STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

1. REPORT NUMBER

CA-16-2934

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE

Development of an Economic Framework to Evaluate Resilience in Recovering from Major Port Disruptions

5. REPORT DATE

September 1, 2016

6. PERFORMING ORGANIZATION CODE

7. AUTHOR

Dr. Dan Wei, Zhenhua Chen and Adam Rose

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

University of Southern California
3500 S. Figueroa St. Suite 102,
Los Angeles, CA. 90089-8001

10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER

65A0533 TO 014

12. SPONSORING AGENCY AND ADDRESS

California Department of Transportation (Caltrans)
Division of Procurements and Contracts
1737 30th St. MS#65
Sacramento, CA. 95816

13. TYPE OF REPORT AND PERIOD COVERED

Final Report
August 15, 2015 to September 1, 2016.

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Ports play a critical role in a nation's economic system. The impact of a major port disruption can reverberate across the entire economy through regional and national supply-chains. This study develops an operational framework to evaluate the effectiveness of a comprehensive list of potential resilience tactics that can help ports and related businesses in the supply-chain recover more rapidly from port disruptions. The TERM multi-regional computable general equilibrium (CGE) model, is adapted to quantify the relative contributions of various resilience tactics in reducing potential economic impacts of major port disruptions. Various types of resilience tactics on both the supplier-side and customer-side are formally integrated in the CGE modeling. Two port disruption scenarios caused by natural disasters that affect major seaports in California, representing lower-bound and upper-bound port disruption cases, are analyzed using the CGE model. The modeling results indicate that the lower-bound scenario could result in a GDP loss of $650.1 million and an employment loss of 7 thousand jobs. The combined effects of various relevant resilience tactics have the potential to reduce the economic losses by about 97%. The upper-bound scenario could cause total GDP losses of over $12 billion in California and $16 billion at the national level. However, resilience can reduce these impacts by about 75% for California and about 89% for the nation as a whole. Major resilience tactics on the supplier-side are ship re-routing and export diversion for import use. Major resilience tactics on the customer-side are use of inventories and production recapture. The port resilience analytical framework developed in this study is readily generalizable to port disruptions from other causes and at other geographical scales.

17. KEY WORDS

Port Disruption, Resilience, Economic Consequence Analysis, TERM Multi-Region CGE Model

18. DISTRIBUTION STATEMENT

UTC Contract with USC

19. SECURITY CLASSIFICATION *(of this report)*

20. NUMBER OF PAGES

104

21. COST OF REPORT CHARGED

DISCLAIMER STATEMENT

Development and Application of an Economic Framework to Evaluate Resilience in Recovering from Major Port Disruptions

by

Dan Wei, Zhenhua Chen, and Adam Rose

with

Josh Banks and Noah Miller

Final Report to the California Department of Transportation

September 8, 2016

Abstract

Ports play a critical role in a nation's economic system. The impact of a major port disruption can reverberate across the entire economy through regional and national supply-chains. This study develops an operational framework to evaluate the effectiveness of a comprehensive list of potential resilience tactics that can help ports and related businesses in the supply-chain recover more rapidly from port disruptions. The TERM multi-regional computable general equilibrium (CGE) model, is adapted to quantify the relative contributions of various resilience tactics in reducing potential economic impacts of major port disruptions. Various types of resilience tactics on both the supplier-side and customer-side are formally integrated in the CGE modeling. Two port disruption scenarios caused by natural disasters that affect major seaports in California, representing lower-bound and upper-bound port disruption cases, are analyzed using the CGE model. The modeling results indicate that the lower-bound scenario could result in a GDP loss of $650.1 million and an employment loss of 7 thousand jobs. The combined effects of various relevant resilience tactics have the potential to reduce the economic losses by about 97%. The upper-bound scenario could cause total GDP losses of over $12 billion in California and $16 billion at the national level. However, resilience can reduce these impacts by about 75% for California and about 89% for the nation as a whole. Major resilience tactics on the supplier-side are ship re-routing and export diversion for import use. Major resilience tactics on the customer-side are use of inventories and production recapture. The port resilience analytical framework developed in this study is readily generalizable to port disruptions from other causes and at other geographical scales.

Table of Contents

Development and Application of an Economic Framework to Evaluate Resilience in Recovering from Major Port Disruptions

1. Introduction

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. Because it serves as a critical element of the nation's supply-chain, a disruption of a major port can reverberate throughout the entire economy. Imported inputs for intermediate and final consumption cannot be delivered, thereby causing production interruptions down the supply chain and reductions in economic well-being of the end-users. Also exports for other markets are blocked, thus causing an ensuing disruption of production up the supply chain as domestic producers cancel their orders for inputs. An increasing number of port disruptions have taken place in recent years, caused by such phenomena as natural disasters, technological accidents, and labor disputes. Moreover, ports are a prime target for terrorist attacks, which can be fine-tuned to yield the maximum disruption at the port site and beyond.

Many studies have estimated the direct and indirect impacts of port disruptions and found them to be quite significant (Chang, 2000; CBO, 2006; Park et al., 2007, 2008; Park, 2008; Jung et al., 2009). However, very few studies have adequately factored in all the possible forms of resilience that could mute these losses by using remaining resources more efficiently or by recovering more rapidly (see, e.g., Bruneau et al., 2003; Rose, 2009; Rose and Wei, 2013; Rose et al., 2016). In the event of a port disruption, port authorities and operators can implement various measures to speed up the resumption of the activities and reduce ship congestion by utilizing excess capacities of undamaged terminals or re-routing ships to other ports. On the customer-side, businesses that are affected by import or export disruptions, would not stand by passively waiting for port re-openings, but would instead initiate a broad range of coping activities, such as use of stockpiles, conservation, input substitution, diversion of exports for import use, and production rescheduling (recapturing lost production by working overtime or extra shifts after the port is opened). These actions are taken not only by importers and exporters, but by others that are indirectly affected by the port disruptions throughout the economy-wide supply chain.

In this study, we develop an operational framework to evaluate the effectiveness of a comprehensive list of potential resilience tactics that can help ports and related businesses in the supply-chain recover more rapidly from port disruptions. A multi-regional computable general equilibrium (CGE) model is adopted and applied to quantify the relative contributions of various resilience tactics in reducing potential economic impacts of major port disruptions. Two port disruption scenarios caused by natural disasters, each representing a lower-bound and an upper-bound port disruption scenario, respectively, are analyzed as case studies using the CGE model. The port resilience analytical framework developed in this study is readily generalizable to port disruptions of other causes and geographical scales.

The report is divided into seven sections. After the Introduction section, we first provide a summary of the literature on port resilience, focusing on how resilience is defined for port economies, the type of resilience tactics that have been discussed in the literature, and the cost-effectiveness of these resilience options. In Section 3, we first provide some basic considerations of economic resilience. We then discuss economic resilience tactics that are applicable to port disruptions. In this section, we also develop the analytical framework to identify and evaluate the resilience tactics on both the supplier-side and the customer-side relating to port disruptions. The approaches to formally incorporate the various port resilience tactics into CGE models are also discussed. In Section 4, we introduce the mutli-regional CGE model and how it was applied to analyze the various types of resilience tactics. In Section 5, we apply our resilience analytical framework and the CGE modeling approach to two port disruption case studies. Economic impacts with and without the consideration of the various resilience tactics are analyzed and evaluated. Policy recommendations to enhance economic resilience to port disruptions are discussed in Section 6. Section 7 provides a conclusion of the study.

2. Literature Review

A literature review was conducted to evaluate resilience strategies for port disruptions (either caused by natural or manmade incidents) that have been assessed and analyzed in previous studies. About a dozen journal articles and research reports were examined that focused on a range of topics relating to port resilience, such as past efforts to recover from natural disasters and labor disputes, future actions to enhance port resiliency, and quantitative assessments of how resilience can help reduce economic loss of port disruptions. We summarize key research focuses and findings of the relevant studies in Appendix Table A. Table 1 first presents the key categories of information we summarized from each of the studies reviewed, which include method of analysis, incident of focus, types of resilience strategies, effectiveness and applicability of resilience measures, as well as major research findings.

In conducting the literature review, a comprehensive search was performed using online search engines, including the University of Southern California library database and Google Scholar.

2.1. Categorization

Most of the articles focused on natural disasters (e.g., hurricanes) as opposed to manmade disruptions (e.g., terrorist or labor disputes). Some studies focus on single major disruptive events (such as Hurricane Sandy), while some other studies looked at port disruption or delay incidents at different magnitudes over a certain historical period of time. Most studies evaluated real world port disruption events, while a few others based the assessment on simulated port disruption scenarios.

Table 1. Categories of Information Summarized from the Literature Review

Category	Description
Author(s) or Organization	Names of authors or organizations; year of publication
Title	Title of the study
Type of Publication	Journal articles, research report, or government report
Method of Analysis	Methods used in the study, e.g., survey/interview, analysis of primary data or secondary data, case study, economic model used (if any)
Incident of Focus	Type of event or cause of disruption (natural disaster, labor dispute, terrorist attack, technical accident); Extent of the affected geographical area; Extent of port disruption; Length of recovery period
Type of Resilience Measures Analyzed	Definition of resilience; Categories of resilience: Supplier-side vs customer-side resilience; Inherent vs adaptive resilience; Static vs dynamic
Effectiveness and Applicability of Resilience Measures	Whether the study qualitatively or quantitatively evaluated the loss reduction potential or cost-effectiveness of resilience measures; Whether the resilience measures can be implemented in multiple types of incidents or only specific ones
Major Research Findings and Policy Implications	Major findings, implications of port resilience to economic competitiveness of ports

Different analytical methods were adopted in the studies we reviewed. Survey and interview is a widely used approach. In evaluating port strategies and actions in response to the disruptive events, many studies employed interviews with terminal operators, port authorities, shippers, carriers, and others who were involved in port operation environment. A few studies made use of different frameworks to analyze the functioning of the port infrastructure systems in order to identify vulnerabilities and potential areas for improvements. Other studies performed simulations to measure disruptions of varying degrees to identify areas of importance for resilience.

2.2. General Insights

While the concept of resiliency, especially in the context of supply chains, is a much studied topic, there has not been much emphasis placed on the resilience of ports or specific measures that can be taken. Studies that do cover this topic typically analyzed ports following an actual disaster and evaluated current practices as well as recommend additional strategies to enhance port resilience for future disruptions. The literature typically recognized the importance of communication, improved technology, increased coordination with land-based points of transfer surrounding the port, and the reliability of labor in improving the resilience of ports.

Other key resilience measures mentioned in the literature include increasing the number of backup generators, additional fuel storage for the backup generators, and investment towards alternative power sources. Increasing the capacity of terminals either through removing chokepoints, coordinating with landside operators to clear cargo, and increasing the amount of equipment also help improve port resilience. When combined with cooperation between ports via ship-rerouting, cargo can be diverted to non-affected ports to accelerate the recovery process. Additionally, arrangement for emergency workers and on-site housing can assist in recovery. Finally, the literature mentioned a number of different actions to enhance the management of ports during a disruption, such as increased training, regularly planned exercises, alternatives for communication, and plans with relevant stakeholders both within and outside the port.

The literature also mentioned that a number of different resilience tactics could lead to increased port competitiveness. For instance, Trepte and Rice (2014) studied the capacity of ports and found that an increased capacity for the entire United States port system is needed to absorb any extra cargo following a possible disruption. The authors suggested that investment in this would aid in both resilience and increased throughput of commodities for all ports. This would contribute to the enhancement of competitiveness of the U.S. seaports and the U.S. economy in the global trade environment. Paixao and Marlow (2003) discussed the concept of just-in-time management in the context of ports, as well as the implementation process and potential benefits. Kai, Shayn, and Ghoth (2002) also discussed port capacity by modeling a number of different port operations and simulating performance following different port actions. The authors found that container carriers tend to lead to significant congestion at the ports, but could be alleviated through the use of inland distribution centers and points of transfer. Benefits from this approach include decreased storage needs, less strain on the environment, and reduced time at berth for ships.

Below we summarize several of the key studies in the port resilience literature. See Appendix A for a detailed presentation of the major findings from all the reviewed studies.

Smythe (2013) assessed the impacts of Hurricane Sandy on the Ports of New York and New Jersey through interviews with respondents to the disruption. Both successful practices and areas for improvement were identified and discussed in detail. The author identified that cooperation between the public and private sectors, as well as the need for an increase in fuel reserves and personnel management, were greatly facilitated thanks to the formal port governance system. However, the loss of electricity, while temporarily handled by generators, led to a series of negative consequences, such as a loss of communication, security concerns, and the shutting down of oil terminals. The loss of petroleum product then exacerbated the situation not only in the port area, but also its surrounding communities. The author also highlighted the problems that arose from personnel that were evacuated from the area and those that did not have transportation to the port.

Rice and Trepte (2012) also surveyed a number of port practitioners regarding different types of disruptions they experienced, as well as which processes and improvements would most lead to increased resiliency. The report found that while ports are generally successful in handling and quickly recovering from small, frequent disruptions (which are most common), most ports are much less resilient to large, extended disruptions. While the survey also found that there is no absolute consensus among port stakeholders on which actions are most important towards resiliency of the port system, flexible labor agreements and improved communication and information services were the most desired measures based on the survey respondents' experience in small scale port delays or disruptions.

Southworth et al. (2014) conducted case studies of the Ports of New York and New Jersey following Hurricane Sandy in addition to the closing of marine ports along the Columbia River in the Pacific Northwest due to the river system rehabilitation project. Following interviews with a number of experts involved with these events, the authors found that a successful communication and an uninterrupted flow of information are considered as the most important factors in returning to a normal level of operation. The authors also highlighted several other actions that would assist in recovery including coordination with landside operators to divert cargo following a disaster, prioritizing incoming vessels by importance of assisting with recovery, and arranging on-site housing for critical staff, emergency responders, and relief workers.

Paixan and Marlow (2003) examined the concept of just-in-time inventory management and its implementation within ports. By incorporating this method of management, ports would take on the role of a distributor rather than a warehouse due to the focus on production meeting demand. The benefits of acting as a distributor include quicker turnaround and greater efficiency, referred to as "leanness" and "agility" by the authors, which would lend towards the resilience of ports in light of disruptions. Furthermore, the authors estimated that ports which implement this philosophy could see total port costs reduce by 10% to 40%.

Other studies still, focused on the development of disruption scenarios to identify insights. Trepte and Rice (2014) analyzed the entire port system within the United States in order to estimate the capacity of the system to absorb the cargo from a disrupted port. This was done by identifying the commodity types and total volume that major ports take in as a baseline and then measuring how much capacity is needed to absorb surrounding ports' good by commodity type. The report emphasized the need for ports to cooperate with others which would assist not only the recovery of disrupted ports, but surrounding ports which would see a sudden increase in demand.

Rose and Wei (2013) estimated the effects of a wide range of resilience tactics on the economic consequences stemming from a port shutdown. This was analyzed by using input-output models to simulate the impacts of a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas. The resilience tactics that are integrated into the input-output modeling include ship re-routing, export diversion, conservation, use of inventories, and production recapture. The authors found that when resilience is taken into account, the initial total economic loss of $13 billion can be reduced by over two-thirds. Additionally, production recapture and ship re-routing were found to be the most effective resilience tactics.

3. Economic Resilience to Port Disruptions

3.1. Basic Considerations of Economic Resilience

In the past few years, many analyses of the impacts of a catastrophe in the U.S. have highlighted the “resilience” of the economy (see, e.g., Chernick, 2005; Boettke et al., 2007; Flynn, 2008; Rose et al., 2009; Rose, 2016). Resilience is often used to explain why regional or national economies do not decline as much as expected after disasters, or why they recover more quickly than predicted. However, the concept of resilience is often poorly specified, or is defined so broadly that it could apply to any and all measures undertaken to reduce disaster losses. Most analysts use resilience in a common sense and non-rigorous fashion, and many discussions make no reference to the various research traditions that inform current resilience thinking (Rose, 2007).

The economics literature discusses resilience in four ways. Most generally, it is framed as an attribute of the economy in studies of economic shocks. In ecological economics, resilience is a major focus of analysis as a key attribute necessary for sustainability. Some attempts have been made to extend this research to the socioeconomic arena and to have the concept overlap with the study of institutions. In the disaster literature, resilience has been inserted as a new factor in the risk equation:

Risk = f (Threat, Vulnerability, Consequences, Resilience)

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; 2007). In Bruneau et al. (2003), economic resilience is one of four major dimensions of the broader concept of resilience. This definition includes pre-event hazard mitigation efforts such as hazard-resistant design and construction as a subset of resilience, as these measures contribute to the “robustness” or “resistance” of systems in the face of disasters. Various disciplines and definitions seem to be evenly split between those that define resilience broadly, to include attributes that contribute to pre-event disaster resistance, and those who prefer to reserve the terms for actions undertaken after a disaster begins that are intended to reduce losses. In this study, we exclude pre-event actions (which fall into the broad category of mitigation), though we do include pre-event actions that enhance resilience capacities that are implemented after the event (e.g., building up inventories, lining up back-up suppliers). The focus, however, is primarily on post-event resilience activities.

Economic resilience can be categorized into two broad types.

Static economic resilience is the ability or capacity of an entity or system to maintain functionality (e.g., continue producing) when shocked (Rose, 2004; 2007). It is thus aligned with the fundamental economic problem -- efficient allocation of scarce resources, which is exacerbated in the context of disasters. Static economic resilience is primarily a demand-side phenomenon involving users of inputs (customers) rather than producers (suppliers). It pertains to ways to use the resources still available as effectively as possible.

In contrast, *dynamic economic resilience* refers to the ability to hasten the speed at which an entity or system recovers ("bounces back") from a severe shock to achieve a desired state. This version of resilience involves a long-term investment problem associated with repair and reconstruction processes, and is primarily a decision by port operators. In this study, we will focus our analysis on static resilience and the decisions of port customers.

In contrast to property damage, which is a "stock" concept measured at a given point, business interruption (BI) refers to the "flow" of goods and services emanating from the stock and is usually measured in terms of loss of gross domestic product (GDP). It begins at the point of the disruption and continues until the port has recovered. Economic resilience is essentially a way of reducing BI and is measured in terms of GDP as well.

Economic resilience can be analyzed at three levels:

- Microeconomic (individual business, household, or government)
- Mesoeconomic (individual industry or market)
- Macroeconomic (combination of all economic entities, including their interactions)

At the microeconomic level, on the business supplier side, static economic resilience includes redundant systems, improved delivery logistics, and planning exercises. Several options also exist on the business customer side. Broadening the supply chain (see, e.g., Sheffi, 2005) by expanding the range of suppliers in place or on a contingency basis is an increasingly popular option. Other resilience tactics include conservation, input and import substitution, use of inventories and excess capacity, cross-training workers, relocation, and production recapture (working overtime and extra shifts when functionality is restored to make up lost production). At the mesoeconomic level, resilience can bolster an industry or market and include, for instance, industry pooling of resources and information and innovative pricing mechanisms. What is often less appreciated is the inherent resilience of market prices that act as the "invisible hand" to guide resources to their best allocation in the aftermath of a disaster (see, e.g., Horwich, 1995). At the macroeconomic level, resilience is very much influenced by interdependencies between sectors. Consequently, macroeconomic resilience is not only a function of resilience measures implemented by single businesses but is also determined by the actions taken by all individual companies and markets, including their interaction.

A basic operational measure of static economic resilience is the extent to which the reduction in BI deviates from the likely maximum potential reduction given an external shock. The notational form for evaluating the static economic resilience as suggested by Rose (2004; 2009b) can be expressed as:

$$SER = \frac{\%\Delta Y^m - \%\Delta Y}{\%\Delta Y^m}$$

where

SER represents Static Economic Resilience

$\%\Delta Y^m$ is the maximum percent change in economic output

$\%\Delta Y$ is the actual percent change in economic output

In essence *SER* is the percentage avoided of the maximum economic disruption that a particular shock could bring about. A major measurement issue involves what should be used as the maximum potential disruption. For ordinary disasters, a good starting point is a linear, or proportional, relationship between an input supply shortage and the direct disruption to the firm or industry. Note that while a linear reference point may appear to be arbitrary or a default choice, it does have an underlying rationale. A linear relationship connotes rigidity, the opposite of the "flexibility" connotation of static resilience defined in this report. In contrast, resilience represents the introduction of non-linearities. An analogous definition pertains to resilience taking into account indirect or macroeconomic effects.

3.2. Economic Resilience Tactics Applied to Port Disruption

Port resilience is a special case of economic resilience. In the event of a port disruption, the port authorities and operators can implement various measures to speed up the resumption of the port activities and reduce ship traffic congestion by utilizing excess capacities of undamaged terminals or re-routing ships to other ports. On the customer-side, businesses that are affected by the import or export disruptions, would initiate a broad range of coping activities. These actions are taken not only by importers and exporters, but by others that are indirectly affected by the port disruptions throughout the economy-wide supply chain.

<u>Supplier-side resilience options</u>:

1. *Excess capacity*. This pertains to the utilization of unused capacity at undamaged terminals of the port to pick up the load of cargos that were originally handled in other terminals that experience facility downtime in the disaster.
2. *Cargo prioritization*. When there is a cutback of port operation capacity, cargo handling can be prioritized based on the characteristics or value of the cargos (e.g., giving perishable cargos a higher priority). A key issue is who should make the decision on the prioritization.
3. *Ship re-routing*. This is a strategy usually applied for prolonged port disruption. It pertains to both imports and exports, and requires a sophisticated assessment of alternative locations, ship and cargo type, and transportation costs. One needs also consider the extent to which some of the cargo can eventually be re-routed to the disrupted port area through land surface or sub-surface (pipeline) transportation.
4. *Export diversion for import use*. This refers to sequestering goods that were intended for export to substitute for lack of availability of imports. This option has the added benefit of opening up some shipping capacity at ports to which the import diversion is being channeled. Care needs to be taken, however, to ensure that the goods diverted from export are adequate replacements for those goods that are in shortfall.
5. *Effective management*. This refers to any improvements in decision-making and expertise that improve functionality, primarily by using existing scarce resources more efficiently.

Much of it refers to improvisation, but some relates to established port-level disaster plans, security plans, and emergency-management plans. This can refer to a range of options to share information and facilitate communications and coordination of stakeholders after the incident; and to effectively allocate manpower and other resources to expedite debris removal, repair, and reconstruction.

6. *Production Recapture (Rescheduling)*. This refers to the resilience option to work extra shifts or over time to clear up the backlog of vessels after the port facilities resume operation after the disruption. This option is usually only viable for short-run disruptions, for which most ships will wait for the re-open of the port in the harbor, rather than re-rout to other ports.

<u>Customer-side resilience options</u>:

1. *Use of inventories*. Inventories refer to stockpiling critical inputs for the production of goods and services by firms. In the port disruption context, this resilience tactic pertains to various types of stockpiles not only for the ports themselves but also for the direct and indirect customers of ports down the supply chain. Note that the cost of inventories is not the actual value of the goods themselves, but simply the carrying costs. The goods themselves are simply replacement for the ordinary supplies.
2. *Conservation*. This pertains to finding ways to utilize less of disrupted imported goods in production processes that are potentially disrupted by the curtailment of imports directly, as well as conserving critical inputs whose production is curtailed indirectly. Examples include reducing nonessential usage, restricting nonessential access, and promoting recycling.
3. *Input Substitution*. This refers to utilizing similar goods in the production process to those whose production has been disrupted (again both directly and indirectly). An example would be using natural gas rather than coal in electric utility and industrial boilers.
4. *Import substitution*. This is basically the same as input substitution but more explicitly bringing in goods and services in short supply from outside the region. Setting up alternatives in advance, or at the minimum, researching options, can ensure smoother substitution of inputs following a disaster. Of course, it can be constrained by damage to transportation infrastructure, as can be resulted from a tsunami.
5. *Production Recapture (Rescheduling)*. This refers to making up lost production by working extra shifts or over time after the port disruption is relieved. This is a viable option for short-run disruptions, where customers are less likely to have cancelled orders.
6. *Technological change* is a tactic that can increase resilience capacity by imparting additional flexibility into production systems both before and after the disaster (Zoli, 2011). It can also refer to important improvisations in the way goods and services are produced in the aftermath of a disaster.

Figure 1 displays the major linkages in tracing port disruptions from closure and damages beginning with direct economic impacts through short-run and longer-run impacts across five analytical time stages of a

Tsunami scenario in the case study. 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 more speedy recovery of the commodity flows at the ports are shown in the blue rounded boxes. At the macroeconomic level, port disruptions lead to intermediate production inputs and final goods shortfalls, and reduction in final demand associated with reduction in exports. Relevant customer-side resilience tactics that can be utilized by the general businesses as well as final users to reduce their potential losses from port disruptions are depicted in orange rounded boxes. The total impacts involve the general equilibrium impacts stemming from the direct impacts that ripple through over the entire supply chain, taking important interactions, such as substitution effects and resource constraints into consideration.

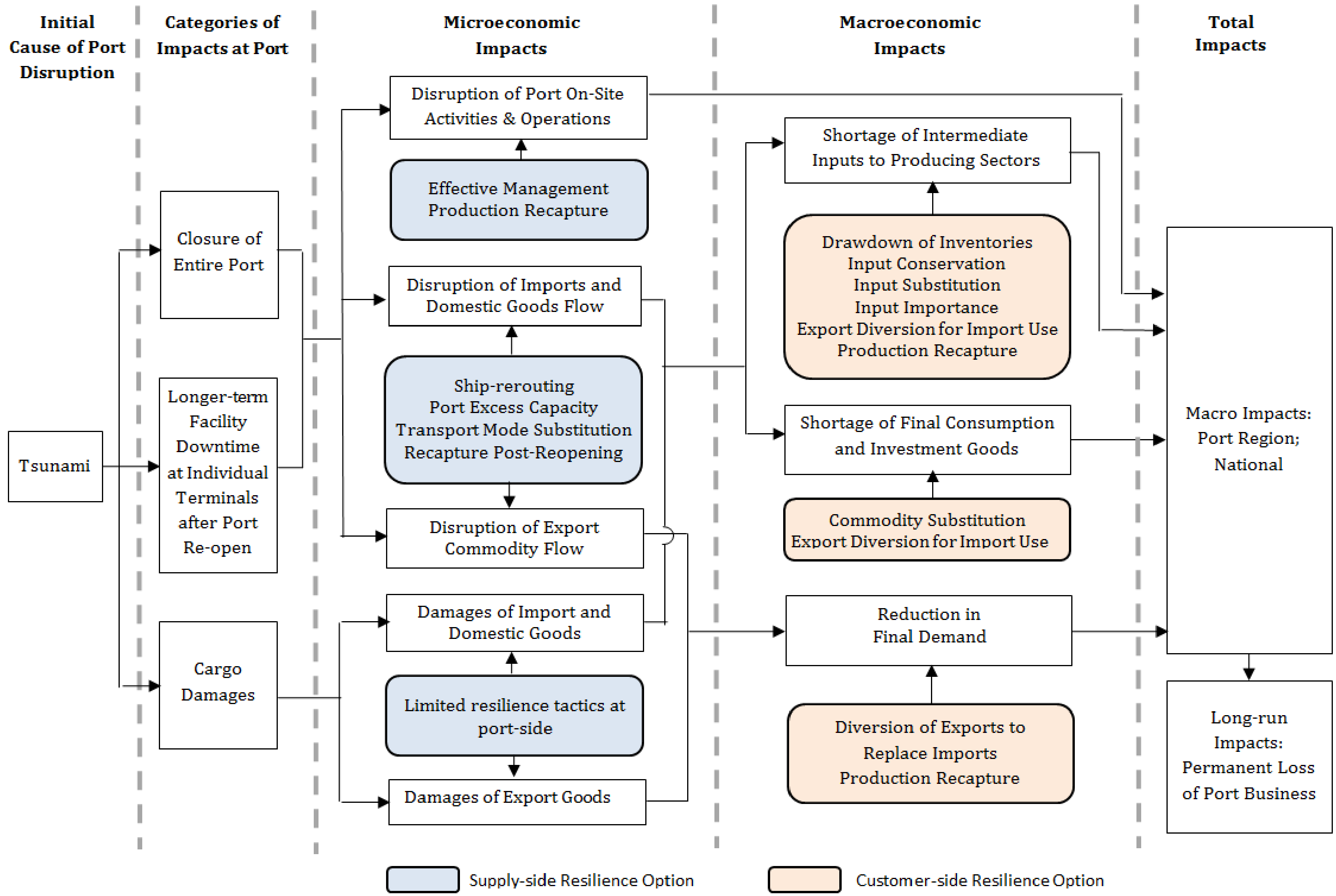

Figure 1. Analytical Framework of Estimating Total Economic Impacts of a Port Disruption with Implementation of Resilience Measures

3.3. Incorporation of Port Resilience into CGE Models

3.3.1. Conceptual Framework

One approach to analyzing and measuring economic resilience is to incorporate it into economic consequence analysis (ECA) models. The state-of-the-art in this area includes sophisticated models of several types. In this paper, we focus on Computable General Equilibrium (CGE) models, which are widely used for ECA (e.g., Rose et al., 2007; Rose et al., 2009; Dixon et al., 2010; Sue Wing et al., 2015). These models have several attractive properties that make them especially valuable for ECA, including being based on behavioral responses of individual producers and consumers, having a role of prices and markets, the ability to trace economic interdependence, and a non-linear structure that can reflect flexibility of various components (Rose, 2005), where flexibility is a key attribute of resilience (Zolli and Healy, 2012).

Several methodological advances have been made in explicitly incorporating resilience into CGE models over the past 15 years (see, e.g., Rose and Liao, 2005; Rose et al., 2009; Sue Wing et al., 2015; Rose, 2015b). At the same time, several types of resilience are inherent in CGE models, in relation to their core focus (e.g., the allocative mechanism of prices) and flexibility (substitution among inputs).

