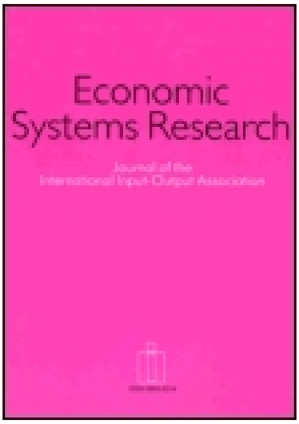

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ESTIMATING THE ECONOMIC CONSEQUENCES OF A PORT SHUTDOWN: THE SPECIAL ROLE OF RESILIENCE

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ESTIMATING THE ECONOMIC CONSEQUENCES OF A PORT SHUTDOWN: THE SPECIAL ROLE OF RESILIENCE

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This paper develops a methodology for the estimation of the total economic consequences of a seaport disruption, factoring in the major types of resilience. The foundation of the methodology is a combination of demand-driven and supply-driven input–output analyses. Resilience is included through a series of *ad hoc* adjustments based on various formal models and expert judgment. Moreover, we have designed the methodology in a manner that overcomes the major shortcomings of the supply-driven approach. We apply the methodology to a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas, which is a major port area that includes a petrochemical manufacturing complex. We find that regional gross output could decline by as much as $13 billion at the port region level, but that resilience can reduce these impacts by nearly 70%.

Keywords: Economic impact methodology; Input–output analysis; Disasters; Port disruptions; Resilience

1. INTRODUCTION

A nation's ports play a key role in its 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. A disruption of a major port thus reverberates throughout the entire economy. Inputs for intermediate and final consumption cannot be delivered, thereby causing disruptions down the supply chain, while exports for other markets are blocked, thus causing an ensuing disruption of production up the supply chain. An increasing number of port disruptions have taken place in recent years, caused by such phenomena as labor unrest, natural disasters, and technological accidents. 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.

Several researchers have estimated the direct and indirect impacts of such disruptions and found them to be quite large (Chang, 2000; CBO, 2006; Park et al., 2007, 2008; Park, 2008; Jung et al., 2009; Rose et al., 2009a). However, none of these studies has adequately factored in all of 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). In the event of a port disruption, economic decision-makers do

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not stand by passively waiting for a resumption of port activities, but instead initiate a broad range of coping activities, such as use of stockpiles, conservation, input substitution, ship re-routing, 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 throughout the economy-wide supply chain.

The purpose of this paper is to develop and apply a methodology for the estimation of the total economic consequences of a port disruption, factoring in the major types of resilience. The foundation of the methodology is a combination of demand-driven and supply-driven input–output (I–O) analyses. Resilience is factored in via a series of *ad hoc* adjustments based on various formal models and expert judgment. We are aware of the criticisms of the supply-driven I–O model (see, e.g. Oosterhaven, 1988; Dietzenbacher, 1997). However, we suggest that this modeling approach is less subject to criticism for a supply disruption (where material shortages do constrain downstream production) than for a supply acceleration (which implies that supply creates its own demand). We have also designed the methodology in a manner that rectifies its major shortcoming according to Oosterhaven's (1988) guidelines. With careful interpretations, the supply-driven I–O model has been used in a number of cases to examine the impacts from supply reductions, though not for ports (Leung et al., 2007; Ai and Polenske, 2008; Park, 2008).

We apply the methodology to a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas, which is a major port area that includes a petrochemical manufacturing complex. We estimate the impacts for the port metropolitan area economy and find that the impacts can be as great as nearly $13 billion, but that resilience can reduce this by nearly 70%.

The research presented here is important for several reasons. As world commerce continues to expand, the role of seaports becomes increasingly prominent, and this paper presents a methodology for evaluating their economic contribution. It provides insights into ordinary investment decisions for expanding and modernizing ports and for decisions on protecting them from natural disasters, technological accidents, and terrorist attacks. In essence, an estimate of the potential losses from a port disruption is the basis for the benefits (when multiplied by the probability of their occurrence) of preventative measures in a risk–benefit analysis of port security.

This paper is divided into seven sections. We first provide a brief summary of the literature on estimating the economic impacts of port disruptions. In Section 3, we present our methodology for estimating the basic economic impacts. In Section 4, we identify the major types of resilience to port disruptions and how most of them can be accommodated in an I–O framework. In Section 5, we summarize the data and the details of the application of our methodology. In Section 6, we apply our model to the estimation of the regional economic impacts of a 90-day port disruption, taking into account major resilience tactics. We conclude with a discussion of the policy implications of our analysis and how it can be generalized to disruptions of other types of major economic facilities.

2. REVIEW OF THE LITERATURE

Only a handful of studies have analyzed the total economic impacts of port disruptions. Park et al. (2007) utilized their sophisticated interregional National Interindustry Economic

Model, or NIEMO, to analyze the impacts of terrorist attacks on three major US ports (Los Angeles/Long Beach (LA/LB), Houston, and New York/New Jersey). This model encompasses all 50 states of the USA and is able to provide details on indirect impacts of a port shutdown of any duration in one state on all others. In this study, however, the only indirect impacts examined pertained to losses stemming from a curtailment of exports. The authors included only the direct effects of the disruption to imports, thereby grossly understating the impacts from this stream of curtailed activity. At the same time, there is an over-estimation in the study because it does not include most forms of resilience. Overall, Park et al. estimated total impacts at \$49 billion at the national level, though the extent of the effects of over- and under-estimation cannot be ascertained. Park (2008) examined the impacts of a 'dirty-bomb' attack on the LA/LB ports and a 1-month closure. NIEMO was again applied, but in both demand-driven and supply-driven forms. Again, resilience was not taken into account. The results indicated a total US loss of output of \$8.5 billion stemming from the export disruption and \$26 billion from the import disruption.

Park et al. (2008) also estimated the economic impacts of the 11-day labor strike shutdown at the LA/LB ports in 2002, though the analysis covered the ensuing 4-month adjustment period as well. They supplemented NIEMO with a multi-level linear regression model to estimate direct (final demand) losses and also included variables to reflect port and other transportation mode substitutions. They estimated US total output losses stemming from export disruptions at \$3 billion and from import disruptions at \$0.6 billion.

