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2012

Optimal Resource Allocation for Preparedness and Recovery of Interdependent Systems

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Abstract

Disruptive events can have severe economic consequences, and input-output models can be used to measure how direct impacts propagate to other economic sectors. Investing in infrastructure and industry sectors can lessen those direct impacts, but it is often difficult to determine the level of resources that should be allocated to prepare for a disruption and how best to allocate resources in response to a disruption. We develop a model to help a decision maker allocate resources to prevent a disruption and to help individual industries recover if the disruption occurs. Resources allocated in advance of the disruption reduce the likelihood of the disruption, and resources allocated if the disruption occurs are divided among allocations to individual industries and allocations that help all industries recover simultaneously. The decision maker chooses these allocation amounts with the objective of minimizing the expected production losses from the disruption. The *Deepwater Horizon* oil spill, which adversely impacted several industries in the Gulf region in 2010, serves as a real-world case study for this decision model.

1. Introduction

Defense and security policy makers must determine the appropriate amount of resources that should be allocated to prepare for potential disruptions. These disruptions could be natural disasters, terrorist attacks, or human-caused accidents. If a disruption occurs, these policy makers must determine how resources should be allocated to minimize the consequences and help the impacted region recover. Consequences can include the loss of human life, severe economic costs, and environmental damage.

Determining how much should be spent to prevent and prepare for a disruption and how resources should be allocated in response to a serious disruption can present dilemmas to government officials. Healy and Malhotra (2009) calculate that from 1985 to 2004 the U.S. federal government spent $195 million per year on disaster preparedness and $3.05 billion on disaster relief. Would spending a little more on disaster preparedness have saved a lot of resources from being spent on disaster relief?

Much of the literature on emergency or disaster management focuses on specific tasks or the best way to plan and prepare for disruptions. Emergency response can be broken up into two-phases: pre-event and post-event. Although pre-event and post-event situations are often analyzed separately, the objectives for these two phases should be combined into a single objective to prevent sub-optimal planning (Tufekci and Wallace 1998). Optimizing recovery after a disruption seems to be neglected in the literature (Altay and Green 2006).

Developing a comprehensive, risk-based preparedness plan in advance of emergencies can reduce the loss of life and property. These plans require decision makers to clearly identify the goals and objectives and the degree of preparedness that is necessary (Bechtel et al. 2000). One approach, called capabilities-based planning, seeks to create capabilities for an organization that are needed for a wide range of scenarios. Capabilities-based planning originated in a military context and has since been applied to homeland security problems. Following a capabilities-based planning approach for emergency management may be more difficult than within the military because of the different organizations (e.g., the national government, state and local governments, the private sector) that are usually involved in disaster planning and response (Caudle 2005).

The goal of this paper is to create a model to determine the optimal level of resources that should be expended during the pre-event phase and also determine the optimal allocation of resources post-event to help a region recover from a disruption. A couple of other papers have incorporated both preparedness and post-disruption decision making (see Crowther 2008, Dillon et al. 2003), but most papers seem to focus on one or the other.

The model seeks to minimize the expected economic impact caused by a disruptive event, and a resource budget serves as the primary constraint. The decision maker chooses how much to allocate in order to reduce the probability of a disruption. If a disruption occurs, the decision maker determines how resources should be allocated to individual industries to help them recover from the disruption. Applying the model to the *Deepwater Horizon* oil spill requires estimating several parameters, which is accomplished by relying on media articles, scholarly work, think-tank reports, and government data. These sources provide a way to relate the allocation decisions to the objective, which is a challenge for many of the resource allocation models.

2. Modeling approach

2.1 Inoperability Input-Output Model

A resource allocation measures the economic consequences from a disruption, and a policy maker wishes to allocate resources to minimize expected production loss caused by the disruption. Production losses derive from both direct and indirect impacts. Direct impacts represent production losses that result directly from final consumers reducing their demand or from facilities that are inoperable due to the disruption. Indirect impacts are production losses incurred by industries or firms who depend on those directly impacted industries.

Industries and economic sectors suffer from indirect impacts because of the interdependencies among industries and infrastructure systems. Two entities are interdependent if each impacts or influences the performance or functionality of the other entity (Rinaldi et al. 2001). Interdependence plays an important role in risk and policy analysis because a disruptive event that directly impacts infrastructure, business, or the economy can induce partial or even total failure in other systems, markets, and businesses that are not directly impacted by the event.

The model presented in this paper measures the economic interdependence among industries using an input-output model. Modeling economic interdependence in the midst of a disruption seeks to quantify production and demand changes resulting from the disruptive event (Okuyama and Chang 2005). The Leontief (1936) input-output model measures these interdependent impacts by assuming that production changes are demand driven. If a disruption forces an industry to produce less or causes final demand to drop, less product is demanded of suppliers. Linear dependencies among industries are driven completely by these changes in final or intermediate demand. Despite the linear and demand-driven assumptions, input-output models provide a reasonable estimate of the economic impacts of disruptions (Boisvert 1992, Gordon et al. 2005, Okuyama 2008), and the models are supported by a large data collection effort undertaken by governments around the world.

