Adversarial Risk Analysis: The Somali Pirates Case

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Outline

• Adversarial Risk Analysis

• The sequential Defend-Attack-Defend Model

• The Somali Pirates Case

• Discussion
Adversarial Risk Analysis

• A framework to manage risks from actions of intelligent adversaries

• One-sided prescriptive support
  – Use a SEU model
  – Treat the adversary’s decision as uncertainties

• New method to predict adversary’s actions
  – We assume the adversary is a expected utility maximizer
    • Model his decision problem
    • Assess his probabilities and utilities
    • Find his action of maximum expected utility
  – But other descriptive models are possible

• Uncertainty in the Attacker’s decision stems from
  – our uncertainty about his probabilities and utilities
The Defend–Attack–Defend model

- Two intelligent players
  - Defender and Attacker

- Sequential moves
  - First, Defender moves
  - Afterwards, Attacker knowing Defender’s move
  - Afterwards, Defender again responding to attack
The Somali Pirates case

• An Illustrative application of the ARA framework

• We support the owner of a Spanish fishing ship managing risks from piracy

• Modeled as a Defend-Attack-Defend decision problem

• Develop predictive models of Pirates’ behaviour
  – By thinking about their decision problem
Why sail through Somali waters?

Best route between Europe and Asia

More than 20,000 ships/year passing through the Suez Canal
Increase in piracy acts around the cost of Somalia

Piracy and armed robbery incidents reported to the IMB Piracy Reporting Centre 2011
Some statistics

• Piracy and armed robbery incidents in 2011
  – IMB Piracy Reporting Centre (updated on 23 May 2011)

• Worldwide
  – Total Attacks: 211
  – Total Hijackings: 24

• Somalia
  – Total Incidents: 139
  – Total Hijackings: 21
  – Total Hostages: 362
  – Total Killed: 7

• Currently
  – Vessels held by Somali pirates: 26
  – Hostages: 522
The Pirates
Problem formulation

• Two players
  – Defender: Ship owner
  – Attacker: Pirates

• Defender first move
  – Do nothing
  – Private protection with an armed person
  – Private protection with a team of two armed persons
  – Go through the Cape of Good Hope avoiding the Somali coast

• Attacker’s move
  – Attack or not to attack the Defender’s ship

• Defender response to an eventual kidnapping
  – Do nothing
  – Pay the ransom
  – Ask the Navy for support to release the boat and crew
Defender’s own preferences and beliefs

• Assessments from the Defender
  – Multi-attribute consequences
  – Preferences over consequences
  – Beliefs about $S | d_1, a^1$
  – Beliefs about $A | d_1$

• Defender’s relevant consequences
  – Loss of the boat
  – Costs of protecting and responding to an eventual attack
  – Number of deaths on her crew

• Defender’s monetary values of
  – a Spanish life: 2.04M Euros
  – the ship: 7M Euros