In the past decade, the inoperability input–output model (IIM) has been developed and widely used to help understand the interdependencies of critical infrastructures. The basic demand-side IIM takes the perturbation of sectors (that can be caused by a number of reasons, including disruptions due to man-made or natural disasters) as inputs and calculates the demand-side inoperability of all the sectors in the economy. Jung et al. (2009) expanded the basic IIM by introducing a new concept of gross trade economy (GTE), which is defined as the sum of GDP and imports. The model is capable of examining the economic impacts of international trade inoperability, which can be caused by disruptions of a major port of entry. For a 10-day shutdown of the Port of Los Angeles, Jung et al. (2009) estimated that the GTE total gross output losses range from \$7.7 billion to \$13 billion. However, this study did not explicitly factor in any forms of resilience. Barker and Santos (2010) extended the dynamic IIM (DIIM) with an inventory model and thus enabled the new model to capture the effect of one type of resilience, utilizing inventories, to reduce the effects stemming from a disruptive incident. However, this new Inventory DIIM has not yet been applied in the context of port disruptions.

Several other methods have been applied to port shutdowns. The INFORUM (conjoined I–O/econometric forecasting) Model was used in a Congressional Budget Office study (CBO, 2006) of the disruption of container ships at the Ports of Los Angeles/Long Beach. Resilience was factored in by imports assumed to being diverted to other ports or modes of transportation. Containerized exports through LA/LB ports are small, so the study assumed that all exports can be diverted to other ports. Overall, the study estimated the effects of a 1-week shutdown on the US economy in terms of gross output as \$65–\$150 million per day and of a 3-year shutdown as \$125–\$200 million per day (in year 2006 dollars).

A reduced-form econometric approach is exemplified by Chang's (2000) study of the economic impacts of the closing of the port of Kobe, Japan, after the major earthquake struck its host region in 1995. The approach involved a single-equation model rather than the integrated (simultaneous equation) model of multiple economic sectors and macroeconomic linkages of the larger macroeconometric modeling approach. Chang estimated that Kobe's port activity did not rebound to pre-earthquake levels even after 2 years, but rather stabilized at about a 25% reduction in activity from the pre-event baseline.

Rose et al. (2009a) used the Regional Economic Models, Inc. (REMI) Model to analyze the macroeconomic impacts of shutting down the US borders in response to a security of public health threat. The authors found it necessary to modify the model to account for various obvious types of resilience to this policy. For example, when imported goods are not available, it is natural to consider the use of domestic substitutes. However, the basic REMI Model did not impose any cost penalty on these substitutions (imports are purchased because they are cheaper than domestic counterparts). It was thus necessary to perform side estimates of increased costs of using domestic substitutes and incorporating those into the analysis. The authors estimated the total impacts of a 1-year total border shutdown on US GDP as more than $1.5 trillion (in year 2000 dollars). However, the analysis did not factor in several other types of resilience.

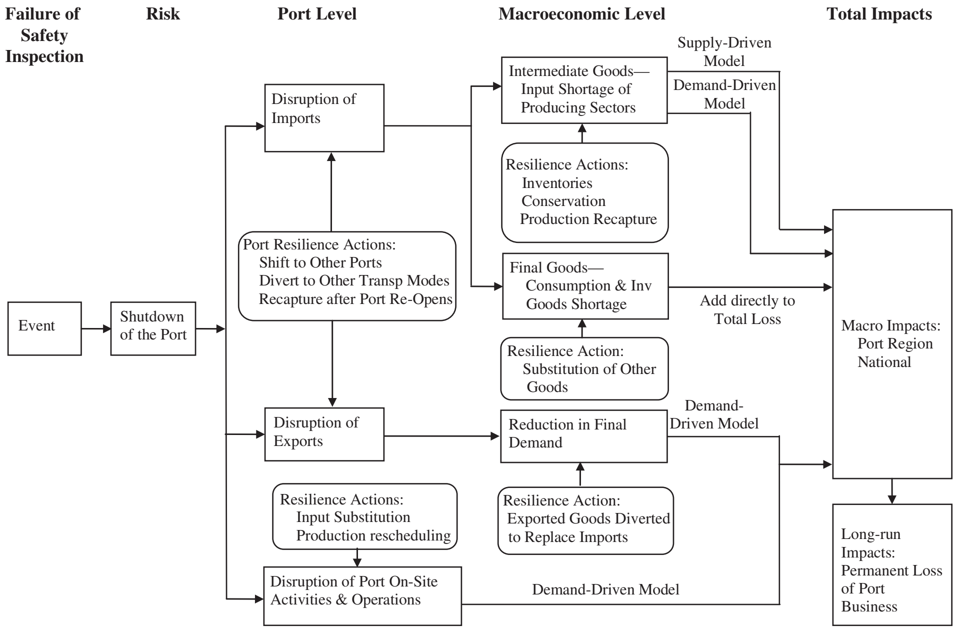
Economic disruptions are usually quite uncertain in terms of their probability of occurrence and consequences. Recently, significant advances have been made in incorporating uncertainty into I–O frameworks to estimating the economic impacts of disruptions, which have applicability to port disruptions. Orsi and Santos (2010) developed a Markov process to analyze uncertainty associated with labor force disruptions. Barker and Haimes (2009) specified probability distributions for demand shocks and Barker and Rocco (2011) used an interval arithmetic approach for cases where data are inadequate to specify probability distributions.

Overall, significant progress has been made in the development of models to analyzing the macroeconomic impacts of port shutdowns. This includes the capability to measure various indirect effects, including those across individual regions beyond the port, the incorporation of econometric analyses of the drivers of the direct disruption, the inclusion of some supply-side effects, and the inclusion of some resilience tactics to mute the negative impacts. However, the models thus far have included only a limited set of supply-side effects, have not heeded Oosterhaven's warning about the appropriate use of the supply-driven model, and have incorporated only a limited set of resilience tactics. This paper is intended to rectify these shortcomings.

3. METHODOLOGY

In this paper, we use an I–O modeling approach to estimate the total economic impacts of a seaport disruption. The I–O approach was chosen because of its strong capabilities of capturing the interdependence of economic sectors upstream and downstream the supply chain of the disrupted goods. We also modify the I–O approach to overcome some of its major limitations by making the model more realistic and flexible. The majority of the modifications pertain to resilience, in this case the ability to mute the impacts of a major port disruption, both at the site and along the supply chain. A final reason for choosing an I–O approach is that it is very facile in its applications. Our approach will involve the modification of I–O methods to better reflect the set of linkages that result in macroeconomic impacts. This will consist of both demand-side and supply-side versions of the model, as well as the modification for resilience in various rounds of the computations. This recursive process will be done in stages, enabling us to more clearly lay out the assumptions

FIGURE 1. Estimating total economic impacts of a port shutdown.



and macro-linkages, as well as to decompose the various aspects of the total economic impacts.

