Resilience System Modeling and Dynamic Economic Impacts

Amvrossios (Ross) Bagtzoglou; Wei Zhang; Jin Zhu; Marisa Chrysochoou; Jintao Zhang; William Hughes; Qin Lu; Brenden Edwards; Sudipta Chowdhury

amvrossios.bagtzoglou@uconn.edu

Please email me for questions and paper requests
Proposed Work & Progress

Project Tasks

- Improve the System Performance Model to incorporate multiple parameter interplays (T1: ongoing)
- Develop fragility response surfaces capturing parameter interplays (T2: ongoing)
- Analyze cost savings for the utility company (T3: ongoing) & society (starting)
- Develop model to optimally allocate resources and resilience strategies accounting for system impact and recovery cost (T5: starting)

Progress

- Power distribution system fragility modeling
  - Physics-based modeling for pole failures
  - Fragility surface (multiple dimensions)
- Resilient System Modeling
  - Power distribution system vulnerability analysis; soil vulnerability is included
  - Power distribution system reliability assessment
  - Power distribution system outage prediction and utility/societal cost analysis
Fragility Modeling

- Finite element method
  - A power distribution system (PDS) finite element model is built.

- Hybrid physics-based and data-driven (HPD) Model
  - Non feasible to model all environmental load combinations, span lengths, etc.
  - A hybrid model could improve both the physics-based modeling and OPM interactions

UConn-OPM Architecture (Cerrai et al. 2019)
Vulnerability Analysis

- Based on graph theory, PDS is modeled as a graph $G(\mathcal{V}, \mathcal{E})$
- Fragility Surface
  - Fragility surface regrading wind speed and span length is developed since the span length is specific
  - $P_{f_{pole}}$ is derived from this surface
- Fragility-based weight
  - Derived from fragility surface based on deterministic wind speed and span length
  - Span length is calculated based on GIS database
  - Pole-wire subsystem failure probability determined as
    $$P_{fsubs} = 1 - (1 - P_{f_{pole,l}}) \times (1 - P_{fwire}) \times (1 - P_{f_{pole,r}})$$
  - The weight of the graph model is determined as
    $$w_{ij} = \frac{1}{1 - P_{fsubs}}$$
Results

Vulnerability analysis
• A power distribution system in Fairfield County, Connecticut
• Static Analysis (after failure, weights become 0)
  • A comparison of vulnerability assessment outcomes is performed for different categories of hurricanes
• Dynamic Analysis (node load is redistributed)
  • The static vulnerability analysis overestimates the failure impact (complementary to efficiency) on PDS performance.
  • The PDS performance is decreasing with increasing number of node failures and fragility-based PDS performance is relatively higher than the topology-based analysis.
Vulnerability analysis

- Fragility surfaces (pole diameter, span, wood type, soil properties)
- Soil Vulnerability maps produced via kriging and SPTN CT data


Results (contd.)

Outage Prediction and Cost Analysis

- Outage prediction and cost analysis
  - Assuming pole fragility is linearly correlated with the outage count per asset $\beta$, rescaled fragility curve can be used to predict outages
    - Scaling will vary with location (different terrain, pole ages, span lengths) and storm (different times, vegetation, weather combinations)
    - These calibrated scaling factors can be predicted using OPM

Example rescaled fragility curve for Hurricane Sandy (left) and random storm (right)
Outage prediction and cost analysis

- Cost analysis for Interventions
  - Demonstrative representation: **pole replacement**
  - Oldest $\delta$% replaced, then pole age distribution is assumed constant
- Notable outage reductions observed for only $\sim$25% of storms
- Total outages reduced annually: 47 (S2), 104 (S3), 246 (S4)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
<th>Cost ($ Mil USD2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Do-nothing</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1 % Replacement</td>
<td>19.2</td>
</tr>
<tr>
<td>3</td>
<td>2 % Replacement</td>
<td>38.4</td>
</tr>
<tr>
<td>4</td>
<td>5 % Replacement</td>
<td>96.0</td>
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</tbody>
</table>

Scenarios and company investment cost (no inflation, discount rate)

CDF outage reductions over storms
Outage prediction and cost analysis

- Cost analysis
  - Customer outage cost and discount rate varied due to uncertainties
  - Low discount rates and high outage counts make interventions favorable

Projected savings under various scenarios

Results (contd.)

Cost analysis accounting for consumer costs/attitudes

- Restoration decisions are primarily made focusing on minimizing restoration time/cost; the social impact is not well addressed.
- Customer outage cost and “attitude” can be factored in as weight utility/consumer.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Most favorable strategy number</th>
<th>Strategy</th>
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</thead>
<tbody>
<tr>
<td>$0 \leq w_{RC} &lt; 0.2$</td>
<td>Strategy 11</td>
<td>40% poles being replaced with upgraded class ones</td>
</tr>
<tr>
<td>$0.2 \leq w_{RC} &lt; 0.42$</td>
<td>Strategy 9</td>
<td>30% poles being replaced with upgraded class ones</td>
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<tr>
<td>$0.42 \leq w_{RC} &lt; 0.72$</td>
<td>Strategy 7</td>
<td>20% poles being replaced with upgraded class ones</td>
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<tr>
<td>$0.72 \leq w_{RC} \leq 1$</td>
<td>Strategy 5</td>
<td>10% poles being replaced with upgraded class ones</td>
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</tbody>
</table>

Fig. 8 Sectional cost of 12 hardening strategies
Social-Cost-Based Dynamic Restoration Decision-Making

- Social impact of power outages can be quantified using the concept of social cost measured by Willingness-to-Pay (WTP) to essential services
- Social cost can be different for residential and commercial consumers
- An October 2017 storm with high wind, strong wind, and flooding was modeled with agent-based software Anylogic
- Data included: Storm duration; 4,516 disrupted poles; 9 damaged asset classes; Repair time for each asset class; Crew information

<table>
<thead>
<tr>
<th>Simulation Experiments</th>
<th>Restoration Prioritization Rule</th>
<th>Number of crew</th>
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</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>Same priority</td>
<td>144</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>Social-cost based priority</td>
<td>144</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>Social-cost based priority</td>
<td>244/344</td>
</tr>
</tbody>
</table>
Summary and Conclusions

- Vulnerability analysis conducted via graph theory augmented by fragility weights
- PDS performance is better with fragility-based than topology-based analysis
- The static analysis overestimates storm impacts
- A hybrid physics-based data-driven model incorporating fragility curves and outage prediction modeling is proposed
- Hybrid model shows reasonable predictive capabilities similar to data-driven OPM while allowing for simulation of grid hardening
- Fragility surfaces are being developed (soil, pole and wind characteristics); soil vulnerability maps are being developed
- Interventions are favored for major events and low discount rates
- When consumer attitude is accounted for more expensive strategies are chosen
- Using social-cost-based prioritization rule in restoration, social cost of outage decreases significantly
- Social cost will continue decreasing as the number of crews increases, with an increase in operational cost
- Social-cost-based prioritization gradually loses its benefits with increased resource level (e.g., crew size)