In this section, we first present a conceptual framework for an analysis of economic resilience based on economic production theory (Rose and Liao, 2005; Rose, 2009). At the core is the concept of the production function or how firms use various inputs to generate their products. Specification of these functions provides insight into the combination of inputs and their productivity, substitution between inputs, and how input relationships with outputs vary according to scale. Various "functional forms" are available, most of which allow for a variety of possibilities in these key relationships. Production functions have been refined over time to include behavioral considerations, which are especially important when considering resilience. These behavioral considerations focus primarily on human factors such as perceptions and motivations.

Other microeconomic units are built on similar bodies of theory. The theory of consumer choice is the counterpart of production theory in a number of ways. It is typically based on utility functions with similar properties to production functions, or various expenditure functions that are less abstract. More recently, production theory has been extended to consumers with the advent of the household production function approach-- households use a combination of inputs, including their own time, to produce household goods and services.

Of all the economy-wide modeling approaches used to study economic consequences of disasters, CGE is the most powerful, in part, because it is able to utilize some of the most sophisticated production functions, such as the constant elasticity of substitution (CES), translog, and Generalized Leontief. It can also incorporate more rigid production functions for short-run analyses (less than 6 months). On the consumer side, CGE models can also utilize sophisticated expenditure functional form, such as CES function, to model consumer's preferences and choice over different types of commodities.

Business resilience has two sides. Customer-side resilience copes with the disruption (quantity and timing) of the delivery of inputs, and pertains to ways to use resources available as effectively as possible by both businesses and households, i.e., it is primarily associated with static resilience. In the context of port shutdown or disruption, customer-side refers to both direct customers to the ports (importers and exporters) and businesses upstream and downstream along the supply chain of the port direct customer businesses. At a given point in time (i.e., with a given fixed capital stock), because of the curtail of any critical production input (e.g., stemming from import disruptions or delays), resilience is mainly a demand-side issue. In contrast, supply- side resilience is concerned with delivering outputs to customers. In the context of port disruption, it mainly refers to the various resilience options undertaken by the ports to hasten the speed to recover port operations. These could include the establishment of system redundancy (a form of static resilience), but usually requires the repair or construction of critical inputs (i.e. dynamic resilience). Repair of the capital stock, or supply- side efforts, are in the domain of the input provider, which is a completely separate matter from customer-side resilience.

3.3.2. Supply-Side Resilience

Resilience options that can be adopted by the port authorities and terminal operators are summarized in Table 2 following Rose (2009). The table lists the major categories of resilience and provides examples in the first column. In the second column, prior actions that can be taken to enhance each type of resilience are specified. In the next two columns, we specify the extent to which the resilience category is inherent and adaptive (Capital X and lower-case x represent higher and lower strength of inherent or adaptive resilience, respectively). In addition, the applicability of the type of resilience to factors of production (operation) of the port is specified in terms of the letters capital (K), labor (L), electricity (E), other transportation (OT) materials (M), as well as for the output (Q) of the port. The output (or level of functionality) of the Ports directly affect the amount of imports and exports that can flow into and out of the country/region without disruption or delay. Capital letters associated with each of these inputs or outputs represent a strong relationship, while lower-case letters represent a weak one.

A wide range of resilience measures can be adopted by the ports to maintain certain level of service or recover back more quickly from major disruptions of its capability to process cargo flows. Rose and Wei (2013) and City College of New York (2013) indicated that utilization of excess capacity of undamaged terminals can help clear up some of the backlog of ships. Ship-rerouting is documented as another major source of resilience for port disruption (Park et al., 2008; Rose et al., 2016). Trepte and Rice (2014) quantified how cooperation among nearby ports can effectively absorb the freight volumes that cannot be handled by disrupted ports. Such capability can be enhanced by pre-existing port networks, which refer to a group of ports that are willing to work together to share information and build long-term relationship in order to achieve higher level of service quality to their customers (Paixao and Marlow, 2003).

The capability of input substitution is also important for port to maintain function and recover more rapidly from disruption. Continued power supply is essential for the operation of cargo handling equipment and proper communications among port authorities, terminal operators, shippers, critical staff and emergency responders. Corresponding resilience measures include increasing the number of backup generators and fuel storage for the backup generators, and investment towards the access to alternative power system (such as solar power, micro-grid system) (Smythe, 2013; City College of New York, 2013). Availability of alternative communication means (such as analog pagers, wireless handheld devices, CB radios, satellite phones) is also crucial since communication and flow of information both within and outside the port are considered essential for the port to quicken the recovery of its operations back to normal (GAO, 2007; Rice and Trepte, 2012; Southworth et al., 2014).

For many of the supply-side resilience tactics (the port side), such as ship re-routing, production recapture, export diversion, the resilience adjustments relate to the output side of the CGE model. This is specified as the general output of port transportation (QPT) in Table 2. Other port-related resilience tactics, such as input substitution, excess capacity, technological change, pertains to the inputs (including, for example, electricity, communication, and equipment) to port on-site operation and business activities. These inputs into economic activity serve as the independent variables for a formal production function in which the influence of these resilience tactics can be linked directly to them or to the production function parameters. Note that although there are several examples of formal incorporation of resilience tactics into CGE modeling on the customer side (which will be discussed in detail in the next subsection), these resilience options have not yet been simulated in CGE models on the supply-side to any significant extent. However, the methodologies are similar to those that will be presented below.

TABLE 2. MICROECONOMIC RESILIENCE OPTIONS: SUPPLIER-SIDE (PORT)

Category	Possible Prior Action	Inherent	Adaptive	Applicability	CGE Incorporation
Ship-rerouting and intermodal substitution • cooperation with nearby ports; • enhance points of transfer through truck or rail	flexible inter-port agreements port networking enhance intermodal coordination	X	X	QPT	
Export Diversion for Import Use • identify adequate replacement potentials • information clearing house between importers and exporters	enhance flexibility	X	X	QPT	Increase export elasticities
Inventories (Stockpiles) • strengthen storage facilities (e.g., marine oil inventory buffer held at ports) • reduce uncertainty	enhance; protect	X	x	QPT	Loosen constraint on output
Input Substitution • use backup system; increase backup generators and fuel capacities; solar power, micro-grid technologies • alternative communication system	enhance flexibility of system increase redundancy	X	X	K, L, OT, E, M	Increase input substitution elasticity Rose and Liao (2005)
Excess Capacity • Excess capacity within terminals and between terminals • maintain in good order	build and maintain	X	x	K	Loosen constraint on output Rose et al. (2009); Sue Wing et al. (2015)
Production Recapture • work extra shift to clear back log of ships after port reopen • practice restarting	arrange long-term agreements	X	X	QPT	ad hoc Rose et al. (2007, 2015b)
Technological Change • change processes	increase flexibility	X	X	K, L, OT, M, Q	ad hoc Rose (1984)
Management Effectiveness	increase versatility	X	X	QPT	ad hoc

Category	Possible Prior Action	Inherent	Adaptive	Applicability	CGE Incorporation
• facilitate communication both within and outside the port and between public-private stakeholders • prioritize and allocate remaining resources • Prioritize importance of vessels	exercise and train				Wein and Rose (2011)
		x	X	K, L, OT, M, QPT	Ad hoc
Reduce Operating Impediments • arrange on-site housing for critical staff, emergency responders, and relief workers	recovery planning alleviate choke points				
• assist worker families • relieve congestion					Wein and Rose (2011)

3.3.3. Customer-Side Resilience

Resilience options for businesses that are direct and indirect customers of Port are summarized in Table 3, which follows the same format as Table 2. Column 1 lists the major categories of resilience with examples applicable to port disruption. Column 2 presents prior actions that can be taken to enhance each type of resilience. The extent to which the resilience category is inherent and adaptive is summarized in Column 3. In addition, the applicability of the type of resilience to factors of production is specified in terms of the letters capital (K), labor (L), port transportation (PT), other transportation (OT), materials (M), as well as for the output (Q) that they produce. Again we use capital letters to represent a strong relationship between the input component (or output) to the resilience measure, while lower-case letters represent a weak one. The same convention is used to denote the strength of inherent or adaptive resilience which is denoted by the letter X. For example, a firm usually holds certain amount of inventories on raw materials to maintain a certain level of production in case of short-term input shortages/disruptions. However, it is more difficult for firms to hold extra capital input (e.g., equipment) as inventory. Moreover, it is impossible for the firms to have any inventories on transportation services. Therefore, we denote capital M and lower-case k in the Applicability column of the inventory row, while PT and OT are excluded for not being applicable. Another example is that inherent conservation is primarily already accounted for by maximizing behavior, but we include it as at least weak, because not all firms actually maximize their production relationships.

The last column of the table indicates how each type of resilience can be incorporated into a CGE model, including a reference to works that have done so. Most resilience tactics can be related to ordinary production function parameters or related to an expanded set of inputs. Some need to be applied in an ad hoc manner, such as loosening input constraints or adjusting output.

For example, Table 3 presents resilience strategies for businesses on the customer side. A major category is Input Substitution, which would include the use of similar goods in place of the curtailed production inputs due to import disruption, and substituting port transportation with other transportation means. A more subtle category is Conservation, the examples of which include reducing non-essential uses of critical imported inputs. Conservation is only minimally inherent because economists typically assume that most inherent conservation options are currently being maximized. Thus, most conservation options pertain to adaptive applications. All inputs can be conserved. The major obstacle is necessity of the input into the production process. Similar explanations are provided for other resilience options for the case of business customers.

The impacts of many resilience tactics presented in Table 3 can be modeled by changing the values of input in the production function or by changing the production function parameters. For example, Rose and Liao (2005) have shown how conservation is linked to the productivity term, and how input and import substitution are linked to the elasticities of substitution of a constant elasticity of substitution (CES) production function. In essence, the methodology of Rose and Liao is as follows: in standard production function analysis, one enters values of the variables into the production function, and one solves for outputs given these variable values and the production function parameters. To recalibrate the production function parameters in the aftermath of the disaster so as to reflect resilience, one uses

TABLE 3. MICROECONOMIC RESILIENCE OPTIONS: CUSTOMER-SIDE (DIRECT/INDIRECT PORT USERS)

Category	Possible Prior Action	Inherent	Adaptive	Applicability	CGE Incorporation
Conservation • reduce non-essential use of critical imported inputs • reduce use of port transportation • promote recycling	minimize use of inputs curtailed by import disruption	x	X	K, L, PT, OT, M	Increase productivity term Rose and Liao (2005)
Input Substitution • utilize similar goods in place of curtailed imported production inputs • substitute port transportation with other transportation means	enhance flexibility of system	X	X	K, L, OT, M	Increase input substitution elasticity Rose and Liao (2005)
Import Substitution • mutual aid agreements • substitute domestic goods for disrupted imports • re-routing of goods/services	broaden supply chain	X	X	k, L, M	Increase import substitution elasticity Sue Wing et al. (2015)
Inventories (Stockpiles) • ordinary inventories on raw materials, work-in-process products, or finished goods • emergency stockpiles	enhance; protect	X	x	k, L, M	Increase inventories; loosen constraint Rose et al. (2016)
Input Isolation • decrease dependence • segment production	reduce dependence on critical imported inputs	X	X	K, l, M	Loosen constraint on inputs ATC (1991); Rose et al. (2007)
Production Recapture • supply-chain clearinghouse • restarting procedures	arrange long-term agreements; contingency plan and practice for supply-chain disruption	x	X	Q	ad hoc Rose et al. (2007, 2015b)
Technological Change • change processes • alter product characteristics	increase flexibility	X	X	K, L, M, Q	ad hoc Rose (1984)
Management Effectiveness • emergency procedures • succession/continuity	train; increase versatility; identify	X	X	k, L, pt, ot, m	ad hoc Wein and Rose (2011)

the value of the inputs (including any fixed, or constant, levels) and a given level of output to solve for the parameters. Rose and Liao were able to solve the changes in the productivity term to reflect adaptive conservation by analytical methods, but solving elasticity of substitution parameter changes required numerical methods (the input and output values were obtained from a business interruption survey performed by Tierney, 1997).

3.3.4. Government and Households

Government has demand-side resilience features in a manner similar to business to cope with the impacts from port disruptions. Of course, government at various levels plays a key role in economic recovery, so this is an added dimension of resilience in this sphere. Improvements in the quality and quantity of emergency services can be considered as resilience enhancement. Increases in financial or in-kind disaster assistance and the effectiveness of their distribution to the affected parties promote recovery as well. However, the provision of aid can have disincentive effects on resilience, just as it does for mitigation when those who suffer from a disaster because they have not undertaken mitigation are "bailed out."

Household resilience on the "customer" side would be analogous to that presented for businesses. For example, a household can readily import all inputs except infrastructure services and physical capital. Another example is that inherent conservation is primarily already accounted for by maximizing behavior, but we include it as at least weak, because not all households actually maximize their "production" relationships. Thus, most conservation options pertain to adaptive applications. All inputs--capital, labor, infrastructure services, and materials--can be conserved, but the moderating factor is the necessity of the input into the household production process or functioning.

3.4. Formally Incorporating Resilience at the Meso and Macro Levels

Following Rose (2009), at the meso level, the predominant source of resilience is the role of markets in allocating resources. This is a major advantage of CGE modeling over all other alternative methods for ECA, such as I-O and macroeconometric modeling. This is an inherent source of resilience is embodied in the formulation of CGE models through their supply and demand functions for factors of production and outputs. One can measure the source of resilience by simulating post-disaster situation at pre-disaster prices and comparing the outcome with a flexible-price post-disaster outcome, including changes in variables and parameters. One caveat, however, needs to be addressed in the case of extreme disasters. Here markets may be in disarray and various imperfections are likely to result in a situation where prices no longer reflect the true value of resources. Several adjustments need to be made for this contingency. Here, CGE does serve as a useful tool to identify the ideal workings of the market, so that policymakers can engage its importance of the source of resilience and take actions to strengthen markets or regulate prices to move toward an ideal outcome.

Resilience at the meso level is also related to supply chains, which have been discussed above. The spatial counterpart to this, and also very relevant to port disruptions, relates to connectivity. One way to model this, albeit the most difficult one, is to overlay the spatial network (such as the network of port service and other transportation service) onto the spatial model of the entire economy.

The macro level can be considered in two perspectives. First, it is an aggregation of individual actions, and the way to model the resilience as discussed above. Second, one should note that the macro level is not just the sum of its parts; instead, it involves various synergies and aspects of aggregate behaviors or policies, which is much difficult to model. One major aspect of the macro economy can be readily modeled in a CGE context is the potential augmented production and the use of domestic substitutes when foreign imports are disrupted. In addition, inherent resilience is explicitly considered in CGE given that imports and domestically produced import-competing goods can be modeled through choice functions. In terms of adaptive resilience, it can also be modeled in a CGE framework by adjusting import substitution elasticities. Similar approach can also be applied to model the resilience tactic of export diversion for import use. Some government fiscal and monetary policies can also be modeled but would only come into play in relation to port disruptions that had a devastating effect on the overall U.S. economy.

4. TERM Multi-Regional CGE Model

In this study, we incorporate the analysis of the various port resilience tactics into a multi-regional computable general equilibrium (CGE) model – TERM (The Enormous Regional Model), and apply this model to analyze the total economic impacts of two port disruption scenarios. TERM is a "bottom-up" multi-regional CGE model which treats each region as a separate economy.[1] The model was developed by Wittwer and Horridge (Wittwer, 2012) on the basis of Monash Multi-Regional Forecasting Model (MMRF). The key feature of TERM, in comparison to other CGE model, is its ability to handle a greater number of regions or sectors, as it is able to handle detailed regional accounts for up to 57 regions and 144 sectors. The high degree of regional detail makes TERM a useful tool for examining the regional impacts of shocks (especially supply-side shocks) that may be region-specific. In addition, TERM has a detailed treatment of transportation costs and is naturally suited to simulating the effects due to damages of transportation infrastructures.

The modeling structure of TERM is similar to those of other CGE models that capture the economic interactions among producers, households, government and trade at the regional levels. Producers in each region are assumed to minimize production costs subject to a combination of intermediate and

[1] A "bottom-up" approach for CGE analysis means that national results are aggregated based on regional economic outputs, which are simulated initially in a multi-regional CGE model. Unlike the single-region CGE or the "top-down" approach of regionalization, 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 spillover effects caused by a policy simulation.

primary factor inputs, which are structured by a series of Constant Elasticity of Substitution (CES) nesting structures. At the top nesting level, output is produced by combining a composite of primary factors with a composite of intermediate inputs in a proportional relation (Leontief fixed-coefficient production assumption). The primary factor aggregate is a CES composite of capital, land, and a labor aggregate—the latter being itself a CES composite of labor by skill group. The aggregate intermediate input is again a CES composite of different composite commodities, which are in turn CES composites of commodities from different sources. A representative household in each region maximizes utility through purchases of optimal bundles of goods in accordance with its preferences and budget constraint.

The TERM database for this analysis consists of 4 regions and 97 economic sectors. Appendix B1 presents the detailed sectoring scheme used in this study that is aggregated from the 512 TERM sectors. The four regions in the model include Northern California, Southern California, the Rest of California and the Rest of the U.S.[2]

Table 4. TERM-USA Modeling Tactics for Economic Resilience

Tactic	Variable	Representation	Note
Conservation	aprim	Primary-factor-augmenting technical change, by industry and region	Adjusting the shift parameter of CES function, which is the same approach as Rose and Liao (2005).
Port Excess capacity	fimps, fqexp	Adjust import and export shocks	Reducing the direct import- and export - disruption impact by the amount of port excess capacity.
Inherent Input Substitution	n/a	n/a	Inherent input substitution ability is captured by the CGE model automatically.
Import Substitution	n/a	n/a	Inherent import substitution ability is captured by the CGE model automatically by the specification of the Armington elasticity of substitution (ARMSIGMA in the TERM Model).
Ship Rerouting	fimps, fqexp	Adjust import and export shocks in different regions	Changes in exports and imports in different regions.
Export Diversion for Import Use	fimps , fqexp	Adjust import and export shocks	Using goods that were intended for export as substitutions for the lack of availability of imports.
Inventory Use	fimps	Adjust import shock	Reducing the direct import disruption by the amount of inventory.
Production Recapture	side-calculation	Application of "Recapture Factor Parameter"	A side-calculation using recapture factor to adjust the total loss estimate by sector is the standard approach to measure production recapture. It would represent employees working overtime or extra shifts.

[2] Northern California includes the following counties: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma. Southern California includes three counties: Los Angeles, Orange, and Riverside.

Both the short-run and the long-run closure rules can be applied to measure the different economic consequences of port disruption simulation using TERM. The short-run closure rule, which is also known as the Keynesian rule, assumes that the real wage is fixed and aggregate employment adjusts. Conversely, a long-run closure rule, which is also known as the neoclassical closure rule, assumes that aggregate employment is fixed and the real wage adjusts.

When we simulate the economic impacts of port disruptions, the major impacts to the regional and national economies come from the interruption of trade flows. In our simulations, we mainly use two variables in the TERM Model, fqexp (Export Quantity Shift Variable) and fimps (Import Price), to simulate the reduction in imports used and exports produced in each region. Table 4 summarizes the analytical approach we use to simulate the effects of various resilience tactics relating to port disruptions. Column 1 of the table lists the various resilience tactics. Column 2 presents the variables in the TERM Model we use to perform the analysis. More detailed discussion on the modeling approach is presented in the last two columns of the table. The effects of the resilience tactics can be analyzed in the TERM Model by performing side calculations to adjust the direct impact input data to the model, or through the adjustments of appropriate parameters and elasticities in the model.

5. Economic Impacts of Two Port Disruption Scenarios

In this report, we analyze the economic impacts of two port disruption scenarios. The first scenario, the USGS SAFRR Tsunami Scenario, is a hypothetical tsunami event generated by a long distance earthquake occurred offshore of the Alaskan Peninsula. This represents a lower-bound port disruption scenario, which is predicted to result in a 2-day port shutdown, and facility downtime at only a few terminals (up to no more than one month) at three major ports in California. The second scenario, which is assumed to be caused by a more extreme local event, is estimated to cause larger disruptions to port operations at Port of Los Angeles (POLA)/ Port of Long Beach (POLB) up to one year. This represents the upper-bound scenario of port disruptions in our analysis.

We use the TERM model to trace the economic ripple effects beyond the ports. The effects of various economic resilience tactics on both the supplier-side and the customer-side of port disruptions are evaluated as well. Major economic impacts are measured and reported with respect to gross domestic product (GDP), employment, and import and export levels for four regions: 3-county Los Angeles Region, 9-county San Francisco Region, Rest of California, and Rest of the U.S. The economic impact analysis is conducted in the following three steps:

1. Estimation of the direct economic impacts in terms of import and export disruption due to shutdown of the ports, extended facilities downtime, and/or cargo damages.
2. Simulation of the total economic impacts including the general equilibrium (essentially quantity and price multiplier) effects of lost production in industries upstream and downstream of directly affected sectors; and

3. Simulation of impacts of various economic resilience tactics that reduce the direct and total impacts.

5.1. Port Disruption Scenarios

5.1.1. USGS SAFRR Tsunami Scenario

The SAFRR tsunami scenario is a hypothetical but plausible tsunami created by a magnitude 9.1 earthquake that occurred offshore of the Alaskan Peninsula. The earthquake is assumed to occur at 11:50 am PDT on March 27, 2014[3], and the first waves hit Southern California around 4:50 pm PDT (SAFFR Tsunami Scenario Modeling Working Group, 2013). Wave surges and inundation are dangerous for two days after the initial tsunami notification (Miller and Long, 2013). Detailed analysis of ocean current heights and velocities, and the resulting damages to ports, marinas, and other coastal property and infrastructure are reported in USGS (2013). In this case study, we focus on the economic impacts of the disruption of operation at three major California ports that are most significantly affected by the Tsunami Scenario: Port of Los Angeles, Port of Long Beach, and Port of Oakland, which rank 1st, 2nd, and 4th, respectively, in terms of port trade flows in California.

5.1.2. Upper Bound Port Disruption Scenario

The USGS SAFRR tsunami scenario, which is a tsunami generated by a distant-sourced earthquake, represents a low level tsunami threat to most areas of Southern California. Many studies indicate that a high impact tsunami to the Southern California region can be generated by a local landslide offshore (Bohannon and Gardner, 2004; Locat et al. 2004; Borerro et al., 2005). Therefore, for the upper-bound scenario, we use the scenario analyzed in Borerro et al. (2005), which is a near shore tsunami generated by a submarine landslide offshore of the Palos Verdes Peninsula. Due to the adjacency of Palos Verdes to POLA/POLB, a tsunami generated by a submarine landslide offshore of Palos Verdes Peninsula is expected to result in significant impacts to the twin ports. Borerro et al. (2005) analyzed four different scenarios with respect to the severity of impacts to POLA/POLB. In the worst case scenario, it is assumed that the two ports, as well as the freeway links in the inundated area would be closed for up to one year.

In order to determine the assumption on the length of port disruption for our own analysis of an upper-bound port disruption scenario, we have also performed a literature review on the duration of port disruption for severe historical or hypothetical disaster events. Table 5 presents a summary of the findings.

[3] March 2014 is the 50th anniversary of the 1964 Alaskan "Good Friday" earthquake and tsunami.

Table 5. Summary of Studies on Port Disruption Events/Scenarios

Study	Event/Scenario	Port Disruption
Borerro et al. (2005)	Submarine landslide offshore of the Palos Verdes Peninsula	Four different levels of damage to POLA/POLB. The worst case scenario is a one-year complete shutdown at the twin ports.
Gordon et al. (2005)	Dirty bomb attack on POLA/POLB	Two Scenarios: 15-day and 120-day port shutdown
Rosoff and Winterfeldt (2007)	Dirty bomb attack on POLA/POLB	Scenarios range from 15 days to 120 days to one year
National Association of Manufacturers (2014)	No specific scenario; analyzing national impact of a west coast port stoppage	Scenario ranges from 5 days to 10 days to 20 days
Novati et al. (2014)	An earthquake scenario similar to the 1995 Hanshin-Awaji Earthquake	Port of Jakarta and the Port of Belawan closed for 2 months
Rose and Wei (2013)	No particular disaster event specified	90-day complete shutdown of Port of Arthur and port of Beaumont
Chang (2000)	1995 Kobe earthquake	The port was completely shut down for about a month after the earthquake. It gradually recovered to about 80% of its pre-earthquake operation by the end of Year 1 and suffered permanent loss of market share thereafter.

In our analysis, we adopted the following assumptions for the upper-bound port disruption scenario:

1. POLA/POLB would be completely shut down immediately after the disaster event.
2. The ports would recover to their pre-disaster operation levels by the end of Year 1.
3. The recovery path of the ports' activities is linear within the one-year period. It is equivalent to a 6-month disruption of the total values of trade flows (on both import and export sides) through POLA/POLB.

5.2. Direct Impacts of Port Disruption Scenarios

5.2.1. USGS SAFRR Tsunami Scenario

Table 6 presents a summary of the direct impacts of the Tsunami to the three ports. Tables 7 to 9 present the detailed impacts to each individual port. Figures 2-4 show the maps of the ports and the locations of the berths. The impact data were gathered from various sources, including USGS Tsunami Research Team, port contacts, and publically available data. Each of the three ports experience three categories of impacts: 1) 2-day entire port shutdown; 2) cargo damages; 3) extended facility downtime at a few terminals. In Tables 7 to 9, Column 1 lists the affected terminals, with terminal features specified in the second column. The last two columns of the tables present the value of damaged cargo, as well as the duration and magnitude of facility downtime.

2-Day Port Shutdown

Moffatt & Nichol (2012 and 2014) concluded that the three ports would be shut down for two days. The first day would be for safely shutting down port operations, removing vessels, and evacuating port personnel. The second day would be for inspection of facilities and preparations to re-open the ports. For the 2-day entire port shutdown, the major types of disrupted import commodities are agriculture product, machinery manufacturing, other transportation equipment manufacturing, and apparel-manufacturing products related to container activities.

Cargo Losses

Cargo losses are related to the inundation of terminals, as well as the nature of the cargo (for example, perishable goods). The major imported cargo losses are automobiles, which consist of nearly 83 percent of the total value of cargo damages in POLA and POLB. The major imported cargo losses in Port of Oakland are steel and containerized cargo.

Facility Downtime

Several port facilities (cargo handling terminals) would also be damaged in the tsunami scenario. For example, several marine oil terminals of POLA would only be able to operate at 50 percent capacity for 1 month due to the damage to the terminal operating systems. A few other terminals are considered unusable during debris clean up. In POLA and POLB, affected commodities include steel, petroleum refineries goods, and chemical products (such as caustic soda). The latter represents only a trivial amount, whereas the former two represent approximately 65 percent and 35 percent of the total impacts to imports, respectively, in this category. Major facility downtimes at Port of Oakland occur in container terminals.

Table 6. Summary Impacts at Port of Los Angles, Port of Long Beach, and Port of Oakland of USGS SAFRR Tsunami Scenario

Port	Port Disruption	Cargo Damages	Longer-term Facility Downtime
Port of Los Angeles	2-day port closure	$24,155,350 (total for various commodities)	Berths 165, 166, 174-181: 100% capacity reduction for 2 weeks Berths 163, 164, 167-169, 187-191: 50% capacity reduction for 1 month
Port of Long Beach	2-day port closure	$68,730,500 (total for various commodities)	Berth 101: 50% capacity reduction for 1 month
Port of Oakland	2-day port closure	$47,332,397 (total for various commodities)	Berths 20, 21, 22: 50% capacity reduction for 2 weeks Berth 25, 26, 30, 55, 56, 67, 68: 50% capacity reduction for 1 week Berths 32, 33, 34, 35, 37, 65: 50% capacity reduction for 1 month

Sources: USGS (2013), Moffatt & Nichol (2012) and Moffatt & Nichol (2014).