The Inoperability Input-Output Model (IIM) (Santos and Haimes 2004) is a risk-based extension of the Leontief input-output framework. A disruption directly impacts m industries in an economy with a total of n industries, where $m \leq n$. A vector $\mathbf{c}^*$ is of length m, and c_i^* measures the direct impacts, in proportional terms, to industry i. The matrix $\mathbf{D} \equiv (\mathbf{I} - \mathbf{A}^*)^{-1}$ is a square matrix of order n, where $\mathbf{A}^*$ is the normalized interdependency matrix in the IIM. The matrix $\mathbf{D}$ translates direct impacts to direct and indirect impacts. Each element in the matrix, d_{ji}, calculates the proportional loss in production for industry j due to a loss in production in the directly impacted industry i. Each element on the diagonal of $\mathbf{D}$ is greater than or equal to one because direct impacts in industry i lead to total impacts at least as large as the direct impacts in that industry. If no interdependencies are present, $\mathbf{D}$ is the identity matrix. Because the disruption does not directly impact all n industries but only m industries, we use $\tilde{\mathbf{D}}$, a $n \times m$ matrix whose columns correspond to the directly impacted industries from $\mathbf{D}$. Thus, $\tilde{\mathbf{D}}$ translates the direct impacts in the m industries to direct and indirect impacts for all n industries in the economy.

Translating the proportional impacts to production losses requires multiplying the total impacts by $\mathbf{x}$, which is a vector of length n representing as-planned production for each industry in the economy. Total production losses due to the disruption is given by $\mathbf{x}^\mathsf{T}\tilde{\mathbf{D}}\mathbf{c}^*$. The IIM has been used to study a number of disruptions that concern policy makers including terrorist attacks (Haimes et al. 2005), cyber security (Dynes et al. 2007), workforce disruptions (Barker and Santos 2010), and waterway port closures (MacKenzie et al. 2012).

2.2 Resource allocation model

A decision maker wishes to effectively allocate resources to minimize the expected production losses from a disruption. We assume that allocating resources prior to a disruption reduces the probability of the disruption and does not change the economic impact if a disruption occurs. The amount of resources allocated before a disruption z_p reduces the initial probability of the disruption $\hat{p}$ to a lower probability p. An exponential function describes the functional relationship between z_p and the chances of the disruption occurring, where k_p describes the effectiveness of allocating resources

prior to the disruption.

If the disruption occurs, production losses are given by the IIM model, as described previously. The total budget, Z, is divided into resources allocated before the disruption z_p, to each industry, $z_1, \ldots, z_m$, and to all industries simultaneously, z_0. The parameters z_i and z_0 are investments to promote recovery following a disruptive event.

$$
\begin{aligned}
\text{minimize} \quad & p\mathbf{x}^\mathsf{T}\tilde{\mathbf{D}}\mathbf{c}^* - (1-p)\,g\,(Z - z_p) \\
\text{subject to} \quad & c_i^* = \hat{c}_i^* \exp(-k_i z_i - k_0 z_0) \qquad i = 1, \ldots, m \\
& p = \hat{p}\exp(-k_p z_p) \\
& z_p + z_0 + \sum_{i=1}^{m} z_i \leq Z \\
& z_p, z_0, z_i \geq 0 \qquad\qquad\qquad\quad i = 1, \ldots, m
\end{aligned}
\tag{1}
$$

The direct impacts to each industry c_i^* is a function of the allocation amounts, k_i (the effectiveness of allocating resources to industry i), k_0 (the effectiveness of allocating resources to all industries simultaneously), and $\hat{c}_i^*$ (direct impacts if no resources are allocated). Direct impacts on an industry can be assessed by (i) estimating the number of consumers that would stop purchasing from an industry because of a disruption or (ii) measuring the amount of production that would be lost if a facility were suddenly closed.

If the disruption does not occur, the resources that would have been allocated to help the region recover from the disruption, $Z - z_p$, can be used on other projects or returned to taxpayers if this is a public sector allocation. The function $g\,(Z - z_p)$, which is strictly increasing in $Z - z_p$, represents what could be done with the resources to help regional production if no disruption occurs. The solution assumes that $g\,(\cdot)$ is continuously differentiable. Because the decision maker desires to minimize the expected production losses if the disruption occurs and maximize the expected production gain if the disruption does not occur, minimizing the objective function requires inserting a negative sign before the expected gain in production $(1-p)\,g\,(Z - z_p)$.

The model assumes that allocating resources reduces the impacts exponentially, which is a frequent assumption in engineering risk problems (Bier and Abhichandani 2003, Dillon et al. 2005, Guikema and Paté-Cornell 2002). With an exponential function, the impacts are completely eliminated only if an infinite amount of resources are allocated. As more resources are allocated to an industry, the impacts on an industry decline at a constantly decreasing rate, and investing an additional dollar to reduce risk returns less benefit than investing the first dollar. Mathematically, an exponential function is continuously differentiable, which is important for arriving at an analytical solution. For each directly impacted industry, the exponential function requires estimating a cost-effectiveness parameter, k_i. As Eq. (2) shows, this parameter can be assessed if z_i, the amount of resources needed to reduce the direct impacts on industry i by a given fraction $c_i^*/\hat{c}_i^*$, is known or can be estimated.

$$
k_i = -\frac{\log\left(c_i^*/\hat{c}_i^*\right)}{z_i}
\tag{2}
$$

Allocating resources to simultaneously benefit all industries, as represented by the parameter z_0, could include activities such as cleaning the area and removing debris after the disruption, repairing infrastructure that all the other industries require (e.g., electric power, transportation), and engaging in risk communication efforts to inform the public that a region is safe.

