

**FULL ARTICLE**

Evaluating the role of resilience in reducing economic losses from disasters: A multi-regional analysis of a seaport disruption

Dan Wei¹ | Zhenhua Chen² | Adam Rose³

¹Sol Price School of Public Policy, Center for Risk and Economic Analysis of Terrorism Events, University of Southern California, 379C VKC, 3518 Trousdale Pkwy, Los Angeles, CA, 90089, USA

²City and Regional Planning, Knowlton School of Architecture, The Ohio State University, 275 W Woodruff Ave, Columbus, OH, 43210, USA

³Sol Price School of Public Policy, Center for Risk and Economic Analysis of Terrorism Events, University of Southern California, 1150 S. Olive St., Suite 1700, Los Angeles, CA, 90015, USA

Correspondence

Dan Wei, Sol Price School of Public Policy, Center for Risk and Economic Analysis of Terrorism Events, University of Southern California, 379C VKC, 3518 Trousdale Pkwy, Los Angeles, CA 90089, USA.
Email: danwei@usc.edu

Funding information

California Department of Transportation, Grant/Award Number: 65A0533; DHS Critical Infrastructure Resilience Institute, Grant/Award Number: 2015-ST-061-CIRC01; USC METRANS, Grant/Award Number: DTRT13-G-UTC57

Abstract

Models to estimate economic impacts of disasters have recently been augmented to include resilience. However, most research has incorporated only a limited set of resilience tactics and has not estimated their individual loss reduction effect. We present a comprehensive framework for estimating the relative effects of a broad set of post-disaster resilience tactics. Our methodological innovation is illustrated by adapting the TERM multi-regional CGE model for a seaport disruption, distinguishing inherent resilience working through the price system from adaptive resilience and other inherent tactics to cope with input shortages. We also overcome a path-dependency problem in the modelling process.

KEYWORDS

computable general equilibrium analysis, economic consequence analysis, port disruptions, resilience to disasters, 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 & Liao, 2005; Resurreccion & Santos, 2012; Rose, Prager et al., 2017; Graveline & Gremont, 2017; Xie et al., 2018). These tactics are applicable at the microeconomic (individual port or business), mesoeconomic (individual market or industry), and macroeconomic (the entire regional and national economies) levels. Studies of actual and hypothetical events have indicated that resilience can significantly reduce the economic losses from disasters (see e.g., Rose, Oladosu, Lee, & Beeler-Asay, 2009; Kajitani & Tatano, 2009; Prager, Chen, & Rose, 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 the production of intermediate and final goods 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 labour disputes, natural disasters and technological accidents. Moreover, and ports are also considered prime targets for terrorist attacks (Rose & Wei, 2013; Rose, Wei, & Paul, 2018).

One modelling approach that can estimate the economic consequences of disasters, including the effect of various resilience tactics, is the 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 used as intermediate inputs or consumed by end-users elsewhere. Hence, it is especially important to have a model capable of analysing the 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 supply chains.

Previous CGE analyses of port disruptions, including those of the authors, have focused on the influence of various *adaptive* resilience tactics (responses that are improvised after the disaster strikes) and have ironically inadequately analysed the role of some important *inherent* resilience tactics (those that exist naturally in the operation of businesses, markets and regional economies, and are often intrinsic, i.e., built into a CGE model). Examples 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. We abbreviated *i*input substitution, *i*import substitution, and *r*elocation of economic activities as IIR below. These tactics have the ability to reduce business interruption in the aggregate substantially as well. While these tactics are automatically included in the economic consequence analysis if CGE models are used, 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 analysing 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. The paper is the first to estimate and compare the relative effectiveness of resilience tactics intrinsic in a CGE model with a set of other resilience tactics that requires more explicit actions and supplemental modelling adjustments. The analysis is that of comparative statics, with snapshots taken at a one-year disruption interval on the impacts of and resilience to a major port disruption. The analysis also resolves a path-dependency issue associated with the sequencing of the inclusion of various resilience tactics when evaluating their individual effects in reducing losses.



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, Gordon, Moore, & Richardson, 2008; Rose & Wei, 2013). 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 intrinsic resilience tactics and have instead focused more on adaptive resilience tactics (see, e.g., Horridge, Madden, & Whittwer, 2005; Rose, Sue Wing, Wei, & Wein, 2016; Wei, Chen, & Rose, 2016; Rose, Prager et al., 2017). This literature on seaport disruptions is representative of the literature on economic consequence analysis and resilience in general (Rose, Prager 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 modelling. 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 and evaluates the loss reduction potentials of both the inherent resilience tactics intrinsic in a CGE model and additional resilience tactics, both inherent and adaptive. Section 8 summarizes the paper and offers conclusions.

Our simulations indicate that resilience tactics are able to reduce potential GDP losses by more than 90%. Moreover, the resilience tactics intrinsic to CGE models have the greatest capability, though they are typically overlooked or not separately estimated in the vast majority of the literature. Other resilience tactics that need to be incorporated in an ad hoc manner turn out to be less powerful.

2 | LITERATURE REVIEW

We summarize the literature on economic impact modelling of disasters in general and port disruptions in particular (see Table 1 for a summary). An, Gordon, Moore, and Richardson (2004) evaluate 19 regional economic impact models (REIMs) capable of evaluating the performance of regional economies subject to disaster damage to infrastructure. The evaluation is 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 behaviour), transferability between regions and countries, operationality, accessibility, and adaptability. The study concludes that the multi-regional linear programming model developed by Rose, Benavides, Chang, Szczesniak and Lim (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.

Okuyama (2007) performs 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 include 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, include changes in consumption behaviour (such as donating goods to the damaged area and reducing discretionary purchases) and input substitution.

Haddad and Teixeira (2015) develop a spatial computable general equilibrium (SCGE) model to analyse the economic impacts of flood scenarios in Sao Paulo, Brazil. GIS is 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 are in turn used as input to the CGE model. However, this study does not include any analysis of economic resilience beyond input substitution.

Park et al. (2007) apply the interregional National Interindustry Economic Model, (NIEMO), to analyse 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 US. However, only indirect impacts of export disruptions are calculated. On the import side, only the direct effects of the import disruption are included in the total loss estimates.

**TABLE 1** Comparison of studies on regional economic impact modelling 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 Teixeira (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, Gordon, Moore, Richardson, and Wang (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



TABLE 1 (Continued)

Study	Disruption event/scenario	Type of model	Geographic impacts	Resilience inclusion	Limitation
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, Rimmer, and Wittwer (2012)	Drought events in Australia	Dynamic TERM-H2O CGE Model	Australia	Inherent resilience intrinsic in 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 US as a whole	Import ship diversion & overland rerouting, strategic petroleum reserve, inventories, export diversion, conservation and 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 US 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



The study also does not consider the effect of most forms of resilience. Park et al. (2008) estimate the economic impacts of the 11-day labour strike shutdown at the LA/LB ports in 2002, and the ensuing 4-month adjustment period as well. The authors supplement NIEMO with a multi-level linear regression model to estimate direct (final demand) losses and also include variables to reflect port and other transportation mode substitutions. However, the study does 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 resilience tactics are not separately analysed nor is the combination 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 analyse 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 2002–2003, which transmitted its effects primarily through agricultural productivity decreases. The authors do not explain intrinsic features of the model that represent various types of resilience. However, they do briefly mention adjustments that reflect adaptive input and import substitution resilience tactics, but they do not separately estimate their effects on losses. Additional aspects of resilience have been incorporated into TERM for application to more recent droughts through explicit modelling of substitution between irrigable and non-irrigable land and between land in general, labour and capital (Dixon et al., 2012) and in a dynamic version that includes excess capacity (Wittwer & Griffith, 2012).