Table 7. Direct Impacts at Port of Los Angeles of USGS SAFRR Tsunami Scenario

Location	Terminal features	Daily throughput on March 27, 2014 (TEUs)	Daily throughput on March 27, 2014 (Bulk MTs)	Value of Damage to Cargo (US Dollar)	Facility Downtime
Berths 135-139	containerized general cargo	2,410		$8,314,500	
Berths 165-166	industrial borates		843	$382,000	100% reduction; 2 weeks
Berth 163 NuStar	marine oil (lube oil and fuel oil)		812	0	50% reduction; 1 month
Berth 164 Ultramar/Valero	fuels and lubricants		4,030	0	50% reduction; 1 month
Berths 167-169 Shell	fuels and lubricants		5,237	0	50% reduction; 1 month
Berths 187-191 Vopak	liquid bulk chemical products (bunker fuel, jet fuel, caustic soda less than 1%)		11,778	0	50% reduction; 1 month
Berths 238-240C ExxonMobil	fuels and lubricants		229	$50,000	
Berths 195-199	storage capacity up to 8000 vehicles		6,400	$13,000,000	
Berths 174-181	steel		5,357	$2,408,850	100% reduction; 2 weeks

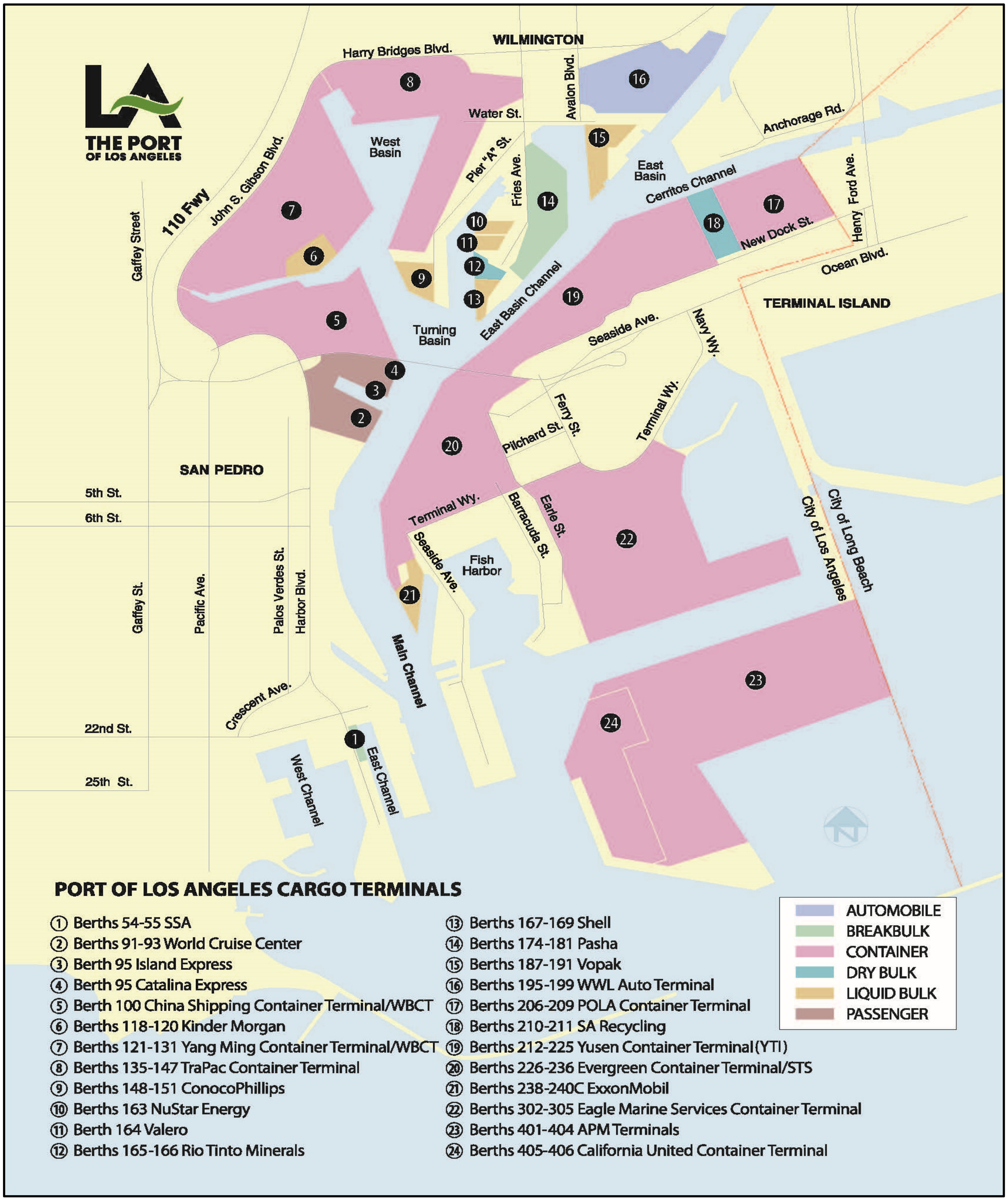

Figure 2. Port of Los Angeles Facility Map

Source: Moffatt & Nichol (2012).

Table 8. Direct Impacts at Port of Long Beach of USGS SAFRR Tsunami Scenario

Location	Terminal features	Daily throughput on March 27, 2014 (TEUs)	Daily throughput on March 27, 2014 (Bulk MTs)	Value of Damage to Cargo (US Dollar)	Facility Downtime
Pier A : Berths A88-A96	containerized general cargo	635		$21,000,000	
Pier C: Berths C60-C62	containerized general cargo	160		$6,000,000	
Pier D – Berth D46	gypsum		205	$140,000	
Pier F – Berth F211	petroleum coke, prilled sulfur		1,954	$148,000	
Pier F – Berth F210	salt			$292,000	
Pier T- Berth T121	crude oil and petroleum products		49,220	$50,000 mooring damage	
Pier S Berth S101	miscellaneous bulk liquid chemicals (petroleum, chemicals and biofuels)		5,580	$1,000,000	50% reduction; 1 month
Pier T, Berth T122	lumber and lumber products		2,474	$50,000	
Pier T Berth T118	recyclable metal & steel products.			$50,000	
Pier B Berth B82, B83	automobiles, office building, processing buildings, body shop & car wash		2,000 vehicles	($20,000/vehicle) $40,000,000	

Figure 3. Port of Long Beach Cargo Types

Source: Port of Long Beach (2016).

Table 9. Direct Impacts at Port of Oakland of USGS SAFRR Tsunami Scenario

Location	Terminal features	Daily throughput on March 27, 2014 (TEUs)	Daily throughput on March 27, 2014 (Bulk MTs)	Value of Damage to Cargo (US Dollar)	Facility Downtime
Berths 20, 21, & 22	containerized general cargo	395		$1,363,905	50% reduction; 2 weeks
Berth 23	containerized general cargo	198		$34,098	
Berth 24	containerized general cargo	198		$34,098	
Berths 25 & 26	containerized	395		$68,195	50% reduction; 1 week

	general cargo				
Berth 30	containerized general cargo	170		$146,462	50% reduction; 1 week
Berths 32, 33 & 34	containerized general cargo	509		$8,787,718	50% reduction; 1 month
Berths 35 & 37	containerized general cargo	543		$9,375,688	50% reduction; 1 month
Berths 55 & 56	containerized general cargo	862		$5,205,343	50% reduction; 1 week
Berths 57, 58 and 59	containerized general cargo	1,293		$1,115,431	
Berths 60, 61, 62, 63	containerized general cargo	1,724		$1,487,241	
Berth 65	steel		12,429	$19,714,219	50% reduction; 1 month
Berths 67 and 68	containerized general cargo	447		$0	50% reduction; 1 week

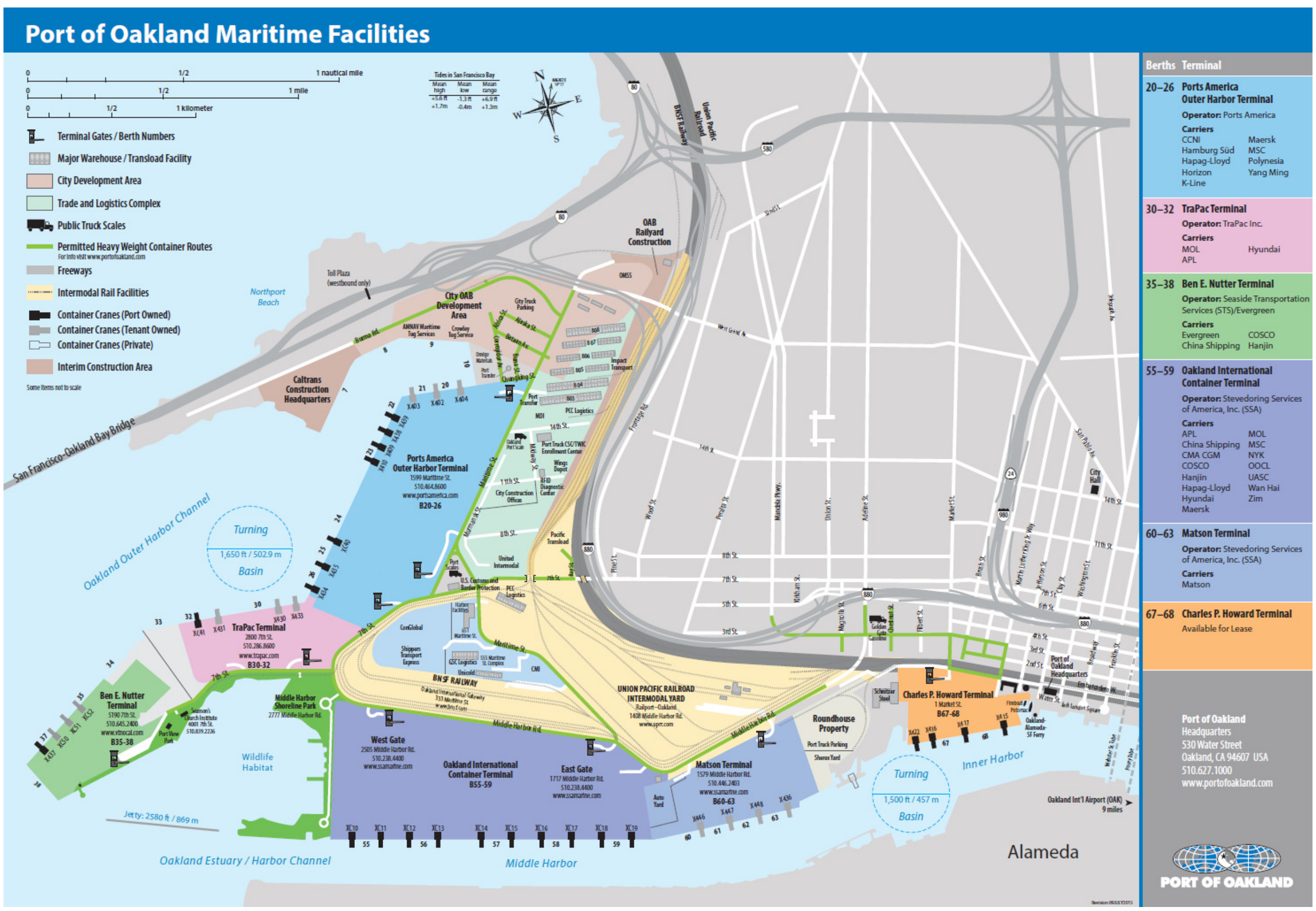

Figure 4. Port of Oakland Maritime Facilities

Source: Port of Oakland (2016).

5.5.2. Upper-Bound Port Disruption Scenario

For this scenario, we assume that the operation of the two ports will be completely or partially disrupted for one year. Since we assume a linear recovery of port operations within the one year period, the direct impacts (without resilience) are equivalent to the value of 6-month import and export flows through the twin ports. Based on the 2014 trade data, the total value of imports for 6-month is $158.7 billion and the total value of exports is $38.6 billion.

5.3. Total Economic Impacts of Port Disruption Scenarios

5.3.1. USGS SAFRR Tsunami Scenario

5.3.1.1. Total Economic Impact Results (Without Resilience)

In order to simulate the total economic impact of the port disruptions caused by the USGS SAFRR Tsunami Scenario, the direct impacts presented in Tables 6 to 9 are translated into percentage trade flow interruptions (in terms of import and export disruptions) in the four regions listed in Table 10.[4] The percentage impact on imports and exports in each region are calculated as the combined impacts of 2-day port shutdown, cargo damages, and extended facilities down in the three California ports.

Table 11 summarizes the results of three sets of simulations for the Base Case (with no resilience taken into consideration): import shocks, export shocks, and import and export shocks combined (known as simultaneous impact, that combines both import and export shocks in one single simulation in the model). In addition, the result of the simple summation of the results from the import and export simulations is also reported.

In the simulations, we entered the negative shocks of import used and export produced in the LA 3-county Region, San Francisco 9-county Region, Rest of CA, and Rest of U.S. by implementing positive shocks of import price and negative shocks of export quantity in the TERM Model. The results in Table 10 indicate that the shocks generate negative impacts on the various Californian regional economies, but positive impacts to Rest of U.S., although it should be noted that the overall impacts to the U.S. national economy are still negative. If we focus on the import shocks, the negative impacts in terms of a volume reduction in imports landed at various regions are much more substantial than the impacts on import volume used in the same regions for the Los Angeles Region and San Francisco Region. The negative impacts on imports landed are also of twice the magnitude of import used in Rest of CA. This indicates that the Tsunami scenario results in a significant impact on import handling capacity in the major ports in California. For the Rest of the U.S., the results show an increase in import landed, which indicates a potential substitution effects between the major ports in California and ports in the rest of

[4] For containerized cargos, we use the U.S. Census Bureau Trade Online Data for containerized commodities imported/exported through the three ports in Year 2014 (at 4-digit HTS code level) to disaggregate the total value of containerized cargo disruptions into the values for different types of commodities.

Table 10. Percentage Import and Export Disruption by Region

		LAOrngRivCA Region		SanFranCtyCA		RoCalifornia		RoUSA	
		Import Disruption	Export Disruption	Import Disruption	Export Disruption	Import Disruption	Export Disruption	Import Disruption	Export Disruption
1	Crops	0.858%	0.859%	2.415%	2.024%	0.857%	0.789%	0.077%	0.207%
2	Poultry & Eggs	0.813%	1.298%	2.782%	1.083%	0.847%	1.242%	0.550%	0.268%
3	Livestock	0.548%	0.548%	0.243%	0.548%	0.215%	0.548%	0.021%	0.344%
4	Other Livestock	0.000%	0.016%	0.000%	0.001%	0.000%	0.001%	0.000%	0.000%
5	Forestry, Fishing, & Hunting	0.594%	0.204%	0.117%	0.093%	0.129%	0.067%	0.010%	0.009%
6	Oil & Gas	0.548%	0.548%	0.156%	0.399%	0.155%	0.256%	0.006%	0.012%
7	Coal	0.004%	0.361%	0.001%	0.141%	0.000%	0.141%	0.000%	0.022%
8	Other Mining	0.358%	0.613%	0.778%	0.095%	0.227%	0.149%	0.020%	0.035%
9	Biomass electricity generation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
10	Coal-fired electricity generation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
11	Gas-fired electricity generation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
12	Hydroelectric generation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
13	Nuclear electricity generation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
14	Renewable electricity generation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
15	Electricity distribution	0.010%	0.010%	0.025%	0.005%	0.007%	0.004%	0.002%	0.001%
16	Natural gas distribution	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
17	Water and sewage services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
18	Residential Construction	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
19	Highway Construction	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
20	Other Non-Residential Construction	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
21	Highway Maintenance	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
22	Other Maintenance	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
23	Food Processing	0.737%	0.826%	1.196%	1.813%	0.529%	0.744%	0.102%	0.314%
24	Beverage & Tobacco Proct Manufacturing	0.565%	1.013%	1.119%	1.646%	0.306%	0.809%	0.072%	0.240%
25	Textile & Textile Product Manufacturing	0.609%	0.249%	0.240%	0.231%	0.228%	0.213%	0.053%	0.077%

26	Apparel	0.776%	0.403%	0.765%	0.678%	0.738%	0.524%	0.136%	0.046%
27	Leather & Allied Products	0.554%	0.627%	0.243%	0.950%	0.246%	0.308%	0.038%	0.193%
28	Wood Product Manufacturing	0.912%	0.472%	0.535%	0.303%	0.588%	0.340%	0.038%	0.077%
29	Paper Mills	0.626%	0.133%	0.623%	0.080%	0.427%	0.082%	0.038%	0.072%
30	Printing & Related Support Activities	0.653%	0.101%	0.942%	0.119%	0.547%	0.093%	0.049%	0.009%
31	Petroleum Refineries	4.194%	4.271%	1.208%	2.765%	1.207%	2.562%	0.085%	0.431%
32	Other Petroleum & Coal Products	0.640%	0.658%	0.538%	2.201%	0.148%	0.668%	0.005%	0.201%
33	Chemicals	0.632%	0.544%	0.210%	0.439%	0.233%	0.353%	0.056%	0.075%
34	Rubber & Plastics	0.711%	0.321%	0.732%	0.366%	0.684%	0.299%	0.233%	0.071%
35	Non-Metallics	0.508%	0.383%	0.552%	0.286%	0.296%	0.243%	0.096%	0.068%
36	Primary Metal Manufacturing	1.546%	1.408%	1.545%	4.642%	1.451%	1.475%	0.114%	0.464%
37	Fabricated Metal Product Manufacturing	4.585%	0.726%	3.570%	1.392%	3.070%	0.578%	1.006%	0.100%
38	Agriculture Machinery	0.063%	0.028%	0.037%	0.036%	0.027%	0.017%	0.007%	0.011%
39	Industrial Machinery	0.674%	0.453%	0.721%	0.366%	0.634%	0.252%	0.333%	0.083%
40	Commercial Machinery	1.246%	0.288%	1.634%	0.138%	1.128%	0.081%	0.545%	0.025%
41	Ventilation, Heating & Air-Conditioning	0.499%	0.086%	0.181%	0.082%	0.131%	0.046%	0.038%	0.016%
42	Metalworking Machinery	0.571%	0.266%	0.219%	0.196%	0.187%	0.141%	0.109%	0.036%
43	Engines & Turbines	0.560%	0.137%	0.132%	0.120%	0.119%	0.073%	0.040%	0.030%
44	Other General Purpose Machinery Manufacturing	0.030%	0.054%	0.018%	0.138%	0.013%	0.043%	0.003%	0.012%
45	Computers	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
46	Computer Storage Devices	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
47	Computer Terminals & Other Peripheral Equipment	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
48	Communications Equipment	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
49	Miscellaneous Electronic Equipment	0.643%	0.156%	1.116%	0.099%	0.638%	0.071%	0.229%	0.035%
50	Semiconductors & Related Devices	0.103%	0.004%	0.261%	0.012%	0.067%	0.003%	0.011%	0.001%
51	Electronic Instruments	0.598%	0.122%	0.646%	0.020%	0.576%	0.046%	0.113%	0.025%
52	Household Equipment, Appliances, & Component Manufacturing	0.679%	0.099%	1.367%	0.154%	0.671%	0.059%	0.205%	0.025%
53	Motor Vehicle and Parts Manufacturing	0.441%	0.151%	0.159%	0.248%	0.135%	0.200%	0.030%	0.029%
54	Aerospace Product & Parts Manufacturing	0.634%	0.473%	0.054%	0.034%	0.114%	0.051%	0.007%	0.006%
55	Railroad Rolling Stock Manufacturing	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%

56	Ship & Boat Building	0.329%	0.748%	0.692%	0.257%	0.565%	0.515%	0.024%	0.025%
57	Other Transportation Equipment Manufacturing	0.189%	0.045%	0.289%	0.076%	0.191%	0.059%	0.057%	0.029%
58	Furniture & Related Product Manufacturing	0.247%	0.058%	0.264%	0.092%	0.190%	0.068%	0.049%	0.008%
59	Miscellaneous Manufacturing	0.653%	0.377%	0.467%	0.202%	0.398%	0.104%	0.055%	0.019%
60	Wholesale Trade	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
61	Air Transport	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
62	Rail Transport	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
63	Water Transport	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
64	Truck Transport	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
65	Transit and Ground Passenger Transport	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
66	Pipelines	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
67	Other Transportation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
68	Warehousing	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
69	Retail Trade	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
70	Publishing Industries	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
71	Motion Picture & Sound Recording Industry	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
72	Broadcasting	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
73	Telecommunications	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
74	Information Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
75	Data Processing Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
76	Finance & Banking	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
77	Real Estate	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
78	Rental & Leasing Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
79	Lessors of Nonfinancial Intangible Assets	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
80	Professional, Scientific, Technical, & Administrative Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
81	Waste Management Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
82	Education Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
83	Health Care & Social Assistance	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
84	Arts, Entertainment & Recreation	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
85	Accommodations	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%

86	Eating & Drinking Places	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
87	Other Services	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
88	Owner-Occupied Dwellings	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
89	Government Enterprises	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
90	State & Local Government	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
91	Federal Government	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
92	Holiday	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
93	Foreign Holidays	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
94	Tourism Exports (including Purchases by Foreigners in Embassies)	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
95	Education Exports	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
96	Water Transport Exports	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
97	Air Transport Exports	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%

Table 11. Simulation Result of Import and Export Shocks from the USGS Tsunami Scenario (Base Case)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-246.5	-2,883	-157.6	-2,237.6	-483.1	-0.0357	-0.0500	-0.1415	-1.9520	-0.4215
SanFranCtyCA	-172.4	-1,660	-75.4	-919.8	-264.0	-0.0424	-0.0591	-0.1409	-1.3467	-0.3866
RoCalifornia	-129.5	-1,935	-76.7	-638.2	-263.9	-0.0268	-0.0354	-0.1525	-0.9208	-0.3808
RoUSA	8.5	896	-1,643.7	2,406.2	-379.2	0.0001	0.0008	-0.1410	0.1384	-0.0218
Total	-539.8	-5,582	-1,953.3	-1,389.5	-1,390.4	-0.0043	-0.0044	-0.1415	-0.0698	-0.0698
Export Shock										
LAOrngRivCA	-12.9	-138	-193.5	-32.0	-27.9	-0.0019	-0.0024	-0.1737	-0.0279	-0.0244
SanFranCtyCA	-7.3	-54	-119.1	-16.6	-15.4	-0.0018	-0.0019	-0.2227	-0.0242	-0.0225
RoCalifornia	-10.1	-169	-70.1	-17.1	-19.6	-0.0021	-0.0031	-0.1394	-0.0247	-0.0283
RoUSA	-82.1	-1,070	-260.3	-471.2	-473.1	-0.0008	-0.0009	-0.0223	-0.0271	-0.0272
Total	-112.5	-1,431	-643.0	-536.8	-536.0	-0.0009	-0.0011	-0.0466	-0.0270	-0.0269
All (Simple Summation)										
LAOrngRivCA	-259.4	-3,021	-351.0	-2,269.6	-511.1	-0.0376	-0.0524	-0.3151	-1.9798	-0.4458
SanFranCtyCA	-179.6	-1,714	-194.4	-936.4	-279.4	-0.0442	-0.0610	-0.3636	-1.3709	-0.4091
RoCalifornia	-139.6	-2,103	-146.8	-655.3	-283.5	-0.0289	-0.0385	-0.2919	-0.9455	-0.4091
RoUSA	-73.6	-175	-1,904.0	1,935.0	-852.4	-0.0007	-0.0002	-0.1634	0.1113	-0.0490
Total	-652.3	-7,013	-2,596.3	-1,926.3	-1,926.4	-0.0052	-0.0055	-0.1880	-0.0968	-0.0968
All (Simultaneous Impact)										
LAOrngRivCA	-258.5	-3,020	-350.8	-2,269.0	-510.9	-0.0375	-0.0524	-0.3149	-1.9793	-0.4457
SanFranCtyCA	-179.1	-1,714	-194.3	-936.1	-279.3	-0.0441	-0.0609	-0.3633	-1.3705	-0.4090
RoCalifornia	-139.0	-2,103	-146.7	-655.2	-283.5	-0.0288	-0.0385	-0.2917	-0.9453	-0.4090
RoUSA	-73.5	-174	-1,903.8	1,934.5	-852.1	-0.0007	-0.0002	-0.1633	0.1113	-0.0490
Total	-650.1	-7,010	-2,595.7	-1,925.8	-1,925.8	-0.0052	-0.0055	-0.1880	-0.0967	-0.0967

a. Level change for GDP and trade are measured in millions of 2010 dollars, change in employment is measured in number of jobs.

the nation when the former is disrupted by the Tsunami event. The simulation of export shocks results in negative overall impacts on regional GDP and employment in all four regions. However, the overall negative impacts from the export shocks were found to be relatively smaller than the impacts from import shocks, since all of the three affected ports in our study have a higher import flows than export flows.

In terms of a regional impact comparison, the results show that the USGS SAFRR tsunami scenario would cause the highest negative impacts on the regional economy in Los Angeles area in terms of reduction in GDP and employment. In particular, the threat is likely to cause a 2.24 percent decline in import volume landed at the Port of Los Angeles and the Port of Long Beach combined, which is associated with a 0.48 percent reduction in import volume used in Los Angeles Region. The reductions in real GDP and employment in the LA Region are 0.038 percent and 0.052 percent, respectively. Overall, the total national impacts were found to be a reduction of $650.1 million in GDP and a loss of seven thousand jobs.

5.3.1.2. Total Economic Impact Results of Resilience Cases

In this section we analyze the effect of resilience on the economic losses from the SAFRR tsunami, especially the port related disruptions and damages. Resilience refers to various tactics that can mute losses by using existing resources more efficiently (static resilience) and recovering more quickly (dynamic resilience) (Rose, 2009). We analyze only the former category in this report. Tables 12 to 16 present the total economic impacts of port disruptions under the USGS SAFRR Tsunami Scenario for six individual resilience cases: Excess Capacity, Ship Rerouting, Export Division, Conservation, Inventory Use, and Production Recapture. Comparisons of the economic impacts under different resilience scenarios and the Base Case are presented in Tables 17 to 19.

<u>Excess Capacity</u>: This resilience tactic is only applicable to facility downtime at the port. Based on our discussions with port contacts at the POLA/POLB ports: 1) most marine oil terminals have enough capacity to handle regular throughput after using excess capacity. The only exception is for Vopak and Valero terminals, for which the operation capacity is reduced by 40% even after using excess capacity; 2) various available alternatives at POLA/POLB can help reduce impacts of downtime at steel break bulk terminal by 50%; 3) for industrial borate, no other terminal in San Pedro can help handle the cargo. For Port of Oakland, due to lack of direct data, we extrapolate the loss reduction potential by using excess capacity at POLA/POLB, and assume excess capacity can reduce 17% of import and export losses at Port of Oakland. The effect of excess capacity is estimated to reduce the total real GDP losses from $650.1 million in the Base Case to $542.5 million (or a reduction of 16.6% of GDP losses). The employment losses are reduced from 7,010 jobs in the Base Case to 5,528 jobs (or a loss reduction of 21.1%).

<u>Ship Rerouting</u>: Based on a consultation with Capt. Dick McKenna (Marine Exchange; oral communication, 2013), we assume that ships will not be rerouted for the 2-day port shutdown. Ship rerouting is also not relevant for cargo damages. As for the extended facility downtime that only affects

a few terminals, for POLA/POLB, it is assumed that there is no ship diversion for imports. On the export side, 100% of the Borate cargos can be diverted to other ports. For Port of Oakland, again due to lack of direct data, we extrapolate the ship-rerouting loss reduction potential of POLA/POLB to Port of Oakland, and assume that 20% of imports and exports affected by the longer-term facility downtime can be re-routed to other ports. The results indicate that ship rerouting is estimated to reduce the total real GDP losses from $650.1 million in the Base Case to $615.7 million (or a reduction of 5.3% of the losses). The employment losses are estimated to decrease from 7,010 jobs to 6,604 jobs (or a loss reduction of 5.8%).

Export Diversion: We considered the diversion of export commodities to importers of the same commodities to reduce the potential losses on both the import and export sides. The application of this resilience tactic relies on export and import disruptions for the same types of commodities in order for exports to substitute for disrupted imports. We assume that during the 2-day port shutdown, import/export shipments will wait until the resumption of the port operation, and no export will be diverted for domestic use. For extended port-facility downtime, although we use a 97-sector TERM Model, we use the trade data at 4-digit HS codes to match the export commodities with import commodities, so that we are diverting the same commodity whose importation is being stifled. The export diversion helps reduce the GDP loss from $650.1 million in the Base Case to $585.8 million (or a reduction of 9.9% of GDP losses). Employment impacts are reduced from 7,010 jobs in the Base Case to 6,036 jobs, or 13.9% of total employment losses.

Conservation: We assume a 2-percent level of conservation for businesses to cope with the import disruptions. This conservation potential is then adjusted by the percentage of import disruption calculated in the Base Case for each individual commodity type. The resulting percentages are used to adjust the shift parameter of the Constant Elasticity of Substitution (CES) production function in the TERM Model. The simulation results indicate that this resilience tactic can help reduce GDP and employment impacts by about 0.1%.

Inventory Use: Inventories refer to stockpiling critical inputs for the production of goods and services by firms. In face of disruptions of imported production inputs, utilization of inventories of raw materials to maintain a certain level of production can cushion the blow of the supply disruption to the businesses. Our main source of inventory data is from the Bureau of Economic Analysis (BEA, 2016). Appendix Table C presents the ratio of inventory to annual sale by manufacturing sector. Since the BEA data only provide total inventory of materials and supplies held by individual manufacturing sectors, we disaggregate the total inventory value into different types of raw material inputs for each industry based on the input coefficients for that industry found in the regional input-output table (IMPLAN, 2013).[5] Note that many businesses nowadays choose to have inventories stored off-site in 3rd party warehouse

[5] Our calculation of inventory availability is conservative from three perspectives. First, we only count the inventories that are held by the manufacturing sectors in the region. However, the inventories held by the other sectors are likely to be small compared with those held by the manufacturing sectors. Major inventories of the agriculture sector may include water, gas, pesticide, and feed. The inventories for the transportation sectors may include oil, gas, and water. Most of the service sectors may only possess limited inventories. Second, we did not take into consideration the consumer goods held by the wholesalers and retailers in the region that can help cushion the f work-in-process and finished goods in our calculation.

than to store inventories on-site in order to save production space to maximize production potentials. However, the BEA inventory data do not differentiate on-site vs. off-site inventories. For the USGS SAFRR Tsunami Scenario, it is estimated that the surface transportation system in the port regions will only experience very minor impacts (USGS, 2013). So we assume that the businesses will still be able to access their off-site inventories in this case study. The import disruptions by commodity are then adjusted by the availability of inventories before they are entered into the TERM Model as direct shocks. The simulation results indicate that use of the available inventories by the producing sector has the potential to reduce the impact from import disruption to nearly zero for the USGS Tsunami Scenario given the relatively short time frame of port shutdown. However, inventory use is not relevant to the economic impact on the export disruption side. The results in Table 16 indicate that with inventory use, total GDP impact of port disruptions under the USGS Tsunami Scenario can be reduced from $650.1 million to $114.7 million, or a reduction of 82.4% of the GDP losses. The employment impact can be reduced from 7,010 jobs to 1,452 jobs, or a reduction of 79.3% of these losses.

<u>Production or Sale Recapture</u>: This resilience strategy refers to the ability of businesses to recapture lost production by working overtime or extra shifts once their operational capability is restored and their critical inputs become available. Appendix Table D presents the production recapture factors by sector. Different from the other types of resilience tactics, for which we simulate their effects by adjusting the direct impact data as inputs to the TERM model, for production recapture, we perform side-calculation to adjust the TERM Model results of total loss estimate by sector by the sectoral recapture factors. As shown in Appendix Table C, the recapture factors range from 30 to 98 percent. This resilience tactic can reduce the total GDP loss from $650.1 million to $102.0 million and employment loss from 7,010 jobs to 1,100 jobs. Both represent a reduction of 84.3% of estimated losses in the Base Case.