Eqs. (3)-(6) depict the Karush-Kuhn-Tucker conditions for optimality where λ, λ_i, λ_0, and λ_p are the Lagrange multipliers for the budget constraint, the nonnegative constraints for z_i, the nonnegative constraint for z_0, and the nonnegative constraint for z_p, respectively. The parameter $\mathbf{d}_{*i}$ is a vector of length n representing the ith column from the interdependency matrix $\tilde{\mathbf{D}}$

$$
\lambda = \left[\prod_{i:z_i>0} \left(\hat{p}\mathbf{x}^\mathsf{T}\mathbf{d}_{*i}\hat{c}_i^* k_i\right)^{1/k_i} \right]^{\left(\Sigma_{i:z_i>0}\,1/k_i\right)^{-1}} \exp\left(Z - z_0 - z_p + \sum_{i:z_i>0} \frac{k_0 z_0 + k_p z_p}{k_i} \right)^{-\left(\Sigma_{i:z_i>0}\,1/k_i\right)^{-1}}
\tag{3}
$$

$$
z_i = \frac{1}{k_i} \log\left(\frac{\hat{p}\mathbf{x}^\mathsf{T}\mathbf{d}_{*i}\hat{c}_i^* k_i}{\lambda - \lambda_i} \right) - \frac{k_p z_p + k_0 z_0}{k_i} \qquad \lambda_i z_i = 0
\tag{4}
$$

$$
z_0 = \frac{1}{k_0} \log\left(\frac{\hat{p}k_0 \sum_{i=1}^{m} \mathbf{x}^\mathsf{T}\mathbf{d}_{*i}\hat{c}_i^* \exp[-k_i z_i]}{\lambda - \lambda_0} \right) - \frac{k_p z_p}{k_0} \qquad \lambda_0 z_0 = 0
\tag{5}
$$

$$z_p = \frac{1}{k_p} \log \left(\frac{\hat{p} \left[-k_p \sum_{z_i=0} \mathbf{x}^\mathsf{T} \mathbf{d}_{*i} \hat{c}_i^* \exp(-k_0 z_0) - k_p g(Z - z_p) + dg/dz_p \right]}{\lambda_p - \lambda + k_p \lambda \sum_{z_i>0} 1/k_i + dg/dz_p} \right) \qquad \lambda_p z_p = 0 \qquad (6)$$

Modern software tools like the "fzero" program in Matlab (2012) can solve Eqs. (3)-(6).

As long as some resources are allocated to industry i, the optimal allocation for that industry, z_i, monotonically increases with $\mathbf{x}^\mathsf{T} \mathbf{d}_{*i}$ and $\hat{c}_i^*$. If an industry has induces large interdependent impacts or if the direct impacts are severe, policy makers should devote more resources to reducing losses in that industry. The optimal allocation to industry i increases as k_i increases for smaller values of k_i but decreases for larger values of k_i. If allocating resources to an industry becomes more effective, the industry requires fewer resources, leaving more resources available for other industries. Any industry whose effectiveness k_i is less than the effectiveness for all industries k_0 should not receive any resources.

Without more specificity on the function $g(Z - z_p)$, little insight into the optimal allocation of z_p can be gleaned from Eq. (6). Because $g(Z - z_p)$ is strictly increasing with $Z - z_p$, $dg/dz_p < 0$. If dg/dz_p remains constant or increases as z_p increases (which implies decreasing marginal returns on the production gained by not allocating as much to prevention), then z_p increases as $\hat{p}$ increases. If dg/dz_p decreases as z_p increases, then z_p may or may not increase as $\hat{p}$ increases.

The function $g(Z - z_p)$ describes what happens to the resources that do not need to be allocated if the disruption does not occur. The portion of the budget originally reserved for recovery could be used to increase demand through a tax cut or by spending on public sector services like education and infrastructure. Eq. (7) assumes that the increase in demand for an industry is proportional to that industry's original demand, where $\mathbf{A}$ is the technical coefficient from the Leontief input-output model, $\mathbf{c}$ is a vector of length n describing the final demand for each industry, C is the sum of total demand in the economy, and $\mathbf{1}$ is a vector of length n of all ones.

$$g(Z - z_p) = \mathbf{1}^\mathsf{T} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{c} \frac{(Z - z_p)}{C} \qquad (7)$$

3. *Deepwater Horizon* oil spill application

On April 20, 2010, an explosion on the *Deepwater Horizon* offshore oil drilling rig claimed 11 lives, injured 16 other employees, and led to nearly 5 million barrels of crude oil spilling into the Gulf of Mexico over a span of three months. This incident became the largest marine oil spill and perhaps the most devastating (Robertson and Krauss 2010). The operator of *Deepwater Horizon*, BP, agreed to establish a $20 billion fund to pay for damage to the Gulf ecosystem, reimburse state and local governments for the cost of responding to the spill, and compensate individuals for lost business. The U.S. government imposed a six-month moratorium on deepwater drilling in the Gulf of Mexico, and it did not issue new leases for oil exploration in the Gulf until December 2011 (Fowler 2011).

The resource allocation model is applied to a case study examining the economic impacts of the *Deepwater Horizon* oil spill. This application quantifies the economic impacts of this disaster by focusing on the spill's direct impacts on five different industries. Parameter estimation for the models derive from publicly available economic data, think-tank and government reports, journal articles, and news stories.