Rose and Wei (2013) develop 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 total regional economic loss can be reduced by over two-thirds after factoring in the effects of several major resilience tactics. Production recapture and ship re-routing are 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 business interruption (BI) losses. However, neither study estimates the effects of resilience intrinsic to CGE models relating to 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 analysed and differentiated from other types of resilience. Since several US regions are involved, the CGE model is multi-regional in order to trace and capture competition and interconnectedness by various transportation networks across space. The economic interdependence is captured in the CGE model not just through quantities of goods and services supplied and demanded along sectoral supply chains, but also through price changes that 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 disaster impact analyses in the US 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 term 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 disaster strikes.

3.1 | 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:

1. 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.
2. 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.

The analysis in this study focuses on *static* economic resilience on both the customer and supplier sides.

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Cutter, 2016; Rose, 2004; Tierney, 2007). 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 through “pre-positioning.” Examples include input substitution, 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 programmes. 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).¹

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

¹The Port makes decisions on such tactics as the use of excess capacity and ship-rerouting, and the various direct and indirect customers make decisions about how to cope with the supply shortages under their own roof. There is a minimal role for government in this decision process, in part because it would interfere with day-to-day operations of businesses. Governments rarely provide financial assistance to port customers, and this only serves as compensation for decisions that businesses are inclined to make on their own to minimize the negative impact on their operations. If the government is more likely to compensate firms for some resilience tactics over others, businesses still need to know the relative effectiveness of those tactics in gauging their response.



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 & Wei, 2013; Xie, Li, Wu, & Hao, 2014).

3.2 | Resilience tactics for port disruptions

Port resilience is a special case of economic resilience (Rose & Wei, 2013). In the context of a port shutdown or disruption, *static* economic resilience refers to the ability the ports and the businesses depending directly and indirectly on port operations along the supply chain to 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.² On the customer side, businesses that are affected by the import or export disruptions could initiate a broad range of coping activities. These actions can also be taken by other businesses that are indirectly affected by the port disruptions throughout the economy-wide supply chain. 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.

3.2.1 | 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, transportation costs, and 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 domestic 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 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.
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 (only viable for short-run disruptions, for which most ships will wait for the re-open of the port).

3.2.2 | Customer-side resilience options³

1. *Use of inventories.* Utilizing stockpiles of critical inputs for the production of goods and services.
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.

²The 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 analysed here.

³By "customer," we are referring to business customers of the port. We do not consider household resilience in this paper but refer the interested reader to Rose (2009) for an overview.



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.
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 intrinsic aspects of CGE models and thus estimated automatically.

4 | MODELLING 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 (Dormady, Rose, Rosoff, & Roa-Henriquez, 2018; Rose & Liao, 2005). 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 modelling 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.

4.1 | Supplier-side (port-side) resilience

Resilience options that can be adopted by port authorities and terminal operators are summarized in Table 2. The table lists the major categories of resilience and provides examples in the first column. In the second column, prior actions that can enhance each type of resilience are specified. The next two columns 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), labour (L), electricity (E), port transportation (PT), other transportation (OT), materials (M), as well as for output (Q). 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 2, including reference to research where this was first introduced in CGE or related models. The novel aspects of the CGE Incorporation column pertain primarily to adaptive resilience, for which explicit changes to a CGE model are necessary and more evident. 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, for example, 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, for example, effective



TABLE 2 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	flexible inter-port agreements		X	Q, PT	ad hoc
- cooperation with nearby ports; - enhance points of transfer through truck or rail	port networking enhance intermodal coordination				loosen constraint on inputs Rose and Wei (2013)
Export diversion for Domestic Use	enhance flexibility		X	Q, PT	increase export elasticity Rose et al. (2016)
- identify adequate replacement potentials - information clearinghouse between importers and exporters					
Inventories (Stockpiles)	enhance; protect	X	x	Q, M, PT	ad hoc loosen constraint on output Rose and Wei (2013)
- strengthen storage facilities (e.g., marine oil inventory buffer stocks) - reduce uncertainty					
Input substitution	enhance flexibility of the system increase redundancy	X	x	K, L, PT, OT, E, M	inherent: Intrinsic in the TERM CGE model adaptive: Increase input substitution elasticity Rose and Liao (2005)
- use back-up systems; alternative inputs - alternative communication systems					
Excess capacity	build and maintain	X		K	ad hoc loosen constraint on output
- unused capacity within terminals and between terminals - maintain in good order					Rose et al. (2009); Wittwer and Griffith (2012); Sue Wing, Rose, and Wein (2016)
Production recapture	arrange long-term agreements		X	Q, PT	ad hoc
- work over-time or extra shifts - practice restarting					apply recapture factors Rose (Rose, 2007), Rose et al. (Rose, Wei, & Wein, 2011)



TABLE 2 (Continued)

Resilience category	Possible action prior to disruption	Inherent resilience	Adaptive resilience	Applicability to factors of production	CGE incorporation
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 labour 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	K, L, OT, M, Q, PT	ad hoc Wein and Rose (2011)



management and cargo prioritization. Adaptive resilience tactics are only applicable after the disaster strikes, for example, production recapture, ship-rerouting, and export diversion.⁴

4.2 | Customer-side resilience

Resilience options for businesses that are direct and indirect customers of ports are summarized in Table 3, which follows the same format and notation convention as in Table 2. For example, a firm usually holds a certain amount of inventories of raw materials for short-term input shortages/disruptions. However, it is more expensive to hold extra capital input (e.g., equipment) as inventory. Moreover, it is impossible for firms to stockpile 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. Again, the last column of the table indicates how each type of resilience can be incorporated into a CGE model.

4.3 | Modelling overview of resilience

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 stages of a disaster scenario (using a 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 a reduction in exports. Customer-side resilience tactics are shown in orange boxes. The total general equilibrium impact includes all indirect (ripple) effects throughout the supply chain.

5 | MODEL FRAMEWORK

5.1 | 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 (IIR) 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, which includes 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 in the subsequent simulations, 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). The analogous problem arises if we simulate the second set of resilience tactics initially and then simulate the first set on top of

⁴Note 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.