<u>Combined Resilience Tactics</u>: After simulating the effects of the resilience tactics separately, we combined all the above six resilience adjustments together. Note, however, that the effects of individual resilience tactics are not additive, since when we compute the effects of each individual resilience tactic above, we assume the resilience potential or effectiveness is relative to the Base Case. For example, if the ports manage to reduce interruptions to trade flows by utilizing excess capacity, the amount of cargos that potentially needs to be re-routed or the amount of exports that can be diverted for import use will decrease, and thus reduce the loss reduction potential of the latter two resilience tactics. There is also a similar sequencing issue of the resilience tactics on the supplier-side and customer-side. When we consider the combined effects of various supplier-side and customer-side resilience tactics, it is necessary to apply the customer-side resilience adjustments to the losses after the various supplier-side resilience adjustments have been applied. Therefore, in this Combined Resilience Simulation, we apply excess capacity and ship rerouting first, followed by export diversion. The above three resilience tactics mainly pertain to the supplier-side or port-side. The two major customer-side resilience tactics, use of inventory and conservation, are applied after the above three supplier-side resilience adjustments have been undertaken. Input substitution and import substitution are captured by the TERM Model automatically. Production recapture is again applied to the simulation results with the incorporation of all of the above resilience tactics. Applying all these resilience tactics at once can help reduce GDP loss from $650.1 million to just $16.6 million, or a reduction of 97.5% of the GDP losses.

The employment impact can be reduced from 7,010 jobs to 215 jobs, or a reduction of 96.9% of these losses.

It is important to note that all the resilience adjustments performed in our analysis represent potential resilience rather than actual resilience. The existence of potential resilience does not mean it can be actually implemented at its full level given many real world circumstances. These include restrictive regulations (e.g., governments or labor unions may have agreements limiting overtime work), bounded rationality (e.g., people have limited information or limited ability to process the information about different available resilience tactics), and market failures (e.g., asymmetric information) (Rose and Krausmann, 2013). Therefore, our results can be viewed as the upper-bound estimates of the loss reduction potential of various types of resilience tactics that are available at both the supplier-side and customer-side to help mute total economic losses from port disruptions. Policies can be devised to help close the gap between actual and potential resilience.

Table 12. Simulation Result of Import and Export Shocks from the USGS Tsunami Scenario (Excess Capacity)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-226.6	-2,632	-140.5	-2,073.5	-449.1	-0.0357	-0.0500	-0.1415	-1.9520	-0.4215
SanFranCtyCA	-145.9	-1,402	-68.0	-762.5	-229.2	-0.0424	-0.0591	-0.1409	-1.3467	-0.3866
RoCalifornia	-104.6	-1,533	-68.9	-513.0	-226.0	-0.0268	-0.0354	-0.1525	-0.9208	-0.3808
RoUSA	42.2	1,439	-1,469.4	2,055.2	-385.7	0.0001	0.0008	-0.1410	0.1384	-0.0218
Total	-434.9	-4,128	-1,746.8	-1,293.6	-1,290.1	-0.0043	-0.0044	-0.1415	-0.0698	-0.0698
Export Shock										
LAOrngRivCA	-12.5	-134	-183.2	-29.3	-25.1	-0.0019	-0.0024	-0.1737	-0.0279	-0.0244
SanFranCtyCA	-6.8	-50	-113.5	-15.4	-13.9	-0.0018	-0.0019	-0.2227	-0.0242	-0.0225
RoCalifornia	-9.5	-159	-63.0	-15.7	-18.0	-0.0021	-0.0031	-0.1394	-0.0247	-0.0283
RoUSA	-80.1	-1,060	-234.0	-430.3	-432.9	-0.0008	-0.0009	-0.0223	-0.0271	-0.0272
Total	-108.8	-1,403	-593.7	-490.7	-489.9	-0.0009	-0.0011	-0.0466	-0.0270	-0.0269
All (Simple Summation)										
LAOrngRivCA	-239.1	-2,765	-323.6	-2,102.8	-474.2	-0.0376	-0.0524	-0.3151	-1.9798	-0.4458
SanFranCtyCA	-152.7	-1,453	-181.5	-777.9	-243.1	-0.0442	-0.0610	-0.3636	-1.3709	-0.4091
RoCalifornia	-114.1	-1,693	-131.9	-528.7	-244.0	-0.0289	-0.0385	-0.2919	-0.9455	-0.4091
RoUSA	-37.9	379	-1,703.4	1,625.0	-818.7	-0.0007	-0.0002	-0.1634	0.1113	-0.0490
Total	-543.8	-5,531	-2,340.5	-1,784.4	-1,780.0	-0.0052	-0.0055	-0.1880	-0.0968	-0.0968
All (Simultaneous Impact)										
LAOrngRivCA	-238.4	-2,764	-323.5	-2,102.4	-474.1	-0.0375	-0.0524	-0.3149	-1.9793	-0.4457
SanFranCtyCA	-152.3	-1,452	-181.4	-777.7	-243.0	-0.0441	-0.0609	-0.3633	-1.3705	-0.4090
RoCalifornia	-113.6	-1,692	-131.9	-528.6	-244.0	-0.0288	-0.0385	-0.2917	-0.9453	-0.4090
RoUSA	-38.1	380	-1,703.3	1,624.7	-818.5	-0.0007	-0.0002	-0.1633	0.1113	-0.0490
Total	-542.5	-5,528	-2,340.0	-1,784.0	-1,779.6	-0.0052	-0.0055	-0.1880	-0.0967	-0.0967

a. Level change for GDP and trade are measured in millions of 2010 dollars, change in employment is measured in number of jobs.

Table 13. Simulation Result of Import and Export Shocks from the USGS Tsunami Scenario (Export Diversion)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-238.6	-2,774	-152.7	-2,198.6	-476.9	-0.0357	-0.0500	-0.1415	-1.9520	-0.4215
SanFranCtyCA	-167.5	-1,607	-73.0	-898.9	-262.4	-0.0424	-0.0591	-0.1409	-1.3467	-0.3866
RoCalifornia	-120.5	-1,768	-74.5	-586.2	-252.2	-0.0268	-0.0354	-0.1525	-0.9208	-0.3808
RoUSA	47.8	1,529	-1,594.9	2,287.3	-407.4	0.0001	0.0008	-0.1410	0.1384	-0.0218
Total	-478.8	-4,621	-1,895.0	-1,396.4	-1,399.0	-0.0043	-0.0044	-0.1415	-0.0698	-0.0698
Export Shock										
LAOrngRivCA	-12.9	-138	-192.2	-31.7	-27.7	-0.0019	-0.0024	-0.1737	-0.0279	-0.0244
SanFranCtyCA	-7.2	-53	-118.0	-16.4	-15.3	-0.0018	-0.0019	-0.2227	-0.0242	-0.0225
RoCalifornia	-10.1	-169	-69.8	-17.0	-19.5	-0.0021	-0.0031	-0.1394	-0.0247	-0.0283
RoUSA	-81.3	-1,059	-258.0	-467.6	-469.4	-0.0008	-0.0009	-0.0223	-0.0271	-0.0272
Total	-111.5	-1,418	-638.0	-532.7	-531.9	-0.0009	-0.0011	-0.0466	-0.0270	-0.0269
All (Simple Summation)										
LAOrngRivCA	-251.5	-2,912	-344.8	-2,230.3	-504.6	-0.0376	-0.0524	-0.3151	-1.9798	-0.4458
SanFranCtyCA	-174.8	-1,661	-191.0	-915.3	-277.7	-0.0442	-0.0610	-0.3636	-1.3709	-0.4091
RoCalifornia	-130.6	-1,937	-144.3	-603.3	-271.7	-0.0289	-0.0385	-0.2919	-0.9455	-0.4091
RoUSA	-33.4	470	-1,852.9	1,819.8	-876.8	-0.0007	-0.0002	-0.1634	0.1113	-0.0490
Total	-590.3	-6,039	-2,533.1	-1,929.1	-1,930.9	-0.0052	-0.0055	-0.1880	-0.0968	-0.0968
All (Simultaneous Impact)										
LAOrngRivCA	-249.3	-2,911	-344.6	-2,229.7	-504.5	-0.0375	-0.0524	-0.3149	-1.9793	-0.4457
SanFranCtyCA	-173.5	-1,660	-190.9	-915.1	-277.6	-0.0441	-0.0609	-0.3633	-1.3705	-0.4090
RoCalifornia	-129.0	-1,936	-144.2	-603.1	-271.7	-0.0288	-0.0385	-0.2917	-0.9453	-0.4090
RoUSA	-34.0	471	-1,852.7	1,819.3	-876.6	-0.0007	-0.0002	-0.1633	0.1113	-0.0490
Total	-585.8	-6,036	-2,532.4	-1,928.7	-1,930.4	-0.0052	-0.0055	-0.1880	-0.0967	-0.0967

a. Level change for GDP and trade are measured in millions of 2010 dollars, change in employment is measured in number of jobs.

Table 14. Simulation Result of Import and Export Shocks from the USGS Tsunami Scenario (Ship Rerouting)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-239.3	-2,807	-153.0	-2,215.5	-474.6	-0.0357	-0.0500	-0.1415	-1.9520	-0.4215
SanFranCtyCA	-155.1	-1,499	-73.2	-827.9	-240.1	-0.0424	-0.0591	-0.1409	-1.3467	-0.3866
RoCalifornia	-115.7	-1,730	-74.3	-557.7	-242.2	-0.0268	-0.0354	-0.1525	-0.9208	-0.3808
RoUSA	1.6	810	-1,599.3	2,234.7	-412.2	0.0001	0.0008	-0.1410	0.1384	-0.0218
Total	-508.5	-5,225	-1,899.9	-1,366.4	-1,369.0	-0.0043	-0.0044	-0.1415	-0.0698	-0.0698
Export Shock										
LAOrngRivCA	-12.0	-129	-159.4	-29.9	-25.3	-0.0019	-0.0024	-0.1737	-0.0279	-0.0244
SanFranCtyCA	-6.6	-50	-104.6	-15.2	-14.2	-0.0018	-0.0019	-0.2227	-0.0242	-0.0225
RoCalifornia	-9.4	-159	-61.1	-15.9	-17.8	-0.0021	-0.0031	-0.1394	-0.0247	-0.0283
RoUSA	-79.3	-1,045	-270.7	-432.8	-435.7	-0.0008	-0.0009	-0.0223	-0.0271	-0.0272
Total	-107.4	-1,382	-595.8	-493.8	-493.0	-0.0009	-0.0011	-0.0466	-0.0270	-0.0269
All (Simple Summation)										
LAOrngRivCA	-251.3	-2,936	-312.4	-2,245.4	-499.9	-0.0376	-0.0524	-0.3151	-1.9798	-0.4458
SanFranCtyCA	-161.7	-1,548	-177.8	-843.1	-254.3	-0.0442	-0.0610	-0.3636	-1.3709	-0.4091
RoCalifornia	-125.1	-1,888	-135.4	-573.6	-260.0	-0.0289	-0.0385	-0.2919	-0.9455	-0.4091
RoUSA	-77.7	-235	-1,870.1	1,801.9	-847.9	-0.0007	-0.0002	-0.1634	0.1113	-0.0490
Total	-615.9	-6,608	-2,495.8	-1,860.1	-1,862.0	-0.0052	-0.0055	-0.1880	-0.0968	-0.0968
All (Simultaneous Impact)										
LAOrngRivCA	-251.3	-2,935	-312.3	-2,244.8	-499.8	-0.0375	-0.0524	-0.3149	-1.9793	-0.4457
SanFranCtyCA	-161.7	-1,548	-177.7	-842.9	-254.2	-0.0441	-0.0609	-0.3633	-1.3705	-0.4090
RoCalifornia	-125.1	-1,888	-135.3	-573.4	-259.9	-0.0288	-0.0385	-0.2917	-0.9453	-0.4090
RoUSA	-77.6	-233	-1,869.8	1,801.4	-847.7	-0.0007	-0.0002	-0.1633	0.1113	-0.0490
Total	-615.7	-6,604	-2,495.2	-1,859.7	-1,861.6	-0.0052	-0.0055	-0.1880	-0.0967	-0.0967

a. Level change for GDP and trade are measured in millions of 2010 dollars, change in employment is measured in number of jobs.

Table 15. Simulation Result of Import and Export Shocks from the USGS Tsunami Scenario (Conservation)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-207.2	-2,626	-155.9	-2,239.1	-483.5	-0.0357	-0.0500	-0.1415	-1.9520	-0.4215
SanFranCtyCA	-172.2	-1,663	-74.8	-920.8	-265.2	-0.0424	-0.0591	-0.1409	-1.3467	-0.3866
RoCalifornia	-129.1	-1,936	-76.2	-639.2	-265.3	-0.0268	-0.0354	-0.1525	-0.9208	-0.3808
RoUSA	4.5	844	-1,634.8	2,386.7	-399.3	0.0001	0.0008	-0.1410	0.1384	-0.0218
Total	-504.0	-5,381	-1,941.7	-1,412.4	-1,413.2	-0.0043	-0.0044	-0.1415	-0.0698	-0.0698
Export Shock										
LAOrngRivCA	-12.9	-138	-193.5	-32.0	-27.9	-0.0019	-0.0024	-0.1737	-0.0279	-0.0244
SanFranCtyCA	-7.3	-54	-119.1	-16.6	-15.4	-0.0018	-0.0019	-0.2227	-0.0242	-0.0225
RoCalifornia	-10.1	-169	-70.1	-17.1	-19.6	-0.0021	-0.0031	-0.1394	-0.0247	-0.0283
RoUSA	-82.0	-1,070	-260.4	-471.2	-473.2	-0.0008	-0.0009	-0.0223	-0.0271	-0.0272
Total	-112.4	-1,431	-643.0	-536.9	-536.1	-0.0009	-0.0011	-0.0466	-0.0270	-0.0269
All (Simple Summation)										
LAOrngRivCA	-220.1	-2,764	-349.4	-2,271.1	-511.4	-0.0376	-0.0524	-0.3151	-1.9798	-0.4458
SanFranCtyCA	-179.4	-1,716	-193.9	-937.3	-280.6	-0.0442	-0.0610	-0.3636	-1.3709	-0.4091
RoCalifornia	-139.2	-2,105	-146.3	-656.3	-284.9	-0.0289	-0.0385	-0.2919	-0.9455	-0.4091
RoUSA	-77.6	-226	-1,895.2	1,915.4	-872.4	-0.0007	-0.0002	-0.1634	0.1113	-0.0490
Total	-616.4	-6,811	-2,584.8	-1,949.3	-1,949.3	-0.0052	-0.0055	-0.1880	-0.0968	-0.0968
All (Simultaneous Impact)										
LAOrngRivCA	-258.5	-3,020	-350.9	-2,269.2	-511.2	-0.0375	-0.0524	-0.3149	-1.9793	-0.4457
SanFranCtyCA	-179.1	-1,713	-194.3	-936.3	-279.5	-0.0441	-0.0609	-0.3633	-1.3705	-0.4090
RoCalifornia	-139.0	-2,102	-146.7	-655.3	-283.7	-0.0288	-0.0385	-0.2917	-0.9453	-0.4090
RoUSA	-73.1	-166	-1,904.4	1,933.9	-852.5	-0.0007	-0.0002	-0.1633	0.1113	-0.0490
Total	-649.6	-7,001	-2,596.3	-1,926.8	-1,926.9	-0.0052	-0.0055	-0.1880	-0.0967	-0.0967

a. Level change for GDP and trade are measured in millions of 2010 dollars, change in employment is measured in number of jobs.

Table 16. Simulation Result of Import and Export Shocks from the USGS Tsunami Scenario (Inventory)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-0.6	-6	-0.5	-14.9	-2.4	-0.0001	-0.0001	-0.0004	-0.0130	-0.0021
SanFranCtyCA	-1.9	-19	-0.2	-9.0	-0.8	-0.0005	-0.0007	-0.0005	-0.0132	-0.0011
RoCalifornia	-3.0	-50	-0.3	-10.8	-2.5	-0.0006	-0.0009	-0.0006	-0.0156	-0.0037
RoUSA	3.3	54	-4.8	31.0	2.6	0.0000	0.0000	-0.0004	0.0018	0.0001
Total	-2.2	-22	-5.8	-3.8	-3.2	0.0000	0.0000	-0.0004	-0.0002	-0.0002
Export Shock										
LAOrngRivCA	-12.9	-138	-193.5	-32.0	-27.9	-0.0019	-0.0024	-0.1737	-0.0279	-0.0244
SanFranCtyCA	-7.3	-54	-119.1	-16.6	-15.4	-0.0018	-0.0019	-0.2227	-0.0242	-0.0225
RoCalifornia	-10.1	-169	-70.1	-17.1	-19.6	-0.0021	-0.0031	-0.1394	-0.0247	-0.0283
RoUSA	-82.0	-1,070	-260.4	-471.2	-473.2	-0.0008	-0.0009	-0.0223	-0.0271	-0.0272
Total	-112.4	-1,431	-643.0	-536.9	-536.1	-0.0009	-0.0011	-0.0466	-0.0270	-0.0269
All (Simple Summation)										
LAOrngRivCA	-13.6	-144	-193.9	-46.9	-30.3	-0.0020	-0.0025	-0.1741	-0.0409	-0.0265
SanFranCtyCA	-9.1	-72	-119.3	-25.6	-16.2	-0.0022	-0.0026	-0.2231	-0.0375	-0.0237
RoCalifornia	-13.1	-219	-70.4	-27.9	-22.2	-0.0027	-0.0040	-0.1399	-0.0403	-0.0320
RoUSA	-78.8	-1,017	-265.2	-440.3	-470.6	-0.0007	-0.0009	-0.0228	-0.0253	-0.0271
Total	-114.6	-1,452	-648.8	-540.7	-539.2	-0.0009	-0.0011	-0.0470	-0.0272	-0.0271
All (Simultaneous Impact)										
LAOrngRivCA	-13.6	-144	-193.9	-46.9	-30.3	-0.0020	-0.0025	-0.1741	-0.0409	-0.0265
SanFranCtyCA	-9.1	-72	-119.3	-25.6	-16.2	-0.0022	-0.0026	-0.2231	-0.0375	-0.0237
RoCalifornia	-13.1	-219	-70.4	-27.9	-22.2	-0.0027	-0.004	-0.1399	-0.0403	-0.0320
RoUSA	-78.9	-1,017	-265.2	-440.3	-470.6	-0.0007	-0.0009	-0.0228	-0.0253	-0.0271
Total	-114.7	-1,452	-648.8	-540.7	-539.2	-0.0009	-0.0011	-0.0470	-0.0272	-0.0271

a. Level change for GDP and trade are measured in millions of 2010 dollars, change in employment is measured in number of jobs.

Table 17. Real GDP Impact -- Import Shock (millions 2010 $)

	LAOrngRivCA	SanFranCtyCA	RoCalifornia	RoUSA	Total
Base Case (No Resilience)	-$246.5 (-0.0357%)	-$172.4 (-0.0424%)	-$129.5 (-0.0268%)	$8.5 (0.0001%)	-$539.8 (-0.0043%)
With Excess Capacity	-$226.6 (-0.0329%)	-$145.9 (-0.0359%)	-$104.6 (-0.0217%)	$42.2 (0.0004%)	-$434.9 (-0.0035%)
With Ship Rerouting	-$239.3 (-0.0347%)	-$155.1 (-0.0382%)	-$115.7 (-0.0240%)	$1.6 (0.0000%)	-$508.5 (-0.0041%)
With Export Diversion	-$238.6 (-0.0346%)	-$167.5 (-0.0412%)	-$120.5 (-0.0250%)	$47.8 (0.0004%)	-$478.8 (-0.0038%)
With Conservation	-$207.2 (-0.0300%)	-$172.2 (-0.0424%)	-$129.1 (-0.0268%)	$4.5 (0.0000%)	-$504.0 (-0.0040%)
With Use of Inventory	-$0.6 (-0.0001%)	-$1.9 (-0.0005%)	-$3.0 (-0.0006%)	$3.3 (0.0000%)	-$2.2 (0.0000%)
With Production Rescheduling	-$40.7 (-0.0059%)	-$27.3 (-0.0067%)	-$22.1 (-0.0046%)	$1.3 (0.0000%)	-$88.7 (-0.0007%)
With All Resilience Adjustments	-$0.1 (0.0000%)	-$0.3 (-0.0001%)	-$0.5 (-0.0001%)	$0.5 (0.0000%)	-$0.4 (0.0000%)

Table 18. Real GDP Impact -- Export Shock (millions 2010 $)

	LAOrngRivCA	SanFranCtyCA	RoCalifornia	RoUSA	Total
Base Case (No Resilience)	-$12.9 (-0.0019%)	-$7.3 (-0.0018%)	-$10.1 (-0.0021%)	-$82.1 (-0.0008%)	-$112.5 (-0.0009%)
With Excess Capacity	-$12.5 (-0.0018%)	-$6.8 (-0.0017%)	-$9.5 (-0.0020%)	-$80.1 (-0.0007%)	-$108.8 (-0.0009%)
With Ship Rerouting	-$12.0 (-0.0017%)	-$6.6 (-0.0016%)	-$9.4 (-0.0020%)	-$79.3 (-0.0007%)	-$107.4 (-0.0009%)
With Export Diversion	-$12.9 (-0.0019%)	-$7.2 (-0.0018%)	-$10.1 (-0.0021%)	-$81.3 (-0.0007%)	-$111.5 (-0.0009%)
With Conservation	-$12.9 (-0.0019%)	-$7.3 (-0.0018%)	-$10.1 (-0.0021%)	-$82.0 (-0.0008%)	-$112.4 (-0.0009%)
With Use of Inventory	-$12.9 (-0.0019%)	-$7.3 (-0.0018%)	-$10.1 (-0.0021%)	-$82.1 (-0.0008%)	-$112.5 (-0.0009%)
With Production Rescheduling	-$2.1 (-0.0003%)	-$1.2 (-0.0003%)	-$1.7 (-0.0004%)	-$12.8 (-0.0001%)	-$17.7 (-0.0001%)
With All Resilience Adjustments	-$1.9 (-0.0003%)	-$1.0 (-0.0002%)	-$1.5 (-0.0003%)	-$12.0 (-0.0001%)	-$16.2 (-0.0001%)

Table 19. Real GDP Impact – Import plus Export Shocks (millions 2010 $)

	LAOrngRivCA	SanFranCtyCA	RoCalifornia	RoUSA	Total
Base Case (No Resilience)	-$258.5 (-0.0375%)	-$179.1 (-0.0441%)	-$139.0 (-0.0288%)	-$73.5 (-0.0007%)	-$650.1 (-0.0052%)
With Excess Capacity	-$238.4 (-0.0347%)	-$152.3 (-0.0376%)	-$113.6 (-0.0236%)	-$38.1 (-0.0003%)	-$542.5 (-0.0043%)
With Ship Rerouting	-$251.3 (-0.0364%)	-$161.7 (-0.0398%)	-$125.1 (-0.0259%)	-$77.6 (-0.0007%)	-$615.7 (-0.0049%)
With Export Diversion	-$249.3 (-0.0361%)	-$173.5 (-0.0427%)	-$129.0 (-0.0267%)	-$34.0 (-0.0003%)	-$585.8 (-0.0047%)
With Conservation	-$258.5 (-0.0375%)	-$179.1 (-0.0441%)	-$139.0 (-0.0288%)	-$73.1 (-0.0007%)	-$649.6 (-0.0052%)
With Use of Inventory	-$13.6 (-0.0020%)	-$9.1 (-0.0022%)	-$13.1 (-0.0027%)	-$78.9 (-0.0007%)	-$114.7 (-0.0009%)
With Production Rescheduling	-$42.7 (-0.0062%)	-$28.3 (-0.0070%)	-$23.7 (-0.0049%)	-$11.4 (-0.0001%)	-$102.0 (-0.0008%)
With All Resilience Adjustments	-$2.0 (-0.0003%)	-$1.3 (-0.0003%)	-$2.0 (-0.0004%)	-$11.5 (-0.0001%)	-$16.6 (-0.0001%)

5.3.2. Upper Bound Port Disruption Scenario

5.3.2.1. Total Economic Impact Results (Without Resilience)

The percentage trade flow interruptions (in terms of import and export disruptions) for this scenario in the four regions are presented in Table 20.

Table 21 summarizes the results of three sets of simulations for the Upper-Bound Base Case (with no resilience taken into consideration): import shocks, export shocks, and the simultaneous simulation with import and export shocks combined. The simple summation of the results from the separate import and export simulations is also reported.

The results in Table 21 indicate that this upper bound port disruption scenario will result in significant negative impacts on the various Californian regional economies, as well as to the Rest of the U.S. The total GDP impact is estimated to be $16.3 billion, or a decline of 0.13% of national GDP. The employment impact is estimated to be a loss of 141 thousand jobs, or a reduction of 0.11% of the baseline employment. If we focus on the import shocks, the negative impacts in terms of a volume reduction in imports landed are much more substantial than the impacts on import volume used in the same regions for the Los Angeles Region and San Francisco Region. The sum of the negative impacts on imports landed is over three times bigger than the magnitude of import used in these two regions. This indicates that the Tsunami scenario results in a significant impact on import handling capacity in the major ports in the Los Angeles and San Francisco Regions. However, for the Rest of the U.S., although the results indicate a $27.9 billion reduction in import used, there is also an increase in import landed of about $30.3 billion. This indicates a substantial substitution effects between the major ports in California and ports in rest of the nation when the former is disrupted by the disaster event. The simulation of export shocks result in negative overall impacts on regional GDP and employment in all four regions. The overall negative impacts from the export shocks were found to be relatively smaller than the impacts from import shocks, since all of the three affected ports in our study have a higher import flow than export flow.

In terms of a regional impact comparison, the results show that the upper-bound tsunami scenario would cause much higher negative impacts on the Los Angeles Region economy in terms of reduction in GDP and employment, in both value and percentage terms, compared to other regions in the state. In particular, the threat is likely to cause a 64.28% decline of import volume landed at the Port of Los Angeles and the Port of Long Beach combined, which is associated with a 16.41% reduction in import volume used in Los Angeles Region. The reductions in real GDP and employment in the LA Region are estimated to be $7.5 billion and 81 thousand jobs, or a reduction of 1.08% and 1.41%, respectively. They account for 46% and 57% of the total GDP and employment impacts to the nation.

