course, using the proportions of loss reduction from the CGE model to estimate the indirect effects of the second set of tactics does include some input, import and locational aspects in the indirect effects. However, the inaccuracy of the decomposition is far outweighed by the potential inaccuracy of the overall estimate of effectiveness of the set of resilience tactics by using the (linear) I-O model.

Figure 2 presents a conceptual overview of the analysis on the economic consequence and the effectiveness of the resilience tactics.

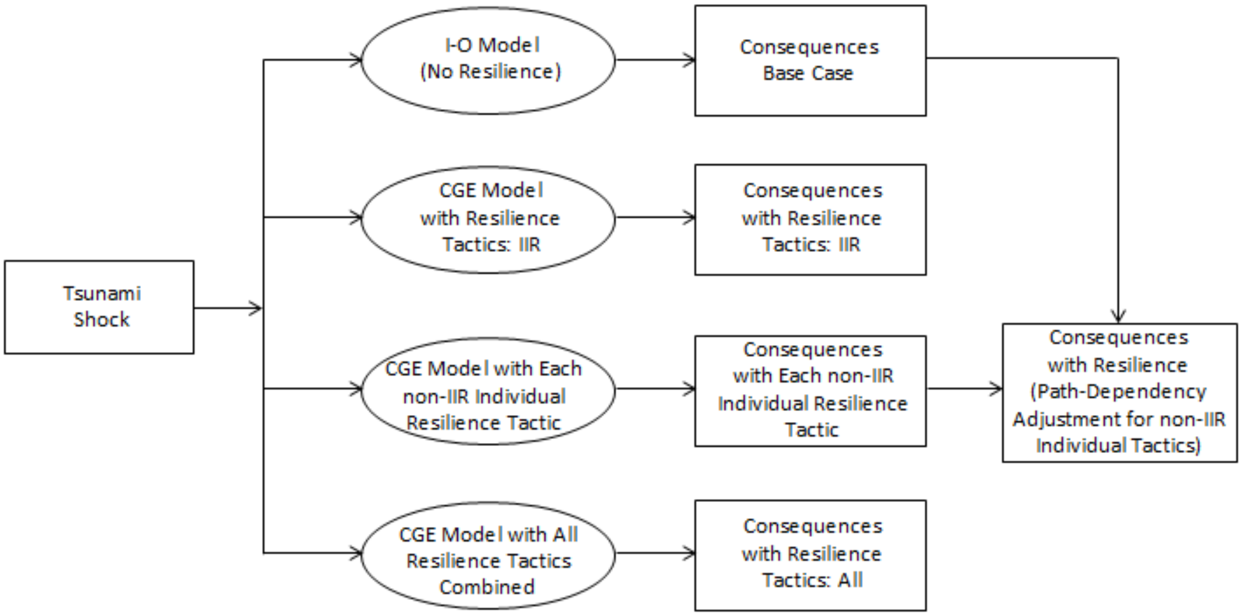

Figure 2. Economic Consequence and Resilience Computational Overview

B. TERM Multi-regional CGE Model

We adapt a multi-regional CGE model – the TERM Model – to analyze the total economic impacts of the port disruption scenario. TERM is a "bottom-up" model that treats each region as a separate economy.[3] The model was custom built by the research team at the Centre of Policy Studies at Victoria University in Australia and has undergone several refinements (Horridge et al., 2005; Wittwer, 2012). It was designed specifically for the U.S. on the basis of regional I-O data for the Year 2010 (IMPLAN, 2012),

[3] A "bottom-up" approach means that national results are aggregated based on regional economic outputs, which are simulated initially in a multi-regional CGE model. Unlike the "top-down" approach of regionalization, typically one of proportioning national values to regional levels (see, e.g., Dixon et al., 2007), a multi-regional CGE model developed through a "bottom-up" approach consists of multiple independent regional accounts and interregional trade involving various commodities and factor flows. Since price and quantities in different regional accounts are determined endogenously in the model by supply and demand both interregionally and intraregionally, the multi-regional model is able to measure distinct regional impacts and associated regional spatial reallocations caused by a policy simulation.

supplemented by various elasticities gleaned from the literature.[4] A key feature of TERM, in comparison to other CGE models, is its ability to handle a greater number of regions and sectors -- regional accounts for up to 205 regions and 182 sectors for Australia. The high degree of regional detail makes TERM a useful tool for examining the region-specific impacts of shocks (especially supply-side shocks). In addition, TERM contains a detailed treatment of transportation costs and is well-suited to simulating the effects due to damages of transportation infrastructures. The TERM Model has been used in many studies that analyze trade-related issues and some analyses of disaster. The model is a static version, which simulates the impacts of port disruptions on the economy on an annual basis. Some limitations of this characteristic are discussed at the end of this Section.

The modeling structure of TERM is similar to that of other CGE models (Horridge, 2012). Producers in each region are assumed to minimize production costs subject to a combination of intermediate and primary factor inputs, which are characterized by a Constant Elasticity of Substitution (CES) nesting structures. As illustrated in Appendix B, at the top nest level, output is produced by combining a composite of primary factors with a composite of intermediate inputs. The primary factor aggregate is a CES composite of capital, land, and labor—the latter being itself a CES composite of labor by skill type. The aggregate intermediate input is also a CES composite of composite commodities, which are in turn CES composites of commodities from various sources. A representative household in each region maximizes utility through purchases of optimal bundles of goods in accordance with its preferences and budget constraint.

