Climate change, natural disasters and adaptation investments with inter- and intra-port competition and cooperation

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Introduction

• With **80% of world trade** carried by maritime transport, ports provide crucial linkages in global supply chains and are essential for countries to access to global markets

• **Seaports** are likely to be affected by climate changes, causing broader implications for trade and regional economy

• Due to their **coastal location**, ports/terminals (e.g. transport infra- and super-structures and utilities, equipment) are particularly vulnerable to extreme weather events, such as storm surge and flooding ([OECD, 2016](#))
Introduction (cont’d)

• Scientific studies suggest that climate change may lead to an increase in the occurrence/frequency or the strength of weather-related natural disasters (e.g., Keohane and Victor, 2010; Min et al., 2011; OECD, 2016)

• IPCC’s (2013) estimates for 2100 range from 0.18 to 0.59 meters of SLR (sea level rise), while other estimates extend as high as 2 meters

• Kafalenos and Lenonard (2008) estimate the vulnerability of ports in the US Gulf Coast to SLR

• Nicholls et al. (2008) assess the exposure to flooding for 136 large port cities around the globe
Coastal and marine natural disasters: very costly

- Damage by Hurricane Harvey, August 2017: Estimated $75 billion (Bloomberg). Port Houston and Port of Corpus Christi were shut down: Maersk, CMA CGM and MSC lines were affected. No plan to reroute to other ports but delays occurred.

- Damage by Hurricane Sandy (2012): $32 billion. Earlier, Katrina had caused fatalities 1,245-1,836 and damages worth $146 billion (National Geographic, 2012).

- Hurricane Sandy’s cost to marine insurers was estimated at $2.5-3.5 billion (Lloyd’s List No. 61014).

- Apart from such ‘one shot’ disasters, there is an increasing risk of coastal and marine natural disasters (in terms of frequency and intensity), owing to climate change.
• With peak accumulations of 51.88 inches (1.32 meter), Harvey is the wettest tropical cyclone on record in the US
In Manhattan, Sandy’s surging tide darkening the city below Midtown. The new WTC’s base is 3 feet above sea level (vs. 14-foot storm surge)
Most Costly US Hurricanes

Source: Swiss Re Sigma, Morgan Stanley Research
• Damages associated with coastal disasters can be prevented or alleviated with proper investments in ports and coastal regions:
  • Raise height of roads (causeways); improve groins, dikes, levees and seawalls; improve a port’s storm water system
  • Example of ‘Terminal Groin’ (a long wall or hardened structure that extends out toward the ocean, usually perpendicular to the coastline, and adjacent to an inlet or at the end of coastal land mass that is prone to beach erosion)
• Becker et al. (2012) survey 93 port directors, engineers, environmental managers, and planners representing 82 ports around the world about their climate-change adaptation strategies. The results show that about half of the ports hold regular meetings to discuss adaptation, and only a third have issued guideline of design to deal with climate change threat.

• Becker et al. (2013) review the adaptation strategies of Port of Rotterdam and Port of San Diego (California):
  “Effective strategy requires collaborations and supports from a broad range of stakeholders including climate science, engineering, port management, operators and policy.”
• Mitigation (rich literature) vs. Adaptation of transport to climate change
  - Literature on transport network vulnerability/resilience

• Xiao, Fu, Ng and Zhang (2015, TR-B) model adaptation of a single port consisting of a port authority and a terminal operator:
  1) **Free riding** of adaptation efforts between the two entities
  2) ‘Invest now vs. wait’ trade-off: Information about disaster occurrence probability improves over time ➔ Option value of wait

• In Xiao et al. (2015):
  - Exogenous port demand
  - Port prices: given
  - Inter-port competition: absent
Port competition: e.g. Hamburg-Le Havre (HLH) port range

- Nine major ports
- Gateways to north Europe and the Baltic sea
- International hub
- Serve 400 million consumers
  - Rotterdam
  - Hamburg
  - Antwerp
Competing ports: Pearl River Delta, South China
Single port authority: New York/New Jersey; Georgia State in the US
This paper

- Investigates adaptation investments made by two ports, with each consisting of a port authority and a private terminal operator (‘Landlord port’)
  - Inter-port competition (Port competition)
  - Intra-port cooperation
  - Endogenous port pricing
  - Abstract from the timing issue (Invest now vs. wait); focus instead on: How does ‘imperfect info’ affect adaptation?
Research questions:

- How does the uncertainty of disaster occurrence probability affect adaptation investments?