Table 20. Percentage Import and Export Disruption by Region

		LAOrngRivCA Region		SanFranCtyCA		RoCalifornia		RoUSA	
		Import Disruption	Export Disruption	Import Disruption	Export Disruption	Import Disruption	Export Disruption	Import Disruption	Export Disruption
1	Crops	6.43%	47.07%	1.99%	3.51%	1.99%	3.51%	1.31%	2.62%
2	Poultry & Eggs	0.09%	1.05%	0.07%	0.15%	0.07%	0.15%	0.06%	1.97%
3	Livestock	0.01%	0.32%	0.01%	0.00%	0.01%	0.00%	0.81%	0.05%
4	Other Livestock	0.00%	0.54%	0.00%	0.02%	0.00%	0.02%	0.00%	0.01%
5	Forestry, Fishing, & Hunting	3.61%	1.40%	1.68%	0.07%	1.68%	0.07%	0.16%	0.25%
6	Oil & Gas	8.08%	0.00%	1.86%	0.00%	1.86%	0.00%	0.38%	0.00%
7	Coal	0.04%	32.90%	0.03%	12.83%	0.03%	12.83%	0.02%	0.20%
8	Other Mining	1.89%	50.00%	1.44%	7.83%	1.44%	7.83%	0.73%	1.61%
9	Biomass electricity generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
10	Coal-fired electricity generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
11	Gas-fired electricity generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
12	Hydroelectric generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
13	Nuclear electricity generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
14	Renewable electricity generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
15	Electricity distribution	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
16	Natural gas distribution	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
17	Water and sewage services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
18	Residential Construction	0.00%	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
19	Highway Construction	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20	Other Non-Residential Construction	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
21	Highway Maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
22	Other Maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
23	Food Processing	7.28%	12.20%	3.24%	4.06%	3.24%	4.06%	4.41%	4.88%
24	Beverage & Tobacco Proct Manufacturing	4.12%	1.98%	2.21%	0.37%	2.21%	0.37%	3.06%	1.42%
25	Textile & Textile Product Manufacturing	28.16%	2.37%	16.54%	6.18%	16.54%	6.18%	5.79%	1.26%
26	Apparel	50.00%	1.15%	45.44%	9.47%	45.44%	9.47%	9.93%	3.51%

27	Leather & Allied Products	1.68%	49.84%	0.86%	18.11%	0.86%	18.11%	0.15%	24.61%
28	Wood Product Manufacturing	17.80%	4.77%	9.90%	1.28%	9.90%	1.28%	4.95%	3.43%
29	Paper Mills	8.44%	11.50%	1.98%	14.97%	1.98%	14.97%	1.36%	2.51%
30	Printing & Related Support Activities	18.87%	1.04%	2.79%	0.91%	2.79%	0.91%	5.40%	0.75%
31	Petroleum Refineries	7.13%	1.86%	1.38%	0.20%	1.38%	0.20%	0.58%	0.49%
32	Other Petroleum & Coal Products	1.49%	50.00%	0.64%	46.87%	0.64%	46.87%	0.84%	9.34%
33	Chemicals	7.60%	4.70%	2.91%	2.77%	2.91%	2.77%	1.25%	2.96%
34	Rubber & Plastics	50.00%	8.05%	24.65%	10.02%	24.65%	10.02%	21.21%	3.27%
35	Non-Metallics	42.23%	13.57%	12.53%	6.32%	12.53%	6.32%	4.58%	2.88%
36	Primary Metal Manufacturing	7.70%	17.53%	3.82%	19.07%	3.82%	19.07%	0.78%	2.15%
37	Fabricated Metal Product Manufacturing	40.22%	3.49%	13.52%	4.68%	13.52%	4.68%	9.43%	2.67%
38	Agriculture Machinery	5.93%	7.18%	1.30%	1.64%	1.30%	1.64%	1.37%	1.27%
39	Industrial Machinery	50.00%	48.78%	37.58%	8.66%	37.58%	8.66%	11.66%	3.21%
40	Commercial Machinery	50.00%	8.17%	33.51%	6.46%	33.51%	6.46%	33.10%	3.06%
41	Ventilation, Heating & Air-Conditioning	50.00%	21.83%	21.44%	14.91%	21.44%	14.91%	9.94%	4.15%
42	Metalworking Machinery	45.54%	9.25%	26.72%	10.04%	26.72%	10.04%	9.51%	2.29%
43	Engines & Turbines	34.76%	18.58%	12.08%	3.25%	12.08%	3.25%	3.95%	2.22%
44	Other General Purpose Machinery Manufacturing	7.22%	2.39%	3.79%	2.66%	3.79%	2.66%	0.79%	0.40%
45	Computers	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
46	Computer Storage Devices	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
47	Computer Terminals & Other Peripheral Equipment	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
48	Communications Equipment	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
49	Miscellaneous Electronic Equipment	48.70%	2.50%	15.93%	1.52%	15.93%	1.52%	9.70%	1.84%
50	Semiconductors & Related Devices	6.79%	0.13%	1.31%	0.03%	1.31%	0.03%	21.14%	0.04%
51	Electronic Instruments	50.00%	0.54%	8.80%	0.11%	8.80%	0.11%	3.87%	0.36%
52	Household Equipment, Appliances, & Component Manufacturing	45.47%	5.22%	17.52%	4.22%	17.52%	4.22%	7.06%	1.35%
53	Motor Vehicle and Parts Manufacturing	45.56%	21.19%	6.86%	20.84%	6.86%	20.84%	1.88%	1.16%
54	Aerospace Product & Parts Manufacturing	1.51%	1.23%	0.52%	2.11%	0.52%	2.11%	0.20%	0.47%
55	Railroad Rolling Stock Manufacturing	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
56	Ship & Boat Building	1.41%	26.45%	0.05%	0.75%	0.05%	0.75%	0.99%	1.07%

57	Other Transportation Equipment Manufacturing	12.70%	1.44%	4.92%	0.57%	4.92%	0.57%	1.22%	1.58%
58	Furniture & Related Product Manufacturing	21.90%	1.30%	16.04%	1.98%	16.04%	1.98%	4.59%	0.49%
59	Miscellaneous Manufacturing	42.30%	4.75%	15.47%	3.48%	15.47%	3.48%	5.88%	2.01%
60	Wholesale Trade	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
61	Air Transport	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
62	Rail Transport	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
63	Water Transport	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
64	Truck Transport	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
65	Transit and Ground Passenger Transport	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
66	Pipelines	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
67	Other Transportation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
68	Warehousing	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
69	Retail Trade	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
70	Publishing Industries	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
71	Motion Picture & Sound Recording Industry	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
72	Broadcasting	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
73	Telecommunications	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
74	Information Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
75	Data Processing Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
76	Finance & Banking	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
77	Real Estate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
78	Rental & Leasing Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
79	Lessors of Nonfinancial Intangible Assets	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
80	Professional, Scientific, Technical, & Administrative Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
81	Waste Management Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
82	Education Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
83	Health Care & Social Assistance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
84	Arts, Entertainment & Recreation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
85	Accommodations	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
86	Eating & Drinking Places	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

87	Other Services	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
88	Owner-Occupied Dwellings	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
89	Government Enterprises	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
90	State & Local Government	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
91	Federal Government	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
92	Holiday	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
93	Foreign Holidays	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
94	Tourism Exports (including Purchases by Foreigners in Embassies)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
95	Education Exports	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
96	Water Transport Exports	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
97	Air Transport Exports	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 21. Simulation Result of Import and Export Shocks from the Upper-Bound Port Disruption Scenario (Base Case)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-6.98	-76.70	-5.44	-64.28	-16.41	-1.0126	-1.3303	-4.8871	-56.0710	-14.3132
SanFranCtyCA	-2.08	-18.73	-2.61	-11.43	-3.92	-0.5111	-0.6662	-4.8743	-16.7312	-5.7356
RoCalifornia	-2.08	-26.42	-2.59	-6.96	-5.38	-0.4314	-0.4837	-5.1568	-10.0476	-7.7601
RoUSA	-0.07	52.00	-55.84	30.29	-27.90	-0.0007	0.0455	-4.7908	1.7421	-1.6050
Total	-11.22	-69.85	-66.48	-52.38	-53.61	-0.0897	-0.0544	-4.8151	-2.6314	-2.6928
Export Shock										
LAOrngRivCA	-0.49	-5.01	-6.15	-0.72	-0.52	-0.0708	-0.0868	-5.5200	-0.6283	-0.4513
SanFranCtyCA	-0.18	-1.53	-1.71	-0.40	-0.29	-0.0435	-0.0546	-3.2018	-0.5926	-0.4237
RoCalifornia	-0.23	-4.06	-1.05	-0.39	-0.41	-0.0482	-0.0744	-2.0899	-0.5634	-0.5904
RoUSA	-4.32	-63.64	-7.70	-10.09	-10.37	-0.0395	-0.0557	-0.6605	-0.5803	-0.5963
Total	-5.22	-74.25	-16.61	-11.60	-11.58	-0.0417	-0.0579	-1.2031	-0.5829	-0.5818
All (Simple Summation)										
LAOrngRivCA	-7.47	-81.71	-11.59	-65.00	-16.93	-1.0834	-1.4171	-10.4072	-56.6993	-14.7645
SanFranCtyCA	-2.25	-20.27	-4.32	-11.83	-4.21	-0.5546	-0.7208	-8.0761	-17.3237	-6.1593
RoCalifornia	-2.31	-30.48	-3.64	-7.35	-5.79	-0.4796	-0.5581	-7.2467	-10.6110	-8.3505
RoUSA	-4.39	-11.64	-63.53	20.20	-38.27	-0.0402	-0.0102	-5.4512	1.1618	-2.2012
Total	-16.43	-144.09	-83.09	-63.99	-65.19	-0.1314	-0.1123	-6.0182	-3.2143	-3.2746
All (Simultaneous Impact)										
LAOrngRivCA	-7.47	-81.20	-11.37	-64.59	-16.86	-1.0837	-1.4083	-10.2109	-56.3452	-14.7112
SanFranCtyCA	-2.26	-20.17	-4.26	-11.79	-4.19	-0.5552	-0.7172	-7.9705	-17.2662	-6.1405
RoCalifornia	-2.32	-30.19	-3.61	-7.33	-5.76	-0.4802	-0.5529	-7.1766	-10.5767	-8.3120
RoUSA	-4.27	-9.84	-63.37	20.10	-38.00	-0.0391	-0.0086	-5.4375	1.1561	-2.1858
Total	-16.32	-141.39	-82.62	-63.62	-64.82	-0.1306	-0.1102	-5.9841	-3.1956	-3.2560

a. Level change for GDP and trade are measured in billions of 2010 dollars, change in employment is measured in number of jobs.

5.3.2.2. Total Economic Impact Results of Resilience Cases

In this section we analyze the effect of various resilience tactics on reducing the economic losses from the upper-bound port disruption scenario. Again, our analysis only focuses on static resilience, which refers to resilience tactics to mute losses by using existing resources more efficiently. Tables 22 to 25 present the total economic impacts of port disruptions under the Upper-bound Disruption Scenario for five individual resilience cases: Ship Rerouting, Export Diversion, Conservation, Inventory Use, and Production Recapture. In this Upper-Bound Scenario, we assume that there would be no excess capacity at the ports to utilize, since a catastrophic disaster event that results in similar impacts as those caused by the Kobe earthquake to the port would damage the majority of the port facilities. And during the recovery period (which is assumed to be a linear recovery process), the port will utilize any restored cargo handling capacity to the maximum extent. Therefore, no excess capacity is applicable in this Scenario. Comparisons of the economic impacts under different resilience scenarios and the Base Case are presented in Tables 26 to 28.

Ship Rerouting: An increasing percentage of vessel operators would divert their ships to other undamaged ports as the length of port disruption increases. However, there are also transportation cost penalty for shipping longer distances, as well as including the use of land routes, to deliver the cargo to the original destination. Therefore, we assume that although a very high proportion of ships would divert to other ports under a severe port disruption scenario, ship rerouting can only reduce direct impact to import and export flows up to 50% due to the aforementioned cost penalties. Under this assumption, the model results indicate that ship rerouting is estimated to reduce total real GDP losses from $16.3 billion in the Base Case to $8.0 billion (or a reduction of 51.2% of the losses). Employment losses are estimated to decrease from 141.4 thousand jobs to 69.5 thousand jobs (or a loss reduction of 50.8%)

Export Diversion: In order to perform the analysis of this resilience tactic, we again use the trade data at 4-digit HTS codes to match the export commodities with import commodities, so that we are diverting the same commodity whose importation is being stifled. Export diversion is estimated to have the potential to reduce the GDP loss from $16.3 billion in the Base Case to $10.9 billion (or a reduction of 33.5% of GDP losses). Employment impacts are reduced from 141.4 thousand jobs in the Base Case to 69.5 thousand jobs, or a reduction of 50.8% of total employment losses.

Conservation: We again assume a 2-percent level of conservation for businesses to cope with the import disruptions. This conservation potential is then adjusted by the percentage of import disruption calculated in the Base Case for each individual commodity type. The resulting percentages are used to adjust the shift parameter of the Constant Elasticity of Substitution (CES) production function in the TERM Model. The simulation results indicate that this resilience tactic can help reduce the GDP loss from $16.3 billion in the Base Case to $15.9 billion (or a reduction of 2.5% of GDP losses). Employment impacts are reduced from 141.4 thousand jobs in the Base Case to 134.0 thousand jobs, or a reduction of 5.3% of total employment losses.

Inventory Use: We again use the inventory data from the Bureau of Economic Analysis (BEA, 2016) that is presented in Appendix Table C in terms of the ratio of inventory to annual sale by manufacturing sector. We disaggregate the total inventory value provided by BEA into different types of raw material inputs for each industry based on the input coefficients for that industry found in the regional input-output table (IMPLAN, 2013). For this upper-bound port disruption scenario, we further adjust the availability of inventory in the aftermath of the disaster. Many studies indicate that more businesses nowadays prefer to store their inventories off-site in 3rd party warehouse than taking production space to store them on-site. The BEA inventory data do not differentiate on-site vs. off-site inventories. We make the assumption that about 20-40% of the inventories are stored on-site. We further assume that the disaster in the upper-bound scenario can potentially damage 50% of both the on-site and off-site inventories. In addition, for the undamaged off-site inventories, they might be difficult to be delivered to the businesses when roads are interrupted by the disaster. Given all the above assumptions, we assume that only one-third of the inventories calculated based on the BEA data can be accessed and utilized by the businesses to reduce impact from import disruptions in the upper-bound scenario. The import disruptions by commodity are then adjusted by the availability of inventories before they are entered into the TERM Model as direct shocks. The results in Table 25 indicate that with inventory use, total GDP impact of port disruptions under the Upper-bound Port Disruption Scenario can be reduced from $16.3 billion to $10.8 billion, or a reduction of 33.8% of the GDP losses.

Production or Sale Recapture: The possibility of production or sale recapture diminishes over time since the customers are likely to cancel orders and seek other suppliers if the disruption period lasts long. Appendix Table D presents the production recapture factors by sector for the first 3-month period after the disaster event. Then we reduce the recapture factors by 25 percent for each of the subsequent three-month periods. Thus, after the first year, there is no production recapture. This resilience tactic can reduce the total GDP loss from $16.3 billion to $5.6 billion and employment loss from 141.4 thousand jobs to 49.2 thousand jobs. Both represent a reduction of about 65% of estimated losses from the Base Case.

Combined Resilience Tactics: After simulating the effects of individual resilience tactics separately, we combined all the above five resilience adjustments together. Note, however, that the effects of individual resilience tactics are not additive, since when we compute the effects of each individual resilience tactic above, we assume the resilience potential or effectiveness is relative to the Base Case. When we consider the combined effects of various supplier-side and customer-side resilience tactics, it is necessary to apply the customer-side resilience adjustments to the losses after the various supplier-side resilience adjustments have been applied. Therefore, in this Combined Resilience Simulation, we apply ship rerouting first, followed by export diversion. The above two resilience tactics mainly pertain to the supplier-side or port-side. The two major customer-side resilience tactics, use of inventory and conservation, are applied after the above two supplier-side resilience adjustments have been undertaken. Input substitution and import substitution are captured by the TERM Model automatically. Production recapture is again applied to the simulation results with the incorporation of all of the above resilience tactics. Applying all these resilience tactics at once can help reduce GDP loss from $16.3 billion to $1.72 billion and the employment impact from 141.4 thousand jobs to 12.2 thousand jobs. For the three regions in California, the combination of all resilience tactics can reduce the total losses by about 75-78%. It is interesting to note that the impacts to Rest of U.S. become positive after incorporating all resilience adjustments. This is mainly due to the inter-regional transportation substitution effects. When there is a major port disruption in California, more imports are diverted to the rest of the country. The positive economic impacts stemming from the increased importing activities in the Rest of the U.S. more than offset the negative impacts caused by the shutdown of the ports in California to other regions in the country. Another offsetting effect is the stimulus effect from the substitution from imported goods to domestically produced goods. The combination of all resilience tactics can potentially reduce nearly 90% of total losses at the national level.

Table 29 presents a summary of the loss reduction potentials of each individual resilience tactics at the national level in the lower-bound and the upper-bound port disruption scenarios. The loss reduction potentials are calculated by dividing the avoided losses by implementing each individual resilience tactic by the total losses calculated in the Base Case (without resilience case).

We again note the difference between potential resilience and actual resilience given the various likely situations, such as restrictive regulations, bounded rationality, and market failures, in the real world as noted in the previous section. Therefore, our results represent the upper-bound estimates of the loss reduction potential of various types of resilience tactics that are available at both the supplier-side and customer-side to help mute total economic losses from port disruptions.

Table 22. Simulation Result of Import and Export Shocks from the Upper-Bound Port Disruption Scenario (Export Diversion)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-6.44	-70.01	-4.71	-61.14	-15.11	-0.933	-1.2142	-4.2297	-53.3334	-13.1766
SanFranCtyCA	-1.79	-15.79	-2.25	-9.55	-3.41	-0.4401	-0.5617	-4.2085	-13.9838	-4.9864
RoCalifornia	-1.88	-23.26	-2.24	-5.83	-4.71	-0.3887	-0.4259	-4.451	-8.4163	-6.7939
RoUSA	0.56	56.13	-47.89	31.50	-23.03	0.0051	0.0491	-4.1092	1.8117	-1.3248
Total	-9.54	-52.94	-57.09	-45.03	-46.25	-0.0763	-0.0413	-4.1352	-2.2619	-2.3233
Export Shock										
LAOrngRivCA	-0.12	-1.22	-1.98	-0.31	-0.25	-0.0176	-0.0211	-1.7793	-0.2702	-0.2186
SanFranCtyCA	-0.05	-0.25	-1.03	-0.16	-0.12	-0.0114	-0.0089	-1.9295	-0.2415	-0.1828
RoCalifornia	-0.08	-1.35	-0.35	-0.17	-0.20	-0.0164	-0.0248	-0.6961	-0.2522	-0.2897
RoUSA	-1.09	-14.31	-3.27	-4.77	-4.83	-0.01	-0.0125	-0.2809	-0.2744	-0.278
Total	-1.34	-17.13	-6.64	-5.42	-5.41	-0.0107	-0.0134	-0.4808	-0.2723	-0.2717
All (Simple Summation)										
LAOrngRivCA	-6.56	-71.23	-6.69	-61.45	-15.36	-0.9506	-1.2354	-6.009	-53.6036	-13.3952
SanFranCtyCA	-1.83	-16.04	-3.28	-9.72	-3.53	-0.4515	-0.5706	-6.138	-14.2253	-5.1691
RoCalifornia	-1.96	-24.62	-2.59	-6.01	-4.91	-0.4052	-0.4507	-5.147	-8.6685	-7.0836
RoUSA	-0.53	41.81	-51.17	26.72	-27.86	-0.0048	0.0366	-4.3901	1.5372	-1.6028
Total	-10.88	-70.07	-63.73	-50.45	-51.66	-0.087	-0.0546	-4.616	-2.5342	-2.595
All (Simultaneous Impact)										
LAOrngRivCA	-6.55	-71.10	-6.65	-61.35	-15.33	-0.9494	-1.2331	-5.9716	-53.5163	-13.3771
SanFranCtyCA	-1.83	-16.03	-3.25	-9.71	-3.53	-0.4511	-0.5702	-6.0836	-14.2175	-5.1658
RoCalifornia	-1.95	-24.54	-2.58	-6.00	-4.90	-0.4044	-0.4494	-5.13	-8.6627	-7.0694
RoUSA	-0.53	42.17	-51.15	26.72	-27.77	-0.0048	0.0369	-4.3882	1.5369	-1.5971
Total	-10.86	-69.51	-63.63	-50.34	-51.53	-0.0869	-0.0542	-4.6087	-2.529	-2.5884

a. Level change for GDP and trade are measured in billions of 2010 dollars, change in employment is measured in number of jobs.

Table 23. Simulation Result of Import and Export Shocks from the Upper-Bound Port Disruption Scenario (Ship Rerouting)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-4.20	-47.49	-2.90	-45.68	-9.57	-0.6084	-0.8237	-2.6069	-39.8439	-8.3483
SanFranCtyCA	-1.12	-9.97	-1.40	-5.82	-2.06	-0.2756	-0.3546	-2.6194	-8.5142	-3.0134
RoCalifornia	-1.21	-15.90	-1.39	-3.36	-3.11	-0.2503	-0.2911	-2.77	-4.841	-4.4889
RoUSA	0.95	40.13	-30.14	26.21	-14.97	0.0087	0.0351	-2.5861	1.5074	-0.8611
Total	-5.58	-33.22	-35.84	-28.64	-29.71	-0.0446	-0.0259	-2.5958	-1.4386	-1.4924
Export Shock										
LAOrngRivCA	-0.24	-2.49	-3.06	-0.36	-0.26	-0.0353	-0.0432	-2.7503	-0.313	-0.2246
SanFranCtyCA	-0.09	-0.77	-0.85	-0.20	-0.14	-0.0218	-0.0272	-1.5973	-0.2955	-0.2113
RoCalifornia	-0.12	-2.03	-0.52	-0.19	-0.20	-0.0241	-0.0371	-1.0424	-0.2809	-0.2944
RoUSA	-2.16	-31.79	-3.84	-5.03	-5.17	-0.0198	-0.0278	-0.3298	-0.2896	-0.2976
Total	-2.61	-37.07	-8.29	-5.79	-5.78	-0.0209	-0.0289	-0.6002	-0.2908	-0.2903
All (Simple Summation)										
LAOrngRivCA	-4.44	-49.98	-5.97	-46.03	-9.83	-0.6438	-0.8669	-5.3572	-40.1568	-8.5728
SanFranCtyCA	-1.21	-10.73	-2.26	-6.02	-2.20	-0.2974	-0.3818	-4.2167	-8.8096	-3.2247
RoCalifornia	-1.32	-17.92	-1.92	-3.55	-3.32	-0.2744	-0.3281	-3.8124	-5.1219	-4.7833
RoUSA	-1.21	8.34	-33.99	21.17	-20.14	-0.0111	0.0073	-2.916	1.2179	-1.1587
Total	-8.19	-70.30	-44.13	-34.43	-35.49	-0.0655	-0.0548	-3.196	-1.7295	-1.7827
All (Simultaneous Impact)										
LAOrngRivCA	-4.34	-49.85	-5.91	-45.93	-9.81	-0.6297	-0.8645	-5.3071	-40.0629	-8.5609
SanFranCtyCA	-1.18	-10.71	-2.24	-6.01	-2.20	-0.2913	-0.3808	-4.1889	-8.7949	-3.2201
RoCalifornia	-1.28	-17.84	-1.91	-3.54	-3.31	-0.2659	-0.3267	-3.7943	-5.1135	-4.7733
RoUSA	-1.16	8.89	-33.95	21.14	-20.07	-0.0106	0.0078	-2.9128	1.216	-1.1546
Total	-7.97	-69.51	-44.01	-34.34	-35.39	-0.0638	-0.0542	-3.1875	-1.7249	-1.7779

a. Level change for GDP and trade are measured in billions of 2010 dollars, change in employment is measured in number of jobs.

Table 24. Simulation Result of Import and Export Shocks from the Upper-Bound Port Disruption Scenario (Conservation)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-6.90	-75.78	-5.47	-64.36	-16.58	-1.0004	-1.3143	-4.908	-56.142	-14.4615
SanFranCtyCA	-2.05	-18.49	-2.62	-11.49	-3.97	-0.5043	-0.6575	-4.895	-16.8207	-5.8194
RoCalifornia	-2.06	-26.08	-2.61	-7.02	-5.45	-0.4263	-0.4775	-5.1812	-10.1307	-7.8639
RoUSA	0.25	57.58	-56.09	29.80	-28.29	0.0023	0.0504	-4.8129	1.7144	-1.6271
Total	-10.76	-62.77	-66.79	-53.06	-54.29	-0.0861	-0.0489	-4.8372	-2.6656	-2.7272
Export Shock										
LAOrngRivCA	-0.49	-4.99	-6.15	-0.72	-0.52	-0.0708	-0.0866	-5.5215	-0.6317	-0.4534
SanFranCtyCA	-0.18	-1.53	-1.71	-0.41	-0.29	-0.0434	-0.0543	-3.2034	-0.5958	-0.4258
RoCalifornia	-0.23	-4.05	-1.05	-0.39	-0.41	-0.0481	-0.0742	-2.0917	-0.5658	-0.5929
RoUSA	-4.31	-63.31	-7.72	-10.12	-10.40	-0.0394	-0.0554	-0.6622	-0.5823	-0.5984
Total	-5.20	-73.88	-16.63	-11.65	-11.62	-0.0416	-0.0576	-1.2048	-0.585	-0.5839
All (Simple Summation)										
LAOrngRivCA	-7.39	-80.77	-11.62	-65.08	-17.10	-1.0712	-1.4009	-10.4296	-56.7737	-14.9149
SanFranCtyCA	-2.23	-20.01	-4.33	-11.90	-4.27	-0.5477	-0.7118	-8.0984	-17.4165	-6.2452
RoCalifornia	-2.29	-30.13	-3.66	-7.41	-5.86	-0.4744	-0.5517	-7.2729	-10.6965	-8.4568
RoUSA	-4.06	-5.73	-63.81	19.68	-38.69	-0.0372	-0.005	-5.4751	1.1321	-2.2255
Total	-15.97	-136.65	-83.42	-64.71	-65.91	-0.1277	-0.1065	-6.0419	-3.2507	-3.3111
All (Simultaneous Impact)										
LAOrngRivCA	-7.42	-80.26	-11.40	-64.67	-17.04	-1.0751	-1.3919	-10.2321	-56.4159	-14.8602
SanFranCtyCA	-2.24	-19.91	-4.27	-11.86	-4.25	-0.5504	-0.7082	-7.9921	-17.358	-6.226
RoCalifornia	-2.30	-29.84	-3.62	-7.39	-5.83	-0.4775	-0.5464	-7.2022	-10.6614	-8.4177
RoUSA	-3.95	-3.95	-63.65	19.58	-38.42	-0.0362	-0.0035	-5.4611	1.1264	-2.21
Total	-15.91	-133.96	-82.94	-64.34	-65.54	-0.1272	-0.1044	-6.0075	-3.2318	-3.2923

a. Level change for GDP and trade are measured in billions of 2010 dollars, change in employment is measured in number of jobs.

Table 25. Simulation Result of Import and Export Shocks from the Upper-Bound Port Disruption Scenario (Inventory)

Region	RealGDP	Employ	Export	Import Landed	Import Used	RealGDP	Employ	Export	Import Landed	Import Used
	Level Change[a]					Percent Change				
Import Shock										
LAOrngRivCA	-6.85	-73.91	-2.20	-54.73	-14.90	-0.9938	-1.2820	-1.9747	-47.7401	-13.0005
SanFranCtyCA	-2.61	-25.23	-1.00	-12.29	-3.33	-0.6428	-0.8973	-1.8732	-17.9968	-4.8797
RoCalifornia	-2.31	-31.81	-1.10	-7.61	-5.00	-0.4793	-0.5824	-2.1917	-10.9829	-7.2179
RoUSA	8.67	63.68	-20.62	60.18	1.93	0.0794	0.0557	-1.7691	3.4615	0.1110
Total	-3.11	-67.27	-24.92	-14.45	-21.31	-0.0249	-0.0524	-1.8052	-0.7261	-1.0704
Export Shock										
LAOrngRivCA	-0.49	-5.01	-6.15	-0.72	-0.52	-0.0708	-0.0868	-5.5200	-0.6283	-0.4513
SanFranCtyCA	-0.18	-1.53	-1.71	-0.40	-0.29	-0.0435	-0.0546	-3.2018	-0.5926	-0.4237
RoCalifornia	-0.23	-4.06	-1.05	-0.39	-0.41	-0.0482	-0.0744	-2.0899	-0.5634	-0.5904
RoUSA	-4.32	-63.64	-7.70	-10.09	-10.37	-0.0395	-0.0557	-0.6605	-0.5803	-0.5963
Total	-5.22	-74.25	-16.61	-11.60	-11.58	-0.0417	-0.0579	-1.2031	-0.5829	-0.5818
All (Simple Summation)										
LAOrngRivCA	-7.34	-78.92	-8.35	-55.45	-15.42	-1.0646	-1.3688	-7.4948	-48.3684	-13.4518
SanFranCtyCA	-2.79	-26.76	-2.71	-12.70	-3.62	-0.6864	-0.9518	-5.0750	-18.5894	-5.3034
RoCalifornia	-2.55	-35.87	-2.15	-8.00	-5.41	-0.5275	-0.6568	-4.2816	-11.5463	-7.8082
RoUSA	4.35	0.03	-28.32	50.09	-8.44	0.0399	0.000	-2.4296	2.8812	-0.4853
Total	-8.33	-141.52	-41.53	-26.06	-32.89	-0.0666	-0.1103	-3.0082	-1.3090	-1.6522
LAOrngRivCA	-7.88	-84.88	-7.78	-41.83	-15.57	-1.1420	-1.4721	-6.9856	-36.4913	-13.5850
SanFranCtyCA	-2.88	-27.67	-2.53	-12.86	-3.76	-0.7089	-0.9840	-4.7383	-18.8240	-5.5015
RoCalifornia	-2.61	-36.97	-1.99	-8.18	-5.56	-0.5410	-0.6768	-3.9564	-11.8009	-8.0191
RoUSA	2.56	11.20	-24.23	45.35	-11.42	0.0235	0.0098	-2.0786	2.6086	-0.6566
Total	-10.81	-138.31	-36.53	-17.52	-36.30	-0.0865	-0.1079	-2.6460	-0.8800	-1.8237

a. Level change for GDP and trade are measured in billions of 2010 dollars, change in employment is measured in number of jobs.