[4] The Armington and factor input elasticities of substitution in the TERM Model have accumulated in the work of Peter Dixon and his collaborators beginning with the ORANI Model (Dixon et al., 1982) up through more recent work on the US Multi-Regional Dynamic CGE Model (USAGE) (Dixon et al., 2017). The Armington elasticities take on values from 2.0 to 10.0 and the input elasticities are typically around 0.5, which falls in between typical short-run and long-run values. They are already more restrictive than most other CGE models employing CES production functions, and much more restrictive than those using Cobb-Douglas production functions, where the elasticity of substitution has to be equal to 1.0.

The TERM database used for our study consists of 4 regions and 97 economic sectors. The regions include: LA Metro Region (including 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), and the Rest of California, and the Rest of the U.S.[5]

With respect to the 11 criteria An et al. (2004) used to evaluate various regional economic impact models, TERM would have ranked among the top had it been included in the evaluation. The only two criteria that the TERM Model used in this study does not meet are: dynamic analysis and endogenous travel behavior. However, the former is not very important for evaluating static economic resilience, and the latter is not particularly relevant for the analysis of port disruptions affecting international commodity trade. In addition, one should note that, similar to other CGE models, TERM also has a major limitation in terms of modeling parameterization (Chen and Haynes, 2017). Many of the key parameters, such as the Armington elasticities of substitution and factor substitution elasticities, were derived from the literature, which provided estimates based on econometric analysis using data for regions other than that of the particular analysis.

Modeling port resilience activities in a CGE framework requires identifying a linkage between each resilience tactic and an appropriate driver (either a parameter or variable) in the model. Table 2 summarizes the analytical approach we use to simulate the effects of various resilience tactics relating to port disruptions in the TERM Model. Column 1 of the table lists the various resilience tactics. More details of the modeling approach are presented in the next two columns.

[5] A major focus of our paper is the methodological contribution, such that our 4-region analysis is capable of providing it and in a generalizable manner. Our 4 regions cover the entire US and thus the analysis can adequately capture the spatial substitution effects among the sub-regions of California and between these regions and Rest of US.

Table 2. Modeling Tactics for Economic Resilience in TERM-USA

Resilience Tactic		Simulation Method	Description
Conservation		Adaptive resilience is captured by adjusting the intermediate goods and Armington elasticites to allow more flexibility of using scare resources.	Adjust the intermediate goods and Armington elasticities, by industry and region
Port Excess capacity		Adjust import and export shocks	Reducing the direct import- and export-disruption impact by the amount of port excess capacity.
Inherent Input Substitution		n/a	Inherent input substitution is captured by the CGE model automatically.
Import Substitution		n/a	Inherent import substitution is captured by the CGE model automatically by the Armington elasticity of substitution.
Ship Rerouting		Adjust import and export shocks in different regions	Steering ships to other nearby ports
Export Diversion for Import Use		Adjust import and export shocks	Using goods that were intended for export as substitutions for the lack of availability of imports.
Inventory Use		Adjust import shock	Reducing the direct import disruption by the amount of inventory.
Production Recapture		Application of "Recapture Factor Parameter" to output changes	A side-calculation to adjust total output losses for production rescheduling.

The TERM-USA model is a static model that simulates the impacts of port disruptions on the economy on an annual basis. When we analyze the loss reduction potentials of inventories, we did take into consideration the current stockpile level of inventories across various industries using BEA data. Therefore, the loss reduction potential of this resilience tactic is limited as inventories become depleted. As for input and import substitutions, our approach does not enable us to measure any immediate impacts, that are likely to reflect very limited substitution, and hence our elasticities represent an average level over the one-year period. Our sensitivity tests on the Armington and factor input elasticities to gauge the sensitivity our results to these important parameters are presented below.

6. Simulation Scenarios

A. Southern California Tsunami

The devastating tsunami that struck Japan's Tohuku Province in 2011 dramatizes the destructive force of this type of natural hazard. It raised concerns about tsunamis in other coastal areas, including California.

The existing scientific consensus for many years was that California is only vulnerable to tsunamis emanating from distant places, such as the Aleutian Islands, and the impacts are therefore likely to be very small compared to the recent Japanese tsunami. However, recent scientific analyses have identified a subduction zone off the coast of California that could potentially cause a devastating event in the state (Borrero et al., 2005; Legg et al., 2015).

In our analysis, the disaster scenario is adopted from Borrero et al. (2005), which analyzed a tsunami generated by an underwater landslide offshore of the Palos Verdes Peninsula. The following assumptions were adopted for a major port disruption scenario for POLA/POLB caused by the simulated tsunami event:[6]

1. POLA/POLB are completely shut down immediately after the disaster event.
2. The ports recover to their pre-disaster operation levels by the end of Year 1.
3. The recovery path of the ports' activities is assumed to be linear within the one-year period.[7] Therefore, the direct disruption to trade flows (on both import and export sides) in dollar terms is calculated by dividing the total values of imports and exports by two (the area of the "loss

[6] In order to determine the duration of a port shutdown that represents a major disruption to port operations and the regional and national economies, we performed a literature analysis of the length and time-path of port disruptions for major historical or hypothetical disaster events. Borrero et al. (2005) analyzed the impacts of a tsunami scenario generated by an underwater landslide offshore of the Palos Verdes Peninsula to POLA and POLB, and in the worst case scenario assumed a one-year complete shutdown. Rosoff and von Winterfeldt (2007) evaluated the impacts of a hypothetical dirty bomb attack at POLA/POLB, with port disruption scenarios ranging from 120 days to one year. depending on many factors, including the length required for decontamination of the port area. Rose and Wei (2013) analyzed the economic impacts and the role of resilience for two port shutdown scenarios at Ports of Port Arthur and Beaumont, Texas with the upper-bound scenario being a 90-day complete shutdown at the two ports. Chang (2000) studied the economic losses, recovery path, and change in market share of Port of Kobe after the 1995 earthquake, where the port was completely shut down for about a month.

