Modelling Distributed Vulnerabilities in a Complex Network

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Infrastructure I: Methods of vulnerability analysis

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EU policy & the reasoning behind the current activity
- The European Programme on Critical Infrastructure Protection (EPCIP)
  - Identification of European critical infrastructures (ECI)

Methodology
- Benefits of a model to aid understanding of a complex network
- Vulnerability and resilience
  - Elements, networks and territories
- The need for an integrated approach

Application to a specific example of a complex network
- An international, high pressure, gas transmission pipeline network
- Data requirements to build a model

Scenario development and analysis
- Identification and removal of a critical network node
- Quantitative network behavior
- Economic impact

Conclusion
European Critical Infrastructure (ECI) Policy context

- Some infrastructure is becoming increasingly European
  - eg. energy transmission & transportation systems
- A National approach is deemed insufficient
- Trans-boundary effects need to be minimized
  - ie. the risk that a member state suffers because another failed to protect their assets adequately
- Develop cross-cutting criteria to identify ECI
  - based on severity of consequences of disruption/destruction
- Owners/operators of ECI will need to establish:
  - Risk analysis: threat scenarios, asset vulnerability, impact and consequence analysis
National cross-border networks

- Failures may propagate through a network
- Network failure results in:
  - Effects on the network itself
  - Effects on society

A methodology is required to integrate:

- Vulnerability of the network components
- The consequences on society
Analysis of infrastructure levels

**Micro**
Physical components
Pipes, substations, etc

**Meso**
Edges (Connections), nodes & service flows

**Macro**
 Territory (Local, Regional, National)
Customers, uses & services
Integrated approach to infrastructure vulnerability

Start

Network (Infrastructure)

Probability of Natural Event or Intelligence Information

Micro

Network Analysis

Failure Scenario (Failure Probability of Node(s))

Rank Nodes

Meso

Quantitative Network behaviour

Reduction of Infrastructure Service

Macro

Territorial User’s Demand

User’s Vulnerability Assessment

Pattern of Service

Territorial Loss

Impact Assessment

Impacts on Economy; Population; Casualties; Public Confidence

Decision-making process
We have considered the European high pressure gas transmission system as an application of the proposed methodology.

It provides a key role in supplying energy across Europe.
Major gas movements in 2006 as % of EU27 supplies

Approaching 0.5 million km of high pressure gas transmission pipelines traverse the EU27

Net supplies
~ 507 billion m³

Imports 62%
~ 315 billion m³

Imports shown as percentages of net supplies

LNG 17% of non-EU imports

16% 38% 23% 7%

16% 16%
We have considered the European high pressure gas transmission system as an application of the proposed methodology.

It provides a key role in supplying energy across Europe.

The system is subject to both natural and man-made threats.
Example potential threats to a pipeline system

Malicious threats

Corrosion

Permafrost

Subsidence

Landslides

Construction activities (TPI)

Floods

Seismic risks

Courtesy: A V Krivolapov

Courtesy: Herman Den Uyl

Courtesy: Michael Riedmann

Courtesy: J. Fortuny-Guasch

Courtesy: N.N Khrenov Ekotekh-Nord Moscow

Courtesy: Pryroda, Kyiv

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Requirements for a detailed network model

- A detailed model - to explore cross-border system interactions

- Modeling software
  - Requires high degree of technical functionality applicable to gas industry
  - Initial requirement for steady state only
  - Calculates all unknown pressures and flow rates in the network from input data

- Limit model size to a representative supply route to central Europe
  - Select a major supply route
  - Include several countries

- Limit model to worst case conditions
  - Use winter peak demand

- Develop model using publicly available data
Requirements to build a detailed model

High pressure pipeline routes in & beyond Europe

- Transmission pipelines - GIS locations
  - Internal diameters; off-take locations, etc

Physical infrastructure – key items

- Supply sources – Known locations & pressures, etc
  - Storage fields • LNG supplies • Production sources
- Compressor stations; Metering transfer stations
  - Locations & technical details

Theoretical requirements

- Flow equations • Gas properties

Country annual consumption

- Peak demand profiles

Gas customers

- Numbers known by category:-
  - Domestic; Commercial
  - Industrial; Power generation
  - Individual daily consumption profiles

Regional demand profiles

- Allocation of gas flows to off-takes
Gas disruption scenario analysis

➢ A four country scenario (Countries A, B, C, D)
The final gas network model

- The current model contains the following:
  - No. of pipes >> 1064
  - No. of nodes >> 974 (where pressures & flows are calculated)
  - No. of facilities >> 15 Compressor stations
  - No. of sources >> 13 Stores; 7 Production sites

- The software solves simultaneous equations iteratively for each component in the system
Selection of a system critical node

Ranking importance of Nodes by connectivity & flow rate

- By Gas Flow:
  - large diameter indicates large flow;

- By degree (K) of connectivity:
  - large diameter indicates high connectivity

K-degree Classification of Nodes

<table>
<thead>
<tr>
<th>No of Nodes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Nodes</td>
<td>1000</td>
<td>100</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>
Schematic diagram of physical network entities

Upstream supply node in Country D – identified for disruption
- Affects gas supplies to countries A, B, C