Table 26. Real GDP Impact -- Import Shock (millions 2010 $) – Upper-Bound Port Disruption Scenario

	LAOrngRivCA	SanFranCtyCA	RoCalifornia	RoUSA	Total
Base Case (No Resilience)	-$6,984.2 (-1.0126%)	-$2,076.9 (-0.5111%)	-$2,082.3 (-0.4314%)	-$72.1 (-0.0007%)	-$11,215.5 (-0.0897%)
With Ship Rerouting	-$4,196.8 (-0.6084%)	-$1,120.1 (-0.2756%)	-$1,208.2 (-0.2503%)	$948.2 (0.0087%)	-$5,577.0 (-0.0446%)
With Export Diversion	-$6,435.1 (-0.9330%)	-$1,788.7 (-0.4401%)	-$1,876.3 (-0.3887%)	$559.3 (0.0051%)	-$9,540.8 (-0.0763%)
With Conservation	-$6,900.5 (-1.0004%)	-$2,049.3 (-0.5043%)	-$2,057.6 (-0.4263%)	$245.8 (0.0023%)	-$10,761.7 (-0.0861%)
With Use of Inventory	-$6,854.8 (-0.9938%)	-$2,612.5 (-0.6428%)	-$2,313.5 (-0.4793%)	$8,671.3 (0.0794%)	-$3,109.4 (-0.0249%)
With Production Rescheduling	-$2,428.4 (-0.3521%)	-$711.1 (-0.1750%)	-$732.6 (-0.1518%)	-$24.5 (-0.0002%)	-$3,896.7 (-0.0312%)
With All Resilience Adjustments	-$1,594.6 (-0.2312%)	-$539.5 (-0.1328%)	-$515.4 (-0.1068%)	$1,220.6 (0.0112%)	-$-1,428.9 (-0.0114%)

Table 27. Real GDP Impact -- Export Shock (millions 2010 $) – Upper-Bound Port Disruption Scenario

	LAOrngRivCA	SanFranCtyCA	RoCalifornia	RoUSA	Total
Base Case (No Resilience)	-$488.4 (-0.0708%)	-$176.8 (-0.0435%)	-$232.4 (-0.0482%)	-$4,318.2 (-0.0395%)	-$5,215.8 (-0.0417%)
With Ship Rerouting	-$243.6 (-0.0353%)	-$88.4 (-0.0218%)	-$116.2 (-0.0241%)	-$2,162.9 (-0.0198%)	-$2,611.1 (-0.0209%)
With Export Diversion	-$121.6 (-0.0176%)	-$46.2 (-0.0114%)	-$79.3 (-0.0164%)	-$1,088.0 (-0.0100%)	-$1,335.2 (-0.0107%)
With Conservation	-$488.1 (-0.0708%)	-$176.4 (-0.0434%)	-$232.4 (-0.0481%)	-$4,307.3 (-0.0394%)	-$5,204.1 (-0.0416%)
With Use of Inventory	-$488.4 (-0.0708%)	-$176.8 (-0.0435%)	-$232.4 (-0.0482%)	-$4,318.2 (-0.0395%)	-$5,215.8 (-0.0417%)
With Production Rescheduling	-$169.8 (-0.0246%)	-$60.5 (-0.0149%)	-$81.8 (-0.0170%)	-$1,470.1 (-0.0134%)	-$1,782.2 (-0.0142%)
With All Resilience Adjustments	-$26.9 (-0.0039%)	-$10.3 (-0.0025%)	-$17.8 (-0.0037%)	-$238.6 (-0.0022%)	-$293.6 (-0.0024%)

Table 28. Real GDP Impact – Import plus Export Shocks (millions 2010 $) – Upper-Bound Port Disruption Scenario

	LAOrngRivCA	SanFranCtyCA	RoCalifornia	RoUSA	Total
Base Case (No Resilience)	-$7,474.7 (-1.0837%)	-$2,256.3 (-0.5552%)	-$2,318.0 (-0.4802%)	-$4,273.4 (-0.0391%)	-$16,322.4 (-0.1306%)
With Ship Rerouting	-$4,343.2 (-0.6297%)	-$1,183.8 (-0.2913%)	-$1,283.6 (-0.2659%)	-$1,160.1 (-0.0106%)	-$7,970.7 (-0.0638%)
With Export Diversion	-$6,548.4 (-0.9494%)	-$1,833.2 (-0.4511%)	-$1,952.1 (-0.4044%)	-$528.7 (-0.0048%)	-$10,862.5 (-0.0869%)
With Conservation	-$7,415.7 (-1.0751%)	-$2,236.9 (-0.5504%)	-$2,304.7 (-0.4775%)	-$3,951.1 (-0.0362%)	-$15,908.4 (-0.1272%)
With Use of Inventory	-$7,877.3 (-1.142.0%)	-$2,881.0 (-0.7089%)	-$2,611.3 (-0.5410%)	$2,556.1 (0.0235%)	-$10,813.5 (-0.0865%)
With Production Rescheduling	-$2,599.0 (-0.3768%)	-$772.5 (-0.1901%)	-$815.5 (-0.1689%)	-$1,454.9 (0.0133%)	-$5.641.9 (-0.0451%)
With All Resilience Adjustments	-$1,621.1 (-0.2350%)	-$549.9 (-0.1353%)	-$532.9 (-0.1104%)	$982.0 (0.0090%)	-$1,7218 (-0.0138%)

Table 29. Loss Reduction Potentials of Individual Resilience Tactics

	Total	
	Lower-Bound Scenario	**Upper-Bound Scenario**
Excess Capacity	16.6%	N/A
Ship Rerouting	5.3%	51.2%
Export Diversion	9.9%	33.5%
Conservation	0.1%	2.5%
Use of Inventory	82.4%	33.8%
Production Rescheduling	84.3%	65.4%
All Resilience Adjustments Together*	97.4%	89.5%

* Not equal to sum of entries above due to overlaps.

5.4. Further Discussion

5.4.1. Further Discussion of the Modeling Results

The results of the economic impacts of the lower-bound port disruption scenario, the USGS Tsunami Scenario, are miniscule compared to the devastation of the Japanese Coast in 2011 and the ensuing cascading disasters. The main reason is that the SAFFR Tsunami scenario produces much smaller waves and less inundation along the California coast than what occurred along the Japanese coast.

Comparing to the results from the latest USGS study of the same scenario (Rose et al., 2016) for California, applying the TERM Model in this study also yields relatively lower impact results in the Base Case even if the former study only considered the impacts of disruptions at POLA/POLB, while the current study also considers the impacts to Port of Oakland. Below, we offer 2 reasons that help explain the difference.

The comparison of elasticities of substitution between TERM (Horridge et al., 2005) and Ian Sue Wing's CGE model (Wein et al., 2013; Rose et al., 2016) shows that the TERM Model has relatively larger Armington elasticities of substitution and elasticities of substitution for factor inputs than Sue Wing's model. This indicates that there is likely to be a relatively lower cost penalty to the economy when a policy shock is implemented using TERM than Sue Wing's model. Hence, the economic consequence results generated from TERM are likely to be relatively smaller than Sue Wing's model.

Another difference between the two models is that the TERM divides California into three regions: 3-County Los Angeles Region, 9-County San Francisco Region, and Rest of California, while Sue Wing's model only divides the state into two regions, Southern California and Rest of California. Potentially, the more regionally disaggregated model can capture higher inter-regional substitution effects and thus yield relatively smaller economic impact results.

Table 30. Elasticities of Substitution, Transformation and Supply for the SAFRR Tsunami Scenarios

Elasticities of substitution:		Ian	TERM
Between value added and a composite of intermediate inputs in production	σ_Y	0.1	
Between capital and labor in production	σ_{KL}	0.25	0.5
Among intermediate inputs to production	σ_Z	0.1	
Among 2 layers of the regions' imports from:			
Rest of World	$\sigma_{YY,i}$	4[1]	4.5
Rest of the U.S.	$\sigma_{DM,i}$	2[2]	6.52
Among inputs to household consumption	σ_C	0.25	
Among inputs to investment	σ_I	0.25	
Among inputs to government	σ_G	0.25	
Elasticities of transformation:			
Between California aggregate supply and rest of world exports in California-wide sectoral supply composite	η_X	2	2
Elasticities of supply:			
Labor	η_L	0.3	0.35

Sources: Wein et al. (2013); Roe et al. (2016).
1. Adjusted from 2 in Wein et al. (2013) by using the parameter value in Rose et al. (2016).
2. Adjusted from 0.5 in Wein et al. (2013) by using the parameter value in Rose et al. (2016).

5.4.2. Economic Impacts of Different Types of Port Disruption: Natural Disasters vs Terrorist Attacks

While there are many parallels between port disruptions as a result of natural disasters and as a result of terrorist attacks, there are enough underlying differences between the two to warrant discussion. First, the impacts of both disruption events lead to different types of economic damage and ripple effects. While port closures in both cases lead to a disruption in trade flows, which also affects shippers, carriers, and the port operators, natural disasters usually lead to significant damages to infrastructure throughout the entire port complex (CUNY, 2013; Paul and Maloni, 2010; Zhang and Lam, 2015). This, in turn, results in a lengthy shutdown period. Additionally, ports that are affected by natural disaster on an increasingly regular basis will begin to see a loss in reputation, which translates into a surcharge on the value of transported cargo placed by insurance companies (Zhang and Lam, 2015).

In contrast to natural disasters, the length of a shutdown due to a terrorist attack is more so a policy rather than a technical decision (Gordon et al., 2005). While there are a variety of event options for a terrorist attack, it is generally assumed that the detonation of a dirty bomb is a likely choice (Gordon et al., 2005; Rosoff and Winterfeldt, 2007). This type of attack can lead to significant economic damage, not necessarily similar to disruptions due to natural disasters. For instance, a radiation plume will require an evacuation of the surrounding area for up to a week, and in some cases, longer depending on the exact specifics of the detonation (Rosoff and Winterfeldt, 2007). Additionally, while a dirty bomb is generally a more confined disaster in terms of physical damage (for example the damage might only be confined to a specific structure in the port complex, such as a bridge or a terminal facility), the decontamination process is a widespread and lengthy process (Rosoff and Winterfeldt, 2007). The concerns of multiple stakeholders, such as shippers and dock workers, for safety standards may complicate and lengthen this process even more. Another long-term effect includes lasting health issues due to the airborne dispersal of radioactive material (Rosoff and Winterfeldt, 2007). Finally, during this disruption process and beyond, shippers may make greater use of the surrounding road network for cargo. This will lead to an increase in congestion which would affect passenger travel time as well as freight trips that were already in place (Gordon et al., 2005).

Another difference associated with terror-based port disruptions are behavioral effects and their economic ramifications. This effect stems from people's perception of risk (or uncertainty) associated with various types of disasters (Fischoff et al., 1981). Studies indicate that the stigma effect associated with hazard situations, especially those that relate to hazardous waste sites, can have long lasting effects, even beyond the physical danger of the attack. These effects include decreased property values and a reduction in business activity (Rosoff and Winterfeldt, 2007). This loss could continue for more than a year after the event before returning to pre-event levels. In addition, employees are likely to require a premium to work at a site previously struck by a terrorist attack or perceived to be a major target. Investors are likely to require an even higher rate of return at such a site as well (Giesecke et al., 2012). These premia and discounts are likely to increase with the insidious nature of the attack. Chemical, biological, radiological and nuclear (CBRN) agents provide little experience and are likely to incite dread on the population. Media coverage of such events will amplify the risk response. The difficulty of decontamination, and sometimes a lack of trust in the government, will cause the adverse reaction to linger, exacerbating losses.

The extent, as well as the number, of occurrences of port disruptions is another difference between terrorist attacks and natural disasters. Most natural disasters that result in a port disruption are large single events, such as hurricanes or tsunamis (Paul and Maloni, 2010; Thekdi and Santos, 2015). This type of event generally affects all aspects of the port, including cranes, bridges, and berths (Paul and Maloni, 2010). Other weather events, like extreme wind, can happen on a much more regular basis, but are still singular events that lead to an entire port shutdown (Zhang and Lam, 2015). Terrorist attacks, on the other hand, are usually much smaller events that are few and far between. While simultaneous detonations can occur, the complexity of planning required for this and the probability of success suggests that may not be likely (Rosoff and Winterfeldt, 2007). Additionally, the extent of a terrorist attack is much more confined than a natural disaster. The initial blast radius of a dirty bomb is limited to 50 to 100 feet (Rosoff and Winterfeldt, 2007), while the ensuing evacuation zone would be three to six miles (Gordon et al., 2005). Finally, the damage to infrastructure would be limited to the general blast radius and only specific aspects of the port, such as bridges, cranes, a berth, etc. would be directly affected (Gordon et al., 2005; Rosoff and Winterfeldt, 2007).

Recovery from a port disruption due to a natural disaster and from a terrorist attack may also lead to significant differences. On a large enough scale, recovery from both events will require the assistance of the Coast Guard as well as the Army Corps of Engineers (CUNY, 2013). Decontamination will most likely be promulgated by EPA. Standards issued by EPA will also place a greater emphasis on the safety of workers rather than just the general public (Rosoff and Winterfeldt, 2007). As such, this will require close cooperation and input from dock workers and shippers on safety standards they feel comfortable with. Additionally, a terrorist attack will undoubtedly lead to federal investigations, which may affect the recovery process in some way.

Finally, the resilience tactics relevant to port disruptions differ depending on whether the disruption is due to a natural disaster or a terrorist attack. For instance, some natural disasters are more likely to occur during certain months. As such, suppliers can take into account this risk and consider contingency plans accordingly for alternative shipping routes (Zhang and Lam, 2015; Zhang and Lam, 2016). Additionally, ports may hold bulk products at the port or off shore for which alternative transportation is usually too costly or impractical to access (Pant et al., 2011). However, this may be tapped into in the event of a port closure. Following a natural disaster, ports usually require extensive repair and reconstruction. It can also be the case that not only the port, but also the highway and railway systems connecting to the port are disrupted. In contrast, terrorist attacks are limited in their damage to some specific structures (Gordon et al., 2005; Rosoff and Winterfeldt, 2007). Therefore, in the event of a terrorist attack (such as a dirty bomb attack), while transportation modal substitution may not be immediately feasible given closure due to radiation, ports can start making use of rail from the port to nearby facilities, deploying additional trucks, and running additional trains to and from nearby cities immediately following the cleanup and decontamination process (Gordon et al., 2005).

5.4.3. The Role of Government Assistance

Our focus in this study is on how businesses recover from the supply disruptions they face when the port is damaged. Nearly all of the resilience tactics we examine are those that businesses are likely to implement to minimize the impact of the disruption on them individually. In fact they are tactics businesses use to avoid losing significant profits and even having to shut down permanently. Thus, many of the tactics would be implemented even without government assistance for the majority of firms, who can count on retained earnings or borrowing in credit markets. Exceptions are small businesses; however, it should be noted that many resilience tactics are not costly.

There are two exceptions to the potential important role of government. One is to fund the US Coast Guard and other government services and agencies to perform duties that may help reduce the impact of the shutdown, such as the activities of the Coast Guard and local or regional port authorities to help remove chokepoints, coordinate with landside operators, or facilitate ship-rerouting to reduce pileup of the ships, facilitate communication among port stakeholders, and arrange on-site housing for emergency responders and relief workers. This is only implicitly taken into account and held constant to reflect the characteristic of the model that market exchanges and other institutions will operate in the same manner as prior to the disruption.

The other exception pertains to any special financial assistance to accelerate debris removal, and the repair and reconstruction of port facilities. We have assumed normal recovery times in our analysis. If government assistance can accelerate this recovery process, then our loss estimates would have to be reduced.

6. Policy Recommendations

This study provides decision-makers and port related businesses with insights into the potential economic impacts from port disruptions of different magnitudes and scales. Our analysis has a particular focus on modeling the effects of various resilience tactics that can help reduce potential losses from disruptions to port operations and thus the supply-chain of the regional and national economies. The study highlights a number of actionable items that government policy makers, port stakeholders, and general businesses that rely on port operations can implement to enhance the resilience of the economy to port disruptions.

- Port disruptions have far reaching regional and national economic impacts. Port authorities and port operators thus need incentives to enhance their resiliency via emergency action plans and business continuity and recovery planning beyond their own business perspective, i.e., to take into account the impacts on the rest of the economy.

- The literature indicates that while ports are generally successful in handling and quickly recovering from small and frequent disruptions (which are most common), most of the ports are much less resilient to large, extended disruptions. Therefore, potential resilience tactics that can be implemented to tackle both the short-turn and longer-turn port disruptions should be examined and assessed in both port and business contingency plans.

- The potential of using some types of resilience tactics diminishes with time (such as use of inventories or production recapture since customers may start cancelling their orders and seeking alternative suppliers as the duration of supply interruption increases), while the possibility of using some other tactics increase over time, but up to a certain limit (such as ship re-routing). Many guidelines that are in place for ports and business continuity or recovery planning have been largely focusing on relatively short time periods. More focus on the time aspects of recovery and resilience will assist with planning for worst case or catastrophic events for which the recovery period can last for months or even years.

- Ports are operated under the effective collaboration of various stakeholders, such as port authorities, private-sector terminal operators, government agencies, vessel operators, shippers, brokers, and others who are involved in the port operation environment. Therefore, high priority should give to maintaining continuous communication and an uninterrupted flow of information in the aftermath of disaster events to expedite the response and recovery process at the ports. Many studies indicate the importance of maintaining emergency communication backup systems for the ports, such as analog pagers, wireless handheld devices, Citizens Band (CB) radios, and satellite phones.

- Port disruption as a result of different types of events, such as disruptions caused by natural disasters versus terrorist attacks, can result in different types of economic damages and ripple effects, have different recovery path, bring different public agencies into play, and call for different types of resilience tactics. All of these factors should be considered in port recovery and resilience planning to better utilize remaining resource and engage in more effective resilience tactics under different types of disaster events.

- Production recapture has been found in many practical and simulated disaster events a powerful resilience tactic to mute potential economic losses. It also requires relatively small additional cost for implementation (such as overtime pays to employees). However, it also suggests the importance of having flexible labor agreements beforehand and the use of 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.

- In this study, we focus our modeling on the economic impacts of port disruptions caused by natural disasters. Other studies in the literature indicate that fear or stigma effect from behavioral responses (by port workers and general public) to port closures caused by terrorist attacks can result in significant offsetting impacts to the effects of the various resilience tactics analyzed in this study. Development of media plans, information sharing through public messaging and information campaigns, and other attempts to guide public response have the potential for reducing the economic impacts from behavioral effects of such events at a relatively low cost.

- Our findings suggest that the effects of various resilience tactics to port disruptions vary substantially under threats of different magnitudes. Resilience tactics such as the use of inventory and production rescheduling were found to have particularly strong contribution to the reductions of economic losses in a relatively small disruption event. However, their effects decrease dramatically in large disruption event, especially when port operation is disrupted over six months. On the other hand, the effects of other resilience tactics, such as ship rerouting and export diversion increase considerably as the magnitude of port disruption enlarges.

    - Port vulnerability and resilience assessment should be considered as a critical initial step to build resilient capacity at U.S. seaports. The assessment will help port managers and operators identify the bottlenecks of the existing status quo of port resilience and the needs for improvement.

    - Resilience strategic plans should be developed to enhance the various resilient capacities in accordance with the probability of hazard risk in their specific region.

    - Given that excess capacity and ship rerouting were identified as two key port resilience tactics, more research should be undertaken to examining optimizing port and ship operations with aims to expand port operating capacity and improve the efficiency of vessel traffic dispatch.

- Future capital investment should be allocated to provide support to infrastructure projects that aim to enhance the interdependency of transportation networks.

7. Conclusion

In this study, we develop a framework to identify and evaluate the relevant set of economic resilience tactics to port disruptions. A comprehensive list of resilience tactics on both the supplier-side and customer-side relating to port disruptions are considered. The assessment of the various resilience tactics are then formally incorporated into the economic consequences analysis. A multi-regional computable general equilibrium model called TERM is adopted and applied to the assessment of the economic consequences and the effects of various resilience tactics of two port disruption scenarios with different magnitudes and durations.

The first scenario is the USGS SAFRR Tsunami Scenario. This scenario represents a lower-bound port disruption scenario, since as a hypothetical tsunami event that is generated by a distant-sourced earthquake, it is only predicted to result in a 2-day port shutdown and facility downtimes at only a few terminals up to no more than one month at three major ports in California. The second scenario, which is assumed to be caused by a more extreme local event (such as a submarine landslide offshore of the Palos Verdes Peninsula or an earthquake resulting in similar impacts as the 1995 Kobe earthquake), represents an upper-bound scenario of port disruptions at POLA/POLB. The total economic consequences of the two port disruption scenarios were assessed using the TERM model.

Our analysis extends beyond the immediate damage to ships or port facilities and evaluates the economic ripple effects beyond the ports. Essentially the curtailment of imports and exports, as well as of the port operations themselves, translates into a chain of ripple effects. For example, with an extended facility downtime at the marine oil terminals at POLA/POLB, petroleum refineries in the port area and elsewhere are unable to keep operating, and their customers will suffer from a decline in the availability of key inputs. A decrease in production in these direct customer sectors will lead to further curtailments of more customers down the supply chain.

At the same time, the economy is resilient at several levels. Ports can utilize excess capacity in undamaged facilities while a couple of damaged facilities are being repaired; ships can be re-routed to other ports; producing sectors in each round of the supply chain can use inventories and conserve inputs; and many businesses can recapture lost production by working overtime or extra shifts following the resumption of normal port operations. Resilience can greatly reduce the business interruption losses on the regional and national economies.

Our results indicate that the USGS SAFRR Tsunami Scenario (which result in a 2-day complete shutdown and extended facility downtimes that last no more than a month at a few terminals at Port of Los Angeles, Port of Long Beach, and Port of Oakland) would result in a GDP loss by $650.1 million and an employment loss of 7 thousand jobs. In the upper-bound port disruption scenario (which leads to a one-year disruption at POLA and POLB with linear recovery path), the estimated GDP loss increased to $16.3

billion GDP and the employment loss also amplified to 141 thousand jobs. However, resilience can greatly reduce the losses in both scenarios. If we examine the different resilience tactics individually, for the USGS Tsunami Scenario's various supplier-side resilience tactics, such as Excess Capacity, Ship Rerouting, and Export Diversion, can reduce the business interruption losses by about 5% to 20% each. The most effective resilience tactics are on the customer-side, Inventory Use and Production Recapture, can help reduce business interruption losses by 80% and 84%, respectively. The combined effects of all the relevant supplier-side and customer-side resilience tactics evaluated in this study have the potential to reduce the GDP and employment impacts to $16.6 million and 215 jobs, respectively, or a reduction of the economic losses in the Base Case by about 97%. As for the upper-bound disruption scenario, higher loss reductions can be potentially achieved from implementing supplier-side resilience tactics. Ship Rerouting and Export Diversion are estimated to reduce total losses by 51% and 33.5%, individually. Use of Inventories and Production Recapture are again very powerful resilience tactics on the customer-side in the upper-bound port disruption scenario; they are estimated to reduce economic losses by about 34% and 65%, respectively. The combined loss reduction effects of all the resilience tactics are about 75-78% for California and 89% for the national economy in the upper-bound scenario.

We note 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 reduction effects of potential resilience to inform and support policy implementation. The policy recommendations presented are based on the research findings and aim to provide insights to port managers and operators, as well as businesses that rely 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.

Acknowledgements

This research was supported by the California Department of Transportation (Caltrans) through USC METRANS Transportation Center. We are grateful for the helpful comments and suggestions from Lee Provost and Ted Knapp of Caltrans on this study. 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 of any of the institutions with which they are affiliated nor the institutions that funded the research.

References

Applied Technology Council (ATC). 1991. *Seismic Vulnerability and Impacts of Disruption of Lifelines in the Coterminous United States, report ATC-25*. Redwood, CA: Applied Technology Council.

Boettke, P., E. Chamlee-Wright, P. Gordon, S. Ikeda, P. Leson, II, and R. Sobel. 2007. "Political, Economic and Social Aspects of Katrina," *Southern Economic Journal* 74(2): 363-76.

Bohannon, R. and Gardner, J., 2004. "Submarine landslides of San Pedro Escarpment," *Marine Geology* 203: 261-268.

Borrero, J., Cho, S., Moore, J., II, Richardson, H., and Synolakis, C. 2005. "Could it Happen Here?" *Civil Engineering* 75(4): 54-65.

Bruneau, M., S. Chang, R. Eguchi, G. Lee, T. O'Rourke, A. Reinhorn, M. Shinozuka, K. Tierney, W. Wallace and D. von Winterfeldt. 2003. "A Framework to Quantitatively Assess and Enhance Seismic Resilience of Communities," *Earthquake Spectra* 19: 733–752.

Bureau of Economic Analysis (BEA). 2016. *2014 Real Inventories and Sales Data*. Available at: https://www.bea.gov/iTable/iTable.cfm?ReqID=12&step=1#reqid=12&step=1&isuri=1

Chang, S.E. 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.

Chang, S.E. and M. Shinozuka, 2004. "Measuring Improvements in the Disaster Resilience of Communities," *Earthquake Spectra* 20(3):739-755.

Chernick, H. ed. 2005. *Resilient City*. New York: Russell Sage Foundation.

City College of New York (CUNY). 2013. "Final Report: Lessons from Hurricane Sandy for Port Resilience". University Transportation Research Center. Retrieved from: http://ntl.bts.gov/lib/51000/51200/51237/Final-Hurricane-Sandy-Resilience.pdf

Congressional Budget Office (CBO). 2006. *The Economic Costs of Disruptions in Container Shipments*. Available at: http://www.cbo.gov/ftpdocs/71xx/doc7106/03-29-Container_Shipments.pdf.

Dixon, P., B. Lee, T. Muehlenbeck, M. Rimmer, A. Rose, and G. Verikios. 2010. "Effects on the U.S. of an H1N1 Epidemic: Analysis with a Quarterly CGE Model," *Journal of Homeland Security and Emergency Management* 7(1): Article 7.

FEMA. 2015. *HAZUS Earthquake Model Technical Manual*. Available at: http://www.fema.gov/media-library/assets/documents/24609.

Flynn, S. 2008. "America the Resilient: Defying Terrorism and Mitigating Natural Disasters," *Foreign Affairs* 87: 2-8.

Giesecke, J., W. Burns, A. Barrett, E. Bayrak, A. Rose, P. Slovic and M. Suher. 2012. “Assessment of the Regional Economic Impacts of Catastrophic Events: A CGE Analysis of Resource Loss And Behavioral Effects of a Radiological Dispersion Device Attack Scenario,” *Risk Analysis* 32: 583-600.

Gordon, P., Moore II, J., Richardson, H. and Pan, Q. 2005. “The Economic Impact of a Terrorist Attack on the Twin Ports of Los Angeles-Long Beach,” Los Angeles, CA: Center for Risk and Economic Analysis of Terrorism Events (CREATE), pp. 1-25. Retrieved from: http://ise.usc.edu/assets/007/64865.pdf

Horridge, M., Madden, J., & Wittwer, G. 2005. The Impact of the 2002–2003 Drought on Australia. *Journal of Policy Modeling 27*(3): 285-308.

Fischhoff, B., P. Slovic, S. Lichtenstein, S. Derby, and R. Keeney. 1981. *Acceptable Risk*, New York: Cambridge.

Horwich, G. 1995. “Economic Lessons of the Kobe Earthquake,” *Economic Development and Cultural Change* 48(3): 521-542.

IMPLAN Group LLC. 2013. *Impact Analysis for Planning (IMPLAN) 2012 California State Package I-O Data*. Huntersville, NC.

Jung, J., J.R. Santos and Y.Y. Haimes. 2009. “International Trade Inoperability Input-Output Model (IT-IIM): Theory and Application,” *Risk Analysis* 29: 137–154.

Kia, M., E. Shayyan, and F. Ghotb. 2002. “Investigation of Port Capacity Under a New Approach by Computer Simulation,” *Computers & Industrial Engineering* 42(1): 533-540.

Locat, J., Lee, H., Locat, P., and Imran, J., 2004. “Numerical analysis of the mobility of the Palos Verdes debris avalanche, California,” *Marine Geology* 203: 269-280.

Mansouri, M., R. Nilchiani, and A. Mostashari. 2010. “A policy making framework for resilient port infrastructure systems,” *Marine Policy* 34(6): 1125-1134.

Miller, K., and Long, K. 2013. “Emergency management response to a warning-level Alaska-source tsunami impacting California,” chap. J in Ross, S.L., and Jones, L.M., eds., *The SAFRR (Science Application for Risk Reduction) Tsunami Scenario*: U.S. Geological Survey Open-File Report 2013–1170, 245 p., http://pubs.usgs.gov/of/2013/1170/j/.

Moffatt & Nichol. 2012. *Tsunami Scenario Engineering Impacts of Port of Long Beach and Port of Los Angeles*. Report to USGS.

Moffatt & Nichol. 2014. *Tsunami Scenario Engineering Impacts of Port of Richmond, Oakland, Hueneme and San Diego*. Report to USGS.

Nair, R., H. Avetisyan and E. Miller-Hooks. 2010. “Resilience Framework for Ports and Other Intermodal Components,” *Transportation Research Record: Journal of the Transportation Research Board* 2166: 54-65. Retrieved from: http://trrjournalonline.trb.org/doi/pdf/10.3141/2166-07

National Association of Manufacturers. 2014. "The National Impact of a West Coast Port Stoppage," *Inforum Report Commissioned by the National Association of Manufacturers and the National Retail Federation*. Retrieved from: https://nrf.com/sites/default/files/Port%20Closure%20Full%20Report.pdf

Novati, M., P. Achurra-Gonzalez, R. Foulser-Piggot, G. Bowman, M. Bell, and P. Angeloudis. 2014. "Modelling the Effects of Port Disruptions: Assessment of Disaster Impacts Using a Cost-Based Container Flow Assignment in Liner Shipping Networks," *Transportation Research Board 94th Annual Meeting*. Retrieved from: http://docs.trb.org/prp/15-4799.pdf

Paixao, A. and P. Marlow. 2003. "Fourth generation ports - a question of agility?" *International Journal of Physical Distribution and Logistics Management* 19(1): 29-41.

Pant, R. et al. 2011. "Interdependent Impacts of Inoperability at Multi-modal Transportation Container Terminals," *Transportation Research Part E: Logistics and Transportation Review* 47(5): 722-737.

Park, J.Y. 2008. "The Economic Impacts of a Dirty-Bomb Attack on the Los Angeles and Long Beach Port: Applying Supply-Driven NIEMO," *Journal of Homeland Security and Emergency Management* 5(1): 1–20, Article no. 21.

Park, J.Y., P. Gordon, J. Moore II and H. Richardson. 2008. "The State-by-State Economic Impacts of the 2002 Shutdown of the Los Angeles-Long Beach Ports," *Growth and Change* 39: 548–572.

Park, J.Y., P. Gordon, J.E. Moore II, H.W. Richardson and L.Wang. 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 and J.E. Moore II (eds.) *The Economic Costs and Consequences of Terrorism*. Cheltenham, UK, Edward Elgar, 208–234.

Pate, A., B. Taylor, and B. Kubu. 2008. "Protecting America's Ports: Promising Practices," United States Department of Justice, Washington, DC. Found in Downloads.

Paul, J. and M. Maloni. 2010. "Modelling the effects of port disaster," *Maritime Economic and Logistics*, 12(2): 127-146.

Port of Long Beach. 2016. *Map of the Port by Cargo Type*. Available at: http://www.polb.com/facilities/maps/cargo.asp

Port of Oakland. 2016. *Map of Port of Oakland Maritime Facilities*. Available at: http://www.portofoakland.com/files/pdf/maritime/mari_map.pdf

Rice, J. and K. Trepte. 2012. "The MIT CTL Port Resilience Survey Report," MIT Center for Transportation & Logistics, Cambridge, MA. Retrieved from: http://ctl.mit.edu/sites/default/files/Port%20resilience%20survey%20report%20v27%20sans%20SEM.pdf

Rose, A. 1984. “Technological Change and Input-Output Analysis,” Socio-Economic Planning Sciences 18(5): 305-318; reprinted in K. Haynes et al. (eds.), Modern Classics in Regional Science, Vol. 2, Regional Dynamics, Cheltenham, UK: Edward Elgar Publishing Co.

