Interdependent, Multi-regional Impacts of Inoperability at Inland Waterway Ports and Network

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Research questions

• How can we measure disruptive flows in a waterway network?
• How can be quantify interdependent effects of disruptions?

The Motivation
Dock-specific Disruptions
Waterway Accidents
The Conclusions
Motivation

• Attacks on CI/KR
  – ...could significantly disrupt the functioning of government and business alike and produce cascading effects far beyond the targeted sector and physical location of the incident...
  – ...could produce catastrophic losses in terms of human casualties, property destruction, and economic effects, as well as profound damage to public morale and confidence [DHS 2009]

• Include, among others: agriculture/food, critical manufacturing, TRANSPORTATION
Inland ports as critical infrastructure

- US inland waterway ports move 2.5 billion tons of commerce via water annually

- As US traffic congestion increases, growth of inland waterways will only increase

- Containerized freight safety important homeland security issue
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Research components

Multi-regional risk propagation model

- Network Topology
- Commodity Flows
- Hazard Impacts
Modeling port operations

• Discrete event simulation model
  – Inputs: arrival schedules, crane and yard capacities
  – Models number of tons at each stage of the queue over time

Port export operations

Port import operations
Disruptions in port operations

Disruption of transport to facility

Breakdown at facility

Disruptions downstream
### Quantifying port operations

**Model inputs**
- Duration of disruption
- Impact of disruption
  - Reduced arrivals
  - Reduced crane capacity
  - Reduced departures

**Economic losses**
Interdependent impacts of tonnage disruptions

**Model results**
Tonnage of exports-imports flowing on the network during the disruption

**Loss estimation**
Difference in tonnage between as-planned and disruptive scenarios
Multi-regional inoperability

- Consequences can be expressed in terms of the losses in output and demand normalized by the as-planned sector output

\[
q = TA^{\ast}q + Tc^{\ast}
\]

Inoperability \((q_i) = \frac{\text{As-planned output } (x_{i,0}) - \text{Perturbed output}(x_i)}{\text{As-planned output } (x_{i,0})}\)

Demand perturbation \((c_i^{\ast}) = \frac{\text{Exogenous demand loss}}{\text{As-planned output } (x_{i,0})}\)

For \(n\) commodities across \(p\) regions
Transportation inoperability

- When a transportation inoperability occurs, a loss of trade results
  - Disruption in port operations
  - Disruption in waterway operations

\[
\text{Demand loss (} c_R^* \text{)} + \text{Output loss (} q_s \text{)} + \text{Demand loss (} c_s^* \text{)}
\]
Illustration: Inland waterway port

- Largest in area in the US
- 2 mil tons annually

Mississippi River System

Port of Catoosa
Tulsa, Oklahoma

McClellan-Kerr
Arkansas River
Illustration: Waterway network

Data Sources:
US Army Corps of Engineers, National Database Center
Illustration: Dock-specific commerce

- Estimated annual amount of export-import through Catoosa in 2007 ($M), Total = $937 million

<table>
<thead>
<tr>
<th>Commodities</th>
<th>2007 Export ($M)</th>
<th>2007 Import ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Dry Cargo</td>
<td>313.2</td>
<td></td>
</tr>
<tr>
<td>Dry Bulk</td>
<td></td>
<td>146.0</td>
</tr>
<tr>
<td>Grains</td>
<td>223.5</td>
<td>66.0</td>
</tr>
<tr>
<td>Food and beverage</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td>Minerals</td>
<td></td>
<td>107.6</td>
</tr>
<tr>
<td>Petroleum products</td>
<td></td>
<td>70.6</td>
</tr>
<tr>
<td>Chemicals</td>
<td></td>
<td>6.2</td>
</tr>
</tbody>
</table>

Data Sources:
US Army Corps of Engineers, Tulsa Port of Catoosa
US Department of Transportation Research and Innovative Technology Administration
Illustration: Dock operations

• Available data for annual flow of commodities through port can be converted to daily flows
  – Also reflects seasonality
• Queueing models apply to the general dry goods, dry bulk, and grain docks
  – For liquid bulk docks, commodities arrive and are transferred to and from barges through pipes to tanks
• Daily capacities of cranes determined by the number of hours they are in operation
Illustration: Port commerce simulation

- Estimated annual amount of export-import through Catoosa in 2007 ($M)