3.1. Overview of Economic Linkages

Figure 1 displays the major linkages in the I–O model framework at five analytical times/stages of a potential port disruption scenario. It begins with the failure of safety inspection, which first translates into a risk of a port shutdown. At the port level, this leads to

- Disruption of imports
- Disruption of exports
- Disruption of port on-site activities and operations

The next stage is the macroeconomic level; impacts stem from three aspects here as well:

- Intermediate goods shortfalls (due to import disruption)
- Final goods shortfalls (due to import disruption)
- Reduction in final demand associated with reduction in exports

The impacts of an import disruption will be estimated through the use of both the supply-driven and demand-driven I–O models. The former captures impacts on customers down the supply chain, and the latter captures the impacts on suppliers up the supply chain. Both the supply-driven and demand-driven I–O models are needed on the import side because not only are the sectors using the imports as intermediate inputs and their successive rounds of customer sectors affected by the initial import disruption and the successive supply shortfalls, but also the reduction in production of import-using sectors also reduces the demand of the goods produced by successive rounds of upstream suppliers within the region or nation. Since the ‘final’ (finished) goods shortfalls to end-users (consumers, government, and purchasers of capital equipment) do not generate any forward or backward linkage effects domestically, they are simply added to the total macro-effects directly.

Restriction of exports requires another perspective on the problem. This involves the use of the more conventional demand-driven I–O model. Here, the cessation of exports from the disruption of port activity will reduce demand for inputs in their production. First-round suppliers will in turn reduce their demand, thereby starting a chain reaction of production activity decreases.

The port on-site operation and activity disruptions generate their own demand-side effects. The demand-side I–O model is again used to capture the total effects for this aspect.

The total impact level is depicted in the right-hand column of Figure 1. The total represents a summing up of all the various types of supply-side and demand-side impacts. Given the nature of the linear I–O model, all of these various partial results in Figure 1 are additive and can be calculated and presented separately to identify the relative influence of the various and offsetting factors.

Another aspect of total impact pertains to any long-run effects on port businesses. These could arise from permanent loss of business for the port due to now realized advantages of newly established logistical patterns or from stigma that stems from real or imagined long-lasting effects of a radiological or biological weapon. However, the long-run effects are beyond the scope of this study.

Various resilience tactics will be implemented to capture the capability of the economy at different levels to mute the impacts of the port shutdown, which include re-routing ships, use of inventories, conservation, export diversion, and production recapture. Sections 4 and 6 summarize the methodology and data we use to incorporate these resilience measures in the port disruption impact analysis.[1]

3.2. Input–Output Methodology

Both the demand-driven and supply-driven I–O models are well known and extensive details need not be presented here (Rose and Miernyk, 1989; Miller and Blair, 2009). We do, however, provide a discussion of how we overcome some of the criticisms of the use of the supply-side (or Ghoshian) model. There are three categories of such criticisms.

The first criticism pertains to the implication of applying the Ghoshian model directly. The supply-side model interprets the basic flow I–O table in terms of marketing (or allocation) coefficients rather than production coefficients. That is, they reflect a fixed, proportional pattern of supplies of each good. Each column of the basic flow table shows the following relationship:

$$x_j = z_{1j} + z_{2j} + \cdots + z_{nj} + v_j, \tag{1}$$

[1] When we simulate the effects of implementing multiple types of resilience actions together, we consider the potential double-counting between these actions in our analysis. We refer the reader to point H in Section 6, in which we discuss the effects of resilience actions, for details on how potential double-counting is addressed.

where x_j is the gross input of sector j; z_{ij} is the intermediate input from sector i that is used in sector j; and v_j is the sum of all of the elements in the payment section of column j, which include primary inputs such as labor, capital and land, and other value-added factors such as indirect business taxes. If we compute the supply-side allocation coefficient matrix $\mathbf{A^s}$ by dividing each element in the row by the row sum, we get $a^s_{ij} = z_{ij}/x_i$. Equation 1 can then be written as

$$x_j = \sum_i a^s_{ij} x_i + v_j. \tag{2}$$

In matrix form:

$$\mathbf{x} = \mathbf{x}\mathbf{A^s} + \mathbf{v}, \tag{3}$$

$$\mathbf{x} = \mathbf{v}(\mathbf{I} - \mathbf{A^s})^{-1}. \tag{4}$$

When the change in $\mathbf{v}$, $\Delta\mathbf{v}$ is known, the change in gross output $\Delta\mathbf{x}$ can be computed as

$$\boldsymbol{\Delta}\mathbf{x} = \boldsymbol{\Delta}\mathbf{v}(\mathbf{I} - \mathbf{A^s})^{-1}. \tag{5}$$

Oosterhaven (1988) illustrated the implausibility of the direct application of the Ghoshian model by examining the Taylor expansion of its solution. The Taylor expansion of $\mathbf{x} = \mathbf{v}(\mathbf{I} - \mathbf{A^s})^{-1}$ can be written as $\mathbf{x} = \mathbf{vI} + \mathbf{vA^s} + \mathbf{v(A^s)^2} + \mathbf{v(A^s)^3} + \cdots$. The first term of the Taylor expansion ($\mathbf{vI}$) implies that the direct effect of a primary factor change in sector 1 is just $x_1^{direct} = v_1$. According to the fixed input coefficient production function of the demand-side (Leontief) model, the correct direct forward effect should be $x_1^{direct} = v_1(1/c_1)$ (in which c_1 is the input coefficient of the primary factor in sector 1). The reciprocal of the primary input coefficient $(1/c_1)$ is missing in the Ghoshian model. Similarly, the second term in the Taylor expansion implies that the first-round indirect effect is $x_j = v_1 a^s_{1j}$ (in which a^s_{1j} is the allocation coefficient of sector 1 to sector j). Again, according to the fixed input coefficient production function of the Leontief model, the correct first-round forward effect should be $x_j = v_1(1/c_1)a^s_{1j}(1/a^d_{1j})$ (in which a^d_{1j} is the technical coefficient of good 1 in sector j). Thus, for the first-round indirect effect, the reciprocals of the input coefficients, $1/c_1$ and $1/a^d_{1j}$, are both missing when we apply the Ghoshian model directly. The model proposed by Oosterhaven is a very complex calculation framework to rectify this problem. In our study, we have made sure that the impact of an import disruption on the direct import-using sectors is computed in accordance with the Leontief production function requirements as emphasized by Oosterhaven. Specifically, we compute the direct output effect of the major import-using sector j as $\Delta x_j = \Delta m_i a^s_{ij}(1/a^d_{ij})$, in which Δm_i is the disruption of import good i; a^s_{ij} is the allocation coefficient of import good i to sector j; and a^d_{ij} is the technical coefficient of import good i of sector j.[2] As will be explained in further detail below, given the fact that the Port Arthur/Beaumont Region is heavily involved in the first stage of refining raw material imports but then ships the vast majority of the processed products elsewhere