Rose, A. 2004. “Defining and Measuring Economic Resilience to Disasters,” *Disaster Prevention and Management* 13: 307-14.

Rose, A. 2005. *Tracing Infrastructure Interdependence Through Economic Interdependence*. USC CREATE Research Report. http://research.create.usc.edu/cgi/viewcontent.cgi?article=1127&context=nonpublished_reports.

Rose, A. 2007. "Economic Resilience to Disasters: Multidisciplinary Origins and Contextual Dimensions," *Environmental Hazards: Human and Social Dimensions* 7(4): 383-98.

Rose, A. 2009a. *Economic Resilience to Disasters*. Community and Regional Resilience Institute Research Report 8, 40 p., accessed August 13, 2013, at http://www.resilientus.org/wp-content/uploads/2013/03/Research_Report_8_Rose_1258138606.pdf.

Rose, A. 2009b. “A Framework for Analyzing and Estimating the Total Economic Impacts of a Terrorist Attack and Natural Disaster,” *Journal of Homeland Security and Emergency Management* 6(1): 1–27, Article no. 9.

Rose, A. 2015a. “Macroeconomic Consequences of Terrorist Attacks: Estimation for the Analysis of Policies and Rules," in V. K. Smith and C. Mansfield (eds.), *Benefit Transfer for the Analysis of DHS Policies and Rules*, Cheltenham, UK: Edward Elgar, pp. 172-201.

Rose, A. 2015b. *A Methodology for Incorporating Cyber Resilience into Computable General Equilibrium Models*. Report to USGS.

Rose, A. 2016. “Economic Resilience to Terrorism and Natural Disasters,” in A. Abbas, M. Tambe and D. von Winterfeldt (eds.), *Improving Homeland Security Decisions*, Camabridge University Press, forthcoming.

Rose, A. and D. Wei. 2013. “Estimating the economic consequences of a port shutdown: the special role of resilience,” *Economic Systems Research* 25(2): 212-232.

Rose, A. and E. Krausmann. 2013. “An Economic Framework for the Development of a Resilience Index for Business Recovery,” *International Journal of Disaster Risk Reduction* 5: 73-83.

Rose, A. and S. Liao. 2005. “Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions,” *Journal of Regional Science* 45(1): 75-112.

Rose, A., G. Oladosu, and S. Liao. 2007. “Business Interruption Impacts of a Terrorist Attack on the Electric Power System of Los Angeles: Customer Resilience to a Total Blackout,” *Risk Analysis* 27: 13-31.

Rose, A., G. Oladosu, B. Lee and G. Beeler Asay. 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: Article 6.

Rose, A., Sue Wing, I., Wei, D., and Wein, A. 2016. "Economic Impacts of a California Tsunami," *Natural Hazards Review*, 10.1061/(ASCE)NH.1527-6996.0000212, 04016002.

Rosoff H. and D. Von Winterfeldt. 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.

SAFRR Tsunami Scenario Modeling Working Group. 2013. "Modeling for the SAFRR Tsunami Scenario: Generation, Propagation, Inundation, and Currents in Ports and Harbors," Chapter D in S. Ross and L. Jones eds., *The SAFRR (Science Application for Risk Reduction) Tsunami Scenario*: U.S. Geological Survey Open-File Report 2013–1170, 168 p., http://pubs.usgs.gov/of/2013/1170/d/.

Sheffi, Y. 2005. *The Resilient Enterprise*. Cambridge, MA: MIT Press.

Smythe, T. 2013. "Assessing the impacts of Hurricane Sandy on the Port of New York and New Jersey's Maritime responders and response infrastructure." Natural Hazards Center. Retrieved from: http://www.colorado.edu/hazards/research/qr/submitted/smythe_2013.pdf.

Southworth, F., J. Hayes, S. McLeod, and A. Strauss-Wieder. 2014. "Making US Ports Resilient as Part of Extended Intermodal Supply Chains," National Cooperative Freight Research Program Report 30. Retrieved from: http://onlinepubs.trb.org/onlinepubs/ncfrp/ncfrp_rpt_030.pdf.

Sue Wing, I., A. Rose, D. Wei, and A. Wein. 2015. "Impacts of the USGS ARkStorm Scenario on the California Economy," *Natural Hazards Review*, 10.1061/ (ASCE) NH.1527-6996.0000173, A4015002.

Thekdi, S. and J. Santos. 2015. "Supply Chain Vulnerability Analysis Using Scenario-Based Input-Output Modeling: Application to Port Operations," *Risk Analysis* 36(5): 1025-1039.

Tierney, K. J. 1997. "Business Impacts of the Northridge Earthquake," *Journal of Contingencies and Crisis Management* 5(2): 87-97.

Trepte K. and J. Rice. 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.

United States Government Accountability Office. 2007. "Port Risk Management: Additional Federal Guidance Would Aid Ports in Disaster Planning and Recovery," Washington, DC. Retrieved from: http://www.gao.gov/assets/260/258193.pdf

U.S. Geological Survey (USGS). 2013. *The SAFRR (Science Application for Risk Reduction) Tsunami Scenario*. Available at: http://pubs.usgs.gov/of/2013/1170/.

Wein, A., and A. Rose. 2011. "Economic Resilience: Lessons from the ShakeOut Earthquake Scenario," *Earthquake Spectra: Special Issue on the ShakeOut Earthquake Scenario* 27(2): 559-73.

Wein, A., Rose, A., Sue Wing, I., and Wei, D. 2013. *Economic impacts of the SAFRR tsunami scenario in California: Chapter H in The SAFRR (Science Application for Risk Reduction) Tsunami Scenario* (No. 2013-1170-H). US Geological Survey.

Wittwer, G. (Ed.). 2012. *Economic Modeling of Water: The Australian CGE Experience*. Heidelberg: Springer Science & Business Media.

Zhang, Y. and J. Lam. 2015. "Estimating the economic losses of port disruption due to extreme wind events," *Ocean and Coastal Management* 116(1): 300-310.

Zhang, Y. and J. Lam. 2016. "Estimating economic losses of industry clusters due to port disruptions," *Transportation Research Part A: Policy and Practice* 91(1): 17-33.

Zolli, A. and A. M. Healy. 2012. *Resilience: Why Things Bounce Back*. New York: Free Press.

Appendix A. Literature Review of Studies on Port Resilience

Appendix Table A. Port Resilience Literature Review Summary Table

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
City College of New York (2013)	Lessons from Hurricane Sandy for Port Resilience	Report	Case Study & Interviews	Hurricane Sandy; New York & New Jersey; Most of the East Coast affected; Entire port closed from October 28 - November 4, other facilities were closed for "several additional weeks";	Definition of resilience: "The capability of a port to provide and maintain an acceptable level of service in the face of major environmental changes or disruptions." Recommendations for future disasters: Remove chokepoints, increase backup generators and fuel capacity, increase communication both within and outside the port, effective management; Static; Adaptive; Supply-side	Qualitative; Focus was on Hurricane Sandy but the suggested actions are broad enough where it can be helpful in other situations	• **Event**: Power was lost which led to seawater flooding after the generators ran out of fuel. The outage also prevented proper communication which further exacerbated the situation. • **Recommendations**: Pre-event preparations for Physical systems: remove choke points (cause obstacles), building redundancy within terminal facilities through both designed and excess capacity of inputs Pre-event prep for human systems: define goals, roles, and responsibilities and outline how to achieve those goals, establish a communication plan, distribute contact info. Post-event activities for physical systems: incident command center, survey impacts, prioritize, allocate resources. Post-event activities for human systems: communication network among staff, share info, highlight successes as you go, allow collaboration between public-private (improving effective management). • While the opening of the port was successful there were considerably more issues with improving the landside surrounding the area (such as with points of transfer for cargo, through truck or rail).
Trepte, K., and J. Rice (2014)	An Initial Exploration of Port Capacity Bottlenecks in the USA Port System and the Implications on Resilience	Journal Article	Estimated the capacity of system to absorb the cargo from a disrupted source: First, measured the amount of cargo by commodity type for the relevant ports; then looking at port disruptions (33 incidents from 2004 to 2010); an assumption was made that disruptions of varying degrees happen regularly. Assuming that the	No specific disruption scenario simulated(The 33 events were studied to establish the fact that disruptions ranging from 6 to 20 days in duration occur with regular frequency) Analyzed the port system as a whole, rather than looking at individual ports	Definition of resilience: "Capability to handle and withstand disruptions to continue [services]." Cooperating with nearby ports to take in extra cargo during a disruption event which prevents ports from backing up and slowing down recovery even more; Static; Adaptive; Supply-side	Quantitative: Study assumes complete disruption of a port.	The following commodities require the associated clearing capacity in order to absorb another port's cargo on any one particular day of a complete disruption: Container (LA and LB): 26% Manufactured Equipment (LA and LB): 18% All other (LA and LB): 16% Manufactured Goods (LA): 7% Insights relating to port-competitiveness: This clearing capacity associated with the entire system (all other US ports) highlights the importance of cooperation among ports towards resilience. With cooperation, "it is

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
			volume of a port is split proportionally among all ports that handle that particular commodity, a carrying capacity was determined (percentage of capacity needed above normal operation for commodity to be absorbed into the port system).				possible stakeholders would see a double benefit of resilience and increased throughput across more than one commodity.” Specifically, cooperating with the Oakland port/Northeast ports would benefit Los Angeles and Long Beach in the long run Observing the importance of certain commodities, the volume and cost of said commodities, as well as the clearing capacity required for said goods can help direct investments towards worthwhile ports.
Mansouri, M., R. Nilchiani, and A. Mostashari (2010)	A Policy Making Framework for Resilient Port Infrastructure Systems	Journal Article	Using a Risk Management-based Decision Analysis framework regarding Port Infrastructure Systems, vulnerabilities can be identified in actual ports. (secondary data)	Analysis of vulnerabilities using the RMDA framework (range of threats include human action, technological failure, and extreme weather); Port of Harbor; Depending on event disruption ranges from 2 - 90 days;	Definition of resilience: “Its adaptive capacity in recovering to an acceptable level of service within a reasonable timeframe after being affected by disruption” Monitoring cargo throughout the entire process, Redundancy for the information systems of the port and waterway control systems of the ships/design an effective support and maintenance system for the facilities, Maintain set of operational equipment in secured area and construct ready-to-use platforms that can be employed at time of disruption; Static, Inherent, Supply-side	Quantitative; Focus in on three broad categories of disruption (human, nature, and technology)	Resiliency should focus on: • Human-based threats: Integrated security and safety design. • Technology: Technological redundancy investment. • Nature: Infrastructural redundancy and support investment. Suggests a framework that employs decision trees to measure cost-effectiveness of different resiliency options (highlights probability of an event). The integrated security and technological resilience strategies (estimated cost of $150m and $20m, respectively) are financially viable options compared to the expected losses that can be avoided given the reduction of risks related to these resilience tactics ($185m and $28m). Infrastructural Redundancy is not a viable option however given its estimated implementation cost of $250m and expected avoided loss of $155m.

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
Nair, R., H. Avetisyan, and E. Miller-Hooks (2010)	Resilience Framework for Ports and Other Intermodal Components	Journal Article	Representation of the network (processes, stakeholders, terminals, etc.), disruption scenarios developed, evaluation of all recovery tools available.	Five disruption scenarios incorporated within a framework (two terrorist, arson, earthquake, flooding); Limited to the port in these scenarios; Port of Swinoujscie in Poland;	Definition of resilience: "The post disruption fraction of demand that can be satisfied by using specific resources while maintaining a prescribed level of service" Resilience measures are focused on: Road, Railroad, Yard Moves, Gantry Crane, Sea Link, and Storage; include any actions that can be taken in the short-term (defined as anywhere from immediate implementation to requiring 300 hours) in order to recover some aspect of the port network as a means of increasing capacity to satisfy demand. (Actions are listed on page 60 of the article) Inherent, Static, Supply-side	Quantitative; Any type of disruption event	Focus is on recovery actions that can be taken immediately following a disruption event. The paper break down scenarios not only by type of disruption but where the event takes place within the port. As such, the actions are first broken down by area of the port and then followed by a list of actions. Similar to the Mansouri et al. (2010) paper, mentions that decisions on resiliency options should incorporate probability of events. Through incorporating the probability of different disruption scenarios, this study concluded that a budget of $10,000 can increase the demand to be satisfied from 77% (zero resilience) to 87%; and to about 99% with $100,000 budget for one of the disruption scenarios developed. Costs of actions range from no cost to $300,000 and require an average of 26 hours to implement.
Paixao, A. and P. Marlow (2003)	Fourth Generation Ports - a Question of Agility?	Journal Article	Discusses the concept of just-in-time (JIT) and how it applies to the leanness and agility of a port as well as how to implement it with a port.	No specific disruption scenario: Discusses port improvement from a cost-effective standpoint. However, it frames the port as a logistic system and discusses how to improve the port's leanness and agility in responding to volatile situations.	No definition of resilience mentioned. Improving the leanness and agility of the port Leanness and Agility: Lean production Theory: Lends towards agility of the port. Production levels match demand which places an emphasis on improving ports' production processes (i.e. moving cargo quickly as possible through port to increase value). Paper lists a range of benefits on page 361. Agility: Strategy responsible for strengthening links between internal and external business environments; can lend towards enhancing ship-rerouting capabilities Static; Adaptive; Supply-side	Qualitative; Any type of disruption event	Port-Competitiveness: - Necessary storage can be reduced allowing for more investments (storage constitutes 20-30% of total logistic costs) - Study claims that total regular port operation costs can be reduced by between 10% and 40%. - Industries that have implemented similar techniques saw a reduction in cycle time of up to 50% (which will reduce costs for customers). External integration requires port networking: a group of ports that are willing to work together in order to achieve desired levels of quality and customer service, share information, and build long-term relationships. JIT transforms ports into more of a distributor rather than warehouse which lends towards development and availability of alternative routes. This additionally frees up space due to lack of need for storage which can allow for fuel, generators, and other important inputs to be stored instead that can enhance port resilience to extreme events.

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
Pate, A., B. Taylor, and B. Kubu (2008)	Protecting America's Ports: Promising Practices	Report	Background information on ports and port security; Created a project advisory board of stakeholders for America's ports; Visited Ports (17 that were considered most important to security) and conducted interviews	Focus on potential terrorist attacks on what is considered the 17 most important ports within the U.S. Lists "promising practices" (as opposed to best practices because situations differ between ports and what is best for one isn't necessarily the best for others).	No definition of resilience mentioned. In-depth training exercises, stronger partnerships with stakeholders to enhance effective management capability in the aftermath of extreme events; Static, Adaptive, Supply-side	Qualitative; Focus on terrorist attacks of any type	Preparedness: Models, Simulations, and Games (MS&G) - Better prepare first responders to a disruption event. Experience dangerous events prior to them happening (captures that experience variable that often helps with resilience). Response: Exercise and Training - (Given the focus on terrorist events, the assumption is that response will involve the cooperation of Federal, State, and local authorities). - Benefits all partners by working out any issues prior to an actual event Team Responses - Need for strong partnerships in responding to a disruption - Some cities have set up training programs for specific departments (e.g., Boston set up a firefighting program that focused on ship-based fires)
Rice, J. and K. Trepte (2012)	The MIT CTL Port Resilience Survey Report	Report	Literature review Survey of port practitioners and other actors within this industry (i.e., shippers, carriers, terminal operators, port authorities, etc.). Survey collected data on opinions regarding critical operating systems, processes, and experience data on delays. Structural Equation Modeling method used to extract data from survey and determine what is associated with resilience.	Survey measures any experienced disruptions respondents have gone through in the past 5 years (2005-2010). About half of the respondents reported disruption frequency annually or less frequent. A third reported short events (.5 – 1,5 days) that occurred quarterly or more frequently.	Definition of resilience: "The ability of the port environment (whether it is an individual port or system of regional or national ports) to react to unexpected disruption and restore normal cargo handling and port operations." Flexible labor agreements, Improve land transportation availability, Flexible inter-port agreements, Reconfigure/improve gate operations, Flexible intra-ort agreements, Add terminal capacity – more equipment, Add terminal capacity – more berths, Add equipment – channel cleaning, Improve communications/information services, Modify waterways, Modify vessel design, Add equipment – more vessels to coordinate, Modify waterway coordination systems, Add utility capacity. Adaptive, Static, Supply-side	Qualitative: Survey is based on experiences of past disruptions. Focus of study placed on aspects of port	The survey found that respondents view processes (specifically communication/information services and flexible labor agreements) as being more critical to resilience than capacity-building measures. Infrequent delays in the components of the port result in frequent delays elsewhere within the port. There is no consensus among stakeholders within the port system about which actions are most important towards the resiliency of the port system. Capacity measures can be important towards enhancing resilience from major disruptions. Small, frequent disruptions suggest that ports are generally resilient against small events. However, ports struggle against large infrequent disruptions, especially those that affect infrastructure.

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
Rose, A. and D. Wei (2013)	Estimating the Economic Consequences of a Port Shutdown: The Special Role of Resilience	Journal Article	Estimation of total economic consequences of a port disruption factoring in for resilience. Uses demand-driven and supply-driven input-output models.	Simulated disruption; Twin seaports of Beaumont and Port Arthur, Texas; a 90-day disruption	Definition of resilience: "Static Economic Resilience refers to the ability or capacity of an entity or a system to maintain functionality when shocked." "dynamic economic resilience refers to the ability to hasten the speed at which an entity or a system recovers from a severe shock to achieve a desired state. It involves a long-term investment problem associated with repair and reconstruction processes" Resilience options included: ship re-routing, export diversion, use of inventories, conservation, unused capacity, input substitution, import substitution, production recapture; Inherent and Adaptive; Static; Supply-side and Customer-side	Quantitative; Any type of disruption event	Shutdown of Port Arthur/Beaumont would result in $13 billion (72.5% of output of the port region). Resilience can reduce loss by two-thirds. Underscores importance of resiliency in mitigating economic losses from port disruption and highlights the indirect business interruptions that occur along the supply chain. Measures and compares the effectiveness of alternative resilience tactics by comparing their respective loss reduction potentials. Most effective resilience tactics are production recapture and ship re-routing.
Southworth F., J. Hayes, S. McLedo, and A. Strauss-Wieder (2014)	Making US Ports Resilient as Part of Extended Intermodal Supply Chains	Report	Interviews with experts within seaport-inclusive freight supply chains; Case studies of Port of New York and New Jersey following Hurricane Sandy & the closing of marine ports along Columbia River	First Scenario: Hurricane Sandy, Most of the East Coast, Port of NY & NJ were impacted; Entire port closed from October 28 - November 4, Length of recovery period is defined as time it takes to return most container terminals to operation. In this case, a week. However major repairs continued for weeks afterwards; Second Scenario: Extended (14-week) lock closures of the Columbia River in the Pacific Northwest;	Definition of resilience: "The ability of a seaport to withstand and bounce back quickly from a serious threat to its ability to process freight in an efficient and cost-effective manner." Inherent; Static; Supply-side (relief workers can be used to push cargo through quicker)	Qualitative; Any type of disruption event. However, actions were listed in relation to different themes of a port such as physical infrastructure, regulation, and communication.	Communication and flow of information are considered the most important factor in returning operations to normal; Prioritize importance of vessels as they arrive post-disruption Harden inland connection facilities; coordinate with landside operators to clear port and/or divert cargo to/from alternative ports. Alternatives for accessing/bringing emergency power to the port (i.e. solar power, micro-grid technologies) Stabilize and relocate important equipment to higher ground outside of risk areas. Arrange on-site housing for critical staff, emergency responders, and relief workers.

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
Smythe, T. (2013)	Assessing the Impacts of Hurricane Sandy on the Port of New York and New Jersey's Maritime Responders and Response Infrastructure	Report	Multiple interviews with relevant individuals of the Hurricane Sandy/Port of NY and NJ situation	Hurricane Sandy, which mainly impacted New York & New Jersey; most of the East Coast also affected; Entire port closed from October 28 - November 4, other facilities were closed for "several additional weeks";	Definition of resilience: Differed depending on each interview. Some described it as the strength of the supply chain, the ability for infrastructure to bounce back from disasters, and the strength of the relationships between port partners. Resiliency measures are based on storage of fuel resources, additional means of communication, flexibility of personnel, formal organization of port governance. Inherent, Adaptive; Static; Supply-side	Qualitative; More so to natural disasters than man-made	Coordination of two port committees (Area Maritime Security Committee - AMSC & Harbor Ops Committee) which includes members from private and public sector who convene regularly to discuss and plan -- This builds social capital (relationship and trust which is more effective when established before a crisis). Power and Fuel: Considered one of the most serious issues once generators ran out. It exacerbated many issues involving communication, moving product, and safety. Also prevented the port from moving petroleum products which led to a fuel shortage beyond the port. Waterfront Infrastructure: Elevating structures or improved design features could prevent saltwater flooding especially for electrical infrastructure. Personnel Management: Transportation to and from the port was compromised which led to issues for evacuated workers trying to return. Additionally, some were required to evacuate their housing and couldn't return to work for an extended period of time. Can be solved by training personnel to operate under multiple capacities. Also mentioned was using emergency ferry services as dockside housing for relief workers.
Kia, M., E. Shayn, and F. Ghotb (2002)	Investigation of Port Capacity Under a New Approach by Computer Simulation	Journal Article	Statistical analysis of port operations (including number of ship visits, inter-arrival time, ship's time at berth, number of straddle carriers, etc.) which is then modelled in simulation software.	No incident. Purpose is an evaluation of port performance and impacts on capacity.	No definition of resilience mentioned. Introduction of a model in which a majority of imported containers are taken away via rail to inland distribution centers where trucks then transport the containers. Inherent; Static; Supply-side	Quantitative; Increases port capacity which can aid in a number of different disruption events	Port-competitiveness: Container carriers and straddle carriers within terminals lead to significant congestion. Ship's time at berth (in the simulation) reduced by 8% leading to $2.7m in savings per annum. Less strain on the environment due to more efficient transportation of containers. Model also creates more available space and reduces ship's time at port.

Author(s) or Organization	Title	Type of Publication	Method of Analysis	Incident of focus	Type of resilience measures analyzed	Effectiveness and Applicability of Resilience Measures	Major Research Findings & Policy Implications
United States Government Accountability Office (2007)	Port Risk Management: Additional Federal Guidance Would Aid Ports in Disaster Planning and Recovery	Report	Reviewed 17 different ports that varied in size and degree by which they had experienced some type of natural disaster since 1998; Review consisted of reading through planning docs for the ports, visits to 7 of the ports and interviews with stakeholders, and phone interviews for remaining 10.	Focus was on 2005 hurricane season.	No definition of resilience mentioned. Diversifying communication capabilities, partnering with other ports, combining disruption plans to increase efficiency of personnel and use of resources Static, adaptive; supply-side	Qualitative; Any type of disruption event	Communication alternatives: Does not rely on traditional landlines such as analog pagers, wireless handheld devices, CB radios, satellite phones. 1-800 phone numbers to receive calls from port personnel. Alternative area codes and out of state call centers. Partner with other ports to use facilities in an emergency as an alternate operation site (Port of New Orleans and Port of Shreveport agreed to cost sharing efforts for information technology infrastructure upgrades to better accommodate New Orleans' needs). Combining port-level natural disaster planning and security planning to increase efficiency of port planning efforts and resource management. Greatest challenges port officials experienced: • Communications - both outside the port and within. • Personnel - evacuation of personnel led to problems with locating them later for work • Coordination - especially in planning and recovery efforts. Coordination with local, state, and federal

Appendix B. TERM Model Sectoring Scheme

Appendix Table B1. Concordance between the 97 Aggregated Sectors and TERM 512 Sectors

Aggregated Sector #	Short names	Aggregated Sector Name	TERM Sector #*
1	Crops	Crops	1-6,8-9,11-13,15-16,18,20-28,30
2	PoultryEggs	Poultry & Eggs	7
3	Livestock	Livestock	10,14,17,29
4	OthLivestock	Other Livestock	19
5	ForestFrsHnt	Forestry, Fishing, & Hunting	31-35
6	OilGas	Oil & Gas	36,44-45
7	Coal	Coal	37
8	OtherMining	Other Mining	38-43,46
9	BiomassGen	Biomass electricity generation	47
10	CoalsGen	Coal-fired electricity generation	48
11	GasGen	Gas-fired electricity generation	49
12	HydroGen	Hydroelectric generation	50
13	NuclearGen	Nuclear electricity generation	51
14	RenewGen	Renewable electricity generation	52
15	ElecDist	Electricity distribution	53
16	NatGasDist	Natural gas distribution	54
17	WaterSewage	Water and sewage services	55
18	ResidConstrt	Residential Construction	56-59
19	OthConstruct	Highway Construction	62
20	HwyBrdgCons	Other Non-Residential Construction	60-61,63-64
21	OthMaintain	Highway Maintenance	67
22	MRstreets	Other Maintenance	65-66,68
23	FoodProc	Food Processing	69-107
24	BevTobManu	Beverage & Tobacco Product Manufacturing	108-114
25	Textiles	Textile & Textile Product Manufacturing	115-128
26	Apparels	Apparel	129-130
27	LeathFtwr	Leather & Allied Products	131-133
28	WoodProds	Wood Product Manufacturing	134-145
29	PulpPaperPbd	Paper Mills	146-158
30	Printing	Printing & Related Support Activities	159-163
31	PetrolRefine	Petroleum Refineries	164
32	OthPetrolCl	Other Petroleum & Coal Products	165-168
33	Chemicals	Chemicals	169-192
34	RubPlastic	Rubber & Plastics	193-202
35	NonMetMinPrd	Non-Metallics	203-223
36	PrimMetals	Primary Metal Manufacturing	224-237
37	FabriMetals	Fabricated Metal Product Manufacturing	238-270
38	AgriMachinry	Agriculture Machinery	271-275

39	IndustrMach	Industrial Machinery	276-283
40	CommrcMach	Commercial Machinery	284-288
41	AirConHeat	Ventilation, Heating & Air-Conditioning	289-292
42	MetalWkMach	Metalworking Machinery	293-298
43	TurbnEngine	Engines & Turbines	299-301
44	OtherMach	Other General Purpose Machinery Manufacturing	302-315
45	Computers	Computers	316
46	CmptrStorage	Computer Storage Devices	317
47	ComptrTrmEtc	Computer Terminals & Other Peripheral Equipment	318-319
48	CommunicEqp	Communications Equipment	320-322
49	MscElctEqp	Miscellaneous Electronic Equipment	323-324,326-332
50	Semicondctr	Semiconductors & Related Devices	325
51	ElecInstrmnt	Electronic Instruments	333-338
52	HholdEqp	Household Equipment, Appliances, and Component Manufacturing	339-357
53	MVPManu	Motor Vehicle and Parts Manufacturing	358-364
54	AerospaceMan	Aerospace Product & Parts Manufacturing	365-369
55	RlrdCars	Railroad Rolling Stock Manufacturing	370
56	ShipsBoats	Ship & Boat Building	371-372
57	OthTrnEqp	Other Transportation Equipment Manufacturing	373-375
58	Furniture	Furniture & Related Product Manufacturing	376-387
59	MiscManuf	Miscellaneous Manufacturing	388-403
60	WholesaleTr	Wholesale Trade	404
61	AirTrans	Air Transport	405
62	RailTrans	Rail Transport	406
63	WaterTrans	Water Transport	407
64	TruckTrans	Truck Transport	408
65	GrdPassTrans	Transit and Ground Passenger Transport	409
66	Pipeline	Pipelines	410
67	OthTransprt	Other Transportation	411-413
68	Warehousing	Warehousing	414
69	RetailTr	Retail Trade	415
70	Publishing	Publishing Industries	416-420
71	MovieSound	Motion Picture & Sound Recording Industry	421-422
72	BroadcastSrv	Broadcasting	423-424
73	Telecomm	Telecommunications	425
74	InfoSvce	Information Services	426
75	DataProcScv	Data Processing Services	427
76	FinancBank	Finance & Banking	428-433
77	RealEstate	Real Estate	434
78	RentLease	Rental & Leasing Services	435-438
79	AssetLessors	Lessors of Nonfinancial Intangible Assets	439
80	PrfSciTchSrv	Professional, Scientific, Technical, Administrative, & Support Services	440-462
81	WasteMgmt	Waste Management Services	463
82	Education	Education Services	464-466
83	HealthSocAs	Health Care & Social Assistance	467-473
84	ArtsRecreat	Arts, Entertainment & Recreation	474-481
85	Accommodatn	Accomodations	482-483
86	EatDrinkPlce	Eating & Drinking Places	484
87	OthService	Other Services	485-497

88	GovEnterprs	Owner-Occupied Dwellings	502
89	StaLocGov	Government Enterprises	498-499
90	OwnOccDwell	State & Local Government	500-501,505
91	FedGovt	Federal Government	503-504
92	Holiday	Holiday	506
93	FgnHol	Foreign Holidays	507
94	ExpTour	Tourism Exports (including Purchases by Foreigners in Embassies etc.)	508, 510
95	ExpEdu	Education Exports	509
96	WT_EXP	Water Transport Exports	511
97	AT_EXP	Air Transport Exports	512

* See the description of the 512 TERM sectors in Appendix Table B2.