- Does port competition increase port adaptation: any ‘competition effect’?

- Does the adaptation ‘free riding’ between port authority and terminal operator still exist; if so, will their cooperation reduce it?

- How does imperfect info affect the competition effect and the free-riding effect?
Model structure: A two-ports system

Port 1
- Port Authority 1
- Terminal Operator 1

Port 2
- Port Authority 2
- Terminal Operator 2

Disaster

Shippers

$p_1$, $p_2$, $\phi_1$, $\phi_2$, $I_1^a$, $I_2^a$, $I_1^t$, $I_2^t$
Model

• Consider **two ports sharing a common hinterland** and facing a **common** potential disaster threat

• A multi-stage game:

  **Investment stage**: Adaptation investments by the port authorities and terminal operators

  1. Adaptation investments:
     i) Costly, and time-consuming
     ii) Lumpy
     iii) Irreversible

  2. **Ambiguous info** about the probability of disaster occurrence
### Timeline of decisions by different parties

<table>
<thead>
<tr>
<th>Adaptation investment</th>
<th>Port pricing and shippers’ port choice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Port authorities and terminal operators</strong> make adaptation investments, ((I_i^a, I_i^t))</td>
<td><strong>Port authority</strong> (i) charges (\phi_i)</td>
</tr>
<tr>
<td><strong>Stage 1</strong></td>
<td><strong>Stage 2</strong></td>
</tr>
<tr>
<td>Probability of disaster occurrence is random (x \sim f(x))</td>
<td>(x) is realized</td>
</tr>
<tr>
<td><strong>Stage 3</strong></td>
<td><strong>Stage 4</strong></td>
</tr>
<tr>
<td>Shippers choose a port</td>
<td>Disaster happens or not</td>
</tr>
</tbody>
</table>

**19**
Model (cont’d)

- **Operation stage**: Port pricing and shippers’ port choice, conditional on the adaptation investments
  - More precise info *(less ambiguity)* about disaster-occurrence probability
  - Prices are more easily to adjust than adaptation investments
  - **Vertical structure**: upstream port authority, downstream terminal operator
Model (cont’d)

• At investment stage, the probability of disaster occurrence, $x$, is uncertain:
  - it follows distribution $f(x)$, with mean $E(x) = \Omega$, variance $Var(x) = \Sigma$, and second moment $E(x^2) = \psi$

• At operation stage, $x$ becomes known:
  - Better knowledge on disaster occurrence is accumulated during the relatively lengthy period when adaptation investments take place

• The belief about the likelihood is a random variable. This form of uncertainty, characterized not by a single probability measure, but by a set of probability measures, is frequently referred to as ambiguity or Knightian uncertainty (Knight, 1921) in economics and decision analysis (Camerer and Weber, 1992; Nishimura and Ozaki, 2007; Gao and Driouchi, 2013)
Derive shippers’ demand (conditional on port charges $p_i$ and adaptation investments $I_i^a, I_i^t$) – We adopt an infinite linear city model (Basso and Zhang, 2007; Wan et al., 2016):