3.1 Assumptions and parameter estimates

The model includes five Gulf states (Texas, Louisiana, Mississippi, Alabama, and Florida). Economic data collected by the U.S. Bureau of Economic Analysis (2010a,b, 2011) provide information on the production of different industries or sectors in each of those states, the vector $\mathbf{x}$, and the interdependencies among sectors, $\tilde{\mathbf{D}}$. The model combines the five Gulf States into a single economy with a total of $n = 63$ economic sectors.

The model focuses exclusively on business interruption losses, which are defined as production losses due to inoperable facilities or reduced demand, and ignores the severe environmental damage. The costs of stopping the oil leak or containing and removing crude oil are modeled to the extent that these activities impact demand and production in the Gulf region. Direct impacts from the oil spill include: (i) demand losses because consumers decide to buy or consume fewer goods and services as a result of the oil spill and (ii) less industry production because facilities are inoperable. Demand losses occurred because people did not travel to the Gulf for vacation or buy fish from the Gulf (and fewer fish were caught). The demand for beachfront property also declined. Firms drilled for less oil in the Gulf because of

Table 1: Input values for *Deepwater Horizon* case study

i	Industry	k_i (per \$1 million)	$\hat{c}_i^*$
0	All industries simultaneously	$8.6 * 10^{-5}$	
1	Fishing and Forestry	0.074	0.0084
2	Real Estate	0	0.047
3	Amusements	0.0038	0.21
4	Accommodations	0.0027	0.16
5	Oil and Gas	0.0057	0.079
	Preparedness	$k_p = 0.0031$	$\hat{p} = 0.045$

the moratorium, the lack of new leases and licenses, and the need for enhanced safety measures. The model considers that the oil spill directly impacted the Fishing and Forestry, Real Estate, Amusements, Accommodations, and Oil and Gas industries ($m = 5$).

The decision maker for this case study is a hypothetical entity responsible for limiting economic losses in the five Gulf states. The decision maker controls resources that can be used to increase demand for seafood, tourism, and real estate in the Gulf, implement new safety requirements in the offshore oil platforms, and remove crude oil from the Gulf which benefits all of the impacted industries. Although the U.S. federal government and the Department of Homeland Security have responsibility for many of these areas, in practice, the federal government, state and local entities, and the private sector all control resources that can be used for these types of tasks.

Table 1 displays the parameter estimates for the effectiveness of allocating resources, k_i, and the direct impacts for each industry, $\hat{c}_i^*$. Allocating resources to one of the industries directly impacted by reduced demand means better communication about the risks, safety, and cleanliness of the products and services produced by these industries. The model assumes that these resources can be expressed in monetary terms. If people are not consuming fish caught in the Gulf of Mexico, resources can be devoted to testing fish for oil contamination and to a public relations campaign explaining that fish are safe for consumption. A National Resources Defense Council (2011) report is the principal source to estimate direct impacts for the Fishing and Forestry industry ($i = 1$), and the report found that fishing revenue decreased by \$63 million. The parameter k_1 is derived from two studies (Richards and Patterson 1999, Verbeke and Ward 2001) examining the effectiveness of positive media stories following two different food scares.

Tourism to the Gulf can be encouraged by ensuring that the beaches are free of oil and debris and demonstrating to potential tourists that the beaches are safe and open. The direct impacts for Amusements ($i = 3$) and Accommodations ($i = 4$) are based on an estimate that tourism declined in Louisiana, Alabama, Mississippi, and Florida by 30% although tourism in Texas does not appear to have been impacted (Market Dynamics Research Group 2010, Oxford Economics 2010). The effectiveness parameters are derived from an Oxford Economics (2010) study that argues for a return on investment of 15 to 1 in tourism marketing. For the Real Estate industry ($i = 2$), the model assumes that the demand for housing in the four states fell 10% and that increasing demand for housing depends entirely on tasks devoted to helping all industries such as stopping the oil leak and cleaning the oil. Hence, $k_2 = 0$.

Allocating resources to the Oil and Gas industry ($i = 5$) means implementing new safety measures to reduce the risk of an accident on an offshore oil platform. The federal government may have lifted the moratorium earlier and granted more licenses and leases if the oil industry had demonstrated the safety of deepwater drilling. Direct impacts are based on domestic oil production from the Gulf of Mexico in 2010 (U.S. Energy Information Administration 2011), and k_5 is derived from an estimate that the new safety measures cost \$183 million (McAndrews 2011).

Capping the oil leak, containing the spill, and removing crude oil from the ocean can simultaneously benefit all five directly impacted industries. If less oil spills or if the oil is cleaned up more quickly, people are more likely to eat fish from the Gulf and vacation on its beaches. The Oil and Gas industry can also benefit because lifting the moratorium is less politically sensitive if the consequences of the oil spill are limited. Approximately \$11.6 billion was spent on stopping the oil leak and cleaning up the oil (Trefis Team 2011), and k_0 is estimated by assuming that $\$11600 k_0 = 1$. This assumption implies that billions of dollars must be allocated in order to reduce substantially the direct impacts on the five industries.