Appendix Table B2. Description of 512 TERM Sectors

	Short name	Description		Short name	Description
1	HayForage	Hay & forage	47	BiomassGen	Biomass electricity generation
2	Almonds	Almonds	48	CoalsGen	Coal-fired electricity generation
3	Apples	Apples	49	GasGen	Gas-fired electricity generation
4	OthFruitNuts	Other fruit & nuts	50	HydroGen	Hydroelectric generation
5	Vegetables	Vegetables	51	NuclearGen	Nuclear electricity generation
6	OthBroadAcre	Other broadacre	52	RenewGen	Renewable electricity generation
7	PoultryEggs	Poultry and eggs	53	ElecDist	Electricity distribution
8	SugarCane	Sugar cane	54	NatGasDist	Natural gas distribution
9	OilSeeds	Oilseeds	55	WaterSewage	Water and sewage services
10	BeefCattle	Beef cattle	56	NRes1Nonfarm	Single family residential building construction
11	MiscelAgri	Miscellaneous agriculture	57	MulResNonf	Multifamily housing construction
12	Corn	Corn	58	ResAddNonf	Residential additions construction
13	Cotton	Cotton	59	FarmRes	Farm residential construction
14	DairyCattle	Dairy cattle	60	ManIndBldg	Manufacturing industry construction
15	Grapes	Grapes	61	CommInstBldg	Commercial and institutional building construction
16	Nursery	Nursery	62	HwyBrdgCons	Highway, street and bridge construction
17	Hogs	Hogs	63	WatSewerCons	Utility construction
18	OthFruit	Other fruit	64	OthNewCons	Other new construction
19	OthLivestock	Other livestock	65	MRresidence	Maintenance and repairs on housing
20	Citrus	Citrus	66	MRNonres	Maintenance and repairs on non-residential buildings
21	Potatoes	Potatoes	67	MRstreets	Maintenance and repairs on streets
22	Rice	Rice	68	OthMRCons	Other maintenance and repairs
23	Sorghum	Sorghum	69	DogCatFood	Dog and cat food
24	Soybean	Soybean	70	OthAnFood	Other animal food
25	Strawberries	Strawberries	71	FlourMill	Flour mill products
26	Sugarbeet	Sugarbeet	72	RiceMill	Rice milling
27	Tobacco	Tobacco	73	Malt	Malt
28	Tomatoes	Tomatoes	74	WetCornMill	Wet corn milling
29	Turkeys	Turkeys	75	SoyProc	Soybean processing
30	Wheat	Wheat	76	OthOilseed	Other oil seed processing
31	Logging	Logging	77	FatsOils	Fats and oils
32	ForTimber	Foretry and timber	78	BrkCereal	Breakfast cereals
33	Fishing	Fishing	79	SugarManuf	Sugar manufacturing
34	HuntTrap	Hunting and trapping	80	ConfCacao	Confectionary chocolate
35	AggForSupp	Agricultural and forestry services	81	ConfChoc	Confectionary cacao
36	OIlGas	Oil and gas	82	ConfNonchoc	Confectionary other
37	Coal	Coal mining	83	FrozFood	Frozen food
38	IronOre	Iron ore minig	84	FrtVegCDry	Fruit and vegetable processed
39	CopNickMine	Copper and nickel mining	85	Milk	Milk
40	GoldOthMetl	Gold and other metal mining	86	Butter	Butter
41	Stone	Stone	87	Cheese	Cheese
42	SandGravel	Sand and gravel	88	DCEDairy	Dairy products except canned and dried
43	OthNonMetl	Other non-metallic minerals	89	IceCream	IceCream
44	OilGasDrill	Oil and gas drilling	90	AnSlauXPlt	Animal slaughtering and processing
45	OilGasSupp	Oil and gas support services	91	Meat	Meat
46	OthMineSupp	Other mining support services	92	RendByprod	rendered and meat byproduct processing

	Short name	Description		Short name	Description
93	PoultryProc	Poultry processing	142	WoodCntnr	Wood container and pallet manufacturing
94	Seafood	Seafood	143	MfMoblHome	Mobile home manufacturing
95	FrozCake	Frozen cakes	144	PrefWdBldgs	Prefabricated wood building manufacturing
96	Bread	Bread	145	MscWoodProd	Miscellaneous wood products
97	Cookies	Cookies	146	PulpMills	Pulp mills
98	PrepDough	Prepared dough	147	PaperMills	Paper mills
99	Pasta	Pasta	148	PprContainer	Paperboard containers
100	Tortilla	Tortilla	149	FlxPkingFoil	Laminated aluminum foil for flexible packaging
101	NutsPnutBtr	Nuts and peanut bars	150	CoatPprbrd	Paperboard
102	OthSnack	Other snacks	151	CoatPprPck	Coated paper packaging
103	CoffTea	Coffee and tea	152	PaperBag	Paper bags
104	FlavorSyrup	Flavored syrups	153	DieCutPpr	Die-cut aper and paperboard office supplies
105	MayoDrsng	Mayonnaise and other dressings	154	Envelopes	Envelopes
106	Spices	Spices	155	Stationery	Stationery
107	OthrFoodMf	Other food manufactures	156	SanitPpr	Sanitary paper product
108	SoftDrinks	SoftDrinks	157	OthPprProd	Other paper product
109	Breweries	Breweries	158	BsnsForms	Business forms
110	Wineries	Wineries	159	BookPrntng	Books printing
111	Distilleries	Distilleries	160	BlnkBook	Blankbook, looseleaf binders and devices
112	TobStmDry	Tobacco stemming and redrying	161	Printing	Printing
113	Cigarette	Cigarette	162	Binding	Binding
114	OthTobacco	OthTobacco	163	PrepressSvc	Prepress services
115	FiberYarn	Fibers and yarns	164	PetrolRefine	Petroleum refineries
116	BroadFabric	Broad fabrics	165	AsphaltPave	Asphalt paving mixture
117	NarrowFabric	Narrow fabrics	166	AsphltShngl	Asphalt shingle and coating materials
118	NonWovFabric	Nonwoven fabrics	167	PetOilGrease	Petroleum oil and grease
119	KnitFabric	Knit fabric mills	168	OthPetCoal	Other petroleum products
120	TxtFabFinish	Textile and fabric finishing	169	Petrochem	Petrochemicals
121	FabCoating	Fabric coating mills	170	IndGas	Industrial gases
122	Carpet	Carpet and rug mills	171	SynthDye	Synthetic dyes and pigments
123	CurtainLinen	Curtain and linen mills	172	OthInorgChem	Other inorganic chemicals
124	TxtBagCanvs	Textile bag and canvas mills	173	OthOrgChem	Other basic organic chemicals
125	TireCord	Tire cord and tire fabric mills	174	Plastics	Plastics material and resin manufacturing
126	MiscTxtl	Miscellanous textiles	175	SynthRubber	Synthetic rubber
127	SheerHosiery	Sheer hosiery mills	176	CelFiber	Cellulosic organic fiber
128	OthHosiery	Other hosiery and sock mills	177	NoncelFiber	Noncellulosic organic fiber
129	Apparel	Apparel	178	NitroFert	Nitrogenous fertilizer
130	AprlAccess	Apparel accessories	179	PhosphFert	Phosphate fertilizer
131	Leather	Leather	180	Pesticide	Pesticide
132	Footwear	Footwear	181	PharmaMeds	Pharmaceuticals and medicines
133	OtherLeath	Other leather products	182	Paint	Paint
134	Sawmills	Sawmills	183	Adhesives	Adhesives
135	WoodPrsrv	Sawmills and wood preservation	184	SoapDetrgnt	Soap and detergent
136	RecWoodPrd	Reconstituted wood product manufacturing	185	Polish	Polish
137	VeneerPlwd	Veneer and plywood manufacturing	186	SurfAgent	Surface active agent
138	WoodTruss	Engineered wood and truss manufacturing	187	ToiletPrep	Toilet preparation
139	WoodWndoDoor	Wood window and door manufacturing	188	Ink	Ink
140	WoodSawPlane	Cut stock, resawing lumber and planing	189	Explosives	Explosives
141	Millwork	Other millwork	190	ResinComp	Custom compounding of purchased resins

	Short name	Description		Short name	Description
191	PhotoFilm	Photographic film and related products	240	RollForming	Custom roll forming
192	MscChemProd	Miscellaneous chemicals	241	OthForgStmp	Other forging and stamping
193	PlstPacking	Plastics packaging	242	Cutlery	Cutlery
194	PlstPipe	Plastics pipe, pipe fitting and unlaminated profile shape	243	HandEdgeTool	Hand and edge tools
195	LamPlstPlate	Laminated plastics plate	244	SawBlade	Saw blades
196	PlstBottle	Plastics bottle	245	KitchenUtn	Kitchen utensils
197	ResFlooring	Resilient floor covering	246	PrefMtlBldg	Prefabricated metal buildings
198	PlstPlumbing	Plastics plumbing fixture	247	FabStrctMtl	Fabricated structural metals
199	FoamProduct	Foam product	248	PlateWork	Plate work and fabrciated structural products
200	Tires	Tires	249	MtlWndoDoor	Metal windows and doors
201	RbrPlstHose	Rubber and plastic hoses and belting	250	SheetMtl	Sheet metal work
202	OthRbrProd	Other rubber products	251	OrnArchMtl	Ornamental and architectural metal products
203	VitChinPlb	Vitreous china plumbing fixture	252	Boiler	Power boilers and heat exchangers
204	VitChinArtcl	Vitreous china, fine earthenware and other pottery	253	MetalTank	Metal tanks
205	PorcElect	Porcelain electrical supply	254	MetalCntnr	Metal containers
206	BrickClyTile	Brick and structural clay tiles	255	Hardware	Hardware
207	CeramTile	Ceramic tiles	256	SprnWirePrd	Spring and wire products
208	NonclayRefr	Nonclay tiles	257	MachShops	Machine shops
209	ClayRefrac	Clay refractory	258	ScrewNut	Bolts, nuts, screws, rivets and washers
210	GlassCntnr	Glass containers	259	MtlHeatTrt	Metal heat treating
211	OthGlassPrd	Other glass products	260	MtlCoatEngrv	Metal coating and engraving
212	Cement	Cement	261	ElcPlatAnod	Electroplating, plating, polish, anodizing and coloring
213	ReadyMix	Ready mix concrete	262	MtlValve	Metal valves
214	ConcrBlock	Concrete block and pipe	263	BallBearng	Roller and ball bearings
215	ConcrPipe	Concrete pipe	264	SmallArms	Small arms
216	OthConcPrd	Other concrete products	265	OthOrdnance	Other ordnance
217	Lime	Lime	266	FabPipeFtng	Fabricated pipe and pipe fitting
218	Gypsum	Gypsum	267	IndPattern	Industrial patterns
219	Abrasives	Abrasives	268	EnamIronMtl	Enameled iron and metal sanitary ware
220	CutStonePrd	Cut stone and stone product	269	MsFabMtlMfg	Miscellenous fabricated metals
221	GrdMinEarth	Ground or treated mineral and earth	270	Ammunition	Ammunition
222	MinWool	Mineral wool	271	FarmMach	Farm machinery
223	MscNonMetMin	Miscellaneous nonmetal mineral products	272	LawnEquip	Lawn equipment
224	IronStlMills	Iron and steel mills	273	ConstMach	Construction machinery
225	Ferroalloy	Electrometallurgical ferroalloy product	274	MiningMach	Mining machinery
226	SteelWire	Steel wire drawing	275	OilGasMach	Oil and gas machinery
227	Alumina	Alumina	276	SawmillMach	Sawmill machinery
228	Aluminum	Aluminum	277	PlstRbrMach	Plastic and rubber industry machinery
229	AlumSheet	Aluminium sheet	278	PaperMach	Paper industry machinery
230	OthAlum	Other aluminium products	279	TxtlMach	Textile machinery
231	CopperSmelt	Copper smelting	280	PrintingMach	Printing machinery
232	NonferrMetl	Other nonferrous metals	281	FoodMach	Food machinery
233	CoprRollDraw	Copper rolling, drawing, extruding and alloying	282	SemicondMach	Semiconductor machinery
234	NonferrShape	Other nonferrous rolling, drawing, extruding and alloying	283	OthIndMach	Other industrial machinery
235	NonFerSecond	Nonferrous secondary smelting	284	OfficeMach	Office machinery
236	FerrFoundry	Ferrous foundries	285	OptInstLens	Optical instruments and lens
237	AlumFoundry	Aluminium foundries	286	PhotoEquip	Photographic and photocopying equipment
238	IronForging	Iron and steel forging	287	OSvcIndMach	Other commercial and service machinery
239	NonForging	Nonferrous forging	288	VendingMach	Vending machinery

	Short name	Description		Short name	Description
289	AirPurMach	Air purification equipment	338	MagOptMedia	Magnetic and optical recording media
290	FanBlower	Fans and blowers	339	Lightbulbs	Light bulbs
291	HeatingEq	Heating equipment	340	LightFxtr	Light fixtures
292	ACRefrig	Airconditioning equipment	341	EleHswrFans	Electric housewares and fans
293	MoldMfg	Industrial mold manufacturing	342	HshldVacuum	Household vacuum cleaners
294	CuttingMach	Cutting machinery	343	HshldStove	Household stoves
295	FormingMach	Forming machinery	344	HshldFridge	Household refridgerators
296	ToolDieJig	Die, tool and jig manufacturing	345	HshldLaundry	Household laundry appliances
297	ToolAccessry	Tool and machine tool accessory	346	OthHshldApp	Household appliances other
298	RollMillMach	Rolling mill machinery	347	PwrTrnsfrmr	Power, distribution and specialty transformers
299	Turbine	Engines, turbines and Power transmission	348	MotorGenratr	Motors and generators
300	OthEngEquip	Other engine equipment	349	Switchboard	Switchgear and switchboard apparatus
301	SpeedChng	Speed changing, industrial high speed drive and gear manufacturing	350	Relays	Relays
302	Pumps	Pumps	351	StorBattery	Storage batteries
303	AirGasCmprs	Air and gas compressors	352	PrimBatter	Primary battery manufacturing
304	MeasDspPump	Measuring and dispensing pumps	353	FibOptCable	Fiber optic cable
305	Elevators	Elevators	354	OtherWire	Other wire
306	Conveyors	Conveyors	355	WireDevice	Wiring devices
307	Hoists	Hoists	356	CarbonProds	Carbon and graphite products
308	IndTrukTrac	Industrial truck, tractor, trailer and stacker machinery	357	MsElEquip	Miscellaneous electrical equipment
309	PdrivnHandTl	Power driven handtools	358	Automobiles	Automobiles
310	WeldEquip	Welding equipment	359	HeavyTruck	Heavy trucks
311	PackngMach	Packaging machinery	360	VehicleBody	Vehicle bodies
312	IndFurnace	Industrial furnaces	361	TruckTrailer	Truck trailers
313	FluidCylindr	Fluid power cylinders and actuators	362	MotorHome	Motor homes
314	FluidPump	Fluid power pumps	363	TravlTrlr	Travel trailers and campers
315	Scales	Scales	364	VehiclParts	Vehicle parts
316	Computers	Computers	365	Aircraft	Aircraft
317	CmptrStorage	Computer storage devices	366	AirEngines	Aircraft engines
318	ComptrTermnl	Computer terminals	367	OthAirParts	Other aircraft parts
319	OCptrPeriph	Other computer peripheral equipment	368	Missiles	Missiles
320	Telephone	Telephones	369	MissilPrts	Missile parts
321	BroadcastEq	Broadcasting equipment	370	RlrdCars	Railroad rolling stock
322	CommunEquip	Other communications equipment	371	Ships	Ships
323	AudVidEquip	Audio and video equipment	372	Boats	Boats
324	ElectTube	Electron tubes	373	MotrBikes	Moter bikes
325	Semicondctr	Semiconductors and related devices	374	ArmyTanks	Army tanks
326	OtElectrnic	Other electronic	375	OthrTransEq	Other transport equipment
327	ElectroMedic	Electromedical and electrotherapeutic	376	WoodKitcCabt	Wood kitchen cabinets and countertops
328	SearchNavig	Search, detection, navigation, guidance etc	377	UphlHldFurn	Upholstered household furniture
329	EnviroContrl	Environmental control manufacturing	378	NonUpHhlFurn	Nonupholstered household furniture
330	ProcVblInsts	Instruments controlling industrial processes	379	MtlHhFurn	Metal household furniture
331	FluidMeters	Fluid meters	380	InstFurn	Institutional furniture
332	ElecTestInst	Electricity and electric signal testing instruments	381	OthInsHhFurn	Other institutional and household furniture
333	LabInsts	Laboratory instruments	382	WoodOffcFurn	Wood office furniture
334	RadiationIns	Radiation instruments	383	CustomWdwrk	Custom architectural woodwork
335	WatchClock	Watches and clocks	384	NonWdOffFurn	Office furniture except wood
336	SoftwareRep	Software reproduction equipment	385	ShcaseShlv	Showcases, partitions, shelving and lockers
337	AudVidReprod	Audio and video reproduction equipment	386	Mattress	Matresses

	Short name	Description		Short name	Description
387	BlindShade	Blinds and shades	436	VideoRental	Video rentals
388	LabAppFurn	Laboratory apparatus and manufacturing	437	MachEquRntl	Machinery and equipment rentals
389	SrgMedInst	Surgical medical instruments	438	GenrlRentl	General rentals
390	SurgAppSupp	Surgical appliances and supplies	439	AssetLessors	Lessors of real estate
391	DentalEquip	Dental equipment and supplies	440	LegalSvces	Legal services
392	Ophthalmic	Ophthalmic goods	441	Accounting	Accounting services
393	DentalLab	Dental laboratories	442	ArchEngSvce	Architectural engineering services
394	Jewelry	Jewelry	443	DesignSvce	Other design services
395	SportGoods	SportGoods	444	CustCptrProg	Customized computer programming
396	Toys	Toys	445	cptrSysDesgn	Computer system design
397	OfficSupply	OfficSupply	446	OthCptrSvce	Other computing services
398	Signs	Signs	447	MgmtCnsltSv	Management consulting services
399	Gaskets	Gaskets	448	EnvCnsltSvc	Environmental consulting services
400	MusicInstr	MusicInstr	449	ResDevelSvc	Residential development services
401	Brooms	Brooms	450	Advertising	Advertising services
402	Caskets	Caskets	451	PhotoSvce	Photography services
403	MiscManuf	Miscellaneous manufacturing	452	VetSvces	Veterinary services
404	WholesaleTr	Wholesale trade	453	MscProfSvces	Miscellaneous professional services
405	AirTrans	Air transport	454	CompanyMgmt	Company management services
406	RailTrans	Rail transport	455	OffAdmSvces	Office administration services
407	WaterTrans	Water transport	456	FacilSupSvc	Facilities support services
408	TruckTrans	Truck transport	457	EmplSvce	Employment services
409	GrdPassTrans	Transit and ground passenger transport	458	BusnsSupSvc	Business support services
410	Pipeline	Pipelines	459	TravelSvce	Travel services
411	ScenSuppTran	Scenic and sightseeing transport	460	DetectivSvce	Detective services
412	PostalSvc	Postal services	461	BldgSvce	Building services
413	Couriers	Couriers	462	OthSuppSvce	Other support servcies
414	Warehousing	Warehousing	463	WasteMgmt	Waste management services
415	RetailTr	Retail trade	464	EleSecSchool	Elementary and secondary schools
416	NewspaperPb	Newspaper publishing	465	Colleges	Colleges
417	PerdclPub	Periodical publishing	466	OtherEducSv	Other education services
418	BookPub	Book publishing	467	HomeHlthSvc	Home health services
419	DataPub	Data publishing	468	MedOffices	Medical offices
420	SoftwrPub	Software publishing	469	AmbHlthSvce	Ambulatory health services
421	MoviesVideo	Movies and videos	470	Hospitals	Hospitals
422	SoundRecord	Sound recording	471	NursingFcil	Nursing facilities
423	RadioTV	Radio and television	472	ChildCare	Child care services
424	CableNetwrks	Cable networks	473	SocialSvce	Social services
425	Telecomm	Telecommunications	474	PerfArts	Performing arts
426	InfoSvce	Information services	475	SpectSports	Spectator sports
427	DataProcScv	Data processing services	476	IndArtists	Independent artists, writers, performers
428	NonDepCredit	Nondepository credit intermediation	477	Promoters	Promoters
429	Securities	Securities	478	MuseumZoo	Museums and zoos
430	InsCarriers	Insurance carriers	479	FitnessCtrs	Fitness centers
431	InsBrokers	Insurance brokers	480	Bowling	Bowling
432	FundsTrusts	Funds and trusts	481	OthAmuseSvce	Other amusement services
433	MonetDepCred	Monetary authorities and depository credit intermediation	482	Hotels	Hotels
434	RealEstate	Real estate services	483	OthAccomod	Other accommodation
435	AutoRental	Automobile rentals	484	EatDrinkPlce	Easing and drinking places

	Short name	Description
485	CarWashes	Car washes
486	AutoRepair	Automobile repairs
487	ElEquiRepair	Electrical equipment reparis
488	MachinerRp	Machinery repairs
489	HhGoodsRpr	Household goods repairs
490	PersCareSvce	Personal care services
491	DeathCareSv	Death care services
492	CleanLaundry	Cleaning and laundering services
493	OthPerSvce	Other personal services
494	ReligiousOrg	Religious organizations
495	GrantOrg	Grantmaking foundations
496	CivSocialOr	Civil and social organisations
497	PrivHhlds	Services to private households
498	OthFedGEnt	Other federal government enterprises
499	OthSLGEnt	Other state and local government enterprises
500	SLGEduc	State and local government education services
501	GenGovInd	General government industries
502	OwnOccDwell	Owner-occupied dwellings
503	NatlDefG	National defence (federal)
504	NonDefG	Non-defence services (federal)
505	SLGOther	Other state and local government spending
506	Holiday	Holiday
507	FgnHol	Foreign holidays
508	ExpTour	Tourism exports
509	ExpEdu	Education exports
510	OthNonRes	Purchases by foreigners in embassies etc.
511	WT_EXP	Water transport exports
512	AT_EXP	Air transport exports

Appendix C. Inventory, Annual Sale, Inventory/Sale Ratio by Sector

Manufacturing Sector	Inventory of Materials and Supplies by the End of 2014 (M 2009$)	Annual Sale (M 2009$)	Inventory / Sale Ratio
Durable goods industries	132,335	892,008	14.84%
Wood product manufacturing	4,755	26,412	18.00%
Nonmetallic mineral product manufacturing	4,990	35,252	14.15%
Primary metal manufacturing	13,095	83,752	15.64%
Fabricated metal product manufacturing	18,281	114,088	16.02%
Machinery manufacturing	22,593	124,456	18.15%
Computer and electronic product manufacturing	22,964	120,740	19.02%
Electrical equipment, appliance, and component manufacturing	6,758	39,752	17.00%
Transportation equipment manufacturing	25,475	270,904	9.40%
Motor vehicle and parts manufacturing	13,492	174,156	7.75%
Other transportation equipment manufacturing	11,940	96,956	12.32%
Furniture and related product manufacturing	4,081	21,916	18.62%
Miscellaneous durable goods manufacturing	9,385	52,836	17.76%
Nondurable goods industries	86,119	830,716	10.37%
Food manufacturing	15,940	213,836	7.45%
Beverage and tobacco product manufacturing	6,936	44,008	15.76%
Textile mills	1,645	9,440	17.43%
Textile product mills	1,103	6,868	16.06%
Apparel manufacturing	2,058	4,228	48.68%
Leather and allied product manufacturing	475	1,604	29.60%
Paper manufacturing	9,401	57,008	16.49%
Printing and related support activities	2,565	26,652	9.62%
Petroleum and coal product manufacturing	8,372	173,708	4.82%
Chemical manufacturing	28,020	222,156	12.61%
Plastics and rubber product manufacturing	10,395	67,972	15.29%

Data Source: BEA, 2016.

Appendix D. Production Recapture Factors

Sector #	Short names	Aggregated Sector Name	HAZUS Occupancy Class	Recapture Factor
1	Crops	Crops	AGR1	0.98
2	PoultryEggs	Poultry & Eggs	AGR1	0.75
3	Livestock	Livestock	AGR1	0.75
4	OthLivestock	Other Livestock	AGR1	0.75
5	ForestFrsHnt	Forestry, Fishing, & Hunting	AGR1	0.75
6	OilGas	Oil & Gas	IND4	0.98
7	Coal	Coal	IND4	0.98
8	OtherMining	Other Mining	IND4	0.98
9	BiomassGen	Biomass electricity generation	COM4	0.90
10	CoalsGen	Coal-fired electricity generation	COM4	0.90
11	GasGen	Gas-fired electricity generation	COM4	0.90
12	HydroGen	Hydroelectric generation	COM4	0.90
13	NuclearGen	Nuclear electricity generation	COM4	0.90
14	RenewGen	Renewable electricity generation	COM4	0.90
15	ElecDist	Electricity distribution	COM4	0.90
16	NatGasDist	Natural gas distribution	COM4	0.90
17	WaterSewage	Water and sewage services	COM4	0.90
18	ResidConstrt	Residential Construction	IND6	0.95
19	OthConstruct	Highway Construction	IND6	0.95
20	HwyBrdgCons	Other Non-Residential Construction	IND6	0.95
21	OthMaintain	Highway Maintenance	IND6	0.95
22	MRstreets	Other Maintenance	IND6	0.95
23	FoodProc	Food Processing	IND3	0.98
24	BevTobManu	Beverage & Tobacco Product Manufacturing	IND3	0.98
25	Textiles	Textile & Textile Product Manufacturing	IND1	0.98
26	Apparels	Apparel	IND2	0.98
27	LeathFtwr	Leather & Allied Products	IND2	0.98
28	WoodProds	Wood Product Manufacturing	IND1	0.98
29	PulpPaperPbd	Paper Mills	IND1	0.98
30	Printing	Printing & Related Support Activities	IND2	0.98
31	PetrolRefine	Petroleum Refineries	IND3	0.98
32	OthPetrolCl	Other Petroleum & Coal Products	IND3	0.98
33	Chemicals	Chemicals	IND3	0.98
34	RubPlastic	Rubber & Plastics	IND2	0.98
35	NonMetMinPrd	Non-Metallics	IND4	0.98
36	PrimMetals	Primary Metal Manufacturing	IND4	0.98

37	FabriMetals	Fabricated Metal Product Manufacturing	IND1	0.98
38	AgriMachinry	Agriculture Machinery	IND1	0.98
39	IndustrMach	Industrial Machinery	IND1	0.98
40	CommrcMach	Commercial Machinery	IND1	0.98
41	AirConHeat	Ventilation, Heating & Air-Conditioning	IND1	0.98
42	MetalWkMach	Metalworking Machinery	IND1	0.98
43	TurbnEngine	Engines & Turbines	IND1	0.98
44	OtherMach	Other General Purpose Machinery Manufacturing	IND1	0.98
45	Computers	Computers	IND5	0.98
46	CmptrStorage	Computer Storage Devices	IND5	0.98
47	ComptrTrmEtc	Computer Terminals & Other Peripheral Equipment	IND5	0.98
48	CommunicEqp	Communications Equipment	IND2	0.98
49	MscElctEqp	Miscellaneous Electronic Equipment	IND2	0.98
50	Semicondctr	Semiconductors & Related Devices	IND2	0.98
51	ElecInstrmnt	Electronic Instruments	IND2	0.98
52	HholdEqp	Household Equipment, Appliances, and Component Manufacturing	IND2	0.98
53	MVPManu	Motor Vehicle and Parts Manufacturing	IND1	0.98
54	AerospaceMan	Aerospace Product & Parts Manufacturing	IND1	0.98
55	RlrdCars	Railroad Rolling Stock Manufacturing	IND1	0.98
56	ShipsBoats	Ship & Boat Building	IND1	0.98
57	OthTrnEqp	Other Transportation Equipment Manufacturing	IND1	0.98
58	Furniture	Furniture & Related Product Manufacturing	IND2	0.98
59	MiscManuf	Miscellaneous Manufacturing	IND2	0.98
60	WholesaleTr	Wholesale Trade	COM2	0.87
61	AirTrans	Air Transport	COM4	0.90
62	RailTrans	Rail Transport	COM4	0.90
63	WaterTrans	Water Transport	COM4	0.90
64	TruckTrans	Truck Transport	COM2	0.87
65	GrdPassTrans	Transit and Ground Passenger Transport	COM4	0.90
66	Pipeline	Pipelines	COM4	0.90
67	OthTransprt	Other Transportation	IND1	0.90
68	Warehousing	Warehousing	COM2	0.87
69	RetailTr	Retail Trade	COM1	0.87
70	Publishing	Publishing Industries	IND2	0.98
71	MovieSound	Motion Picture & Sound Recording Industry	COM4	0.90
72	BroadcastSrv	Broadcasting	COM8	0.60
73	Telecomm	Telecommunications	COM8	0.60
74	InfoSvce	Information Services	COM4	0.90
75	DataProcScv	Data Processing Services	COM4	0.90
76	FinancBank	Finance & Banking	COM4 and COM5	0.90
77	RealEstate	Real Estate	COM4	0.90

78	RentLease	Rental & Leasing Services	COM4	0.90
79	AssetLessors	Lessors of Nonfinancial Intangible Assets	COM4	0.90
80	PrfSciTchSrv	Professional, Scientific, Technical, Administrative, & Support Services	COM4	0.90
81	WasteMgmt	Waste Management Services	GOV1	0.80
82	Education	Education Services	EDU1	0.60
83	HealthSocAs	Health Care & Social Assistance	RES6, COM6, and COM7	0.60
84	ArtsRecreat	Arts, Entertainment & Recreation	COM8	0.60
85	Accommodatn	Accommodations	RES4	0.60
86	EatDrinkPlce	Eating & Drinking Places	COM8	0.60
87	OthService	Other Services	COM3	0.51
88	GovEnterprs	Government Enterprises	COM3	0.51
89	StaLocGov	State & Local Government	GOV1	0.80
90	OwnOccDwell	Owner-Occupied Dwellings	GOV1 & GOV2	0.80
91	FedGovt	Federal Government	GOV1 & GOV2	0.80
92	Holiday	Holiday	COM8	0.60
93	FgnHol	Foreign Holidays	COM8	0.60
94	ExpTour	Tourism Exports (including Purchases by Foreigners in Embassies etc.)	COM8	0.60
95	ExpEdu	Education Exports	EDU1	0.60
96	WT_EXP	Water Transport Exports	COM4	0.90
97	AT_EXP	Air Transport Exports	COM4	0.90

Data Source: FEMA, 2015.