**Exports**

<table>
<thead>
<tr>
<th>Product Category</th>
<th>Cumulative Exports in $M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food and Beverage Products</td>
<td>211.5</td>
</tr>
<tr>
<td>Petroleum and Coal Products</td>
<td>92.1</td>
</tr>
<tr>
<td>Chemical Products</td>
<td>72.2</td>
</tr>
<tr>
<td>Non-metallic Mineral Products</td>
<td>67.1</td>
</tr>
<tr>
<td>Machinery</td>
<td>27.7</td>
</tr>
<tr>
<td>Miscellaneous Manufacturing</td>
<td>466.6</td>
</tr>
</tbody>
</table>

**Imports**

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<tr>
<td>Primary Metals</td>
<td>67.1</td>
</tr>
<tr>
<td>Fabricated Metal Products</td>
<td>27.7</td>
</tr>
</tbody>
</table>

Main trading states

- Louisiana: 466.6
- Alabama: 211.5
- Texas: 92.1
- Mississippi: 72.2
- Ohio: 67.1
- Kentucky (17.8)
- Illinois (7.1)
- Iowa (2.1)
- Arkansas (0.7)
Illustration: Dock disruption

- Floods, snowstorms, (hurricanes) could disable the entire port
- Dock disruption scenarios modeled separately
  - Complete shut down of dock for duration of two workweeks

<table>
<thead>
<tr>
<th>Liquid Bulk</th>
<th>Other Docks</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Spillages</td>
<td>- Crane outages</td>
</tr>
<tr>
<td>- Dock shut during cleanup</td>
<td>- Partial/total shut down</td>
</tr>
<tr>
<td>- Impact of disruption</td>
<td>- Impact of disruption</td>
</tr>
<tr>
<td>- No arrivals</td>
<td>- Reduced crane capacity</td>
</tr>
<tr>
<td>- No departures</td>
<td>- Reduced departures</td>
</tr>
</tbody>
</table>
Illustration: Export-import losses

Sector-wise accumulation of export-import losses

- Onset of disruption chosen arbitrarily

Dock specific losses
Illustration: Interdependent effects

• Output losses across Oklahoma industries due to port shutdown

Entire port shutdown

Only general cargo dock shutdown
Illustration: Interdependent effects

- Oklahoma has more direct loss because the port is mainly importing
- Texas has almost no direct impact but large indirect impact

Total direct losses: $72.9 million
Total indirect losses: $111.8 million
Total losses: $184.7 million
Illustration: Risk management

• We use the interdependency model to measure the efficacy of risk management
  – What does extra capacity (e.g., crane) do to minimize large-scale impacts?
  – On which dock should we put most emphasis?

• The future: robust decision making framework
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Modeling waterway operations

- Network topology model tracks the flow of freight between ports
  - Captures spatial and temporal nature of freight flow
  - Tracks commodity type, position, and tonnage at each period
Disruptions on waterway network

\[ M = \text{Total number of trips along path} \]

\[ m = \text{Number of trips that result in accident and loss of freight} \]

\[ L = \text{Total length of path} \]

\[ d = \text{Length of segment along which incident occurs} \]

\[ p = \text{Probability of loss of cargo due to accident} \]

\[ D = \text{Amount of cargo on path} \]

\[ \Delta D = \text{Expected amount of loss of cargo} \]

\[ p = \left( \frac{d}{L} \right) \times \left( \frac{m}{M} \right) \]

\[ \Delta D = p \times D \]
Illustration: Waterway network

Data Sources:
US Army Corps of Engineers, National Database Center
Illustration: Waterway accidents

- If it is assumed
  - Accidents are spread uniformly over topology
  - One accident accounts for one trip
Illustration: Estimating accident losses

\[ p = \left( \frac{d}{L} \right) \times \left( \frac{m}{M} \right) \]

\[ \Delta D = p \times D \]

- OK-IA route has higher likelihood to result in accident due to length and fewer number of trips
- OK-TX route subject to greater losses due to higher value of cargo: liquid bulk like petroleum
Illustration: Risk management

• We can integrate with the interdependency model
  – What navigable paths lead to the largest multi-regional economic losses?

• The future: integrate with interdependency model, robust framework
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Concluding remarks

• Network analysis
  – Network topology to track the flow of freight between ports
  – Model captures spatial and temporal nature of freight flow
  – Model tracks commodity type, position, and tonnage at each period

• Interdependent disruptions
  – Direct port losses of $88 million result in $184.7 million output losses across states
  – Oklahoma has more direct loss because the port is mainly importing
  – Texas has almost no direct impact but large indirect impact
Concluding remarks

• Waterway accident risk
  – OK-IA route has higher likelihood to result in accident due to length and fewer number of trips
  – OK-TX route subject to greater losses due to higher value of cargo most of which is liquid bulk like petroleum
Appreciation

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End of Presentation

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