Table 2: Optimal allocation amounts for different budgets

i	Industry	Allocation (millions of dollars)				
p	Preparedness	299	262	282	324	374
0	All industries	0	2,517	7,596	12,455	17,406
1	Fishing and Forestry	0	16	16	16	16
2	Real Estate	0	0	0	0	
3	Amusements	153	638	638	638	638
4	Accommodations	241	935	935	935	935
5	Oil and Gas	307	631	631	631	631
Z	Total budget	1,000	5,000	10,000	15,000	20,000

Calculating the probability of a large oil spill similar to the *Deepwater Horizon* oil spill in the Gulf of Mexico relies on the percentage of oil spills that exceeded 10,000 barrels (U.S. Bureau of Ocean Energy Management 2011) and the fact that 40 oil spills occurred in the Gulf of Mexico from 2006 to 2010 (U.S. Bureau of Ocean Energy Management 2012). Because the 5 million barrels spilled from the *Deepwater Horizon* is much greater than the lower limit of 10,000 barrels, the initial probability $\hat{p} = 0.0445$ per year overestimates the chances of repeating a *Deepwater Horizon*-type spill. Estimating the effectiveness of allocating resources to reduce the chances of a spill poses a challenge. An assumption is made that the fiscal year 2013 budget request ($222.2 million) for the new federal Bureau of Safety and Environmental Enforcement reduces the chances of a spill by 0.5. The Bureau regulates offshore drilling, inspects offshore facilities, and prepares for oil spills. This assumption may overestimate the effectiveness of allocating resources to reduce the chances of an oil spill.

3.2 Results
The optimal allocation was calculated for a variety of budgets ranging from $0 to $20 billion, where $20 billion reflect the amount in BP's fund for reimbursing cleanup costs and lost business. As Table 2 shows, the optimal allocation recommends spending approximately $300 million to reduce the probability of an oil spill. This recommendation increases slightly as the budget increases. Fig. 1 depicts the probability of an large oil spill given an optimal allocation of budget. Surprisingly, more money should be spent on preventing an oil spill if the budget is $1 billion than if the budget is between $3 billion and $10 billion. If the budget is only $1 billion, a policy maker should not spend money to help all industries recover simultaneously (i.e., $z_0 = 0$). It is preferable to spend much of the budget prior to a disruption and to target industries individually if a disruption occurs. As the budget increases, more money is available to spend to help all industries recover, and it is preferable to spend relatively less on prevention and get the added benefit of production gains if no oil spill occurs.

Fig. 2 displays total production losses if an oil spill occurs and a decision maker optimally allocates the remainder of his or her budget. If no money is spent to help the region recover economically, the model estimates that that the region's production would decrease by $49 billion. If a budget of $20 billion is optimally spent, production losses are reduced to $5.1 billion. Production losses decline from $49 to $22 billion with a budget of just $3 billion, but the reduction occurs at a much slower rate for larger budgets. This slower rate is due to the exponential function. The rate of decrease is governed by k_0 because almost every additional dollar above $3 billion should spent to help all industries.

If the budget is less than $3 billion, the decision maker should not devote any resources to simultaneously help all industries because these industries do not benefit as much as they do from each one being targeted individually. For budgets of $3 billion or more, the decision maker should allocate $2.7 billion to Fishing and Forestry, Amusements, Accommodations, and Oil and Gas, and this amount remains the same even for a $20 billion budget (Table 2). As the budget gets larger, it is optimal to allocate more and more money to helping all industries recover simultaneously. Because the direct impacts in Fishing and Forestry are less severe than those in the other industries and because allocating resources to this industry is the most effective, only allocating $16 million for this industry is optimal if the budget is $3 billion or more.
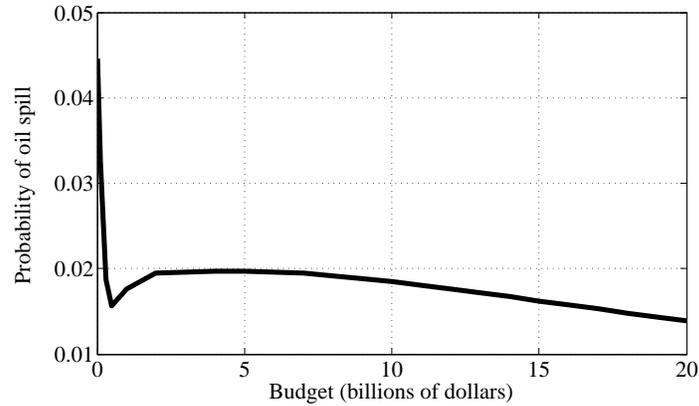
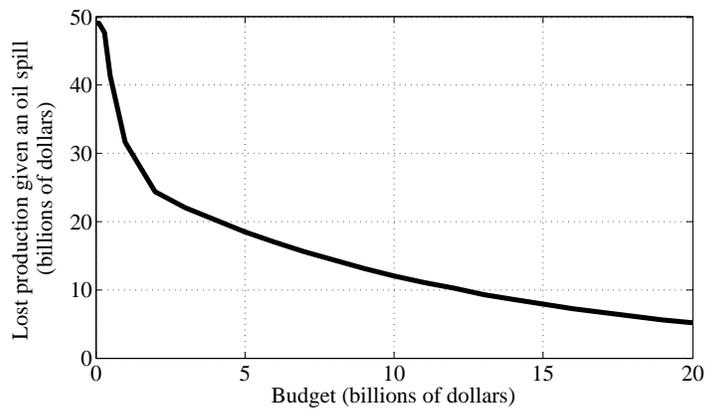Figure 1: Probability of an oil spill given optimal allocation of budget

Figure 2: Production losses from an oil spill given optimal allocation of budget

Overall, these results suggest that a relatively small portion of the budget should be spent on preventing a large oil spill. The probability of such a large oil spill is fairly small, and the model assumes that money not spent on preparedness activities can be used to increase regional production. Although spending billions of dollars to prevent a large oil spill is sub-optimal, this model is not considering small and medium oil spills. Although the economic consequences of those spills are smaller than the *Deepwater Horizon* oil spill, spending money to reduce the chances of a large oil spill also reduces the probability of a small or medium oil spill and thus carries environmental and economic benefits.