Target

Major compressor station

Note size & complexity
Gas disruption scenario basis

- 3 months required to repair/re-instate supply node in D
- All countries can maintain required supplies for 2 months
  - Either from:
    - Storage gas - but has an additional cost
    - Alternative supply sources and routes and temporary arrangements
- During the third month
  - All countries assumed to have lost supply from country D
  - All countries retain sufficient gas supplies for electrical power production
  - A, B & C retain supplies from alternative sources
  - Country D has no other alternative supply sources
### Final patterns of territorial gas losses

<table>
<thead>
<tr>
<th>Months</th>
<th>Country &gt;&gt;</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>% of demand capacity (from storage &amp; production)</td>
<td>90</td>
<td>100</td>
<td>73</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Maximum time (weeks) at this capacity {but due to uncertainties in distribution - assume to 2 months supply for all countries}</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Final gas deficit {based on 3(^{rd}) month assumptions}</td>
<td>75</td>
<td>77</td>
<td>57</td>
<td>100</td>
</tr>
</tbody>
</table>
The objective of a socio-economic analysis is to assess the impact of an event on the economy of a member state, to estimate the net national cost of an event.

When discussing economic damage due to infrastructure failure, the aim is to evaluate the economic value of the loss of service, based on:

- intensity of use of a certain service provided through an infrastructure, and/or alternatives
- reduction in productive capacity by users of a service
- indirect effect this reduction in productive capacity has on the rest of the economy
The input-output approach includes detailed information for a given year on the following:

- production activities
- supply and demand of goods and services
- intermediate consumption
- primary inputs
- foreign trade

The tables (available from Eurostat) include:

- structure of production and the value added in the production process
- inter-dependencies of industries
- flows of goods and services produced within the national economy
- flows of goods and services with the rest of the world
Impacts are modeled by formulating:

A. Resilience of the sectors, based on real impact and alternatives
B. Value of lost production based on intensity of use - based on Eurostat statistics
C. Industry linkages
D. Loss

\[
\begin{bmatrix}
Va \\
Vb \\
Vc \\
Vd \\
\end{bmatrix}
\times
\begin{bmatrix}
a \\
b \\
c \\
d \\
\end{bmatrix}
\times
\begin{bmatrix}
1.14 & 0.22 & 0.13 & 0.12 \\
0.19 & 1.10 & 0.16 & 0.07 \\
0.16 & 0.16 & 1.16 & 0.06 \\
0.08 & 0.05 & 0.08 & 1.09 \\
\end{bmatrix}
= 
\begin{bmatrix}
\text{Loss} \\
\end{bmatrix}
\]
For the loss of gas the following assumptions were made:

- Production sectors dependent on gas would stop production
- Where appropriate, electrical production from gas would have maximum priority and would be maintained
- Economic losses resulting from the service sector excluded
- Economic losses resulting from domestic gas use excluded

Estimated economic losses for the 4 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9075</td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>39393</td>
<td>37785</td>
<td>0</td>
<td>15701</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>6452</td>
<td>4414</td>
<td>1968</td>
<td>2813</td>
<td></td>
</tr>
<tr>
<td>Household</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>45845</td>
<td>42198</td>
<td>1968</td>
<td>27590</td>
<td></td>
</tr>
</tbody>
</table>

The values in the above table may then be compared with pre-set criteria to identify the criticality of the supply loss to each of the individual countries’ economies.
Future work linked to ECI

- The current analysis was based on a worst-case scenario analyzed at national level
  - With improvements to the gas model, future analysis will consider national consequences integrated from regional levels

- The current model only addresses economic impacts
  - Future work is anticipated to include other areas of impact, including number of casualties, public and environmental consequences
Conclusion

- A need to develop methods for assessing consequences of failures in European Critical Infrastructures (ECI) that form parts of complex networks has been identified.
- An interdisciplinary methodology has been developed to address disruptions in such complex networks that includes an assessment of the territorial economic impacts.
- An international gas transmission pipeline network has been used to demonstrate the principles of the methodology.
- Added value has been created that aims to assist decision making processes in evaluating the importance of ECI.

Thank you for your attention.

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Example I/O analysis

Statistics on industrial linkages are used to derive the model

Table: Transactions in a Three Sector Economy

<table>
<thead>
<tr>
<th>Economic Activities</th>
<th>Inputs to Agriculture</th>
<th>Inputs to Manufacturing</th>
<th>Inputs to Transport</th>
<th>Final Demand</th>
<th>Total Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>5</td>
<td>15</td>
<td>2</td>
<td>68</td>
<td>90</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Transportation</td>
<td>10</td>
<td>15</td>
<td>5</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Labor</td>
<td>25</td>
<td>30</td>
<td>5</td>
<td>0</td>
<td>60</td>
</tr>
</tbody>
</table>

Table: Input-Output Model for Hypothetical Economy Total requirements from regional industries per dollar of output delivered to final demand

<table>
<thead>
<tr>
<th>Purchasing Industry</th>
<th>Agriculture</th>
<th>Transport</th>
<th>Manufacturer</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selling Industry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td>1.14</td>
<td>0.22</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.19</td>
<td>1.10</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>0.16</td>
<td>0.16</td>
<td>1.16</td>
<td>0.06</td>
</tr>
<tr>
<td>Services</td>
<td>0.08</td>
<td>0.05</td>
<td>0.08</td>
<td>1.09</td>
</tr>
<tr>
<td>Total</td>
<td>1.57</td>
<td>1.53</td>
<td>1.53</td>
<td>1.34</td>
</tr>
</tbody>
</table>