[7] The one-year linear recovery path is a simplified assumption to approximate the actual possible seaport recovery path. First, the port has many terminals, and some may be less damaged and take less time to repair and resume function. Therefore, it is not a zero/one outcome, but a step function of recovery. In addition, it is possible that the port will have a complete shutdown for a short period of time until safety inspections are performed prior to restoring operations in any undamaged/slightly-damaged terminals. The subsequent restoration will be cumulative and can take on various trajectories. The linear recovery path is intended to approximate the more complicated non-linear paths such as the ones described.

triangle"). Based on the 2014 trade data, the total value of imports for 6-months is $158.7 billion, and the total value of exports is $38.6 billion.

B. Overview of the Analysis

Previous studies by the authors have found the potential for port resilience to be very high. For example, Rose and Wei (2013) estimated the potential for resilience at the regional level for a 90-day shutdown of the twin ports at Beaumont and Port Arthur, Texas, to be 67%. Rose et al. (2016) found a similar level of resilience applicable to a two-meter wave height tsunami. The Rose-Wei study was done with an I-O model and considered a limited number of resilience tactics. The Rose et al. study used a multi-regional CGE model and did not explicitly measure the inherent resilience associated with ordinary input and import substitution and business relocation, but it did measure various other inherent and adaptive resilience tactics. Some resilience tactics are "naturally" incorporated in the TERM Model because they are inherent in a CGE model in general (Input and Import Substitution) and in a multi-region CGE model (Import Substitution and Relocation).

The first category of inherent economic resilience pertains to Input and Import Substitution. The former is somewhat limited because elasticities of substitution between material inputs in most CGE models are either zero or are very low (typically < 0.1). However, substitution across transportation modes and between capital and labor are typically relatively high (typically close to 1.0). The major source of resilience in a multi-region context, however, is Relocation of economic activity across regions. A disruption of port activity and in production of downstream customers in one region results in partially offsetting production increases in others. This can be thought of as shifting production to branch plants or outright loss of production opportunities by one company whose slack is taken up by its competitors in other regions. The extent to which this takes place is determined by trade elasticities in a CGE model and is likely to be a major source of resilience because import and export elasticities usually exceed 2.0.

One can perform a simple test of the extent of Input Substitution, Import Substitution, and interregional Relocation in the following way: If capital stock (port capacity) in the multi-region system is reduced by X% and overall output in the system is reduced by Y % (where Y<X), then according to the resilience metric presented above, the loss reduction potential of resilience would be (X% - Y%) / X% = 1 – Y%/X%. Of course, this assumes a linear reference base relationship, i.e., an X% reduction in the capital stock would result in an X% total output loss in a rigid system – one that lacks any resilience. This is in contrast to a resilient system, which is characterized by the opposite of rigidity – flexibility.

7. Simulation Results

A. Base Case (No Resilience) Results

The economic impacts of the port disruption scenario for the Base Case are estimated by the application of the ordinary (linear) I-O analysis approach, with no resilience tactics incorporated. The first rows of Table 3, Table 4, and Table 5 present the Base Case GDP impacts for import disruption, export disruption, and import and export disruptions combined, respectively. The impacts are dominated by import disruptions. For the LA Metro Region, a one-year disruption at POLA/POLB is estimated to result in a GDP loss of about $93 billion (or a 13.4% decline) on the import-side and a $6.5 billion GDP loss (or a 0.95% decline) on the export-side. The impacts for California are $178 billion (or an 11.3% decline) on the import-side and $9.5 billion (or a 0.1% decline) on the export-side. The GDP impacts from import and export declines for the U.S. as a whole are estimated to be $534 billion (4.3%) and $35 billion (0.3%), respectively.[8] In the next two sub-sections, the Base Case results are used as the reference to evaluate the loss reduction potential of the two sets of resilience tactics.

[8] We simulated the Base (No Resilience) Case using a demand-side I-O model closed with respect to households. We have compared the Type-II multipliers we used with the Type SAM multipliers reported by IMPLAN (the leading I-O data provider) for the U.S., and found that the differences between these two types of multipliers are rather small (within 8% for the majority of sectors). This means that if Type SAM multipliers are used, the losses in the Base Case will increase by about 8%.

B. Inherent Resilience Results

Row 2 in Tables 3 to 5 presents the results of the CGE analysis that takes into consideration three major types of inherent resilience tactics — input substitution, import substitution, and business relocation (IIR). For the LA Metro Region, combining the impacts from both import and export disruptions, we estimate that the tsunami scenario would result in a $7.5 billion loss in GDP, or slightly more than a 1%. Not surprisingly, the losses are larger for this region than any of the others in both dollar and percentage terms and both before and after the application of IIR resilience tactics. This is due to two reasons: 1) the fact that the LA Region is the direct recipient and direct user of the majority of the import shipments (for inputs into production and final demand), and 2) the negative impacts in other regions are offset through an increase in the demand for their exports and more general relocation of economic activity. The sum total of GDP losses for the US as a whole is more than $16 billion, though this is only slightly more than a one-tenth of one percent decline at this level. The overall negative impacts from the export shocks were found to be relatively smaller than the impacts from import shocks. One reason is because POLA/POLB have a higher import flow than export flow. The other reason is that there are only backward linkage effects associated with export disruptions.