3.3 Sensitivity analysis

Several assumptions are necessary to apply this model to a major oil spill like the *Deepwater Horizon* oil spill. We explore the impact of changing some of these assumptions by performing sensitivity analysis on key parameters. We vary the probability of an oil spill $\hat{p}$ and the effectiveness of allocating resources to prevent an oil spill k_p. Fig. 3 depicts the fraction of a $10 billion budget that should be allocated to reduce the probability an oil spill.

As $\hat{p}$ increases, more money should be allocated to reduce the probability of an oil spill, but even if $\hat{p} = 0.3$, which is extremely high, only 18% of the budget should go toward preparedness activities. As k_p increases, the amount allocated to reduce the probability initially increases but then decreases. If the allocation of resources to reduce the probability is effective, less than 2% of the budget should be allocated for preparedness, even if the initial probability of an oil spill is large.

The model recommends $282 million in prevention for the initial values of $k_p = 0.0031$ and $\hat{p} = 0.045$. If these values overestimate these two parameters, sensitivity analysis demonstrates that even less money should be allocated toward
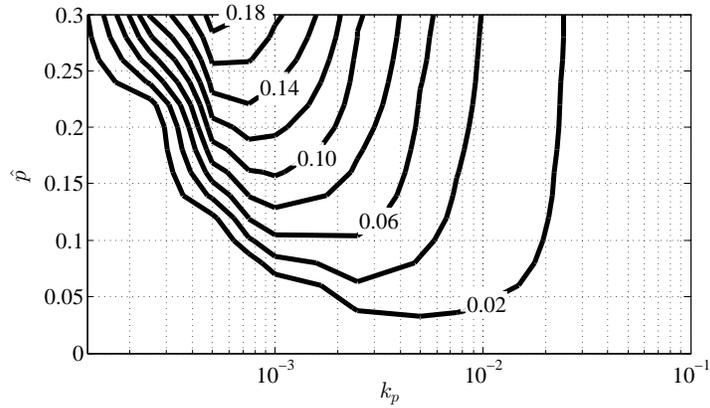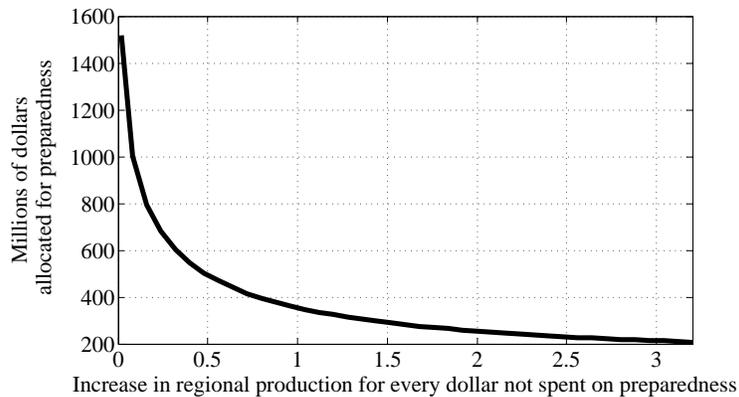
Figure 3: Fraction of $10 billion budget that should be allocated to prevent an oil spill

Figure 4: Impact of changing the constant parameter in the function $g(Z - z_p)$

preparedness. If $\hat{p} \leq 0.04$ and $k_p \leq 0.001$, no money should be spent to reduce the probability of a large oil spill. Both the chances of an oil spill and the effectiveness of preventing one provide less benefit than using the money to increase regional production as represented by the function $g(Z - z_p)$.

The function $g(Z - z_p)$ as given by Eq. (7) increases regional production by $1.60 for every dollar not spent on preparedness if no oil spill occurs. It may be unrealistic to assume such a large multiplier effect. We vary that multiplier from 0.02 to 3.2, and Fig. 4 shows the optimal amount that should be allocated to z_p when the budget is $10 billion. As long as regional production increases by $0.50 for every dollar not allocated to z_p, the amount to spend to reduce the probability is $500 million or less.

4. Conclusion

The model presented in this paper can help officials determine how to allocate resources prior to and following a disruption. An input-output model translates the direct impacts to regional production losses and provides an overall economic objective for a decision maker.

Newspaper accounts, think-tank reports, journal articles, and government data provide information to estimate parameters in order to apply these models to the 2010 *Deepwater Horizon* oil spill. If no money is spent on economic recovery after the Gulf spill, total production losses equal $49.1 billion. Several financial institutions estimated damages from the oil spill between $10 and $20 billion (Aldy 2011), and the Oxford Economics (2010) study concludes that tourism revenues could have declined by as much as $23 billion over a three-year span. If the total budget for recovering from the spill is $11.6 billion (the amount that BP spent to stop the spill), the model estimates that total

production losses are \$10.5 billion. This estimate is within the range of the other estimates.

