Probabilistic Resilience Assessment of Critical Infrastructures Enabled by Complex Systems Tools

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Power Grids as Complex Networks: Formulating Problems for Useful Science and Science Based Engineering

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Motivation (1/3)

- Metrics used in practice for performance assessment

Reliability

Resilience
Motivation (2/3)

• Contemporary infrastructure systems
  - Essential for modern society function
  - Large scale and high exposure systems
  - Reached accelerated phase of aging and deterioration
  - More interdependent for optimized operation
Motivation (3/3)

- Emerging complex infrastructure systems
Presentation Outline

1. System decentralization and hierarchies
2. Resilience assessment under uncertainty
3. Interdependence interfaces and response
4. Concluding remarks and future research
1. Decentralization and Hierarchy (1/6)

Geographical and seismological context of Chile 2010 Earthquake
1. Decentralization and Hierarchy (2/6)

- Power system after the 2010 Chilean Earthquake
  - Chilean Interconnected Systems (CIS) back in 48 hours
    - N-1 security
    - Emergency plans
1. Decentralization and Hierarchy (3/6)

• Observed interdependencies that delayed restoration
  - Road infrastructure
  - Telecommunication systems
  - Logistics

• Actions to cope with interdependencies that delayed restoration
  - Private telecommunications
  - Mobile generation
    - Transmission autonomy
    - Decentralized dispatch
1. Decentralization and Hierarchy (4/6)

- Clustering and decentralized optimization for quantifying resilience

Hierarchical Clustering

Resilience-Performance Space
1. Decentralization and Hierarchy (5/6)

- Clustering for identifying appropriate decision making levels

- 2 clusters
- 4 clusters
- 5 clusters
- 37 clusters

Texas Road Network
1. Decentralization and Hierarchy (6/6)

- Trade off between specificity and uncertainty via hierarchical clustering
2. Resilience Assessment (1/3)

- Quantification of system resilience $R(T)$

$$R(T) = \frac{\int_0^T P(t) \, dt}{\int_0^T TP(t) \, dt}$$
2. Resilience Assessment (2/3)

- Application to power transmission systems

\[
\text{Time Period } T_f = \log_{10}(1-R(T_f))
\]

Legend:
- Power Plant
- Electrical Substation
- Power Transmission Line

Harris County, TX

Resilience and resources \( u \)
2. Resilience Assessment (3/3)

- Impact of consumer demand management on resilience

![Load Profile](image1)

![Resilience transitions](image2)
3. Interdependencies (1/9)

• Research on interdependent infrastructure systems
  - Inoperability input-output Leontief methods
  - Agent-based modeling
  - Data-based methods
  - Network, complexity, and reliability theory approaches
3. Interdependencies (2/9)

- Simulation-based network modeling approach
  - Hazard and Action on Components (HAC)
  - Systemic Damage Propagation (SDP)
  - Cascading Failures Assessment (CFA)
  - Interdependence Damage Propagation (IDP)
  - Systemic Performance Assessment (SPA)

\[ I_{str} = P(F(i)|F(j)) \]

\( I_{str} \): Interdependence Strength
3. Interdependencies (3/9)

- Assess the effects of probabilistic seismic hazards
3. Interdependencies (4/9)

- Risk-level effects of interdependence

\[ I_{str} = 0 \quad I_{str} = 1.00 \]

- Interdependence effects persist after convolution of fragility with seismic hazards
3. Interdependencies (5/9)

- Effects of interface topology across systems

- Optimal interfaces exhibit high $D$ and low $Istr$
- Strengthen power nodes and water links
3. Interdependencies (6/9)

- Design and retrofit of interface topologies
  - Best interface is informed by enriched PageRank

- Best interface is informed by enriched PageRank
3. Interdependencies (7/9)

- Water and power systems in Concepcion, Chile
3. Interdependencies (8/9)

- Fragility point validation

\[ S_2 \rightarrow S_1 \]

\[ (I_{str}^{P-W}, C_{L,eg}) \]

\[ Power \]

\[ S_1 \rightarrow S_2 \]

\[ (I_{str}^{P-W}, C_{L,eg}) \]

\[ Water \]
3. Interdependencies (9/9)

- Additional validation from practical recommendations

VULNERABILITY OF INTERCONNECTED INFRASTRUCTURE
A case of EU gas and electricity networks

K. Poljanšek, F. Bono, E. Gutiérrez
4. Conclusions and Future Work

• System decentralization could enable computational tractability and controlled autonomy for optimized decision making

• Resilience assessment with conditions of uncertainty in hazards, system response, growth and evolution could be enabled by enriched network theory

• The essence of infrastructure system interdependencies can be reasonably captured by complexity theory approaches

• Evolve restoration models to enable resilience assessment

• Update protocols of post-event data collection to enable interdependence strength quantification

• Explore recursive combinatorial approaches to learn about system state contingencies
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