The last two columns in Tables 3 to 5 present the loss reduction potential for various types of resilience tactics in percentage terms. A comparison of the results from the TERM Model (second row) and the I-O analysis (first row) indicates that the inherent economic resilience estimated by the TERM CGE Model (input substitution, import substitution, and production activity relocation) reduces the potential GDP losses by 92.5% on both the import and export disruption sides for the LA Metro Region.[9] At the national level, the loss reduction potentials are 97.9% and 85.4% on the import- and export-side, respectively.[10]

Table 3. Real GDP Impact of an Import Shock – Base Case and Resilience Cases (million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	CA Total	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (I-O Results)	-$92,665 -13.43%	-$40,793 -10.04%	-$44,603 -9.24%	-$178,060 -11.28%	-$355,446 -3.45%	-$533,506 -4.27%		
With Inherent Resilience (IIR) (Basic TERM)	-$6,984 -1.01%	-$2,077 -0.51%	-$2,082 -0.43%	-$11,143 -0.71%	-$72 0.00%	-$11,216 -0.09%	92.46%	97.90%
With Ship Rerouting	-$55,682 -8.07%	-$22,000 -5.41%	-$25,879 -5.36%	-$103,562 -6.56%	-$161,728 -1.57%	-$265,290 -2.12%	39.91%	50.27%
With Export Diversion	-$85,380 -12.38%	-$35,132 -8.65%	-$40,190 -8.33%	-$160,702 -10.18%	-$293,141 -2.85%	-$453,843 -3.63%	7.86%	14.93%
With Conservation	-$91,554 -13.27%	-$40,251 -9.91%	-$44,073 -9.13%	-$175,878 -11.14%	-$336,041 -3.26%	-$511,919 -4.09%	1.20%	4.05%
With Use of Inventories	-$80,383 -11.65%	-$42,315 -10.41%	-$41,640 -8.63%	-$164,338 -10.41%	-$61,489 -0.60%	-$225,827 -1.81%	13.25%	57.67%
With Production Rescheduling	-$62,442 -9.05%	-$27,380 -6.74%	-$30,147 -6.25%	-$119,969 -7.60%	-$239,462 -2.32%	-$359,431 -2.87%	32.62%	32.63%
With All Resilience Adjustments	-$2,594 -0.38%	-$884 -0.22%	-$834 -0.17%	-$4,311 -0.27%	$2,005 0.02%	-$2,306 -0.02%	97.20%	99.57%

Table 4. Real GDP Impact of an Export Shock – Base Case and Resilience Cases (million 2010 $ and percent reduction from pre-disaster levels)

[9] Note that dockers cannot immediately take on jobs in many other sectors, so the Model's assumption of labor mobility leads to an overestimate of resilience. This is also the case for workers valuing leisure and hence not being as keen to switch jobs.

[10] Additional simulations were performed in relation to the Base Case CGE run for the IIR resilience tactics by reducing the Armington and factor input elasticities to reflect more restrictive (shorter-run) conditions. The maximum reductions on the Armington elasticities we could achieve with the TERM Model was 40%,and still obtain a solution. To be consistent for comparison, we reduce both types of elasticities by 40% in our additional simulations. In the case of the reduction of Armington elasticities alone, GDP impacts were increased by 74% for the LA Metro Area and were slightly more than doubled in the SF Metro Area and the Rest of California. The simulations of a 40% reduction in factor input elasticities were less sensitive than the previous simulations, with only a 52% increase in GDP impacts in the LA Metro Area, a 70% increase for the SF Metro Area, and an 81% increase for the Rest of California. Thus, the IIR results are very sensitive to the elasticity parameters in the Model. Note, however, that the reduced elasticities would have a much lower impact on the other resilience tactics because these other tactics are not related to or farther removed from elasticity parameters.

	LA Metro	SF Metro	Rest of CA	CA Total	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (I-O Results)	-6,526 -0.95%	-1,845 -0.45%	-1,134 -0.23%	-9,505 -0.09%	-9,505 -0.60%	-26,139 -0.25%		
With Inherent Resilience (IIR) (Basic TERM)	-488 -0.07%	-177 -0.04%	-232 -0.05%	-898 -0.01%	-898 -0.06%	-4,318 -0.04%	92.52%	85.37%
With Ship Rerouting	-3,255 -0.47%	-923 -0.23%	-567 -0.12%	-4,745 -0.05%	-4,745 -0.30%	-13,099 -0.13%	50.12%	49.94%
With Export Diversion	-1,625 -0.24%	-482 -0.12%	-387 -0.08%	-2,494 -0.02%	-2,494 -0.16%	-6,631 -0.06%	75.10%	74.40%
With Conservation	-6,522 -0.95%	-1,841 -0.45%	-1,134 -0.23%	-9,497 -0.09%	-9,497 -0.60%	-26,067 -0.25%	0.06%	0.22%
With Use of Inventories	-6,526 -0.95%	-1,845 -0.45%	-1,134 -0.23%	-9,505 -0.09%	-9,505 -0.60%	-26,139 -0.25%	0.00%	0.00%
With Production Rescheduling	-4,398 -0.64%	-1,238 -0.30%	-766 -0.16%	-6,403 -0.06%	-6,403 -0.41%	-17,509 -0.17%	32.61%	32.92%
With All Resilience Adjustments	-44 -0.01%	-17 0.00%	-29 -0.01%	-89 0.00%	-89 -0.01%	-392 0.00%	99.33%	99.91%