TABLE 3 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	minimize use of inputs curtailed by disruption	x	X	K, L, PT, OT, M	increase productivity term Rose and Liao (2005)
• reduce non-essential use of critical imported inputs					
• promote recycling					
Input substitution	enhance flexibility of the system	X	x	K, L, OT, M	inherent: intrinsic in the TERM CGE model adaptive: increase input substitution elasticity Rose and Liao (2005); Horridge et al. (2005)
• utilize similar goods in place of curtailed imported inputs					
• substitute port transportation by other transportation means					
Import substitution	broaden supply chain	X	x	k, L, M	inherent: intrinsic in the TERM CGE model adaptive: increase import substitution elasticity Horridge et al. (2005); Sue Wing et al. (2016)
• mutual aid agreements					
• substitute domestic goods for disrupted imports					
Inventories (stockpiles)	enhance; protect	X	x	k, L, M	ad hoc increase inventories; loosen constraint Rose et al. (2016)
• ordinary inventories					
• emergency stockpiles					
Input isolation	reduce dependence on critical inputs	x	X	K, I, M	ad hoc
• decrease dependence					
• segment production					
Production recapture	arrange long-term agreements; contingency plan and practice for supply-chain disruption		X	Q	loosen constraint on inputs ATC (1991); Rose (2007) ad hoc
• supply-chain clearinghouse					apply recapture factors
• restarting procedures					Rose (2007), Rose et al. (2011)

(Continues)



TABLE 3 (Continued)

Resilience category	Possible action prior to disruption	Inherent resilience	Adaptive resilience	Applicability to factors of production	CGE incorporation
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	x	X	k, L, PT, OT, m	change labour productivity Wein and Rose (2011)
Relocation • utilize branch plants • give way to competition	shift production to other regions	X	x	Q	Inherent geographic production shift: intrinsic in the TERM CGE model Park et al. (2007); Sue Wing et al. (2016)

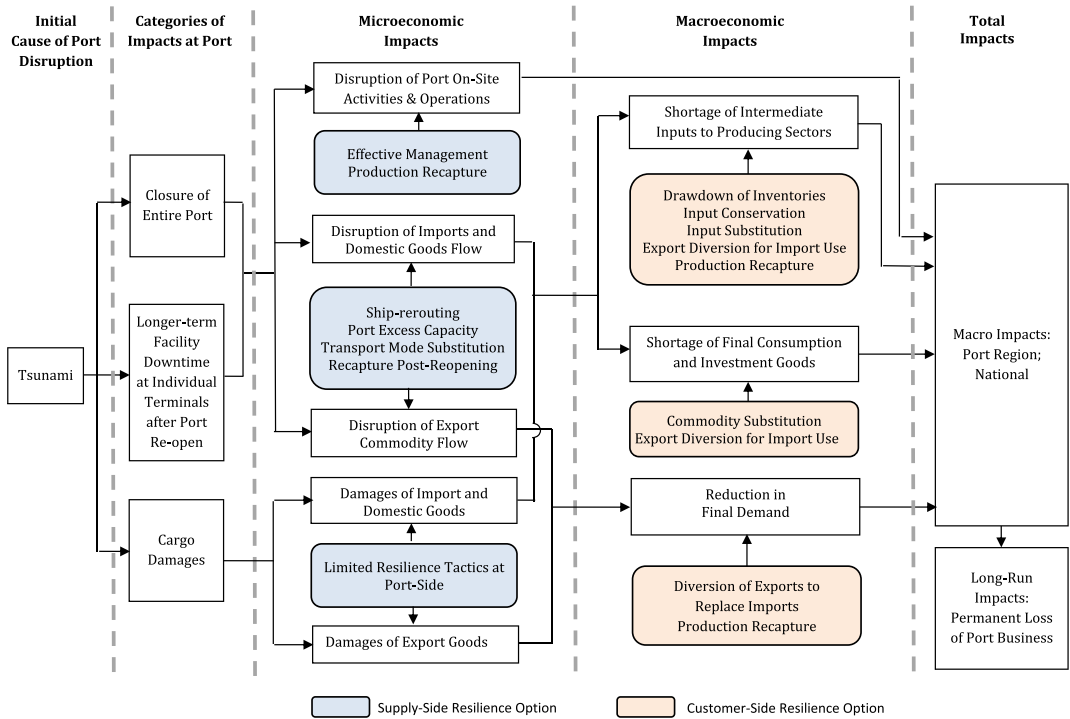


FIGURE 1 Analytical framework of estimating total economic impacts of a port disruption with implementation of resilience tactics

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.⁵ However, we simulate the second group one at a time.

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.

Figure 2 presents a conceptual overview of the analysis of the economic consequence and the effectiveness of the resilience tactics. Note that we invoke a short-cut in our calculations for the second set of resilience tactics (adaptive and inherent other than IIR). We first simulate each tactic in the second set separately in the CGE model. We then calculate the proportions of loss reduction from each of these comparative static analyses and apply these proportions to base case BI loss levels estimated from the I-O model. If we simulated the second set of resilience tactics within the CGE model directly (as represented by the dashed line in Figure 2), they would simply become a small residual. Also, if we applied each resilience tactic to the I-O simulation directly, we would overestimate the indirect effects because of the linearity of the model (I-O multipliers are larger than CGE multipliers because of this linearity and the absence of price adjustments, which typically run counter to (offset) quantity adjustments somewhat).

Not all resilience tactics will be available to all ports or their customers. Therefore, one of the main practical uses of our results is a ranking of resilience effectiveness that can help ports and their customers identify their best options subject to their own constraints.

⁵We 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 because the model will not solve (see Bodenstein, 2010; Rose & Guha, 2004). Also, to stifle the inter-regional relocation of economic activity would require running the model for each sub-region separately, which is difficult in an interregional model.

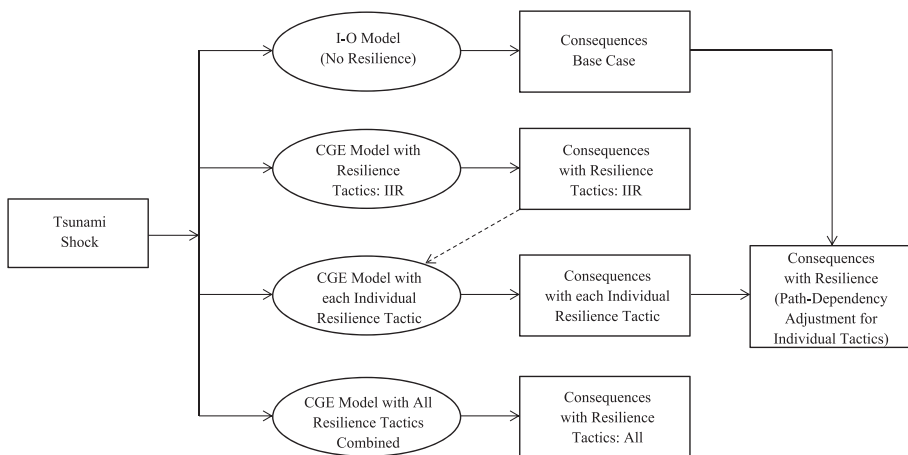


FIGURE 2 Economic consequence and resilience computational overview

5.2 | The TERM multi-regional CGE model

TERM is a “bottom-up” model that treats each region as a separate economy.⁶ 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). The TERM modelling framework was adapted to the US on the basis of regional I-O data for the Year 2010 (IMPLAN, 2012), supplemented by various elasticities gleaned from the literature.⁷ A key feature of TERM is its ability to handle a large number of regions and sectors. 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 model is static, which simulates the impacts of port disruptions on the economy on an annual basis.

The modelling 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 constant elasticity of substitution (CES) nesting structures. As illustrated Figure A1 in the Appendix, 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 labour—the latter being itself a CES composite of labour by skill type. The aggregate intermediate input is also a CES function of composite commodities, which are in turn CES composites of commodities from various sources. A representative household maximizes utility through purchases of optimal bundles of goods in accordance with its preferences and budget constraint.

The TERM database used for our study consists of four 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), the Rest of California, and the Rest of the US.⁸

⁶A “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 to regionalization, typically one of proportioning national values to regional levels on the basis of regional control totals, such as sectoral gross output, as a proportion of national totals (see e.g., Dixon, Rimmer, & Tsigas, 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.