[2] $\Delta x_j = \Delta m_i a^s_{ij}(1/a^d_{ij})$ can be rewritten as $\Delta x_j = \Delta m_{ij}\left(\frac{1}{m_{ij}/x_j}\right) = \frac{\Delta m_{ij}}{m_{ij}} x_j$, in which $\Delta m_{ij} = \Delta m_i a^s_{ij}$ is the shortfall of import i in section j; m_{ij} is the total amount of import i used in sector j; and x_j is the total output of sector j. This indicates that if import i is disrupted by $x\%$, the direct output of the major import using sector j is reduced by $x\%$. In Section 5.2, we will explain how we also consider the cases in which a sector purchases the same type of production input from both local producers and importers.

in the USA, our calculation of the first-round adjustment is sufficient to capture nearly all the impacts that are underestimated in the direct Ghoshian model.[3]

The second criticism relates to its economic rationale. Several authors characterize this model as being based on the discredited Say's law that supply creates its own demand. This is surely the case in a positive stimulus application. However, there is an important asymmetry in the case of a negative stimulus, such as a port disruption. Here, the application is in spirit much more like the conventional demand-side model, where a material input shortage will reasonably lead to a chain of direct and indirect reductions of output – it has no relationship to Say's law. In the supply-side case, these multiplier effects are downstream, however, rather than upstream.

The third criticism is that when the supply-driven I–O model is applied, the technical coefficients of the demand-driven model are altered (Chen and Rose, 1991; de Mesnard, 1997). Rose and Allison (1989) examined the relationship between the demand-driven and supply-driven models in terms of this 'joint stability' of their respective coefficients for the case of a supply disruption simulation on the Washington State economy. They found the variation between the technical and allocation coefficients to be very small because of an inherent 'dampening effect' in the application of the two versions of an I–O model. Thus, while absolute joint stability is unattainable, relative joint stability in empirical applications can be expected.

4. ECONOMIC RESILIENCE

4.1. Basic Considerations

In the past few years, nearly every analysis of the impacts of a catastrophe in the USA has highlighted the 'resilience' of the economy (see, e.g. Chernick, 2005; Boettke et al., 2007; Flynn, 2008). Resilience is sometimes used to explain why regional or national economies do not decline as much as might be expected after disasters or why they recover more quickly than predicted. 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 (cf. Rose, 2007).

The concepts and definitions discussed next represent the synthesis of knowledge on the topic of economic resilience, both within economics and in other disciplines, with an emphasis on measures that reduce losses after a disaster begins. *Static economic resilience*

[3] Dietzenbacher (1997) showed that "the supply-driven input-output model yields exactly the same results as the Leontief price model". This new interpretation of the supply-driven model provides the plausibility of using the supply-driven model in cases where the exogenous changes are caused by price changes in primary factors only. However, this interpretation does not apply if the analyses are focused on the impacts of shortfalls of primary factors. Dietzenbacher (1997) stated that "in analyzing quantity effects by means of the Ghosh model, the Oosterhaven (1988) critique applies undiminishedly" (p. 635). However, Gruver (1989), Klein (1953), and others have pointed out that in empirical I–O models, usually expressed in value terms rather than just pure quantity terms, the production function is actually Cobb–Douglas, simply requiring fixed value shares. Thus, it would seem that Dietzenbacher's finding supports the use of the supply-driven I–O model for value-based I–O models (as in this paper), where the change in the coefficient can be interpreted as either a price or a quantity change.

(SER) is the ability or capacity of an entity or a 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. SER 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 a system recovers ('bounces back') from a severe shock to achieve a desired state. This version of resilience is relatively more complex because, unlike static resilience, it involves a long-term investment problem associated with repair and reconstruction processes.

A basic operational measure of *SER*, abstracting from the difference between direct and indirect effects for the moment, equates to the extent to which the reduction in business interruption deviates from the likely maximum potential reduction given an external shock. An analogous definition pertains to resilience taking into account indirect or macroeconomic effects.[4]

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. In contrast, resilience represents the introduction of nonlinearities.

4.2. Resilience Options for Port Economies

The following several types of microeconomic static resilience options should be considered in a study of the impact of a port disruption:

(1) *Ship re-routing*. This applies to both imports and exports and requires a sophisticated assessment of alternative locations, ship and cargo type, and transportation costs (see, e.g. Jones et al., 2008). One needs to 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.
(2) *Export diversion*. This refers to sequestering goods that were intended for export to substitute for the 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

[4] An example of the application of this simple resilience metric is the assessment of the economic consequences of the 11 September terrorist attacks (Rose et al., 2009b). More than 1,100 firms in the World Trade Center impact area suddenly found their places of business destroyed. Had all of these businesses closed permanently, the direct business interruption losses (in terms of lost GDP) would have been $43 billion in the first year (the maximum potential loss). However, 95% of the businesses relocated to places in Midtown Manhattan or Northern New Jersey. Had relocation been immediate, the actual loss would have been zero. However, it took affected businesses an average of a few weeks to move, resulting in a loss of $12 billion. Avoided losses were thus $31 billion. According to the formula, then, 72% of the losses to affected businesses were avoided due to business relocation, much of which took advantage of the existence and utilization of spare office space, representing a resilience factor of 72%. At the same time, it is noteworthy that this sort of excess capacity is rarely mentioned in current research on the compilation of resilience indicators.

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.

(3) *Use of inventories*. This pertains to various types of stockpiles of the ports themselves and of direct and indirect customers of ports down the supply chain. A sub-set of this option would be to use some of the contents of the Strategic Petroleum Reserve (SPR) to replace crude oil imports.

(4) *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.

(5) *Unused capacity*. This is a potentially important source of resilience for the entire regional economy. It has the effect of lowering the percentage of business interruption below the level of the percentage damage to plant and equipment, if the unused capacity can be brought on line.

(6) *Input substitution*. This refers to utilizing in the production process goods that are similar 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.

(7) *Import substitution*. This is basically the same as input substitution but more explicitly replacing an imported good with a domestic substitute.

(8) *Production recapture (rescheduling)*. This refers to making up lost production once the port disruption is relieved. This is a viable option for short-run disruptions, where customers are less likely to have canceled orders.

Resilience at the meso- and macro-levels could also be taken into account, in both the inherent and adaptive forms. The workings of the market in reallocating goods to their highest value use are a major example of inherent resilience. An example of meso-adaptive resilience would be the establishment of clearinghouses to match customers who have lost their suppliers with suppliers who have lost their customers. At the macro-level, many background conditions represent inherent resilience, including the extent of economic diversification, which cushions the blow from the disruption to select sectors.

Dynamic resilience can be examined as well in terms of reducing the time to recovery. This is implemented by the prompt clearing of debris, repair, and reconstruction. These actions are in turn facilitated by considerations such as expedited government and private sector aid, mutual assistance programs, prompt insurance payments, and effective planning and management.

