Mitigating Risk of Disruptive Events: Application to Supply Chains and Allocating Resources for Preparedness

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IMSE Grad Seminar
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Outline

• Supply chain risk and disruptions
  • Severe supply chain disruptions (simulation)
  • Fault tree analysis
  • Contamination in food supply chains
• Resource allocation for emergency preparedness
Interdependent economy
Simulation

Supplier’s facility is closed

- Yes: Firms receive required supplies
- No: Move production to alternate facility?

Move production to alternate facility?

- Yes: Firms receive required supplies
- No: Supply inventory?

Supply inventory?

- Yes: Supply shortage for firms
- No: Demand not satisfied or customers buy from other firms

Demand not satisfied or customers buy from other firms

- Yes: Supplier’s facility reopens?
- No: Supplier’s facility reopens?

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Firm’s decision

- How much to produce?
  - Maximize profit in current period
  - Satisfy demand
    - Time when suppliers’ facilities reopen
  - Customer loyalty
  - Inventory on hand
  - Selling price
  - Cost of alternate suppliers

- Value
Results in automobile sector

Average percent of total demand satisfied

<table>
<thead>
<tr>
<th></th>
<th>Maximize profit and no alternate facility</th>
<th>Sacrifice profit to meet demand and no alternate facility</th>
<th>Sacrifice profit to meet demand and alternate facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford, GM, and Chrysler</td>
<td>91.7</td>
<td>98.7</td>
<td>99.0</td>
</tr>
<tr>
<td>Toyota and Honda</td>
<td>68.7</td>
<td>86.7</td>
<td>93.4</td>
</tr>
<tr>
<td>Nissan</td>
<td>82.5</td>
<td>92.7</td>
<td>96.1</td>
</tr>
</tbody>
</table>

Previous work

Chemical products
- Hydrogen peroxide
- Anode graphite for lithium ion-battery
- Ethylene-propylene-diene rubber
- Poly-propylene

Electronic materials
- Electrolytic copper foil
- Synthetic quartz

Silicon wafer
- Semiconductor
  - Micro-processor
  - Chip for controlled machining

Automotive

Industry machine

Home electronics

Preliminary results (concept demonstration)

Average percent of total demand satisfied

<table>
<thead>
<tr>
<th>Industry</th>
<th>Maximize short-term profit and no alternate facility</th>
<th>Sacrifice profit to meet demand and no alternate facility</th>
<th>Sacrifice profit to meet demand and alternate facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>57.9</td>
<td>87.2</td>
<td>95.7</td>
</tr>
<tr>
<td>Electronics</td>
<td>38.9</td>
<td>98.1</td>
<td>99.4</td>
</tr>
<tr>
<td>Chemical</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>44.3</td>
<td>97.3</td>
<td>100</td>
</tr>
</tbody>
</table>

Collaborators: Xue (Snow) Bai and Andre Fristo
Fault tree analysis for supply chain risk

Dynamic fault tree

- Dynamic fault trees (DFT) are used to calculate reliability over time in engineered systems
- Apply DFT to supply chains
  - Main-backup supply chain
    - Multiple units
    - Single unit
  - Mutual-assistant supply chain
    - Multiple units
    - Single unit

Four scenarios

A: information system
B: supplier 1
C: supplier 2
Fresh produce contamination

- *Salmonella*
- *E. coli*
- *Listeria Contamination*
- *Outbreak*
Model flowchart

At demand node

Where is contamination node (CN)?

CN is distribution node

Can produce be rerouted?

Is safety stock useable?

Disruption mitigated

Disruption not mitigated

CN is producing node

Is safety stock useable?

Can production be increased?

Disruption mitigated

Disruption not mitigated
E. coli in bagged spinach

- E. coli discovered in bagged spinach in September 2006
- Source of contamination traced back to Natural Selection Foods, a supplier to Dole
- Fresh and bagged spinach was pulled from shelves for 5 days
- Spinach from California unavailable for an additional 10 days

Dole’s production of spinach

![Graph showing the daily consumption and demand for Dole's spinach over days after contamination announcement.](image)
RESOURCE ALLOCATION FOR EMERGENCY PREPAREDNESS
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 between different disruptions?
• How can we train decision makers to help them prepare for disruptions?
Outline

1. Resource allocation model
   • Theoretical results: 1 disruption
   • Example: 2 disruptions (oil spill, hurricane)

2. Hurricane decision simulator
Resource allocation model

Normal production

Interdependent matrix

Subject to

Constraint

Effectiveness of recovery allocation

Effectiveness of preparation

Effectiveness of prevention

Allocation to industry

Allocation to benefit all industries

Pre-disruption allocation

Direct impacts with no resources

Probability with no resources

Probability of disruption

Vector of direct impacts (proportional)

Increased production if no disruption

Increased production if no disruption

Increased production if no disruption

Increased production if no disruption

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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

probability of disruption

Effectiveness of prevention

Effectiveness of preparedness

Effectiveness of response

Opportunity cost function

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

$1 - \hat{p}$

$\hat{p}$

$z_p = 0$

$k_p + k_q > k_0$

$z_p > 0$
Optimal pre-disruption allocation

\[ g(z_p, Z) \]
Risk aversion
Example: multiple disruptions

- Gulf states: Texas, Louisiana, Mississippi, Alabama, Florida
- 2 disruptions: oil spill (*Deepwater Horizon*) and hurricane (Katrina)
  - Probability of each disruption
- Economic losses
  - Demand losses
  - Production shut-down
- Hypothetical decision maker

### Input parameters

<table>
<thead>
<tr>
<th></th>
<th>Oil spill</th>
<th>Hurricane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>$\hat{p} = 0.045$</td>
<td>$\hat{p} = 0.56$</td>
</tr>
<tr>
<td>Prevention</td>
<td>$k_p = 2.8 \times 10^{-4}$</td>
<td>$k_p = 0$</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>Directly impacted</td>
<td>$m = 5$</td>
<td>$m = 31$</td>
</tr>
<tr>
<td>industries</td>
<td>Fishing, Real estate, Amusements, Accommodations, Oil and gas</td>
<td>Service industries, Farms, Fishing, Construction, Manufacturing industries, Utilities, Ports, Oil and gas,</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
$\rightarrow$ 0.84% of region’s fishing and forestry production

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

Optimal pre-disruption allocation

![Graph showing optimal allocation before disruption (billions of dollars) vs. budget (billions of dollars). The graph compares two scenarios: Oil spill and Hurricane. The red line represents the Oil spill scenario, while the brown line represents the Hurricane scenario. The graph shows a peak in allocation at around a budget of 15 billion dollars, after which the allocation decreases.]
Economic losses

![Graph showing economic losses vs. budget](image-url)

- **Economic losses (billions of dollars)**
- **Budget (billions of dollars)**

- Red line: Oil spill
- Orange line: Hurricane

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Iowa State University  
Industrial and Manufacturing Systems Engineering
Sensitivity analysis (pre-disruption allocation as initial impacts vary)

$30$ billion budget
Conclusions

- Model benefits
  - Consider one disruption versus another disruption
  - Pre versus post-disruption allocation
  - Consider spending on disruptions versus other priorities
- Decision maker should allocate more for hurricane than oil spill → more probable and more consequential
- Lei Yao: allocating resources under deep uncertainty
Final thoughts

• Models for disruptions provide insight into the consequences of disruptions
• Models provide insight into how to make decisions
• Getting data is difficult

If you are a new graduate student
• Find problems that interest you
• Don’t worry if data is not available: think about how you might want to solve the problem first

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