⁷The 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, 1982) up through more recent work on the US multi-regional dynamic CGE model (USAGE) (Dixon et al., 2007).



TABLE 4 Modelling tactics for economic resilience in TERM-USA

	Simulation method	Description	Adjustment level or range for base case resilience
Conservation	Adaptive resilience is captured by adjusting import and export shocks in different regions	Adjust import and export shocks by 2% in all regions	Reduce base case import and export shocks by 0.001% to 4.585% across sectors, depending on import shares in production.
Inherent input substitution	N/A	Inherent input substitution is captured by the CGE model automatically.	N/A
Import substitution	N/A	Inherent import substitution is captured by the CGE model automatically by the Armington elasticity of substitution.	N/A
Ship rerouting	Adjust import and export shocks in different regions	Steering ships to other nearby ports	Reduce base case import and export shocks by 50% across sectors
Export diversion for domestic use	Adjust import and export shocks	Using goods that were intended for export as substitutions for the lack of availability of imports.	Reduce import and export disruptions between 0% and 100% across sectors (depending on availability of similar 10-digit HTS exported commodity that can be sequestered for import use)
Inventory use	Adjust import shock	Reducing the direct import disruption by the amount of inventory.	Reduce import disruptions between 0% and 100% across sectors (based on a comparison of BEA inventory data and Base Case import disruptions by sector)
Production recapture	Application of “recapture factor parameter” to output changes	A side-calculation to adjust total output losses for production rescheduling.	Recapture factors range from 0.255 to 0.490 across sectors, and decline over time.



With respect to the 11 criteria An et al. (2004) used to evaluate various regional economic impact models (as listed in Section 2), the only two criteria that the TERM model does not meet are: dynamic analysis and endogenous travel behaviour. 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 modelling parameterization (Chen & Haynes, 2017; Zhou & Chen, 2020). 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.

Modelling 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 4 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 modelling approach are presented in the next two columns.

The TERM-USA model is a static model that simulates the impacts of port disruptions on an annual basis. When we analyse the loss reduction potentials of inventories, we take into consideration the current stockpile level of inventories across various industries using the Bureau of Economic Analysis (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 of our results to these important parameters are presented below.

6 | SIMULATION SCENARIOS

6.1 | Southern California tsunami

The devastating 2004 Indian Ocean tsunami that caused over 200,000 fatalities and the 2011 tsunami that struck Japan's Tohoku Province dramatize the destructive force of this type of natural hazard. These events raised concerns about tsunamis in other coastal areas, including California. Recent scientific analyses have identified a subduction zone off the coast of California that could potentially cause a devastating event in the state (Borrero, Cho, Moore, Richardson, & Synolakis, 2005; Legg, Kohler, Shintaku, & Weeraratne, 2015).

In our analysis, the disaster scenario is adopted from Borrero et al. (2005), which analysed 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:⁹

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.

⁸A 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 four 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 the US.

⁹In 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) analysed 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) analysed the economic impacts and the role of resilience for two port shutdown scenarios at Port Arthur and Port Beaumont, 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 the Port of Kobe after the 1995 earthquake, where the port was completely shut down for about a month.



3. The recovery path of the ports' activities is assumed to be linear within the one-year period.¹⁰ Therefore, the direct disruption to trade flows (on both the 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 triangle"). Based on 2014 trade data, the total value of imports for 6-months for these ports is \$158.7 billion, and the total value of exports is \$38.6 billion.

6.2 | Overview of the analysis

Some resilience tactics are "naturally" incorporated in the TERM Model because they are intrinsic in a CGE model in general (input and import substitution) and in a multi-region CGE model (import substitution and relocation). The former category 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, elasticities of substitution across transportation modes and between capital and labour is 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 other regions. 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.

7 | SIMULATION RESULTS

7.1 | Base case (no resilience) results

The first rows in Tables 5 to 7 present the base case (no resilience) GDP impacts for import disruption, export disruption, and import and export disruptions combined, respectively, estimated by the application of the ordinary (linear) I-O analysis approach. 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 US as a whole are estimated to be \$534 billion (4.3%) and \$35 billion (0.3%), respectively. 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.

7.2 | Inherent resilience results

Row 2 in Tables 5 to 7 presents the results of the CGE analysis that takes into consideration three major types of intrinsic resilience tactics (IIR). For the LA metro region, the tsunami scenario would result in a \$7.5 billion loss in GDP, or slightly more than a 1% decline, for a combined disruption on imports and exports. Not surprisingly, the losses are larger for this region than for any other in both dollar and percentage terms and both before and after the

¹⁰The 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 linear ramp-up of recovery. It is possible that the port will have a complete shutdown, but only 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.

**TABLE 5** Real GDP impact of an import shock—base case and resilience cases (million 2010 \$ and percentage 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 6 Real GDP impact of an export shock—base case and resilience cases (million 2010 \$ and percentage 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)	-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 7** 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%



application of IIR resilience tactics. This is due to two reasons: (i) 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 (ii) 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 total GDP losses for the US as a whole is more than \$16 billion, though this is only slightly more than a one-tenth of 1% 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 5 to 7 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 reduces the potential GDP losses by 92.5% on both the import and export disruption sides for the LA metro region.¹¹ At the national level, the loss reduction potentials are 97.9% and 85.4% on the import and export sides, respectively.

7.3 | Additional inherent and adaptive resilience results

7.3.1 | 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 5 to 7. In this analysis, we assume that there would be no excess capacity at the ports 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 would 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 individual resilience cases and the base case (no resilience).

7.3.2 | 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 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 & Rice, 2014; Xing & Zhong, 2017). Given our limited data and limited real world experience at major ports,¹² 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 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).

¹¹Note that dockers cannot immediately take on jobs in many other sectors, so the model's assumption of labour mobility leads to an overestimate of resilience.

¹²This 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 & Baskin, 2017).



7.3.3 | 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 code level (which disaggregates imports and exports into over 1,000 types of commodities) to more accurately match the disrupted export commodities with import commodities. Export diversion is estimated to reduce the GDP loss from \$569 billion in the Base Case to \$463 billion (or a decrease of 18.7% of the GDP losses).¹³

7.3.4 | Conservation

We assume a 2% 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 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 the GDP losses.

7.3.5 | Inventory use

Our main source of inventory data is the Bureau of Economic Analysis (BEA) (2016). 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 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.

7.3.6 | Production recapture

The possibility of production or sales recapture diminishes over time since customers are likely to seek other suppliers. We adapt the recapture factors from HAZUS, the FEMA (2013) loss and risk assessment software for disasters. 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% for each three-month period within a year. This resilience tactic can reduce the total GDP loss from \$569 billion to \$383 billion, which represents a decrease of about 32.6% of the GDP losses.

7.3.7 | 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 and customer sides. Therefore, in this combined resilience simulation, we apply ship rerouting first, followed by export diversion. These two resilience

¹³Note one other possible inherent (intrinsic) substitution. If the price of a good on the domestic market increases due to the disruption, firms may change their domestic/export supply proportions. Note, however, that the overall numerical results for the inherent tactics are the same as have been presented, but there may be an inherent aspect related to export diversion to be considered in future decompositions, extending the acronym to IIRE.



tactics mainly pertain to the supplier, 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. The combined resilience tactics can reduce GDP losses from \$569 billion to \$2.8 billion, or a reduction of GDP losses by about 97.3% for California and 99.5% for the US as a whole. Interestingly, the impacts on the rest of US become slightly positive (a 0.02% increase) after incorporating these resilience adjustments. First, compared to the port region, inventories are more widely available throughout the country with respect to the amount of curtailed import commodities. The lack of imports also stimulates an increase in the production of domestic goods as substitutes.¹⁴ Second, with more imports diverted to the rest of the country, the positive economic impacts stemming from the increased importing activities there offset the negative spillover impacts caused by the shutdown of the ports in California.

