# Resilience System Modeling and Dynamic Economic Impacts

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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)

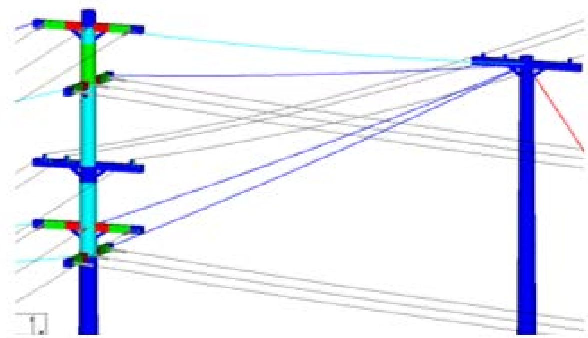
**Progress**

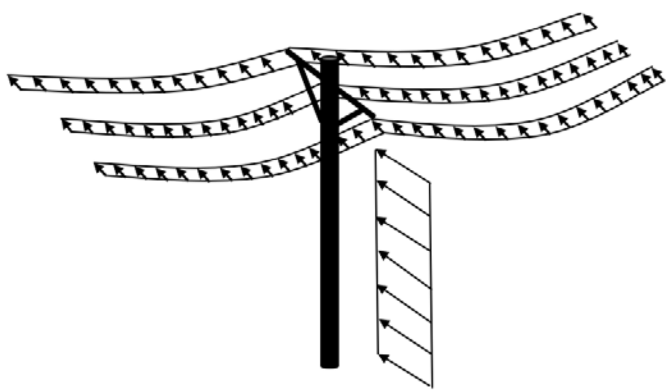
- Power distribution system fragility modeling
  - Physics-based modeling for pole failures
  - Fragility surface (multiple dimensions)
- Resilient System Modeling
  - Power distribution system vulnerability analysis; soil vulnerability is included
  - Power distribution system reliability assessment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

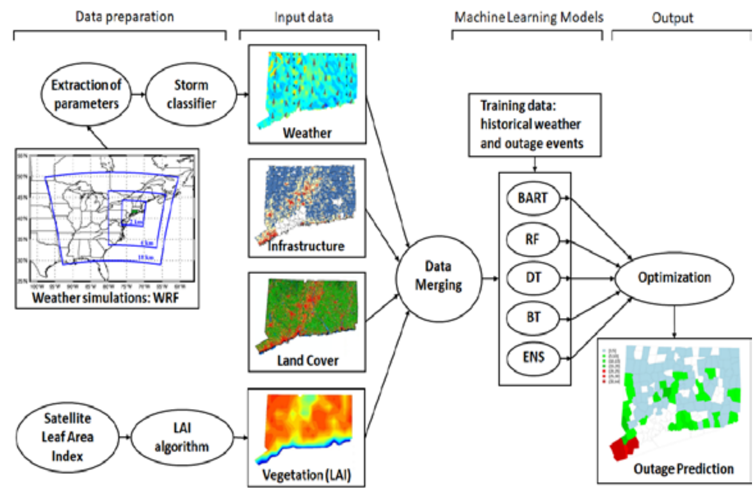
# Fragility Modeling

- 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

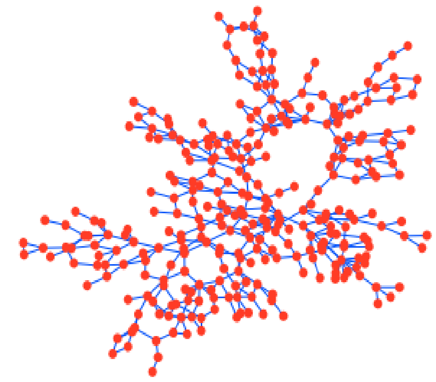







UConn-OPM Architecture (Cerrai et al. 2019)

# Vulnerability Analysis



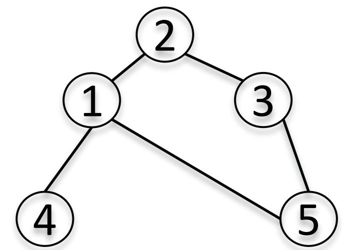
Topology of a large-scale PDS

- Based on graph theory, PDS is modeled as a graph ***G (V, E)***
- Fragility Surface
  - Fragility surface regrading wind speed and span length is developed since the span length is specific
  - $P_{fpole}$ 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

$$P_{fsubs} = 1 - (1 - P_{fpole,l}) * (1 - P_{fwire}) * (1 - P_{fpole,r})$$

  - The weight of the graph model is determined as

$$w_{ij} = \frac{1}{1 - P_{fsubs}}$$




| | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 1 | 0 |
| 2 | 1 | 0 | 1 | 0 | 0 |
| 3 | 1 | 1 | 0 | 1 | 1 |
| 4 | 1 | 0 | 1 | 0 | 1 |
| 5 | 0 | 0 | 1 | 1 | 0 |