Table 5. Real GDP Impact of Import and Export Disruptions – Base Case and Resilience Cases (million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	CA Total	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (I-O Results)	-99,191 -14.38%	-42,638 -10.49%	-45,736 -9.48%	-187,566 -11.88%	-381,584 -3.70%	-569,150 -4.55%		
With Inherent Resilience (IIR) (Basic TERM)	-7,473 -1.08%	-2,254 -0.55%	-2,315 -0.48%	-12,041 -0.76%	-4,390 -0.04%	-16,431 -0.13%	92.47%	97.11%
With Ship Rerouting	-58,937 -8.55%	-22,923 -5.64%	-26,446 -5.48%	-108,307 -6.86%	-174,828 -1.70%	-283,134 -2.26%	40.58%	50.25%
With Export Diversion	-87,004 -12.61%	-35,614 -8.76%	-40,577 -8.41%	-163,196 -10.34%	-299,772 -2.91%	-462,967 -3.70%	12.29%	18.66%
With Conservation	-98,077 -14.22%	-42,092 -10.36%	-45,207 -9.37%	-185,376 -11.74%	-362,108 -3.52%	-547,484 -4.38%	1.12%	3.81%
With Use of Inventories	-86,909 -12.60%	-44,160 -10.87%	-42,774 -8.86%	-173,843 -11.01%	-87,628 -0.85%	-261,471 -2.09%	12.38%	54.06%
With Production Rescheduling	-66,840 -9.69%	-28,618 -7.04%	-30,914 -6.40%	-126,372 -8.00%	-256,971 -2.49%	-383,343 -3.07%	32.62%	32.65%
With All Resilience Adjustments	-2,637 -0.38%	-901 -0.22%	-862 -0.18%	-4,401 -0.28%	1,613 0.02%	-2,788 -0.02%	97.34%	99.51%

D. Additional Inherent and Adaptive Resilience Results

Individual Resilience Effectiveness

We next simulate each of the other major resilience tactics presented in Section 3, with the results shown in the remaining rows of Tables 3 to 5. In this analysis, we assume that there would be no excess capacity at the ports to utilize, since a catastrophic disaster event that results in a complete shutdown would damage the majority of the port facilities. In addition, during the recovery period, the port will utilize any restored cargo handling capacity to the maximum extent.

The discussions of the effects of the resilience tactics below are based on comparisons between the results of individual resilience cases and the I-O simulation results of the Base Case (No Resilience).

Ship Rerouting

An increasing percentage of vessel operators would divert their ships to other undamaged seaports as the length of the port disruption increases. However, there are also transportation cost "penalties" for shipping longer distances, as well as including the use of land routes, to deliver the cargo to the original destination. In order to fully understand the re-routing potential and the extent to which it will affect transportation costs for a major seaport disruption scenario, a comprehensive and holistic inter-port logistic and facilitated inland transportation network model is needed (Trepte and Rice, 2014; Xing and Zhong, 2017). Given our limited data and limited real world experience at major ports,[11] we assume that, although a very high proportion of ships could divert to other ports, after taking into consideration the potential "cost penalties" of longer-range ship re-routing, this resilience tactic can help reduce 50% of the

[11] This assumption was made based on ship diversions during many real disaster events that led to short-run or long-run port disruptions. After the 1995 Great Hanshin Earthquake, imports going through the Port of Kobe were reduced by over 75%, the majority of which was absorbed by other major ports in Japan (Chang, 2000). During Superstorm Sandy in 2012, Port of New York/New Jersey closed for nearly one week. During this time, more than 25,000 shipping containers were diverted to other ports, which accounted for about 40% of the container throughputs during a week (Strunsky, 2013). In the wake of Hurricane Harvey in 2017, more than 90% of the cargo ships, tankers, and other vessels rerouted to other ports (Page and Basin, 2017).

direct impacts in the Base Case. Under this assumption, ship re-routing is estimated to reduce total real GDP losses from $569 billion in the Base Case to $283 billion (or a reduction of 50.3% of the losses) for this resilience tactic.

Export Diversion

We considered the diversion of export commodities to be used by importers of the same commodities to reduce the potential losses. Although we use a 97-sector model, we examine the trade data at 4-digit Harmonized Tariff Schedule (which disaggregates imports and exports into over 1000 types of commodities) codes to more accurately match the disrupted export commodities with import commodities. Export diversion is estimated to have the potential to reduce the GDP loss from $569 billion in the Base Case to $463 billion (or a decrease of 18.7% of GDP losses).

Conservation

We assume a 2-percent level of conservation for businesses to cope with the import disruptions. This conservation potential is then adjusted by the percentage of import disruption calculated in the Base Case for each individual commodity type. The resulting percentages are used to adjust the intermediate Armington elasticity of subsitution in the TERM Model. The simulation results indicate that this resilience tactic can help reduce the GDP loss from $569 billion in the Base Case to $547 billion, or a decrease of 3.8% of GDP losses.

Inventory Use

Our main source of inventory data is from the Bureau of Economic Analysis (2014). However, since the BEA data only provide total inventory of materials and supplies held by individual manufacturing sectors, we disaggregate the total inventory value into different types of raw material inputs for each industry based on the input coefficients for that industry found in the relevant regional I-O table (IMPLAN, 2013).

The results indicate that with inventory use, the total GDP impact can be reduced from $569 billion to $261.5 billion, or a decrease of 54.1% of the GDP losses.