7.3.8 | Comparison of the results

The GDP impacts of a one-year disruption at POLA/POLB are estimated to be \$569 billion (or 4.6% of the US annual GDP) if no resilience is taken into consideration. The three major types of inherent economic resilience (IIR) automatically captured by the TERM 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 analysed in this study, the total impacts on the US economy can be reduced to only \$2.8 billion (or 0.02% of the US annual GDP), representing 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 US indicates that the various resilience tactics (including use of inventories, ship rerouting, export diversion, and IIR) are more effective at the national level than at the port region level. This is because the inventory to import disruption ratio is much higher in the rest of the US than in the port region. Another major reason is the relatively stronger pull of general business relocation and supplying inputs for export demand from outside regions because they suffer lower direct impacts from the port disruption than does the port region itself.

7.4 | Sensitivity analysis

Sensitivity analyses on three sets of key model parameters or assumptions are performed to gauge their effects on the bottom-line simulation results. Table 8 presents a comparison of the GDP losses in the LA metro region between the base case CGE simulation (referred to as basic TERM case in Table 8) and the various sensitivity cases.

First, sensitivity analyses were performed by reducing the Armington and factor input elasticities to reflect more restrictive (shorter-run) conditions.¹⁵ The maximum reduction on the Armington elasticities we could achieve (and still obtain a solution to the TERM model) was 40%.¹⁶ To be consistent, we simulated both an increase and a decrease of both types of elasticities by 40% in our additional simulations. In the case of the reduction of Armington elasticities alone, GDP losses increased 3 times for the LA metro area (the region most affected by the port disruption). The simulation of a 40% reduction in factor input elasticities was less sensitive, with a 1.46 times increase in

¹⁴This result could also stem from changing prices, thus increasing the endowment of the rest of the US.

¹⁵The 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 (have lower numerical values) 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. Overall, the estimation of the elasticities in the TERM model is relatively weak in comparison to a CGE model whose elasticities were estimated from a consistent set of time series data, though we point out that very few such models exist.



TABLE 8 Real GDP impact of import and export disruptions on LA metro region for the basic TERM case and various sensitivity cases

	Basic TERM case	Armington elasticities		Factor input elasticities		Recovery period		Ship-rerouting reducing import/export disruption ^a	
		Reduced by 40%	Increased by 40%	Reduced by 40%	Increased by 40%	Reduced by 50%	Increased by 50%	by 25%	by 75%
GDP impacts (M 2010\$)	-7,473	-29,933	-912	-18,348	-3,132	-4,844	-14,912	-6,643	-4,567
GDP impacts (%)	-1.08%	-4.33%	-0.13%	-2.65%	-0.45%	-0.70%	-2.16%	-0.96%	-0.66%

^aNotes: The Base Case resilience analysis on ship-rerouting assumes that this resilience tactic could effectively reduce the import and export disruptions by 50%. Including this resilience adjustment in the basic TERM simulation yields GDP losses of \$3,875 million (or a 0.56% reduction) in the LA metro region. In the sensitivity analyses, we simulated a 50% increase or decrease of ship-rerouting in relation to the 50% level in the Base Case ship-rerouting value, i.e., 75% and 25% respectively.



GDP losses in the LA Metro Area. When the Armington elasticity and the factor input elasticity increase by 40% (in separate sensitivity simulations), the GDP losses are reduced by 87.8% and 58.1%, respectively. In general, the sensitivity analysis results indicate that the IIR results are very sensitive to the elasticity parameters in the model, with the Armington elasticities having a relatively larger impact on the GDP impacts than the factor input elasticities. Note, however, that the reduced or increased elasticities would have a much lower impact on the other resilience tactics because the latter are not related to or are farther removed from elasticity parameters. Second, a key assumption of the port disruption scenario is the time it takes for the seaports to fully recover to their pre-disaster operation level. The Base Case assumes that the full recovery takes one year, based on the upper-bound recovery scenario in Borrero et al. (2005). The recovery time-path can potentially be accelerated if, for example, the ports receive post-disaster assistance from the state or federal government. Therefore, we performed a sensitivity analysis to evaluate to what extent the economic impacts and the effectiveness of various resilience tactics change as the duration of the port's recovery is shortened to 6 months. The results indicate that the GDP losses were reduced by half to \$49.6 billion in the Base Case (no resilience) in the LA metro region, because of the linear nature of the I-O model. The effectiveness of most resilience tactics remains the same, with two exceptions. The effectiveness of inventories in terms of percentage of GDP loss reductions are increased in the 6-month disruption case because nearly all inventories are exhausted by six months. Also, the ability to recapture lost production does not degrade as much in our sensitivity case, since customers are less likely to abandon their suppliers over shorter periods of time—the weighted average recapture factor increases from 27.8% for a one-year disruption to 39.1% for a 6-month disruption. The loss reduction potential of all resilience tactics combined increases from 97.34% to 97.64%. The very small increase in the combined resilience potential stems from the fact that the effects of all the resilience tactics applied simultaneously are not additive because of their interactions and overlaps. For comprehensiveness, we also ran a sensitivity test to examine how the economic impacts and the effectiveness of various resilience tactics change if the full recovery of the ports takes 50% longer to achieve than in the base case. The GDP losses in the first year after the disaster event are increased to \$14.9 billion (nearly doubled) in the basic TERM case. An estimated additional \$3.3 billion in GDP losses is projected to occur in the second year after the disaster event. The effectiveness of resilience tactics, such as inventories and production recapture, further decreases because all inventories are exhausted by the end of the first year and because the weighted average recapture factor decreases from 27.8% for a one-year disruption to 22.7% for a 1.5-year disruption, as customers to increase their search for alternative suppliers.

The third set of sensitivity analyses pertains to the assumption on the ship rerouting potential. The base case resilience analysis assumed that this resilience tactic could effectively reduce the import and export disruptions by 50%. In the sensitivity simulations, we assumed that the disruptions can be reduced by 25% and 75%, respectively. The GDP losses were increased by 71% for the LA metro region in the former sensitivity case. Interestingly, the latter sensitivity case resulted in the seemingly counter-intuitive result of increasing GDP losses slightly over the base case. One possible explanation is that price declines were smaller in this case, thereby yielding lower offsetting effects to quantity disruptions.

8 | CONCLUSION

This paper has adapted and applied both an I-O model and a multi-regional CGE model to estimate the economic consequences of and resilience to port disruptions caused by 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 direct and indirect (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

¹⁶A CGE model may not reach a feasible solution in the presence of very low elasticity parameters because such elasticities reduce the convexity of the feasible set (e.g., very low elasticities reflect nearly kinked, or non-differentiable, isoquants). For further discussions of the issues related to the assumptions of CGE specifications and shocks, see Rose and Guha (2004) and Bodenstein (2010).



the immediate damage to ships or port facilities by evaluating economic ripple effects beyond the ports. 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 (the resilience tactics intrinsic to CGE models), which were often ignored or not separately 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. The modelling framework established in this study can also be applied to economic consequence and resilience analysis of many other disaster types, such as earthquakes, floods, terrorist attacks, etc.