Traditional adjacency matrix

| | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| 1 | 0 | $w_{12}$ | 0 | $w_{14}$ | $w_{15}$ |
| 2 | $w_{12}$ | 0 | $w_{23}$ | 0 | 0 |
| 3 | 0 | $w_{23}$ | 0 | 0 | $w_{35}$ |
| 4 | $w_{14}$ | 0 | 0 | 0 | 0 |
| 5 | $w_{15}$ | 0 | $w_{35}$ | 0 | 0 |

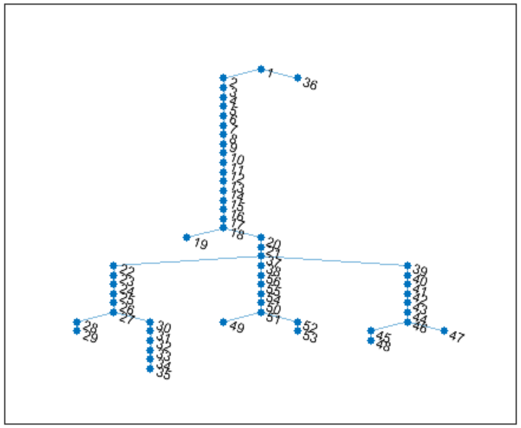
Fragility-based adjacency matrix

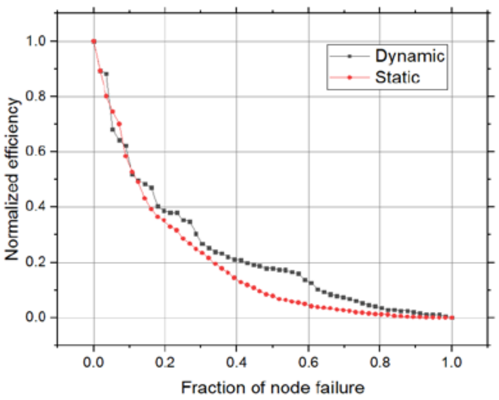
# Results

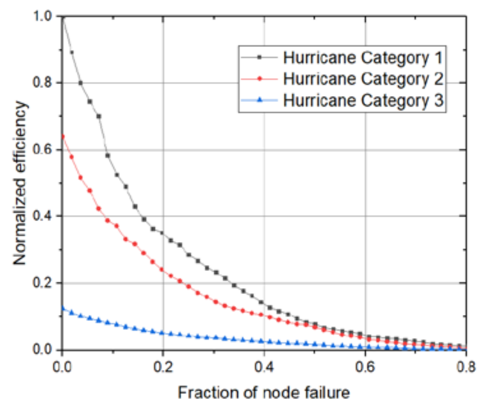
## Vulnerability analysis

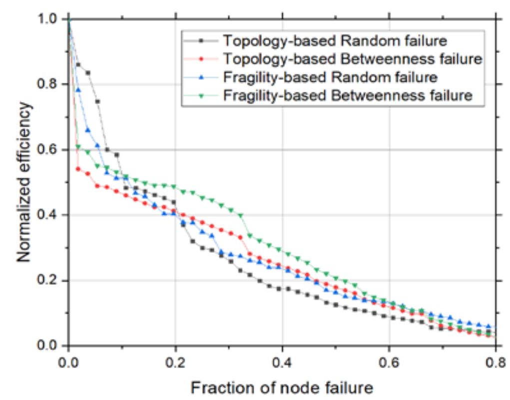
- A power distribution system in Fairfield County, Connecticut
- Static Analysis (after failure, weights become 0)
  - A comparison of vulnerability assessment outcomes is performed for different categories of hurricanes
- Dynamic Analysis (node load is redistributed)
  - The static vulnerability analysis 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.