5. DATA AND APPLICATION OF THE METHODOLOGY

5.1. Data

The Port Arthur/Beaumont Metropolitan Statistical Area includes three counties in south-eastern Texas: Jefferson County, Orange County, and Hardin County. In 2008, the total gross output of the region was about $71 billion. The Petroleum Refining sector accounts for 50% of the total regional gross output. However, nearly 90% of the refined petroleum products are shipped to elsewhere in the USA or abroad. Other petroleum and chemical product manufacturing sectors account for another 17% of the total regional output. Other major sectors in the region include construction and services.

We model the Port Area Economy with the use of an I–O model provided by the Impact Analysis for Planning (IMPLAN) System (MIG, 2010), the major provider of I–O models in the USA. The I–O model is based on Year 2008 Port Arthur/Beaumont MSA Region data and contains 51 sectors, which are aggregated from the IMPLAN 440 sectors. The sectoral aggregation scheme is established to include the top 10 economic sectors in terms of gross output in the Port MSA Region and 20 economic sectors corresponding to the major imports shipped to the two Ports. The other IMPLAN sectors are aggregated into the remaining 21 sectors in the I–O model.

In this study, foreign import and export data for major commodities of the two Ports are collected from the WiserTrade Database (WISER, 2011). In 2008, the total value of import was over $33 billion, of which nearly 90% was crude oil. In order to make the calculation manageable, we only include import commodities with import values more than $1 million in the analysis. The total value of these commodities accounts for more than 99% of the total value of foreign import shipped to the two Ports. The total foreign export value at the two Ports in 2008 was about $5.3 billion. The same $1 million value criterion is also applied on the foreign export side when we determine which export commodities to be included in the study. In total, 39 types of foreign import commodities and 38 types of foreign export commodities are considered in this study. These correspond to 16 sectors in our 51-sector I–O model.

The data source of the domestic trade data for the year 2008 is Waterborne Commerce Statistics Center (WCSC, 2011). The WCSC data files only provide the trade data in terms of short tons. The cut-off criterion of the domestic import or export commodities that are included in this study is 10,000 short tons, which ensures the inclusion of more than 99% of the total quantity of domestic import or export shipped to or from the two Ports. In order to convert the WCSC short ton data into dollar values, we use the Energy Information Administration price data of crude oil and a number of petroleum refinery goods. For other commodities, we use the WiserTrade data to compute the prices of the corresponding foreign imports or exports and use these prices to get the dollar values of those domestically traded commodities. In total, 28 types of domestic import commodities and 23 types of domestic export commodities are considered in this study, which correspond to 13 sectors in the 51-sector I–O model.

For both the foreign and domestic import commodities, we first map each commodity to the relevant I–O sector. Then, we separate the import commodity use between intermediate use and final use based on the Industry Import Matrix of IMPLAN, which shows how each imported commodity is distributed to the producing sectors and to end-users within the region.[5]

5.2. Application of the Methodology

A few steps are needed to compute the vector of value-added changes of the major import-using sectors, $\Delta\mathbf{v}$, in the import disruption impact analysis:

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[5] Note that for the US economy at the level of aggregation used in our paper, all imports are competitive. In a more disaggregated sectoring scheme, it would be important to make the distinction between competitive imports and non-competitive imports, because only the former have domestic substitutes.

(a) The port shutdown would result in import losses of many categories of commodities. The import commodity data are categorized by harmonized system (HS) commodity codes. In the analysis, we first convert the HS codes into the sectoral scheme of the I–O model. The disruption percentage of each import commodity is computed by dividing the amount imported through ports at Port Arthur and Beaumont by the total amount of this commodity that is imported from outside of the region and used in the regional production activities, that is, for each commodity

$$\%\text{Import Disruption} = \frac{\text{Import Coming through Port Arthur and Beaumont}}{\text{Total Import}}.$$

(b) Based on the Industry Import Matrix of IMPLAN, which shows how each imported commodity is distributed to the producing sectors of the region, we identify the major using sectors of this imported commodity as being a sector that uses more than 10% of the total amount of this imported commodity among all the producing sectors in the region.

(c) For the same type of production input, many sectors purchase the commodity from both local producers and importers. If we assume that the same type of input makes no difference in the production process regardless of its source (locally produced or imported), the disruption percentage of a production input equals the import disruption percentage of this input (calculated in Step a) times the percentage of this input that is imported from outside of the region:

$$\%\text{Input Disruption} = \%\text{Import Disruption} \times \%\text{Input Imported}.$$

(d) According to the Leontief (fixed proportion) production function, $x\%$ reduction of one input in one sector would lead to $x\%$ reduction of output of this sector. Therefore, based on Steps a–c, for each import commodity disruption, the direct output reduction of the major using sectors of the import commodity can be computed. Also note that, as discussed in detail in Rose and Wei (2011), in the case of multiple input disruptions for a given sector, to eliminate double-counting, we only count the input disruption that represents the largest production constraint in percentage terms for each sector.

(e) Assume that b_{jj}^S is the diagonal element of sector j in the Ghosh inverse matrix of the allocation coefficient matrix ($\mathbf{A^s}$), Equation 5 implies that

$$\Delta v_j = \frac{\Delta x_j}{b_{jj}^S}. \tag{6}$$

In other words, after the computation of the output reduction of sector j (Δx_j) in Step d, Δv_j can be computed by Equation 6.

(f) After computing the vector of $\Delta\mathbf{v}$, the total supply-side impact, $\Delta\mathbf{x}$, associated with import losses can be computed using Equation 5.

The shutdown of a port will also prevent the shipment of exports. Export data are also categorized by HS commodity codes. In the export disruption impact analysis, we first convert the export commodity disruption data into a vector of final demand decrease, $\Delta\mathbf{y}$, of the corresponding sectors in the I–O model by using the bridging table between the HS codes and the sectoring scheme used in the I–O model. The final demand decrease of one sector will reduce its demand of intermediate inputs from its upstream suppliers, which in turn will affect successive rounds of suppliers up the supply chain. We use the standard demand-driven I–O model to compute the total impacts of an export disruption.

The daily operation of the port itself requires inputs such as electricity, other fuels, technical services, and food services. The disruption of the port operations will reduce the demand of goods and services from these sectors that support the port activities. The total impacts can again be captured by the demand-driven I–O model.

6. IMPACTS OF A 90-DAY COMPLETE PORT SHUTDOWN

The economic impacts of a 90-day complete shutdown of the ports at Port Arthur/Beaumont are analyzed in terms of the impacts of import, export, and port on-site operation disruptions. Analyses are performed both with and without the consideration of various types of resilience adjustments.

