Lifeline System Interdependencies: Field Observations and Modeling Challenges

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City and County of San Francisco Lifelines Council
Meeting # 8: Lifeline Interdependencies During Post-Disaster Recovery

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Motivation (1/7)

- Contemporary complex 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
• Emerging complex infrastructure systems
Motivation (3/7)

- Research on interdependent infrastructure systems
  - Inoperability input-output Leontief methods
  - Agent-based modeling
  - Data-based methods
  - Network and complexity-theory approaches
Motivation (4/7)

- Efforts to understand interdependencies and quantify their strength of coupling in practice
  - European Union’s Institute for the Protection and Safety of Citizens
  - U.S. Department of Homeland Security
  - Technical Council on Lifeline Earthquake Engineering
  - San Francisco’s SPUR initiative
• Implementations to cope with potential interdependencies and their cascading effects in practice
- MLGW’s ring of telecommunications
- British Columbia’s Olympic games scenarios
- Houston’s water and gas decoupling from grid
Japanese efforts to link interdependence with resilience
Motivation (7/7)

- 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)

\[ Istr = P(F(i)|F(j)) \]

\( Istr \): Interdependence Strength
Presentation Outline

1. Recent field observations of lifeline system interdependencies

2. Modeling of infrastructure interdependence

3. Quantification of coupling strengths

4. Concluding remarks and future research / implementation
1. Recent Field Observations (1/2)

- Power system after the 2010 Chilean Earthquake
  - Chilean Interconnected Systems (CIS) back in 48 hours
  - $N$-1 security
  - Emergency plans
1. Recent Field Observations (2/2)

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

- Observed actions to cope with interdependencies that delayed restoration
  - Private telecommunications
  - Transmission autonomy
  - Decentralized dispatch
  - Mobile generation
2. Insights from Modeling (1/8)

- A set of realistic yet streamlined systems

\[ S_1 \rightarrow S_2 \quad \text{Power effects on Water} \]
\[ S_2 \rightarrow S_1 \quad \text{Water effects on Power} \]
2. Insights from Modeling (2/8)

- Water Connectivity Loss from interdependence with power

\[ S_1 \rightarrow S_2 \]

\[ Istr = 0.30 \]
2. Insights from Modeling (3/8)

- Water Connectivity Loss from interdependence with power
  \[ S_1 \rightarrow S_2 \]

- Coupling contributes significantly to water fragility
- Interdependence control must be activated early
2. Insights from Modeling (4/8)

- Added Connectivity Loss \( C_L \) from interdependencies

- Power system is less sensitive to coupling
- Interdependencies manifest at select hazard levels
2. Insights from Modeling (5/8)

- **Effects of capacity increase of congested elements on** $C_L$

  \[ S_1 \rightarrow S_2 \]

  $PGA = 0.20$

  $PGA = 0.50$

- **Local capacity increase to manage intra- and inter-dependent cascades is insufficient to control** $C_L$
2. Insights from Modeling (6/8)

- Effects of interface topology across systems

- Optimal interfaces exhibit high $D$ and low $Istr$
- Strengthen power nodes and water links
2. Insights from Modeling (7/8)

- Assess the effects of probabilistic seismic hazards
2. Insights from Modeling (8/8)

• Risk-level effects of interdependence

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

- Interdependence effects persist after convolution of fragility with seismic hazards
3. Coupling Strength Quantification (1/8)

Geographical and seismological context of Chile 2010 Earthquake
3. Coupling Strength Quantification (2/8)

- Restoration time series in the Bio-Bio Region VIII
3. Coupling Strength Quantification (3/8)

- Restoration time series in the Maule Region VII

![Graph showing restoration time series in the Maule Region VII](image-url)
3. Coupling Strength Quantification (4/8)

- Sample of *strong* cross-correlation (coupling strength)
3. Coupling Strength Quantification (5/8)

- Sample of weak cross-correlation (coupling strength)
3. Coupling Strength Quantification (6/8)

- Pair-wise cross-correlations CCFs in Region VIII

<table>
<thead>
<tr>
<th>Series</th>
<th>F_VIII</th>
<th>M_VIII</th>
<th>P_VIII</th>
<th>P_C_VIII</th>
<th>P_T_VIII</th>
<th>W_C_VIII</th>
<th>W_T_VIII</th>
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<tr>
<td></td>
<td>Peak ρ</td>
<td>Lag h</td>
<td>Peak ρ</td>
<td>Lag h</td>
<td>Peak ρ</td>
<td>Lag h</td>
<td>Peak ρ</td>
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<td>0.00</td>
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<td>0.74</td>
<td>11.00</td>
<td>0.79</td>
<td>13.00</td>
<td>0.53</td>
</tr>
</tbody>
</table>

F: Fixed lines  W: Water
M: Mobile lines  C: Concepción
P: Power        T: Talcahuano

- Strong operational coupling between telecommunication systems and with power systems
- Measurable logistical coupling with water systems
3. Coupling Strength Quantification (7/8)

- Water and power systems in Concepcion, Chile

Legend:
- Reservoir/Pumping Plant
- Mochita Treatment Plant
- Distribution Nodes
- Study Area
- Pipelines

Liquefaction Probability:
- High
- Low
- Medium

Water Status After 42 Days:
- Intermittent
- No Water
3. Coupling Strength Quantification (8/8)

- Fragility point validation

\[ S_2 \rightarrow S_1 \]

\[ S_1 \rightarrow S_2 \]
4. Conclusions and Future Work

• There is a need for modeling tools with predictive capabilities that merge *physical and institutional* systems

• Interdependencies are significant at *specific ranges of hazard* intensities and tend to *quickly propagate main effects*

• Infrastructure interfaces that promote coordination and prevent propagation are *denser and weaker than current designs*

• Time-series analyses of restoration curves enable *coupling strength quantification* and interdependence *model validations*

• Expand analyses of interdependence effects to system *resilience assessment*

• *Prioritize critical components and restoration tasks* to achieve target multi-system performance levels
Thank you!

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Insights from Modeling

• Effects of interface topology on performance

Distance

Clustering

Degree

Betweenness

Hybrid Distance-Betweenness

Water node

Power node
Insights from Modeling

- Systems with distinct physical operating principles

- Congestion is a dominant failure mode for telecommunication systems
Recent Field Observations

- Autocorrelation (ACF) in power systems