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 \$569 billion GDP loss at the national level. After taking into consideration the major types of inherent economic resilience integrated in the TERM CGE model, total contraction of US GDP is reduced to only slightly over \$16 billion. Major inherent resilience tactics combined provide substantial (over 97%) loss reduction potentials. Other effective resilience tactics include ship rerouting on the supplier side and inventories and production recapture on the customer side, which individually can help reduce GDP losses by 50%, 54%, and 33%, respectively. In other words, our results indicate that the resilience tactics intrinsic to CGE models have the greatest loss reduction capability, while other resilience tactics that need to be incorporated in an ad hoc manner turn out to be less powerful. The total GDP impacts on the US could be reduced to about \$3 billion if all the resilience tactics analysed in this study are combined.

We suggest 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. Our analysis indicates that the potential effectiveness of some types of resilience tactics diminishes with time. For example, inventories are finite, and the potential for production recapture starts to evaporate as customers start cancelling their orders and seeking alternative suppliers as the duration of supply interruption increases. On the other hand, the effectiveness of other tactics such as ship re-routing increases over time. Therefore, the potential of resilience tactics that can be implemented to tackle short-term and longer-term port disruptions should be examined and assessed in ports and business continuity or recovery planning. Moreover, some of these resilience tactics have significant loss reduction potentials, but only require relatively small costs of implementation. For example, production recapture only requires overtime pay to employees. However, to effectively implement this resilience tactic, it is important to have flexible labour agreements beforehand and to use various incentive measures after the disaster events to encourage individuals to return to work sooner and make up for lost work through flexible working hours.

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.

We also note certain limitations of our analysis. For instance, since our CGE model, like most others, is calibrated around a base case, the simulation outcome may only depict informative results as long as the counterfactuals do not deviate too far from the base case. In addition, elasticities of substitution may vary across input combinations, so some of the modelling assumptions, such as the CES function characterization of factor input and trade substitution may not be realistic. Finally, our assessment only focuses on how markets respond to a shock. Hence, we did not examine the role of government disaster response. All these limitations deserve further investigation and improvement in future research.

Overall, we have incorporated the broadest range of resilience tactics and analysed their effectiveness in reducing business interruption losses from port disruptions of any study to date, and have isolated and decomposed their effectiveness in a macroeconomic framework within and across regions, and with regard to direct and indirect impacts. 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.

ACKNOWLEDGMENTS

This research was supported by the California Department of Transportation (Caltrans) through USC METRANS Transportation Center and by the DHS Critical Infrastructure Resilience Institute (CIRI). We are grateful for the helpful comments and suggestions from Lee Provost and Ted Knapp of Caltrans on the original report. We also benefited from the valuable research assistance of Joshua Banks and Noah Miller. We are also grateful to Glyn Wittwer and Terrie Walmsley for helping us with questions about the use of the TERM Model. We also wish to thank three anonymous reviewers for their detailed helpful comments. Of course, any remaining errors and omissions are solely those of the authors. Moreover, the views expressed in this article represent those of the authors and not necessarily those of any of the institutions with which they are affiliated nor the institutions that funded the research.

ORCID

Dan Wei  <https://orcid.org/0000-0003-0738-2286>

Zhenhua Chen  <https://orcid.org/0000-0003-0473-1508>

Adam Rose  <https://orcid.org/0000-0003-3347-7684>

REFERENCES

- An, D., Gordon, P., Moore, J., & Richardson, H. (2004). Regional economic models for performance-based earthquake engineering. *Natural Hazards Review*, 5(4), 188–194. [https://doi.org/10.1061/\(ASCE\)1527-6988\(2004\)5:4\(188\)](https://doi.org/10.1061/(ASCE)1527-6988(2004)5:4(188))
- Applied Technology Council (ATC). (1991). *Seismic vulnerability and impacts of disruptions of utility lifelines in the coterminous United States. Report ATC-25*. Redwood, CA: Applied Technology Council.
- Bodenstein, M. (2010). Trade elasticity of substitution and equilibrium dynamics. *Journal of Economic Theory*, 145(3), 1033–1059. <https://doi.org/10.1016/j.jet.2010.01.008>
- Boettke, P., Chamlee-Wright, E., Gordon, P., Ikeda, S., Leeson, P. T., & Sobel, R. (2007). The political, economic, and social aspects of Katrina. *Southern Economic Journal*, 74(2), 363–376.
- Borrero, J., Cho, S., Moore, J., Richardson, H., & Synolakis, C. (2005). Could it happen here? *Civil Engineering*, 75(4), 54–65.
- Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., ... Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance seismic resilience of communities. *Earthquake Spectra*, 19, 733–752. <https://doi.org/10.1193/1.1623497>
- Bureau of Economic Analysis. (2016). *2014 Real Inventories and Sales Data*. URL: <https://www.bea.gov/iTable/iTable.cfm?ReqID=12&step=1#reqid=12&step=1&isuri=1>
- Cho, S., Gordon, P., Moore, J. E., Richardson, H. W., Shinozuka, M., & Chang, S. E. (2001). Integrating transportation networks and regional economic models to estimate the costs of a large earthquake. *Journal of Regional Science*, 41(1), 39–56. <https://doi.org/10.1111/0022-4146.00206>
- Chang, S. (2000). Disasters and transport systems: Loss, recovery and competition at the Port of Kobe after the 1995 earthquake. *Journal of Transport Geography*, 8(1), 53–65. [https://doi.org/10.1016/S0966-6923\(99\)00023-X](https://doi.org/10.1016/S0966-6923(99)00023-X)
- Chang, S., & Shinozuka, M. (2004). Measuring improvements in the disaster resilience of communities. *Earthquake Spectra*, 20(3), 739–755. <https://doi.org/10.1193/1.1775796>
- Chen, Z., & Haynes, K. E. (2017). Measuring the impact of infrastructure systems using computable general equilibrium models. In R. Jackson & P. Schaeffer (Eds.), *Regional research frontiers* (Vol. 2). Advances in Spatial Science—The Regional Science Series. (pp. 79–103). Cham, Switzerland: Springer.
- Chernick, H. (2005). *Resilient city: The economic impact of 9/11*. New York: Russell Sage Foundation.
- Congressional Budget Office (CBO). (2006). *The Economic Costs of Disruptions in Container Shipments*. URL: http://www.cbo.gov/ftpdocs/71xx/doc7106/03-29-Container_Shipments.pdf
- Cutter, S. (2016). The landscape of disaster resilience indicators in the USA. *Natural Hazards*, 80(2), 741–758. <https://doi.org/10.1007/s11069-015-1993-2>
- Cutter, S. (2017). The changing context of hazard extremes: Events, impacts, and consequences. *Journal of Extreme Events*, 3(2), 1671005. <https://doi.org/10.1142/S2345737616710056>
- Dixon, P., Rimmer, M., & Tsigas, M. (2007). Regionalizing results from a detailed CGE model: Macro, industry and state effects in the US of removing major tariffs and quotas. *Papers in Regional Science*, 86(1), 31–55. <https://doi.org/10.1111/j.1435-5957.2006.00101.x>