Row 1 in Table 1 presents the total impacts of the import disruption without the incorporation of any resilience adjustments. The direct output losses refer to direct activity reduction of major importers and are estimated to be \$7.0 billion, which results in total supply-side impacts of \$8.0 billion. Total demand-side impacts refer to the upstream implications of the reduction of final demand of the major importers and amount to \$8.9 billion. The total impacts are the sum of supply-side and demand-side impacts, net of the double-counted direct output losses. In addition, we cap the total losses of a sector at its total output in the

TABLE 1. Regional economic impacts of a 90-day disruption of intermediate imports through Port Arthur/Beaumont (in million 2008 dollars).

Case	Direct output loss	Total supply impacts	Total demand impacts	Total impacts after cap[a]	Total impacts after cap (%)
A. Base case (no resilience)	\$6,959	\$7,978	\$8,856	\$9,622	53.9
B. With re-routing	\$4,549	\$5,025	\$5,021	\$5,498	30.8
C. With SPR	\$6,555	\$7,536	\$8,423	\$9,178	51.5
D. With use of inventories	\$4,958	\$5,651	\$6,065	\$6,757	37.9
E. With export diversion	\$5,962	\$6,811	\$7,538	\$8,372	46.9
F. With conservation	\$6,820	\$7,819	\$8,679	\$9.475	53.1
G. With production rescheduling	[b]	[b]	[b]	\$5,078	28.5
H. With all resilience adjustments	[c]	[c]	[c]	\$2,092	11.7

[a] Total impacts equal total supply-side impacts plus total demand-side impacts, net the double-counting of direct output impacts. Also, for each sector, the total impact is capped at its total gross output in the 90-day period.
[b] This resilience adjustment is applied to the total supply + demand impacts.
[c] Total is non-additive of B, C, D, E, F, G to adjust for overlaps.

90-day period.[6] The total regional output impacts of all port import disruptions are $9.6 billion, which represents a reduction of 53.9% of economic activity in the Port Arthur MSA. This implies an overall multiplier effect of 1.38 ($9.6 billion/$7.0 billion).[7]

Various resilience measures can help reduce the impacts from import disruption to the Port Region. The effects of the various resilience measures are analyzed both individually and simultaneously:

A. Base case. In the case without the consideration of any resilience tactics, the direct output loss to the Port Region in a 90-day complete port shutdown scenario is nearly $7.0 billion. Total gross output loss is estimated to be $9.6 billion or 53.9% of the regional total gross output in the 90-day period.
B. Re-routing ships carrying imports. Based on the input from the US Coast Guard, we assume that 90% of the import shipping can be re-routed to other ports in the case of a 90-day port shutdown. However, it is also assumed that none of the re-routed crude oil and other petroleum refining products can be transported back to the Port Region through pipelines. The crude oil will be refined at the refineries that are close to the alternative ports. Re-routing has the effect of reducing the direct output losses of the region to $4.5 billion. Total gross output losses can be reduced to $5.5 billion or 30.8% of the total gross output.
C. Release of SPR. We assume that 4.16 million barrels of SPR (equivalent to around 20% of the total SPR drawdown in the aftermath of Hurricane Katrina) will be released to the Port Region to ensure the minimum-level operation of the key refineries in the region.[8] The use of SPR can reduce the direct output losses of the Port Region from $7.0 billion to $6.5 billion. Total gross output losses are reduced to $9.2 billion or 51.5% of the total gross output.
D. Use of inventories. Inventories of raw materials and finished goods used as inputs or intended for final customers through wholesale and retail markets can cushion the blow of a supply disruption. We make use of data from the BEA (2010) on manufacturing inventories by the stage of fabrication in our analysis.[9] The use of inventories helps

[6] This assumption is reasonable for this study since Petroleum Refining and Chemical Manufacturing sectors account for nearly 70% of the Port Region economy. Petroleum refineries and large chemical plants usually operate at full capacity (unused capacity is typically just for maintenance downtime). However, if the methodology established in this study is applied to other contexts for impact analysis on supply-chain disruption, this assumption may need adjustment if the economy is not fully utilizing the production capacity or the disruption takes place in a boom year, in which the output can be larger than the base year's total gross output.

[7] Not all the imports are used as intermediate inputs in the production processes. A portion of imports are final (finished) goods that are purchased by domestic end-users (consumers and government). The 90-day import disruption would also result in final goods losses of about $217 million or about 2.2% of $9.6 billion. However, these losses do not generate any supply-side impacts because they are at the end of the production chain.

[8] In response to Hurricane Katrina, in September 2005, President Bush issued a Finding of a Severe Energy Supply Interruption as defined in section 161(d) of the Energy Policy and Conservation Act, 42 U.S.C. 6 241(d). This authorized and directed the Secretary of Energy, at his discretion, to drawdown and sell crude oil from the SPR. The total US response to Hurricane Katrina, considering both the emergency loans of 9.8 million barrels and the 11 million barrels of oil that was sold, was 20.8 million barrels.

[9] Unfortunately, the data pertain to the total amount of inventories held by each producing sector, but without reference to the type of input. We, therefore, assume that this percentage holds across the board for all material inputs into production for each sector. We adjust the supply constraint by the amount of these inventories in terms of both a quantity and a time dimension. That is, a given quantity of inventories is only half as effective if the disruption is twice as long as originally believed.

reduce the direct output losses to \$5.0 billion. Total gross output losses can be reduced to \$6.7 or 37.9% from the baseline level.[10]

E. 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. However, it is rare that exactly the same good is simultaneously imported and exported from the same location, so this is likely to be minimal at the regional level. Note that we use a 51-sector I–O table in our analysis, but we use the trade data at 6-digit HS codes to make the export diversion adjustment, so we can avoid the 'cross-hauling' possibility. Again, this adjustment comes in the form of a relaxation of the input disruption constraint. The export diversion helps reduce the import disruption-induced direct output loss from \$7.0 billion to \$6.0 billion. Gross output impacts are reduced to \$8.4 billion or 46.9% of total gross output in the region.
F. Conservation. The ability to conserve on scarce materials (i.e. producing the same output but with fewer inputs) can reduce the shock as well. This represents the potential for a more careful use (less spillage, breakage, etc.) of these inputs. We assume that the possibility of conservation of all inputs is 2%. This has the effect of reducing the supply constraint for each good by this constant amount. The results indicate that conservation can reduce the direct output losses to \$6.8 billion, and total net losses to \$9.5 billion, or lead to an overall reduction of 53.1% in total gross output in the region.
G. Production recapture can help the economic sectors to make up their production losses during the port shutdown period at a later date.[11] This resilience tactic can reduce the total gross output loss in the region from \$9.6 billion to \$5.1 billion or from 53.9% to 28.5% of the regional gross output. Compared with the previous five resilience measures, production recapture has the greatest potential to reduce the total gross output loss.[12]
H. After simulating the effects of the resilience measures separately, we combined all the above five resilience adjustments together. Note, however, that these resilience adjustments are not additive. Conservation is applicable after re-routing, SPR release, inventories, and export diversion are applied. Production rescheduling is applied directly to overall losses after all the other resilience adjustments have taken place. Applying all of the six resilience adjustments can reduce the output losses to \$2.1 billion or lead to a reduction of only 11.7% of regional economic activity in the Port MSA Region. Therefore, in this 90-day complete port shutdown scenario, resilience has the potential to reduce the economic disruption to the Port Region resulting from import disruption by 78%.