- Shippers are uniformly distributed on the linear city with density 1
- Unit cost $t$ to transport cargo from its location to each port
- Shippers have a constant value of using the port service, $V$
- $D$ is the damage without any adaptation when disaster occurs
- $\eta (I_i^a + I_i^t)$ is the damage reduction with adaptation when disaster occurs

\[ V-p_i - x \max \{0, D - \eta (I_i^a + I_i^t)\} \]

\[ V-p_2 - x \max \{0, D - \eta (I_2^a + I_2^t)\} \]
At operation stage, shippers choose a port conditional on realized probability of disaster occurrence $\mathcal{X}$ and port adaptations $I^a, I^t$

$$E[U_1|x, I^a, I^t] = V - p_1 - x \text{Max}[0, D - \eta(I^a_1 + I^t_1)] - tz$$

$$E[U_2|x, I^a, I^t] = V - p_2 - x \text{Max}[0, D - \eta(I^a_2 + I^t_2)] - t(1 - z)$$

$$|z^l| = \frac{V - p_1 - x \text{Max}\{0, D - \eta(I^a_1 + I^t_1)\}}{t}$$

$$z^r = 1 + \frac{V - p_2 - x \text{Max}\{0, D - \eta(I^a_2 + I^t_2)\}}{t}$$

$$z^m = \frac{1}{2} + \frac{p_2 - p_1 - x \text{Max}\{0, D - \eta(I^a_1 + I^t_1)\} + x \text{Max}\{0, D - \eta(I^a_2 + I^t_2)\}}{2t}$$

$$Q_i(p)|x, I^a, I^t = \frac{1}{2} + \frac{2V + p_j - 3p_i + x \text{Max}\{0, D - \eta(I^a_j + I^t_j)\} - 3x \text{Max}\{0, D - \eta(I^a_i + I^t_i)\}}{2t}$$
Port authorities and terminal operators can have different kinds of adaptation (Becker et al., 2012)

- Port authorities:
  building breakwaters, storm barriers, flood-control gates

- Terminal operator:
  retrofitting the drainage system, repositioning sensitive equipment or building from potential flood prone areas, redesigning and constructing the terminal facilities

- For Terminal Operator, profit at operation stage,
  \[ \Pi_i \mid x, I^a, I^t = (p_i - \phi_i)Q_i \]

- For Port Authority, profit at operation stage,
  \[ \pi_i \mid x, I^a, I^t = \phi_i Q_i \]
social welfare: \( SW = CS + \sum \pi_i + \sum \Pi_i \)

- with shippers’ surplus \( CS \) as,

\[
CS|x, I^a, I^t = \int_0^{z^l} [V - p_1 - x \text{Max}\{0, D - \eta(I^a_1 + I^t_1)\} - z \ t] \ dz + \\
\int_0^{z^m} [V - p_1 - x \text{Max}\{0, D - \eta(I^a_1 + I^t_1)\} - z \ t] \ dz
\]

\[
+ \int_{z^m}^{z^r} [V - p_2 - x \text{Max}\{0, D - \eta(I^a_2 + I^t_2)\} - (1 - z) \ t] \ dz + \\
\int_1^{z^r} [V - p_2 - x \text{Max}\{0, D - \eta(I^a_2 + I^t_2)\} - (z - 1) \ t] \ dz
\]
Pricing of terminal operators (Operation stage)

- Port charges within a port are determined in a ‘vertical structure’: Port authority chooses its concession fee ($\phi_i$) on terminal operator first, and the operator then chooses its service charge ($p_i$) on shippers.

- Terminal operator maximizes profit conditional on $\phi$,

\[
\max_{p_i} \Pi_i | \phi, x, I^a, I^t = (p_i - \phi_i)Q_i
\]

\[
p_i(\phi)|x, I^a, I^t = \frac{1}{35} \{14V + 7t + 18 \phi_i + 3\phi_j - 17x \max\{0, D - \eta(I^a_i + I^t_i)\} + 3x \max\{0, D - \eta(I^a_j + I^t_j)\}\}
\]
Pricing of port authorities (Operation stage)

- Competing port authorities (port competition):

\[
\text{Max } \pi_i \mid x, I^a, I^t = \phi_i Q_i
\]