- Dixon, P. (1982). *ORANI: A multisectoral model of the Australian economy*. Amsterdam: North-Holland.
- Dixon, P., Rimmer, M., & Wittwer, G. (2012). The Theory of TERM-H2O. In G. Wittwer (Ed.), *Economic modeling of water*. Amsterdam: Springer. https://doi.org/10.1007/978-94-007-2876-9_5
- Dormady, N., Rose, A., Rosoff, H., & Roa-Henriquez, A. (2018). Estimating the cost-effectiveness of resilience to disasters: Survey instrument design and refinement of primary data. In M. Ruth & S. G. Reiemann (Eds.), *Handbook on resilience of socio-technical systems* (pp. 227–246). Cheltenham: Edward Elgar.
- FEMA. (2013). HAZUS-MH2.1 Earthquake Model Technical Manual. URL: https://www.fema.gov/media-library-data/20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf
- Flynn, S. (2008). America the resilient: Defying terrorism and mitigating natural disasters. *Foreign Affairs*, 87(2), 2–8.
- Graveline, N., & Gremont, M. (2017). Measuring and understanding the microeconomic resilience of businesses to lifeline service interruptions due to natural disasters. *International Journal of Disaster Risk Reduction*, 24, 526–538. <https://doi.org/10.1016/j.ijdr.2017.05.012>
- Haddad, E., & Teixeira, E. (2015). Economic impacts of natural disasters in megacities: The case of 604 floods in Sao Paulo, Brazil. *Habitat International*, 45, 106–113. <https://doi.org/10.1016/j.habitatint.2014.06.023>
- Holling, C. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1–23. <https://doi.org/10.1146/annurev.es.04.110173.000245>
- Horridge, M. (2012). The TERM model and its database. In G. Wittwer (Ed.), *Economic Modelling of Water: The Australian CGE Experience* (pp. 13–35). Amsterdam: Springer. https://doi.org/10.1007/978-94-007-2876-9_2
- Horridge, M., Madden, J., & Whittwer, G. (2005). The impact of the 2002–2003 drought on Australia. *Journal of Policy Modeling*, 27, 285–308. <https://doi.org/10.1016/j.jpolmod.2005.01.008>
- IMPLAN Group LLC. (2013). *2012 Impact analysis for planning (IMPLAN) California state package I-O data*. Huntersville, NC: Minnesota IMPLAN Group Inc.
- Kajitani, Y., & Tatano, H. (2009). Estimation of lifeline resilience factors based on empirical surveys of Japanese industries. *Earthquake Spectra*, 25(4), 755–776. <https://doi.org/10.1193/1.3240354>
- Legg, M., Kohler, M., Shintaku, N., & Weeraratne, D. (2015). High-resolution mapping of two large-scale transpressional fault zones in the California Continental Borderland: Santa Cruz-Catalina Ridge and Ferrel faults. *Journal of Geophysical Research - Earth Surface*, 120(5), 915–942. <https://doi.org/10.1002/2014JF003322>
- Minnesota IMPLAN Group. (2012). *Impact analysis for planning (IMPLAN) system*. Stillwater, MN: Minnesota IMPLAN Group Inc.
- Okuyama, Y. (2007). Economic modeling for disaster impact analysis: Past, present, and future. *Economic Systems Research*, 19(2), 115–124. <https://doi.org/10.1080/09535310701328435>
- Oosterhaven, J., & Bouwmeester, M. (2016). A new approach to modelling the impact of disruptive events. *Journal of Regional Science*, 56(4), 583–595. <https://doi.org/10.1111/jors.12262>
- Page, P., & Baskin, B. (2017) Freight companies scramble to reroute goods in wake of Harvey. *The Wall Street Journal*. 28 August 2017. URL: <https://www.wsj.com/articles/freight-companies-scramble-to-reroute-goods-in-wake-of-harvey-1503943228>
- Park, J., Gordon, P., Moore, J., & Richardson, H. (2008). The state-by-state economic impacts of the 2002 shutdown of the Los Angeles–Long Beach ports. *Growth and Change*, 39(4), 548–572. <https://doi.org/10.1111/j.1468-2257.2008.00446.x>
- Park, J., Gordon, P., Moore, J., Richardson, H., & Wang, L. (2007). Simulating the state-by-state effects of terrorist attacks on three major U.S. ports: Applying NIEMO (national interstate economic model). In H. W. Richardson, P. Gordon, & J. E. Moore (Eds.), *The economic costs and consequences of terrorism* (pp. 208–234). Cheltenham: Edward Elgar. <https://doi.org/10.4337/9781847205506.00020>
- Pimm, S. (1984). The complexity and stability of ecosystems. *Nature*, 307, 321–326. <https://doi.org/10.1038/307321a0>
- Prager, F., Chen, Z., & Rose, A. (2018). Estimating and comparing economic consequences of multiple threats: A reduced-form computable general equilibrium approach. *International Journal of Disaster Risk Reduction*, 31, 51–67.
- Resurreccion, J., & Santos, J. (2012). Multiobjective prioritization methodology and decision support system for evaluating inventory enhancement strategies for disrupted interdependent sectors. *Risk Analysis*, 32(10), 1673–1692. <https://doi.org/10.1111/j.1539-6924.2011.01779.x>
- Rose, A. (1984). Technological change and input-output analysis: An appraisal. *Socio-Economic Planning Sciences*, 18(5), 305–318. [https://doi.org/10.1016/0038-0121\(84\)90039-9](https://doi.org/10.1016/0038-0121(84)90039-9)
- Rose, A. (2004). Defining and measuring economic resilience to disasters. *Disaster Prevention and Management*, 13(4), 307–314.
- Rose, A. (2007). Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions. *Environmental Hazards: Human and Social Dimensions*, 7(4), 383–398. <https://doi.org/10.1016/j.envhaz.2007.10.001>
- Rose, A. (2009). *Economic resilience to disasters, community and regional resilience*. Institute Report No. 8. Oak Ridge, TN: Oak Ridge National Laboratory.