Production or Sale Recapture

The possibility of production or sales recapture diminishes over time since customers are likely to seek other suppliers as, for example, their inventories of disrupted inputs run out. We adapt the recapture factors from HAZUS, the FEMA loss and risk assessment software for disasters (FEMA, 2013). Since the HAZUS recapture factors pertain to the maximum potential recapture capability, in the analysis we cut the recapture percentages in half in order to account for obstacles to implementation. Furthermore, we assume that the recapture factors are reduced by 25 percent for each three-month period within a year. Thus, after the first year, there is no production recapture. This resilience tactic can reduce the total GDP loss from $569 billion to $383 billion, which represents a decrease of about 32.6% of GDP.

Combined Resilience Tactics

After simulating the effects of the two sets of resilience tactics (i.e., inherent resilience IIR and the above five additional inherent and adaptive resilience tactics) separately, we combined these resilience adjustments in an additional simulation. Note, however, that the effects of individual resilience tactics are not additive, since, when we compute the effects of each tactic, we assume the resilience potential or effectiveness is relative to the Base Case. There is also a sequencing issue in relation to the resilience tactics on the supplier-side and customer-side. Therefore, in this Combined Resilience Simulation, we apply ship rerouting first, followed by export diversion. These two resilience tactics mainly pertain to the supplier-side or port-side. The two customer-side resilience tactics, use of inventories and conservation, are applied next. TERM is used in the combined resilience simulation to capture the effects of IIR. Production recapture is applied to the simulation results after the incorporation of all of the above resilience tactics. Referring to the first and last rows of Table 5, the combined resilience tactics can reduce GDP losses from $569 billion to $2.8 billion, a reduction of GDP losses by about 97.3% for California and 99.5% for the U.S. as a whole compared to the Base Case. It is interesting to note that the impacts on the rest of U.S. become slightly positive (a 0.02% increase) after incorporating these resilience adjustments. This is mainly due to two reasons. First, compared to the port region, inventories are more widely available throughout the country with respect to the amount of imported commodities that are in short supply. The lack of imports also stimulates an increase in the production of domestic goods as substitutes for the disrupted imports. Second, with more imports diverted to the rest of the country, the positive economic impacts stemming from the increased importing activities in the rest of the U.S. offset the negative spillover impacts caused by the shutdown of the ports in California.

Comparison of the Results

Again referring to Table 5, at the national level, the GDP impacts of a one-year disruption at POLA/POLB are estimated to be $569 billion (or 4.6% of the U.S. annual GDP) if no resilience is taken into consideration. The three major types of inherent economic resilience (IIR) captured by the TERM Multi-regional CGE Model can reduce the GDP losses by about 97%. For the other set of resilience tactics, Inventories, Ship Rerouting and Production Rescheduling, are the three most effective resilience tactics, being able to reduce losses by 54%, 50% and 33%, respectively. Combining all the resilience tactics analyzed in this study, the total impacts on the U.S. economy can be reduced to only $2.8 billion (or 0.02% of the U.S. annual GDP), a resilience effectiveness of 99.5%.

A comparison of the impact results for the port region (i.e., the Los Angeles Metro Region) and for the U.S. indicates that the various resilience tactics are more effective at the national level than at the port region level. These include Use of Inventories, Ship Rerouting, Export Diversion, and IIR inherent resilience tactics. This is because inventory use becomes very effective in the rest of the U.S. compared to the port region since the inventory to import disruption ratio is much higher in the rest of the U.S. than in the port region. Another major reason is because of the relatively stronger pull of general business relocation and supplying inputs for export demand from regions outside of the port region because these regions suffer lower direct impacts from the port disruption than does the port region itself.

8. Conclusion

This paper has developed and applied both an I-O model and multi-regional CGE model to estimate the economic consequences of and resilience to a major tsunami scenario for California. The CGE model is specially tailored to the context of this type of disaster and its economic repercussions. The advantage of using a multi-regional CGE model is that it is able to capture partial and general equilibrium impacts on GDP across regions stemming from quantity interdependencies and price change responses that result in shifts in economic activity across ports and production sites, transportation modes, and supply chains. Our analysis extends far beyond the immediate damage to ships or port facilities and evaluates the economic ripple effects beyond the ports. Essentially, the curtailment of imports and exports, in addition to the port operations themselves, translates into a chain of intraregional and interregional effects. Our major contribution is that we developed a novel approach to measure various types of port resilience, with a specific focus on input substitution, import substitution, and production relocation, which were often ignored or not previously measured in previous studies. For the first time in resilience studies, we decompose the results to examine the separate effects of these major types of inherent resilience from other forms of resilience.

Our analysis indicates that the major port disruption scenario (which leads to a one-year disruption at POLA and POLB with linear recovery path), would result in a decline of nearly $569 billion GDP at the national level. After taking into consideration the major types of inherent economic resilience integrated in the TERM CGE Model, the total impacts on the U.S. decrease to only slightly over $16 billion. Major inherent resilience tactics combined (including input and import substitution and production relocation) provide substantial loss reduction potentials. Other effective resilience tactics include Ship Rerouting on the supplier-side and Inventories and Production Recapture on the customer-side.

We intend that a more complete understanding of resilience will help decision-makers make more effective resource allocations to improve the recovery of ports and their host economies following disasters. The modeling framework can also be applied to economic consequence and resilience analysis of many other disaster types, such as earthquake, flood, hurricane and etc.

One should note, however, the important difference between potential resilience and actual resilience. The existence of various coping measures does not mean they will be optimally used given the likelihood of restrictive regulations, bounded rationality, and market failures. Our study estimates the loss reduction effects of potential resilience to inform and support policy implementation, which may provide insights to port managers and operators, as well as businesses that rely directly and indirectly on port operations, to identify and implement to the maximum extent possible powerful resilience tactics and enhance business contingency and continuity planning to cope with port disruptions.