Defender’s own preferences and beliefs

- Consequences of the tree paths for the Defender

<table>
<thead>
<tr>
<th>$D_1$</th>
<th>$S$</th>
<th>$D_2$</th>
<th>Boat loss</th>
<th>Action costs</th>
<th>Lives lost</th>
<th>Aggregate cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d^1_1$ (nothing)</td>
<td>$S = 1$</td>
<td>$d^1_2$ (nothing)</td>
<td>1</td>
<td>0 + 0</td>
<td>0 + 4</td>
<td>15.16</td>
</tr>
<tr>
<td>$d^1_1$ (nothing)</td>
<td>$S = 1$</td>
<td>$d^2_2$ (pay)</td>
<td>0</td>
<td>0 + 2.3M</td>
<td>0 + 0</td>
<td>2.3</td>
</tr>
<tr>
<td>$d^1_1$ (nothing)</td>
<td>$S = 1$</td>
<td>$d^3_2$ (army)</td>
<td>0</td>
<td>0 + 0.2M</td>
<td>0 + 2</td>
<td>4.28</td>
</tr>
<tr>
<td>$d^1_1$ (nothing)</td>
<td>$S = 0$</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$d^2_1$ (man)</td>
<td>$S = 1$</td>
<td>$d^1_2$ (nothing)</td>
<td>1</td>
<td>0.05M + 0</td>
<td>1 + 4</td>
<td>17.25</td>
</tr>
<tr>
<td>$d^2_1$ (man)</td>
<td>$S = 1$</td>
<td>$d^2_2$ (pay)</td>
<td>0</td>
<td>0.05M + 2.3M</td>
<td>1 + 0</td>
<td>4.39</td>
</tr>
<tr>
<td>$d^2_1$ (man)</td>
<td>$S = 1$</td>
<td>$d^3_2$ (army)</td>
<td>0</td>
<td>0.05M + 0.2M</td>
<td>1 + 2</td>
<td>6.37</td>
</tr>
<tr>
<td>$d^2_1$ (man)</td>
<td>$S = 0$</td>
<td></td>
<td>0</td>
<td>0.05M</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>$d^3_1$ (team)</td>
<td>$S = 1$</td>
<td>$d^1_2$ (nothing)</td>
<td>1</td>
<td>0.15M + 0</td>
<td>2 + 4</td>
<td>19.39</td>
</tr>
<tr>
<td>$d^3_1$ (team)</td>
<td>$S = 1$</td>
<td>$d^2_2$ (pay)</td>
<td>0</td>
<td>0.15M + 2.3M</td>
<td>2 + 0</td>
<td>6.53</td>
</tr>
<tr>
<td>$d^3_1$ (team)</td>
<td>$S = 1$</td>
<td>$d^3_2$ (army)</td>
<td>0</td>
<td>0.15M + 0.2M</td>
<td>2 + 2</td>
<td>8.51</td>
</tr>
<tr>
<td>$d^3_1$ (team)</td>
<td>$S = 0$</td>
<td></td>
<td>0</td>
<td>0.15M</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>$d^4_1$ (alternative route)</td>
<td></td>
<td></td>
<td>0</td>
<td>0.5 M</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Costs in Million Euros*
Defender’s decision analysis

A
\[ d_1^1 \text{ (nothing)} \]
\[ d_1^2 \text{ (man)} \]
\[ d_1^3 \text{ (team)} \]
\[ d_1^4 \text{ (alternative route)} \]

S
\[ a^1 \text{ (attack)} \]
\[ a^0 \text{ (no attack)} \]

S = 1
\[ D_2 \]
\[ d_2^1 \text{ (nothing)} \]
\[ d_2^2 \text{ (pay)} \]
\[ d_2^3 \text{ (Navy)} \]

S = 0
\[ d_3^1 \text{ (nothing)} \]
\[ d_3^2 \text{ (pay)} \]
\[ d_3^3 \text{ (Navy)} \]

\[ 15.16 \]
\[ 2.3 \]
\[ 4.28 \]
\[ 0 \]
\[ 0 \]
\[ 0.05 \]
\[ 0.05 \]
\[ 0.05 \]
\[ 0.15 \]
\[ 0.15 \]
\[ 0.5 \]
Defender’s own preferences and beliefs

• The Defender is constant risk adverse to monetary costs
  – Defender’s utility function strategy equivalent to
    \[ u_D(c_D) = -\exp(c \times c_D), \text{ with } c > 0 \]

• We perform sensitivity analysis on “c”

• Defender's beliefs about \( S|a^1,d_1 \)
  \[ p_D(S = 1|a^1,d_1^1) = 0.40 \]
  \[ p_D(S = 1|a^1,d_1^2) = 0.10 \]
  \[ p_D(S = 1|a^1,d_1^3) = 0.05 \]
Predicting Attacker’s behavior