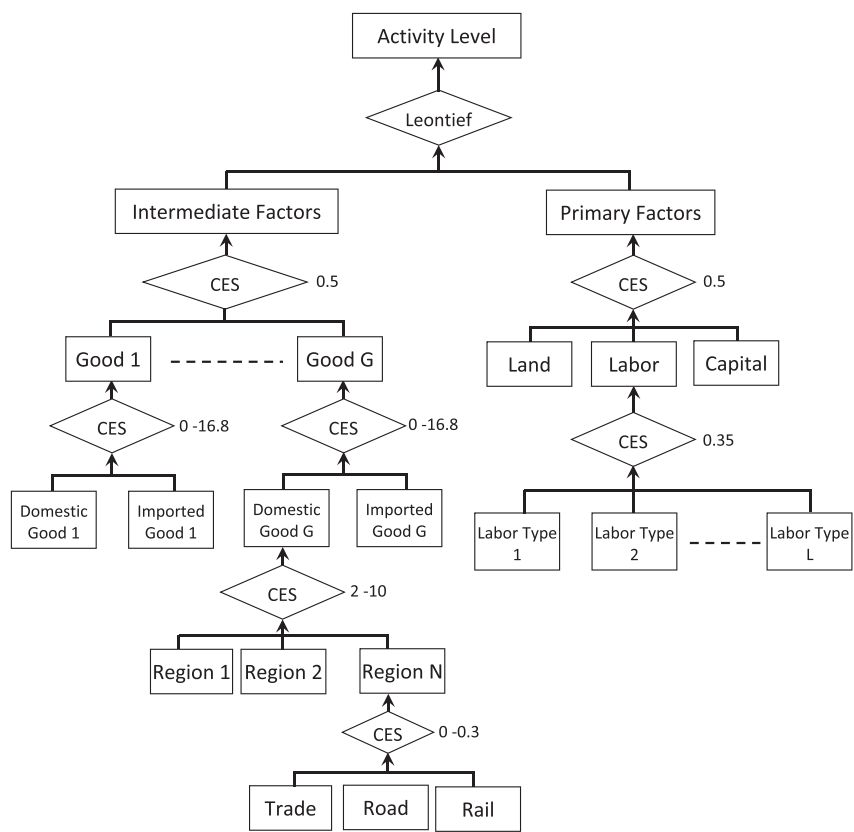


- Rose, A. (2017). Benefit-cost analysis of economic resilience actions. In S. Cutter (Ed.), *Oxford research encyclopedia of natural hazard science*. Oxford: Oxford University Press. <https://doi.org/10.1093/acrefore/9780199389407.013.69>
- Rose, A., Benavides, J., Chang, S. E., Szczesniak, P., & Lim, D. (1997). The Regional Economic Impact of an Earthquake: Direct and Indirect Effects of Electricity Lifeline Disruptions. *Journal of Regional Science*, 37(3), 437–458.
- Rose, A., & Guha, G. S. (2004). Computable general equilibrium modeling of electric utility lifeline losses from earthquakes. In Y. Okuyama & S. E. Chang (Eds.), *Modeling spatial and economic impacts of disasters* (pp. 119–141). New York: Springer. https://doi.org/10.1007/978-3-540-24787-6_7
- Rose, A., & Liao, S. (2005). Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruption. *Journal of Regional Science*, 45(1), 75–112. <https://doi.org/10.1111/j.0022-4146.2005.00365.x>
- Rose, A., Oladosu, G., Lee, B., & Beeler-Asay, G. (2009). The economic impacts of the 2001 terrorist attacks on the World Trade Center: A computable general equilibrium analysis. *Peace Economics, Peace Science and Public Policy*, 15, 6 (2), 1–28.
- Rose, A., Prager, F., Chen, Z., Chatterjee, S., Wei, D., Heatwole, N., & Warren, E. (2017). *Economic consequence analysis of disasters: The E-Cat software tool*. Singapore: Springer. <https://doi.org/10.1007/978-981-10-2567-9>
- Rose, A., Sue Wing, I., Wei, D., & Wein, A. (2016). Economic impacts of a California tsunami. *Natural Hazards Review*, 17 (2), 1–12.
- Rose, A., & Wei, D. (2013). Estimating the economic consequences of a port shutdown: The special role of resilience. *Economic Systems Research*, 25(2), 212–232. <https://doi.org/10.1080/09535314.2012.731379>
- Rose, A., Wei, D., & Paul, D. (2018). Economic consequences of a disruption of oil imports: The role of seaports in U.S. energy security. *Energy Policy*, 115, 584–615. <https://doi.org/10.1016/j.enpol.2017.12.052>
- Rose, A., Wei, D., & Wein, A. (2011). Economic impacts of the ShakeOut scenario. *Earthquake Spectra*, 27(2), 539–557. <https://doi.org/10.1193/1.3587204>
- Rosoff, H., & von Winterfeldt, D. (2007). A risk and economic analysis of dirty bomb attacks on the ports of Los Angeles and Long Beach. *Risk Analysis*, 27(3), 533–546. <https://doi.org/10.1111/j.1539-6924.2007.00908.x>
- Strunsky, S. (2013). Port authority puts Sandy damage at \$2.2 billion, authorizes \$50 million to power wash PATH tunnels. URL: https://www.nj.com/news/2013/10/port_authority_sandy_22billion_outlines_recovery_measures.html
- Sue Wing, I., Rose, A., & Wein, A. (2016). Economic consequence analysis of the ArkStorm scenario. *Natural Hazards Review*, 17(4), A4015002.
- Tierney, K. (1997). Business impacts of the Northridge earthquake. *Journal of Contingencies & Crisis Management*, 5(2), 87–97. <https://doi.org/10.1111/1468-5973.00040>
- Tierney, K. (2007). In H. Rodríguez E. Quarantelli & R. Dynes (Eds.), *Businesses and disasters: Vulnerability, impacts, and recovery*. *Handbook of disasters* (pp. 275–296). Heidelberg: Springer.
- Tobben, J. (2017). Effects of energy- and climate policy in Germany: A multiregional analysis. Ph. D thesis, University of Groningen, SOM Research School, The Netherlands
- Trepte, K., & Rice, J. (2014). An initial exploration of port capacity bottlenecks in the USA port system and the implications on resilience. *International Journal of Shipping and Transport Logistics*, 6(3), 339–355. <https://doi.org/10.1504/IJSTL.2014.060800>
- Wei, D., Chen, Z., & Rose, A. (2016). *Economic impacts of two port disruption scenarios (Report to Caltrans)*. Los Angeles, CA: METTRANS Center, University of Southern California.
- Wein, A., & Rose, A. (2011). Economic resilience lessons from the ShakeOut earthquake scenario. *Earthquake Spectra*, 27(2), 559–573. <https://doi.org/10.1193/1.3582849>
- Wittwer, G. (2012). *Economic modeling of water: The Australian CGE experience*. Heidelberg: Springer. <https://doi.org/10.1007/978-94-007-2876-9>
- Wittwer, G., & Griffith, M. (2012). The economic consequences of a prolonged drought in the Southern Murray-Darling Basin. In G. Wittwer (Ed.), *Economic Modelling of Water* (pp. 119–141). Heidelberg: Springer.
- Xie, W., Li, N., Wu, J., & Hao, X. (2014). Modeling the economic costs of disasters and recovery: Analysis using a dynamic computable general equilibrium model. *Natural Hazards and Earth System Sciences*, 14, 757–772. <https://doi.org/10.5194/nhess-14-757-2014>
- Xie, W., Rose, A., Li, S., He, J., Li, N., & Ali, T. (2018). Dynamic economic resilience and economic recovery from disasters: A quantitative assessment. *Risk Analysis*, 38(6), 1306–1318. <https://doi.org/10.1111/risa.12948>
- Xing, J., & Zhong, M. (2017). A reactive container rerouting model for container flow recovery in a hub-and-spoke liner shipping network. *Maritime Policy & Management*, 44(6), 744–760. <https://doi.org/10.1080/03088839.2017.1319580>
- Zhou, L., & Chen, Z. (2020). Are CGE Models Reliable for Disaster Impact Analyses? *Economic Systems Research*, 1780566-1–1780566-27. <https://doi.org/10.1080/09535314.2020.1780566>



How to cite this article: Wei D, Chen Z, Rose A. Evaluating the role of resilience in reducing economic losses from disasters: A multi-regional analysis of a seaport disruption. *Pap Reg Sci.* 2020;1–32. <https://doi.org/10.1111/pirs.12553>

APPENDIX:



Note: the ranges of elasticity parameters for various sectors are shown as the numbers beside the diamond-shape boxes that represent CES function nests.

Source: Authors' adaptation of Horridge (2012).