Overall, we have incorporated the broadest range of resilience tactics and analyzed their effectiveness in reducing business interruption losses from port disruptions of any study to date, and have isolated and decomposed their effectiveness within a macroeconomic framework for both within and across regions, and with regard to direct and indirect impacts in a decomposition analysis. Research on economic resilience is booming, but much of it is confused by vague or misleading definitions and lack of operational metrics. Identifying and quantifying the various types of impacts of alternative resilience tactics is a critical element of fine-tuning risk management policy at the regional and multi-regional levels.

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Appendix A. Incorporating Resilience into a CGE Models

A. Supplier-Side (Port-Side) Resilience

Resilience options that can be adopted by the port authorities and terminal operators are summarized in Table A1. The table lists the major categories of resilience and provides examples in the first column. In the second column, prior actions that can be taken to enhance each type of resilience are specified. In the next two columns, we denote the extent to which the resilience category is inherent and adaptive (upper-case X and lower-case x represent relatively high and low strength of inherent or adaptive resilience, respectively). In addition, the applicability of the type of resilience to factors of production in port operation is specified in terms of inputs of capital (K), labor (L), electricity (E), port transportation (PT), other transportation (OT), materials (M), as well as for the output (Q) of the port. The output (or level of functionality) of the port directly affects the amount of imports and exports that can flow into and out of the country/region without disruption or delay. Upper-case letters associated with each of these inputs or outputs represent a strong relationship, while lower-case letters represent a weak one.

Methods for incorporating resilience into CGE models are displayed in the last column of Table A1, including a reference to research where this was first introduced in CGE or related models. The novel aspects of the Incorporation column pertain primarily to adaptive resilience, for which explicit changes to a CGE model are necessary and more evident. Many inherent tactics are already built into a CGE model, such as Input and Import Substitution and Relocation of Economic Activity, and can be analyzed with existing parameter specifications. Adaptive versions of these tactics involve changing the relevant parameters, in this case elasticities of substitution, or through ad hoc adjustments. Other types of inherent resilience are also embodied in a CGE model but are more difficult to detect and parameterize, e.g., Excess Capacity and Inventories. Some other tactics, such as inherent Conservation, are assumed to be optimized before the disruption. Some can be enhanced but are not generally applicable to a disaster situation unless in adaptive form, e.g., Effective Management, Cargo Prioritization. Adaptive resilience tactics are only applicable post-disaster, e.g., Production Recapture, Ship-Rerouting, and Export Diversion.[12]

B. Customer-Side Resilience

Resilience options for businesses that are direct and indirect customers of ports are summarized in Table A2, which follows the same format as Table A1. In addition, the same convention as in Table A1 is used to denote the strength of inherent or adaptive resilience as denoted by the letter X (or x). For example, a firm usually holds a certain amount of Inventories of raw materials to maintain a desired level of production in case of short-term input shortages/disruptions. However, it is more expensive for firms to hold extra capital input (e.g., equipment) as Inventory. Moreover, it is impossible for the firms to have any inventories of transportation services. Therefore, we denote the relative strength of each tactic with regard to relevant production function variables by upper-case and lower-case letters in the Applicability column of the Inventory row. Again, the last column of the table indicates how each type of resilience can be incorporated into a CGE model.

[12] Note that many of the methods of analysis in Tables 1 and 2 have been discussed in the context of related models, such as I-O models, including Rose (1984), Rose and Wei (2013), Wein and Rose (2011), Rose et al. (2018). Yet others have been discussed or incorporated into CGE models, such as Rose and Liao (2005), Rose et al. (2016), and Sue Wing et al. (2016), but mostly on the customer-side.

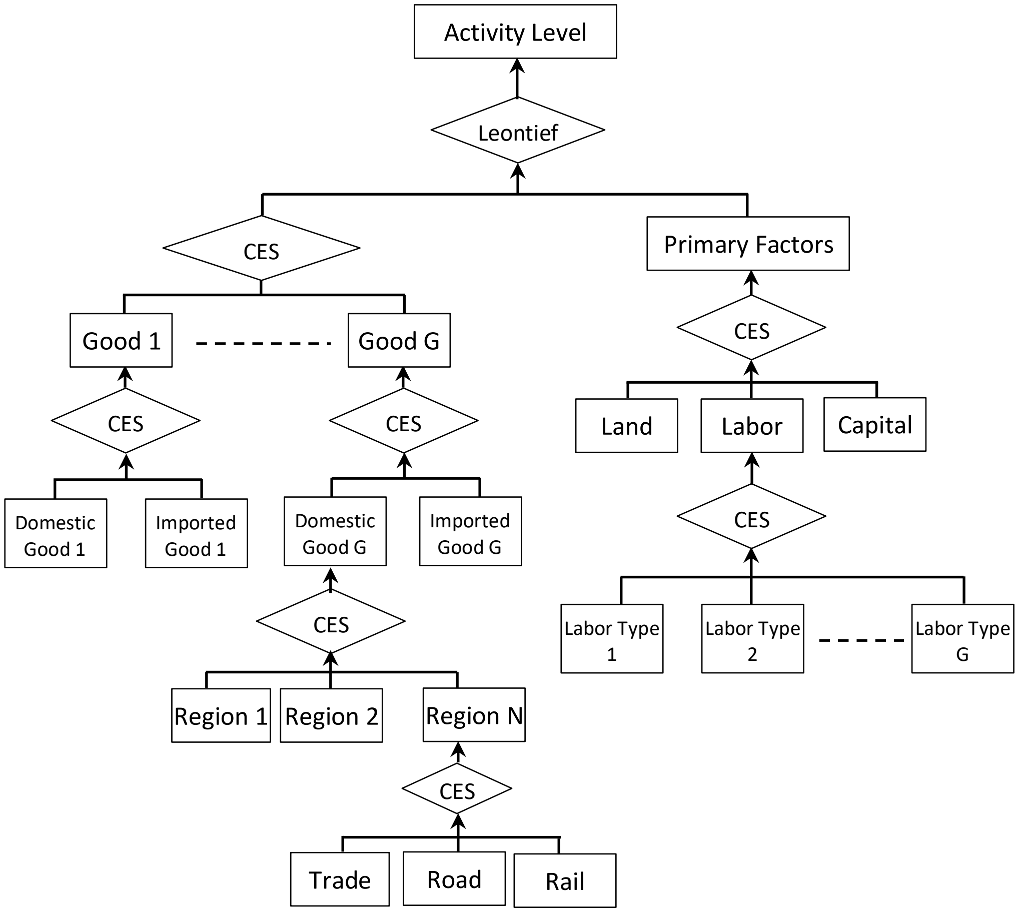
Appendix Table A1. Microeconomic Resilience Options: Supplier-Side (Port)