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[10] Note that the use of inventories in one period warrants replacement (and hence increased production) in subsequent periods. This represents a further offset to lost production much like production recapture, though at a very much smaller level.

[11] Unlike a hurricane situation that may cause a port disruption, where factories are damaged and may not be able to operate even when critical inputs become available, an ordinary port disruption allows for factories to turn their production lines back on immediately and at a minimal cost of cleaning the system or overtime pay. We use the recapture factors from the Federal Emergency Management Agency's HAZUS loss estimation software (FEMA, 2009).

[12] There are many other forms of resilience tactics. Input substitution has the potential to alleviate the negative impacts of a supply disruption. However, information is rather scarce on this possibility. Moreover, this form of resilience is less operative for shorter periods. Finally, it is especially difficult to incorporate substitution into an I–O model. Due to these reasons, we have not included input substitution as a tangible form of resilience. Another form of resilience – excess capacity – is not included because it is not pertinent to a port shutdown.

Rows 2–7 of Table 1 present the results of import disruption impacts on the Port Region with the adjustment of different types of resilience. The results indicate that production rescheduling and ship re-routing have the greatest potential, and that conservation and access to the SPR have the lowest potential. The application of the full set of resilience tactics can reduce the disruption from 53.9% to 11.7% or by more than 78% of the pre-resilience estimate. Note that the various resilience tactics are not additive, but involve some overlap when applied simultaneously.

An export disruption would not only result in direct impacts to the export-producing sectors, but also generate demand-side effects to successive rounds of input-supplying sectors of the export-producing sectors. Total gross output impacts are \$4.0 billion, which represents a reduction of another 22.5% of economic activity in the Port Arthur MSA. The overall multiplier effect is 1.23 (\$4.0 billion/\$3.3 billion).

The resilience tactic of export diversion can reduce the losses on both the import and export sides. When we take the export diversion adjustment into account, the total gross output impacts decrease from \$4 billion to \$1.9 billion or from 22.5% to 10.6% of the baseline total gross output in the Port Region.

In order to estimate the economic impacts of the disruption of Port on-site operations and activities, we first determine the direct output (or revenue) of port operations. The demand-side I–O model is then applied to compute the total impacts of port operation disruption. Based on the Martin Associates (2006a, 2006b) studies, the direct revenues of the Port of Port Arthur and the Port of Beaumont are \$112.6 million and \$107.8 million, respectively. However, the direct revenues reported in these studies include not only the port operation itself, but also the revenues of firms and businesses that provide direct services to the ports. Martin Associates' (2006b, 2007) data for several ports indicate that, on average, 51% of the total revenues pertains to Maritime Services, which is equivalent to the direct operation revenues of the ports. Therefore, the annual revenues of port operations of the two ports are about \$112.4 million (= (\$112.6 + \$107.8) × 51%) or \$28.1 million over 3 months. The total demand-side output impacts of port on-site operation disruption to the Port MSA Region are \$46 million. The ratio of the total impact to direct impact, which is 1.64, reflects the demand-side multiplier of the port operation.

The total impacts of the 90-day port shutdown are presented in Table 2 with and without resilience. Gross output impacts stemming from the disruptions of imports, exports, and port on-site operations are \$9.8, \$4.0, and \$0.05 billion, respectively, without the consideration of any resilience. Note that when we compute the total output impact to the region, we cap each sectoral impact at its total output level in the 90-day period; that is, any overage is treated as double-counting in the multi-source disruption computation. Total gross output impacts are \$12.9 billion or a 72.5% reduction of economic activity in the Port Arthur/Beaumont MSA. The top three most affected sectors in terms of output losses are Petroleum Refineries, Other Basic Organic Chemical Manufacturing, and Petrochemical Manufacturing.

The import resilience and export resilience tactics have the potential to reduce the output loss by \$7.6 and \$2.1 billion, respectively. The total output loss for the region after factoring in resilience is \$4.2 billion or a reduction of only 23.5% of regional economic activity in the Port MSA below the baseline level. When we compute the total output impacts with resilience, we make the resilience adjustments first before applying the sectoral 90-day output cap to the sectoral output loss result. In the aggregate, the resilience measures have

TABLE 2. Gross output impacts of a 90-day disruption of Port Arthur/Beaumont, with and without resilience (in 2008 million dollars).

Impact component	Gross output impact
Import disruption impact	$9,839
Export disruption impact	$4,012
Port on-site operation disruption impact	$46
Total impact without resilience[a]	$12,947
Import resilience impact	$7,583
Export resilience impact	$2,128
Total impact with resilience[b]	$4,186

[a] Total output loss without resilience impact is lower than the sum of the three impact components in the first three rows because, for each sector, the total impact is capped at the 90-day sectoral total gross output.
[b] The sectoral 90-day total output cap is applied after the implementation of the resilience adjustments.

the potential to mute the regional economic losses by 68% in the 90-day complete port shutdown scenario.[13]

We also evaluated the impacts of the 90-day port disruption at Port Arthur/Beaumont on the national economy using US I–O models. The total output impacts of the Base Case (without any resilience adjustments) for the USA are $166.8 billion (compared with a $12.9 billion output loss at the Port Region level). The difference in the total impacts between the regional and national levels stems from both the differences in the direct output losses and the multiplier effects. First, only a portion of the import commodities are used in the production activities in the Port Region. For example, only about 45% of foreign crude oil imported through the two ports is refined in the Region. Therefore, the full impacts of the total foreign import crude oil disruption can only be captured in the national level analysis. Second, for many types of import and export commodities, the Port Region does not have the

[13] In addition to the major direct and indirect economic consequences modeled through the use of I–O analysis in this paper, three additional cost impacts were estimated (see Rose and Wei, 2011, for details):