The optimal decisions are: \(\bar{\phi}_i \mid x, I^a, I^t\); \(\bar{p}_i \mid x, I^a, I^t\); \(\bar{Q}_i \mid x, I^a, I^t\).
Pricing of port authorities (cont’d)

- Single (monopoly) port authority:

\[
\text{Max} \sum_{i=1}^{2} \pi_i \mid x, I^a, I^t = \sum_{i=1}^{2} (\phi_i Q_i)
\]

The optimal decisions are: \(\tilde{\phi}_i \mid x, I^a, I^t; \tilde{p}_i \mid x, I^a, I^t; \tilde{Q}_i \mid x, I^a, I^t\).
\[ \tilde{\phi}_i - \bar{\phi}_i > 0; \tilde{\rho}_i - \bar{\rho}_i > 0 \]

Proposition 1:

Conditional on the disaster occurrence probability and adaptation investments at two ports, **competition** between two port authorities leads to **lower concession fees** and **lower terminal operator charges**.
\[ \frac{\partial \Phi_i}{\partial I_i^a} \geq 0; \frac{\partial \Phi_i}{\partial I_i^t} \geq 0; \frac{\partial \Phi_i}{\partial I_j^a} \leq 0; \frac{\partial \Phi_i}{\partial I_j^t} \leq 0; \frac{\partial \bar{p}_i}{\partial I_i^a} \geq 0; \frac{\partial \bar{p}_i}{\partial I_i^t} \geq 0; \frac{\partial \bar{p}_i}{\partial I_j^a} \leq 0; \frac{\partial \bar{p}_i}{\partial I_j^t} \leq 0 \]

\[ \frac{\partial \tilde{\Phi}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{\Phi}_i}{\partial I_i^t} \geq 0; \frac{\partial \tilde{\Phi}_i}{\partial I_j^a} = 0; \frac{\partial \tilde{\Phi}_i}{\partial I_j^t} = 0; \frac{\partial \tilde{p}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{p}_i}{\partial I_i^t} \geq 0; \frac{\partial \tilde{p}_i}{\partial I_j^a} \leq 0; \frac{\partial \tilde{p}_i}{\partial I_j^t} \leq 0 \]

**Proposition 2:**

- **For ports with competing port authorities,** concession fees and terminal operator charges **increase** with *own port’s adaptation*, and **decrease** with *the other port’s adaptation*.

- **For single port authority,** concession fees and terminal operator charges also **increase** with *own port’s adaptation*, and decreases (or is not affected) with the *other port’s adaptation*. 
\[ \frac{\partial (\bar{\phi}_i | x, I^a_i, I_t^i - \phi_i | x, I^a_i, I_t^i)}{\partial I} > 0 \]

\[ \frac{\partial (\bar{\rho}_i | x, I^a_i, I_t^i - \rho_i | x, I^a_i, I_t^i)}{\partial I} > 0 \]

where \( I \in \{I^a_i, I_t^i, I^a_j, I_t^j\} \).

**Proposition 3:**

*Increased port adaptation at either port would enlarge the difference in concession fees and terminal operator charges between the ports with competing port authorities and single port authority.*
Adaptation investments

• Competing port authorities (port competition):

For port authorities,

\[
\max_{I_i^a} E[\pi_i]; \text{ s.t. } \eta (I_i^a + I_i^t) \leq D
\]

For terminal operators,

\[
\max_{I_i^t} E[\Pi_i]; \text{ s.t. } \eta (I_i^a + I_i^t) \leq D
\]

At the interior Nash equilibrium,

\[
\bar{I}_i^a = \frac{\eta [2V + t \Omega - 2D \Psi]}{6.1 \omega t - 3 \Psi \eta^2} \geq \bar{I}_i^t = \frac{\eta [(2V + t) \Omega - 2D \Psi]}{2.1 (6.1 \omega t - 3 \Psi \eta^2)}
\]
Adaptation investments