Resilience Category	Possible Action Prior to Disruption	Inherent Resilience	Adaptive Resilience	Applicability to Factors of Production	CGE Incorporation
Ship-rerouting and intermodal substitution • cooperation with nearby ports; • enhance points of transfer through truck or rail	flexible inter-port agreements port networking enhance intermodal coordination	X	X	Q, PT	ad hoc loosen constraint on inputs Rose and Wei (2013)
Export Diversion for Import Use • identify adequate replacement potentials • information clearinghouse between importers and exporters	enhance flexibility	X	X	Q, PT	increase export elasticity Rose et al. (2016)
Inventories (Stockpiles) • strengthen storage facilities (e.g., marine oil inventory buffer stocks) • reduce uncertainty	enhance; protect	X	x	Q, M, PT	ad hoc loosen constraint on output Rose and Wei (2013)
Input Substitution • use back-up systems; alternative inputs • alternative communication systems	enhance flexibility of system increase redundancy	X	X	K, L, PT, OT, E, M	inherent: Intrinsic in the CGE model adaptive: Increase input substitution elasticity Rose and Liao (2005)
Excess Capacity • unused capacity within terminals and between terminals • maintain in good order	build and maintain	X	x	K	ad hoc loosen constraint on output Rose et al. (2009); Wittwer and Griffith (2012); Sue Wing et al. (2016)
Production Recapture • work over-time or extra shifts • practice restarting	arrange long-term agreements	X	X	Q, PT	ad hoc apply recapture factors Rose et al. (2007, 2011)
Technological Change • change processes	increase flexibility	X	X	K, L, OT, M, Q	change production function Rose (1984)
Management Effectiveness • facilitate communication both within and outside the port • prioritize remaining resources • prioritize importance of vessels	increase versatility exercise and train	X	X	Q, PT	change labor productivity Wein and Rose (2011)
Reduce Operating Impediments • arrange on-site housing for critical staff and emergency responders • assist worker families • relieve congestion	recovery planning alleviate choke points	x	X	K, L, OT, M, Q, PT	ad hoc Wein and Rose (2011)

Appendix Table A2. Microeconomic Resilience Options: Customer-Side (Direct/Indirect Port Customers)

Resilience Category	Possible Action Prior to Disruption	Inherent Resilience	Adaptive Resilience	Applicability to Factors of Production	CGE Incorporation
Conservation • reduce non-essential use of critical imported inputs • promote recycling	minimize use of inputs curtailed by import disruption	x	X	K, L, PT, OT, M	increase productivity term Rose and Liao (2005)
Input Substitution • utilize similar goods in place of curtailed imported inputs • substitute port transportation by other transportation means	enhance flexibility of system	X	X	K, L, OT, M	inherent: Intrinsic in the CGE model adaptive: increase input substitution elasticity Rose and Liao (2005); Horridge et al. (2005)
Import Substitution • mutual aid agreements • substitute domestic goods for disrupted imports	broaden supply chain	X	X	k, L, M	inherent: intrinsic in the CGE model adaptive: increase import substitution elasticity Horridge et al. (2005); Sue Wing et al. (2016)
Inventories (Stockpiles) • ordinary inventories • emergency stockpiles	enhance; protect	X	x	k, L, M	ad hoc increase inventories; loosen constraint Rose et al. (2016)
Input Isolation • decrease dependence • segment production	reduce dependence on critical imported inputs	X	X	K, l, M	ad hoc loosen constraint on inputs ATC (1991); Rose et al. (2007)
Production Recapture • supply-chain clearinghouse • restarting procedures	arrange long-term agreements; contingency plan and practice for supply-chain disruption	x	X	Q	ad hoc apply recapture factors Rose et al. (2007, 2011)
Technological Change • change processes • alter product characteristics	increase flexibility	X	X	K, L, M, Q	change production function Rose (1984)
Management Effectiveness • emergency procedures • succession/continuity	train; increase versatility; identify	X	X	k, L, PT, OT, m	change labor productivity Wein and Rose (2011)
Relocation • utilize branch plants • give way to competition	shift production to other regions	X	X	Q	Park et al. (2007); Sue Wing et al. (2016)

Appendix B. Nesting Structure of Production Activities in TERM CGE Model



Source: Authors' update based on Horridge (2012).