How much should we spend on preparing for disruptions?

Cameron MacKenzie, Industrial and Manufacturing Systems Engineering, Iowa State University

SRA Annual Meeting, December 9, 2015
U.S. spending on disasters

• $85 - $136 billion per year (Weiss and Weidman, 2013; Kostro et al., 2013)
• From 1985-2004 (Healy and Malhotra, 2009)
  • $195 million per year on disaster preparedness
  • $3.04 billion per year on disaster relief

Cost-benefit analyses

Benefit-cost ratio of FEMA mitigation grants (Rose et al., 2005)

• 1.5 for earthquake mitigation grants
• 5.1 for flood mitigation grants

Research questions

• What is the optimal allocation of resources pre-disruption (prevention and preparedness) and post-disruption (response and recovery)?
• How should resources be allocated among different industries to help those industries recover?
• How does the optimal allocation change based on risk preferences?
Resource allocation model

Normal production

Vector of direct impacts (proportional)

Interdependent matrix

Probability of disruption

Direct impacts with no resources

Effectiveness of prevention

Probability with no resources

Effectiveness of preparation

Direct impacts with no resources

Effectiveness of recovery allocation

Allocation to industry

Allocation to benefit all industries

Allocation to industry

Effectiveness of recovery allocation

Subject to

$\min \ p x^\top D c$

$p = \hat{p} \exp(-k_p z_p)$

$c_i = \hat{c}_i \exp(-k_q z_p - k_i z_i - k_0 z_0)$

$z_p + z_{Fish} + z_{RealEstate} + z_{Amuse} + z_{Accom} + z_{oil} + z_{General} \leq Z$

$z_p \geq 0, \ z_i \geq 0, \ z_{General} \geq 0$

Overall budget
Optimal recovery allocation

Consequence * Effectiveness

• If $\mathbf{x}^\top \mathbf{d}_{*i} \hat{c}_i k_i \leq \mathbf{x}^\top \mathbf{d}_{*j} \hat{c}_j k_j$ and $z_i > 0$, then $z_j > 0$

Effectiveness to all industries

• If $k_0 > (\sum_{z_i>0} \frac{1}{k_i})^{-1}$ then some $z_i > 0$ is not optimal

• If $z_0 > 0$ then

$$z_i = \frac{1}{k_i} \log \left( \frac{\mathbf{x}^\top \mathbf{d}_{*i} \hat{c}_i k_i \left( 1 - k_0 \sum_{z_j>0} \frac{1}{k_j} \right)}{k_0 \sum_{z_j=0} \mathbf{x}^\top \mathbf{d}_{*j} \hat{c}_j} \right)$$
Optimal pre-disruption allocation

\[ \frac{1 - \hat{\rho}}{\hat{\rho}} \]

\[ \frac{-k_p g(0, Z)}{\frac{\partial g}{\partial z_p}(0, Z)} \]

\[ k_p + k_q > k_0 \rightarrow z_p > 0 \]

\[ z_p = 0 \]
Optimal pre-disruption allocation

\[ g(z_p, Z) \]
Risk aversion
Deepwater Horizon oil spill
Input parameters for oil spill

<table>
<thead>
<tr>
<th>Industry</th>
<th>$k_i$ (per $1$ mil)</th>
<th>$\hat{c}_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevention</td>
<td>$k_p = 2.8 \times 10^{-4}$</td>
<td>$\hat{p} = 0.045$</td>
</tr>
<tr>
<td>Preparedness</td>
<td>$k_q = 1.6 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>All industries</td>
<td>$k_0 = 1.1 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Fishing</td>
<td>0.074</td>
<td>0.0084</td>
</tr>
<tr>
<td>Real estate</td>
<td>0</td>
<td>0.047</td>
</tr>
<tr>
<td>Amusements</td>
<td>0.0038</td>
<td>0.21</td>
</tr>
<tr>
<td>Accommodations</td>
<td>0.0027</td>
<td>0.16</td>
</tr>
<tr>
<td>Oil and gas</td>
<td>0.0057</td>
<td>0.079</td>
</tr>
</tbody>
</table>

$$g(z_p, Z) = 1.6(Z - z_p)$$
Parameter estimation for fishing

$62$ million lost sales from Gulf Coast fishing
→ $0.84\%$ of region’s fishing and forestry production

Studies on food safety and impact of positive media stories
→ $792,000$ to reduce losses by $40$ million

Model results

<table>
<thead>
<tr>
<th>Industry</th>
<th>Millions of dollars allocated to each industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fishing</td>
<td>0 0 46 46 46</td>
</tr>
<tr>
<td>Real estate</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>Amusements</td>
<td>250 1,209 1,209 1,209</td>
</tr>
<tr>
<td>Accommodations</td>
<td>379 1,752 1,752 1,752</td>
</tr>
<tr>
<td>Oil and gas</td>
<td>372 1,011 1,011 1,011</td>
</tr>
<tr>
<td>All industries</td>
<td>0 981 5,981 15,981</td>
</tr>
<tr>
<td><strong>Total budget</strong></td>
<td><strong>1,000 5,000 10,000 20,000</strong></td>
</tr>
</tbody>
</table>

Production losses if oil spill occurs:

- **Budget ($ billion)**: 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20
- **Production losses ($ billion)**: 0, 10, 20, 30, 40
Sensitivity analysis

\[ g(z_p, Z) = 1.6(Z - z_p) \]
Sensitivity analysis

$10$ billion budget

Pre-disruption allocation ($\$\text{billions}$) for different effectiveness and initial probability

\[\hat{p}, \ k_p\]

\[0, 0.05, 0.1, 0.15, 0.2\]

\[10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}\]
Allocation with risk aversion

$10$ billion budget

$0 \sim 1 - p^*$

$+$50 bil

$-$50 bil

Very risk averse

Risk neutral

Probability

$p^*$
Future research

• Multiple disruptions: allocating resources prior to disruption can help prevent and prepare for multiple disruptions
• Application to other disruptions
• Budget constraint or impact constraint?
• Temporal aspects

Email: camacken@iastate.edu