• Single port authority (inter-port cooperation):

For port authorities,

\[
\max_{I_1^a, I_2^a} \mathbb{E}[\pi_1 + \pi_2]; \text{ s.t. } \eta (I_1^a + I_1^t) \leq D \text{ and } \eta (I_2^a + I_2^t) \leq D
\]

For terminal operators,

\[
\max_{I_1^t} \mathbb{E}[\Pi_i]; \text{ s.t. } \eta (I_i^a + I_i^t) \leq D
\]

At the interior Nash equilibrium,

\[
\tilde{I}_i^a = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{6.7\omega t - 3\Psi \eta^2} \geq \tilde{I}_i^t = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{14\omega t - 6.1\Psi \eta^2}
\]
Adaptation investments

Intra-port coordination between port authority and terminal operator:

• Competing port authorities

Port authority and terminal operator maximize joint profit

\[
\text{Max } E[\pi_i + \Pi_i];
\]

\[
I^a_i, I^t_i
\]

At the interior Nash equilibrium,

\[
\hat{I}^a_i = \hat{I}^t_i = \frac{\eta \left[ (2V + t) \Omega - 2D\Psi \right]}{4.1 \omega t - 4 \Psi \eta^2}
\]
Model structure: A two-ports system

Port Authority 1

Port Authority 2

Terminal Operator 1

Terminal Operator 2

Disaster

Shippers

\[ \phi_1 \]

\[ \phi_2 \]

\[ p_1 \]

\[ p_2 \]
## Summary of equilibrium adaptation investments: competition cases

<table>
<thead>
<tr>
<th>Port authority adaptation</th>
<th>Terminal operator adaptation</th>
<th>SOCs and Non-negativity</th>
<th>Interior solution requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competing Port Authorities</td>
<td>$\bar{I}_i^a = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{6.1\omega t - 3\Psi\eta^2}$</td>
<td>$\bar{I}_i^t = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{2.1 (6.1 \omega t - 3 \Psi \eta^2)}$</td>
<td>$\omega &gt; 0.49 \frac{\eta^2}{t} \psi$</td>
</tr>
<tr>
<td>Monopoly Port Authority</td>
<td>$\bar{I}_i^a = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{6.7\omega t - 3 \Psi \eta^2}$</td>
<td>$\bar{I}_i^t = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{13.7 \omega t - 6.1 \Psi \eta^2}$</td>
<td>$\omega &gt; 0.45 \frac{\eta^2}{t} \psi$</td>
</tr>
<tr>
<td>Competing Port Authorities with Intra-port Coordination</td>
<td>$\bar{I}_i^a = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{4.1\omega t - 4 \Psi \eta^2}$</td>
<td>$\bar{I}_i^t = \frac{\eta [(2V + t) \Omega - 2D\Psi]}{4.1 \omega t - 4 \Psi \eta^2}$</td>
<td>$\omega &gt; 0.98 \frac{\eta^2}{t} \psi$</td>
</tr>
</tbody>
</table>
• Proposition 4

In all the cases of interior Nash equilibria, we have

\[ \frac{\partial I_i^a}{\partial \Omega} \geq 0, \frac{\partial I_i^t}{\partial \Omega} \geq 0, \text{ i.e., a higher expected value of disaster probability leads to more adaptation investments;} \]

\[ \frac{\partial I_i^a}{\partial \Sigma} \leq 0, \frac{\partial I_i^t}{\partial \Sigma} \leq 0, \text{ i.e., higher variance of disaster occurrence probability lowers adaptation investments.} \]
• “People prefer to bet on events they know more about, even when their beliefs are held constant. (They are averse to ambiguity, or uncertainty about probability.)”- (Camerer and Weber, 1992)

• The effect of **Knightian uncertainty** (ambiguity) decreases the value of irreversible investment while the increase in risk increases it (Nishimura and Ozai, 2007)