The application to the *Deepwater Horizon* oil spill recommends that about \$300 million should be spent to reduce the probability of the oil spill, and this amount increases slowly even if the budget is \$20 billion. The model assumes that resources not spent on preparedness can be used to increase economic production in the Gulf Region if an oil spill does not occur. Performing sensitivity analysis reveals that even if production increases by less than what the model assumes, only a small fraction of the budget should still used for prevention. Because the true probability of an oil spill on the scale of *Deepwater Horizon* oil is likely smaller than 4.5%, a decision maker may want to spend even less than \$300 million.

Other factors not considered in this resource allocation model may encourage policy makers to spend more on prevention and preparedness. First, resources spent on preparing for an oil spill may help the government or businesses respond better if an oil spill does occur so that the losses are less. Second, spending resources to prevent a large oil spill may also reduce the chances of small and medium oil spills, which benefits the Gulf Region. Finally, a decision maker be risk averse or loss averse, which means that minimizing expected production losses is not an appropriate objective. If a decision maker is fearful of a large oil spill and the significant production losses that could be generated by a spill, more money should be spent to reduce the chances of a spill.

References

Aldy, J. E. (2011). Real-time economic analysis and policy development during the BP *Deepwater Horizon* oil spill. Faculty Research Working Paper Series, Harvard Kennedy School, Cambridge, MA. http://dash.harvard.edu/bitstream/handle/1/5241379/RWP11-037_Aldy.pdf? sequence=1. Accessed 2 April 2012.

Altay, N., and Green III, W. G. (2006). OR/MS research in disaster operations management. *European Journal of Operational Research* **175**, 475-493.

Barker, K., and Santos, J. R. (2010). A risk-based approach for identifying key economic and infrastructure systems. *Risk Analysis*, **30**(6), 962-974.

Bechtel, G. A., Hansberry, A. H., and Gray-Brown, D. (2000). Disaster planning and resource allocation in health services. *Hospital Materiel Management Quarterly* **22**(2), 9-17.

Bier, V. M., and Abhichandani, V. (2003). Optimal allocation of resources for defense of simple series and parallel systems from determined adversaries. In Y. Y. Haimes, D. A. Moser, E. Z. Stakhiv, G. I. Zisk, D. Dirickson, & B. I. Zisk (Eds.), *Risk-based decisionmaking in water resources X* (pp. 59-76). Reston, VA: American Society of Civil Engineers.

Boisvert, R. N. (1992). Indirect losses from a catastrophic earthquake and the local, regional, and national interest. *Indirect Economic Consequences of a Catastrophic Earthquake* (pp. 207-265): Development Technologies, Inc.

Caudle, S. L. (2005). Homeland security capabilities-based planning: Lessons from the defense community. *Homeland Security Affairs* **1**(2). http://www.hsaj.org/?article=1.2.2. Accessed 13 June 2013.

Crowther, K. G. (2008). Decentralized risk management for strategic preparedness critical infrastructure through decomposition of the Inoperability Input-Output Model. *International Journal of Critical Infrastructure Protection* **1**, 53-67.

Dillon, R. L., Paté-Cornell, M. E., and Guikema, S. D. (2003.) Programmatic risk analysis for critical engineering systems under tight resource constraints. *Operations Research* **51**(3), 354-370.

Dillon, R. L., Paté-Cornell, M. E., and Guikema, S. D. (2005). Optimal use of budget reserves to minimize technical and management failure risks during complex project development. *IEEE Transactions on Engineering Management* **52**(3), 382-395.

Dynes, S., Johnson, M. E., Andrijcic, E., and Horowitz, B. (2007). Economic costs of firm-level information infrastructure failures: Estimates from field studies in manufacturing supply chains. *The International Journal of Logistics Management* **18**(3), 420-442.

Fowler, T. (2011). Return to gulf: Big oil grabs leases. First auction of deep-water blocks since BP disaster draws \$337.6 million in winning bids. *Wall Street Journal*, 15 December. http://online.wsj.com/article/SB10001424052970203893404577098773281211592.html. Accessed 17 December 2011.

Gordon, P., Moore II, J. E., Richardson, H. W., and Pan, Q. (2005). The Economic Impact of a Terrorist Attack on the Twin Ports of Los Angeles-Long Beach. In P. G. H.W. Richardson, and J.E. Moore II (Ed.), The Economic Impacts of Terrorist Attacks (pp. 262-286). Cheltenham, U.K.: Edward Elgar.

Guikema, S. D., and Paté-Cornell, M. E. (2002). Component choice for managing risk in engineered systems with generalized risk/cost functions. *Reliability Engineering and System Safety* **78**(3), 227-237.

Haimes, Y. Y., Horowitz, B. M., Lambert, J. H., Santos, J. R., Lian, C., and Crowther, K.G. (2005). Inoperability Input-Output Model for Interdependent Infrastructure Sectors. II: Case Studies. *Journal of Infrastructure Systems* **11**(2), 80-92.

Healy, A., and Malhotra, N. (2009). Myopic voters and natural disaster policy. *American Political Science Review* **103**(3), 387-406.