- The objective is to assess $p_D(A = a^1 | d_1)$
- Attacker’s decision problem as seen by the Defender

```
\begin{align*}
  & d_1 \\
  \rightarrow & \quad D_1 \\
  \rightarrow & \quad A \\
  \rightarrow & \quad S \\
  & a^0 \quad (no \ attack) \\
  & S = 0 \\
  \rightarrow & \quad D_2 \\
  \rightarrow & \quad S \\
  & a^1 \quad (attack) \\
  & S = 1 \\
  \rightarrow & \quad D_2 \\
  \rightarrow & \quad S \\
  & a^i \quad (attack \ others) \\
  & S = 1 \\
  \rightarrow & \quad D_2 \\
  \rightarrow & \quad S \\
  & d_1^1 \quad (nothing) \\
  & S = 0 \\
  \rightarrow & \quad D_2 \\
  \rightarrow & \quad S \\
  & d_2^1 \quad (pay) \\
  & S = 1 \\
  \rightarrow & \quad D_2 \\
  \rightarrow & \quad S \\
  & d_2^2 \quad (Navy) \\
  & S = 0 \\
  \rightarrow & \quad D_2 \\
  \rightarrow & \quad S \\
  & d_2^3 \quad (Navy) \\
  & S = 0
\end{align*}
```
Defender's beliefs over the Attacker's beliefs and preferences

- Assess from the Defender the Pirates’ preferences $U_A(a, s, d_2)$
- Perceived relevant consequences for the Pirates
  - Whether they keep the boat
  - Money earned.
  - Number of Pirates' lives lost.

<table>
<thead>
<tr>
<th>$A$</th>
<th>$S$</th>
<th>$D_2$</th>
<th>Boat kept</th>
<th>Profit</th>
<th>Lives lost</th>
<th>Aggregate profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a^0$ (no attack)</td>
<td>$S = 1$</td>
<td>$d_1^2$ (nothing)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$a^i$ (attack)</td>
<td>$S = 1$</td>
<td>$d_2^i$ (pay rescue)</td>
<td>1</td>
<td>-0.03M</td>
<td>0</td>
<td>0.97</td>
</tr>
<tr>
<td>$a^i$ (attack)</td>
<td>$S = 1$</td>
<td>$d_3^i$ (Navy sent)</td>
<td>0</td>
<td>2.27M</td>
<td>0</td>
<td>2.27</td>
</tr>
<tr>
<td>$a^i$ (attack)</td>
<td>$S = 0$</td>
<td></td>
<td>0</td>
<td>-0.03M</td>
<td>2</td>
<td>-0.53</td>
</tr>
</tbody>
</table>

$i = 1, \ldots, n$ (no difference in consequences of attacking the Defender’s and other boats)
• The Defender thinks the Pirates are increasing constant risk prone for money
  – Pirates' utility function strategically equivalent to
    \[ U_A(c_A) = \exp(c \times c_A), \text{ with } c \sim \mathcal{U}(0, 20) \]

• Defender assessment of Pirates’ beliefs on
  – \( S \mid a, d_1 \)
    \[ P_A(S = 1|a^1, d_1^1) \sim \mathcal{B}e(40, 60) \]
    \[ P_A(S = 1|a^1, d_1^2) \sim \mathcal{B}e(10, 90) \]
    \[ P_A(S = 1|a^1, d_1^3) \sim \mathcal{B}e(50, 950) \]
    \[ P_A(S = 1|a^i) \sim \mathcal{B}e(1, 1) \quad \text{for boat } i = 2, \ldots, n \]
  – \( D_2 \mid d_1, a^1, S=1 \)
    \[ P_A(D_2 \mid d_1^1, a^1, S = 1) \sim \mathcal{D}ir(1, 1, 1) \]
    \[ P_A(D_2 \mid d_1^2, a^1, S = 1) \sim \mathcal{D}ir(0.1, 4, 6) \]
    \[ P_A(D_2 \mid d_1^3, a^1, S = 1) \sim \mathcal{D}ir(0.1, 1, 10) \]
  – \( D_2 \mid a^i, S=1 \)
    \[ P_A(D_2 \mid a^i, S = 1) \sim \mathcal{D}ir(1, 1, 1) \text{ for } i = 2, \ldots, n \]
Predicting Pirates’ uncertain behavior