1. *Economic cost of oil and chemical spills*. We measured the direct economic impacts on water quality and ecosystems of a hypothetical 27,000-gallon oil spill in the Neches River, Jefferson County, TX, which could contribute to the closing of the ports for a short time period such as 7 days. Indirect impacts caused by these spills are limited because the impacts are 'non-market values' except for recreation, tourism, and commercial fishing. Still, total economic impacts of the spill are estimated at less than $0.7 million. Even a major spill of one or two orders of magnitude higher would be tiny in comparison with the impacts presented in Table 2.
2. *Cost of delay caused by port shutdowns and diversions of shipping*. These are real resource costs, but their indirect effects cannot be readily modeled in an I–O framework. The indirect effects stem from the increased costs of production/delivery of key products, which would ordinarily stunt demand directly and then lead to further multiplier effects. A 7-day direct delay effect was estimated at $4 million. Scaling this up to 90 days yields a direct effect of $51 million. Price multiplier effects are likely to be less than twice this figure.
3. *Security value of oil released from the SPR.* Crude oil released from the SPR for use by refineries in the Port Arthur/Beaumont Area to compensate for tanker disruptions cannot simultaneously safeguard the USA from a strategic disruption like the 1973 Arab oil embargo or any other interruption. We estimated the direct security premium cost associated with these SPR releases at $15.6 million. Only direct costs are relevant, since this is a non-market value that does not translate into any price or quantity multiplier effect.

corresponding producing sectors in both the regional I–O table and the Industrial Import Table. That means that these commodities are neither used as inputs nor produced in the Port Region. In such cases, the import and export disruption of these commodities will not affect the economic activity of the Port Region, but will affect the rest of the USA. Finally, the multiplier effects on both the demand side and supply side at the national level are much larger than those at the Port MSA regional level. In a small region such as Port Arthur/Beaumont, the production inputs largely depend on the goods that are produced in other regions. At the same time, successive rounds of spending also leak out of a small region.[14] Note, however, that although the nation-wide economic impacts are much higher than the impacts on the Port Region in absolute terms, the losses in the Region are a much larger proportion of its economy than are the national losses in relation to the entire US economy. The post-resilience total impacts for the USA are $9.2 billion, which are again higher than the post-resilience impacts for the Port Region of $4.2 billion. However, resilience has a much higher potential to mute the total losses at the national level (95%) than at the Port regional level (68%). The major reason is that import shipment re-routing and export diversion only play a relatively limited role in loss reduction in the Port Region, while they have the highest potential to reduce losses among all the resilience tactics at the national level.[15]

Compared with the impact results from other port disruption studies, the post-resilience total impacts for the US economy found in this study are at the lower end. Park et al. (2007) estimated $1.63 billion per day losses to the US economy for a 1-month disruption to three major ports of the USA. For a 1-month disruption to the Ports of LA/LB, Park (2008) estimated that the economic impact to the US economy is $1.15 billion per day. The results in Jung et al. (2009) yielded an impact result of $0.77–$1.3 billion per day. In these three studies, no resilience tactics were modeled. Park et al. (2008) and CBO (2006) took inter-port and inter-modal substitutions into consideration, and, thus not surprisingly, the economic losses estimated by these two studies are lower than those estimated by the previous three studies. For an 11-day disruption and a 1-week disruption at the Ports of LA/LB, Park et al. (2008) and CBO (2006) reported daily losses of $0.23 billion and $0.07–$0.15 billion to the US economy, respectively. The post-resilience output losses to the US economy for the 90-day disruption in Port Arthur/Beaumont found in this study are about $0.1 billion per day. Overall, there are two major reasons for the lower estimates yielded by this study. First, the Ports of Port Arthur/Beaumont are smaller seaports compared with the Ports of LA/LB, in terms of both the volume and value of the cargos. Second, a comprehensive list of resilience tactics is considered in this study.

We offer some caveats regarding our results. First, the loss estimates should be considered upper bounds. I–O analyses usually yield impacts higher than those of macroeconometric or computable general equilibrium (CGE) models. In CGE models, for example, dampening of the economy usually leads to price decreases that help stimulate demand somewhat to partially offset the downward pressure. Also, our resilience impacts are upper bounds, in

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[14] Our model is not currently capable of analyzing effects of a port shutdown on multiple regions, as in the model of Park et al. (2007, 2008). Interregional feedback effects are likely to be minor in this case because Port Arthur/Beaumont is such a specialized economy dominated by Petroleum Refining and Chemical Manufacturing. Note, however, that the general methodology can be applied to multi-regional and inter-regional models.

[15] Based on consultation with the US Coast Guard, we conclude that the re-routed crude oil and refined petroleum products will not be further transported overland or via pipeline to the Port Arthur/Beaumont Region. In addition, most of the export diversions happen to the commodities that are not used or produced in the Port Region.

that they better represent the potential of the various resilience tactics we simulated and do not fully incorporate obstacles to their implementation. At the same time, we have not included all resilience options. For example, input substitution cannot readily be analyzed with an I–O model, though the effectiveness of this tactic is likely to be limited in actuality during a 90-day period. Apart from the omission of substitution, the biases in the impact results and the resilience results move in opposite directions and hence cancel each other out to some extent.

7. SUMMARY

This paper presents simulations of a 90-day disruption of the ports at Port Arthur and Beaumont, Texas. The estimates of total regional and national economic losses are key to developing risk management strategies for marine safety, natural hazard mitigation, and anti-terrorism programs at ports. In a risk–benefit analysis framework, the avoidance of these losses represents the first step in measuring benefits of safety programs. These benefits next need to be multiplied by their probability of occurrence, and then this risk-adjusted benefit measure needs to be juxtaposed to the direct and indirect costs of implementing mitigation programs.

Our analysis extends far beyond the immediate damage to ships or port facilities. It focuses on nearly all direct and indirect business interruptions in the ports' surrounding economic area and the nation as a whole. Essentially, the curtailment of imports and exports, as well as of the port operations themselves, translates into a chain of ripple, or multiplier, effects. For example, 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 off-site will lead to further curtailments of more customers down the supply chain. Also, for example, reductions in port operation mean a decrease in the ports' purchases of electricity, business services, labor, etc. These in turn cause further decreases in demand up the supply chain, as business service industries purchase fewer inputs and workers as a whole have less income to spend.

At the same time, the economy is resilient at several levels. Producing sectors in each round of the supply chain can use inventories and conserve inputs, ships can be re-routed to other ports, 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.

Our results indicate that a 90-day Port Arthur/Port Beaumont shutdown would result in BI losses of $13 billion or 72.5% of the Port Arthur/Port Beaumont MSA total output for that period. However, resilience can reduce these losses by two-thirds. The most effective resilience tactics at the regional level are production recapture and ship re-routing.

Our methodology has been carefully developed for the study at hand. However, it is readily generalizable to disruptions of other types and at other sites. We have thus developed and successfully applied an important risk management tool.

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