• Ng et al. (2016)’s survey of 23 Canadian ports’ adaptation finds that ports subject to higher climate change risk adapt more (\(\Omega \uparrow \rightarrow I_i^a, I_i^t \uparrow\))

• Most ports cite ‘**inadequate information**’ and need to know more about the issue as major reasons for the slow development of adaptation. (Ng et al., 2016, Becker et al., 2012) (\(\Sigma \uparrow \rightarrow I_i^a, I_i^t \downarrow\))
Proposition 5:

- **Competing port authorities lead to higher adaptation** (the ‘competition effect’) i.e. $\bar{I}_i^a \geq \tilde{I}_i^a ; \bar{I}_i^t \geq \tilde{I}_i^t$.

- **Intra-port coordination** between port authority and terminal operator at each port also increases adaptation i.e. $\hat{I}_i^a \geq \bar{I}_i^a ; \hat{I}_i^t \geq \bar{I}_i^t$. Without intra-port coordination, port authority and terminal operator at the same port **free ride** each other on adaptation (the ‘free-riding effect’).
Model structure: A two-ports system

Port 1

- Port Authority 1
  - Terminal Operator 1

Port 2

- Port Authority 2
  - Terminal Operator 2

Disaster

Shippers

\[
\begin{align*}
\phi_1 & \quad \phi_2 \\
p_1 & \quad p_2
\end{align*}
\]
How does imperfect info affect the competition effect and the free-riding effect?

\[
\frac{\partial}{\partial \Omega} \left( \frac{\bar{I}_i^a}{I_i^a} \right) > 0; \quad \frac{\partial}{\partial \Sigma} \left( \frac{\bar{I}_i^a}{I_i^a} \right) > 0; \quad \frac{\partial}{\partial \Omega} \left( \frac{\hat{I}_i^a}{I_i^a} \right) > 0; \quad \frac{\partial}{\partial \Sigma} \left( \frac{\hat{I}_i^a}{I_i^a} \right) > 0
\]

**Proposition 6**

- *Both an increased expectation of disaster occurrence probability Ω and an increased variance of disaster occurrence probability Σ strengthen the ‘competition effect’ and the ‘free-riding effect’.*
Expected Social Welfare

\[ E[\hat{SW}] > E[\overline{SW}] > E[\tilde{SW}] \].

**Proposition 7:**
The expected welfare increases with adaptation investment. The intra-port coordination between the port authorities and terminal operators results in the highest expected welfare by overcoming the free-riding effect. The single port-authority case has the lowest expected welfare with the lowest adaptation investment by eliminating port competition.
Effects of Port Competition Intensity

• Let the shipper in the common hinterland to have a different transport cost $t'$.

• The parameter $t'$ thus helps capture port service heterogeneity in the common hinterland market.

• A smaller $t'$ suggests a higher port service homogeneity, equivalent to a more intense port competition.
Figure: Numerical values of $\frac{\tilde{I}_i^a(t')}{\tilde{I}_i^a(t''')}$, $\frac{\tilde{I}_i^t(t')}{\tilde{I}_i^t(t''')}$, $\frac{\tilde{I}_i^x(t')}{\tilde{I}_i^x(t''')}$, $\frac{\tilde{I}_i^z(t')}{\tilde{I}_i^z(t''')}$ with changing $t'$ ($\Psi = 0.1$, $\eta = 2$, $\omega = 25$, $t = 0.1$)
Effects of Port Competition Intensity

Proposition 8:

The *more intense port competition* (service homogeneity) *strengthens both the ‘competition effect’ on adaptation between two ports, and the ‘free-riding effect’ on adaptation between port authority and terminal operator within one port.*
Thank you
\[ \eta (I_i^a + I_i^t) = D \]
\[ I_i^a = D - I_i^t \]

\[ I_j^a(I_j^a) \]

\[ I_j^a(I_i^a) \]

\[ I_i^a = D - I_i^t \]

\[ I_i^a = D - I_i^t \]