• Based on the above assessments, the Defender solves the Pirates’ decision problem

• Random Pirates’ EU of $a^1$ given $d_1 \in D_1 \setminus \{d_4^1\}$

\[
\Psi_A(d_1, a^1) = P_A(S = 1 \mid d_1, a^1) \sum_{d_2 \in D_2} U_A(a^1, S = 1, d_2) P_A(D_2 = d_2 \mid d_1, a^1, S = 1) + P_A(S = 0 \mid d_1, a^1) U_A(a^1, S = 0)
\]
Predicting Pirates’ uncertain behavior

- Random Pirates’ EU of $a_i$ for $i = 2, \ldots, n$

\[
\Psi_A(a_i) = P_A(S = 1 | a_i) \sum_{d_2 \in \mathcal{D}_2} U_A(a_i, S = 1, d_2) P_A(D_2 = d_2 | a_i, S = 1) + P_A(S = 0 | a_i) U_A(a_i, S = 0)
\]
Predicting Pirates’ uncertain behavior

- Defender’s predictive probs of being attacked \((A = a^1)\) given 
\[d_1 \in D_1 \setminus \{d^A_1\}\]

\[p_D(A = a^1 \mid d_1) = \Pr(\Psi_A(d_1, a^1) > \max\{U_A(a^0), \Psi_A(a^2), \ldots, \Psi_A(a^n)\})\]
Predicting Pirates’ uncertain behavior

• We use MC simulation to approximate $p_D(A = a^1 \mid d_1)$ by

$$\frac{\#\{1 \leq k \leq N : \psi_A^k(d_1, a^1) > \max\{\psi_A^k(a^0), \psi_A^k(a^2), \ldots, \psi_A^k(a^n)\}\}}{N}$$

• For illustrative purposes, assume that $n = 4$
  – There will be 3 boats (of similar characteristics) at the time the Defender's boat sails through the Gulf of Aden

• Based on 1000 MC iterations, we have

  - $\hat{p}_D(A = a^1 \mid d^1_1) = 0.1931$
  - $\hat{p}_D(A = a^1 \mid d^2_1) = 0.0181$
  - $\hat{p}_D(A = a^1 \mid d^3_1) = 0.0002$
Max EU defense strategy

- **We solve the Defender’s decision problem**
  - At decision node $D_2$
    - $d^*_2(d_1, a^1, S = 1) = \arg\max_{d_2 \in D_2} u_D(d_1, S = 1, d_2)$

- At chance node $S$
  
  $\psi_D(d_1, a^1) = p_D(S = 1 \mid d_1, a^1) u_D(d_1, S = 1, d^*_2(d_1, a^1, S = 1)) + p_D(S = 0 \mid d_1, a^1) u_D(d_1, S = 0)$
Max EU defense strategy

- At chance node $A$

\[
\psi_D(d_1) = \psi_D(d_1, a^1) \hat{p}_D(A = a^1 | d_1) + u_D(d_1, S = 0) (1 - \hat{p}_D(A = a^1 | d_1))
\]

- At decision node $D_1$

\[
d_1^* = \arg\max_{d_1 \in D_1} \psi_D(d_1)
\]
Max EU defense strategy

• For different risk aversion coefficients “c”

  – $c = 0.1$ and $c = 0.4$

    \[ d_1^* = d_1^2 \] (protect with an armed man) and
    if kidnapped ($S = 1$), pay the ransom ($d_2^* = d_2^4$)

  – $c = 2$

    \[ d_1^* = d_1^4 \] (Going through GH Cape)
Discussion

• ARA vs. GT

• Incorporate more information about \( a^i, i = 2, \ldots, n \)
  
  \[ c_A(a^i, s, d_2) \]

  \[ P_A(S = 1 \mid a^i) \]

• Incorporate analysis modeling strategic decision behavior of other Defenders

  \[ P_A(D_2 \mid a^i, S = 1) \]