Leontief, W. W. (1936). Quantitative input and output relations in the economic systems of the United States. *Review of Economics and Statistics* **18**(3), 105-125.

MacKenzie, C. A., Barker, K., and Grant, F. H. (2012a). Evaluating the consequences of an inland waterway port closure with a dynamic multiregional interdependence model. *IEEE Transactions on Systems, Man, and Cybernetics A: Systems and Humans* **42**(2), 359-370.

Market Dynamics Research Group. (2010). Oil spill research report, national wave 2. Louisiana Office of Tourism Research Section. 16 August. http://crt.louisiana.gov/tourism/research/researchcurrent.aspx. Accessed 2 April 2012.

Matlab. 2012. fzero: Find root of continuous function of one variable. R2012a documentation. http://www.mathworks.com/help/techdoc/ref/fzero.html. Accessed 4 April 2012.

McAndrews, K. L. (2011). Consequences of Macondo: A summary of recently proposed and enacted changes to U.S. offshore drilling safety and environmental regulation. Society of Petroleum Engineers, SPE-143718-PP. www.jsg.utexas.edu/news/files/mcandrews_spe_143718-pp.pdf. Accessed 30 December 2011.

National Resources Defense Council. (2011) The BP oil disaster at one year: A straightforward assessment of what we know, what we don't, and what questions need to be answered. 20 April. http://www.nrdc.org/energy/bpoildisasteroneyear.asp. Accessed 30 December 2011.

Okuyama, Y. (2008). *Critical Review of Methodologies on Disaster Impacts Estimation*. Background paper for the World Bank - UN Assessment on the Economics of Disaster Risk Reduction. http://gfdrr.org/gfdrr/node/284. Accessed 23 September 2011.

Okuyama, Y., and Chang, S. E. (Eds.). (2004). *Modeling Spatial and Economic Impacts of Disasters*. Berlin: Springer-Verlag.

Oxford Economics. (2010). Potential impact of the Gulf oil spill on tourism. A report prepared for the U.S. Travel Association. 22 July. http://www.ustravel.org/news/press-releases/bp-oil-spill-impact-gulf-travel-likely-last-3-years-and-cost-227-billion. Accessed 30 September 2011.

Richards, T. J., and Patterson, P. M. (1999). The economic value of public relations expenditures: Food safety and the strawberry case. *Journal of Agricultural and Resource Economics*, **24**(2), 440-462.

Rinaldi, S. M., Peerenboom, J. P., and Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine* December, 11-25.

Robertson, C., & Krauss, C. (2010). Gulf spill is the largest of its kind, scientists say. *New York Times*. 3 August . http://www.nytimes.com/2010/08/03/us/03spill.html?_r=1&fta=y. Accessed 20 December 2011.

Santos, J. R., and Haimes, Y. Y. (2004). Modeling the demand reduction input-output (I-O) inoperability due to terrorism of interconnected infrastructures. *Risk Analysis*, **24**(6), 1437-1451.

Trefis Team. (2011). BP rising from *Deepwater Horizon* abyss but not free yet. *Forbes*, 4 March. http://www.forbes.com/sites/greatspeculations/2011/03/04/bp-rising-from-deepwater-horizon-abyss-but-not-free-yet/. Accessed 30 December 2011.

Tufekci, S., and Wallace, W. A. (1998). The emerging area of emergency management and engineering. *IEEE Transactions on Engineering Management* **45**(2), 103-105.

U.S. Bureau of Economic Analysis. (2010a). Make table, before redefinitions, 2009. 1998-2009 summary make annual I-O table before redefinitions. U.S. Department of Commerce. http://www.bea.gov/industry/ io_annual.htm. Accessed 17 April 2012.

U.S. Bureau of Economic Analysis. (2010b). Use table, before redefinitions, 2009. 1998-2009 summary use annual I-O table before redefinitions. U.S. Department of Commerce. http://www.bea.gov/industry/ io_annual.htm. Accessed 17 April 2012.

U.S. Bureau of Economic Analysis. (2011). Gross domestic product by state. Regional economic accounts. U.S. Department of Commerce. http://www.bea.gov/regional/index.htm. Accessed 17 April 2012.

U.S. Bureau of Ocean Energy Management. 2011. *Draft description of the cost and benefit calculations in the offshore environmental cost model: Temporary supplement to the economic analyses summarized in the decision document for the proposed 5-year OCS oil and gas program for 2012-2017*, by Industrial Economics, Applied Science Associates, Northern Economics, and Nicholas Z. Muller. http://www.boem.gov/Oil-and-Gas-Energy-Program/Leasing/Five-Year-Program/2012-2017/PP.aspx. Accessed 20 March 2012.

U.S. Bureau of Ocean Energy Management. 2012. Incident statistics and summaries 1996-2011. http://www.boemre.gov/incidents/IncidentStatisticsSummaries.htm. Accessed 22 March 2012.

U.S. Energy Information Administration. (2011). Table 4a. U.S. crude oil and liquid fuels supply, consumption, and inventories. In *Short-Term Energy Outlook*. http://www.eia.gov/forecasts/ steo/data.cfm?type=tables. Accessed 6 December 2011.

Verbeke, W., and Ward, R. W. (2001). A fresh meat almost ideal demand system incorporating negative TV press and advertising impact. *Agricultural Economics* **25**(2/3), 359-374.