Power Distribution System with $N = 56$ nodes, $E = 55$ edges





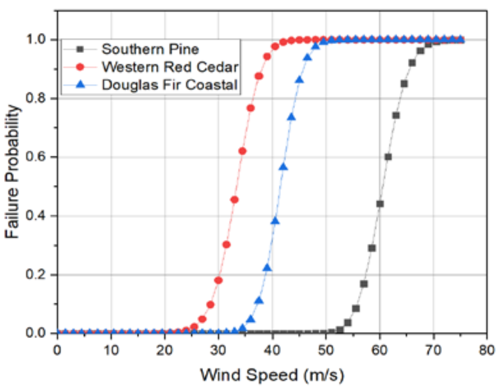



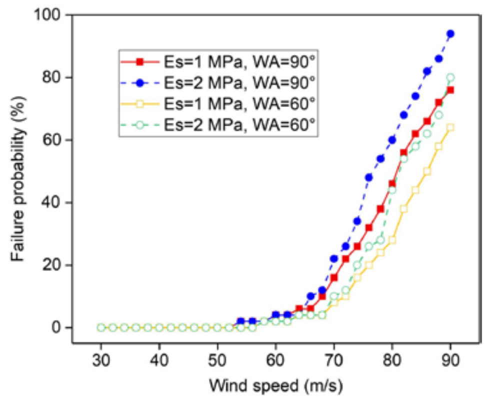



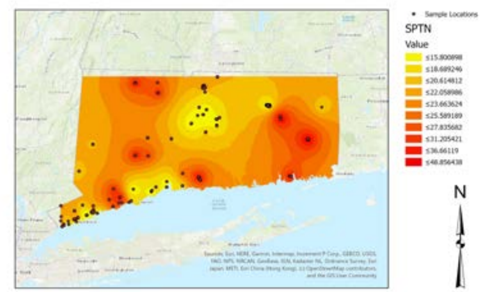
# Results (contd.)

## Vulnerability analysis

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



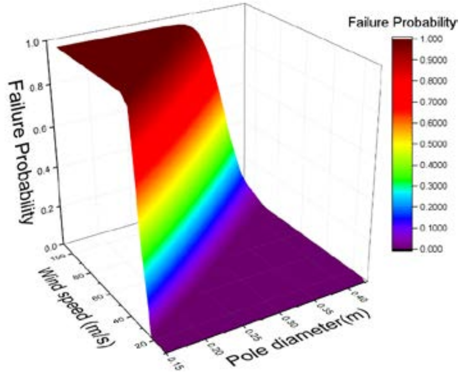



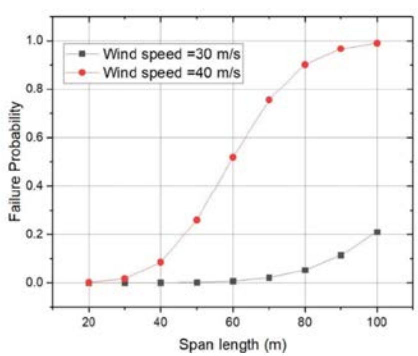



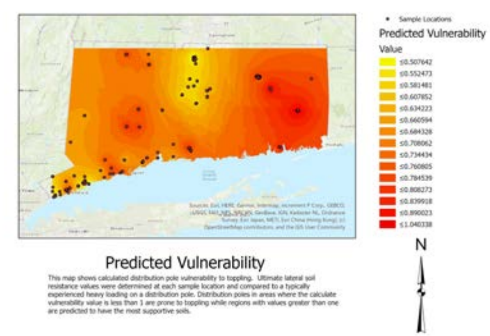

Boring Locations and SPTN Values

This map illustrates interpolated SPTN values based on the data from each sample location. Kriging, a type of geospatial analysis allowed for the determination of SPTN values in between data points.

Ma et al., 2021, “Local System Modeling Method for Resilience Assessment of Overhead Power Distribution System under Strong Winds”, *ASCE-ASME J. Risk Uncertainty Eng. Syst., Part A: Civ. Eng.*, 2021, 7(1): 04020053



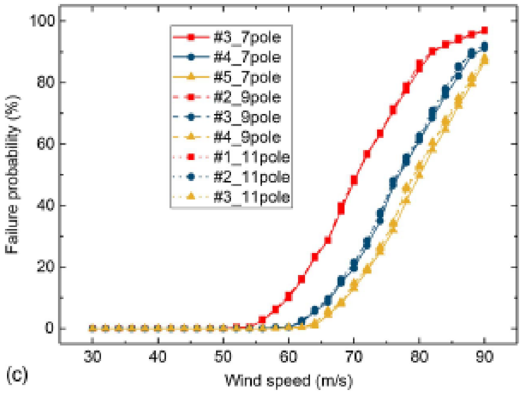



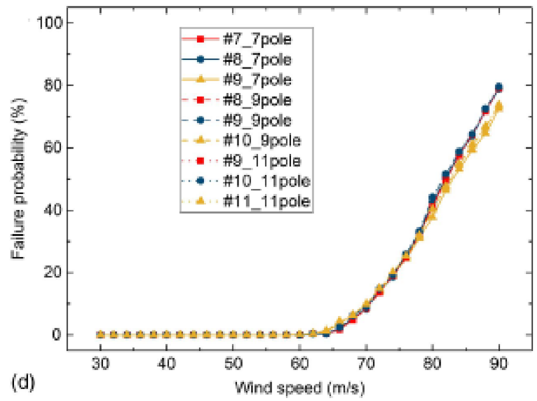

Predicted Vulnerability

Edwards, B., 2021, MS Thesis, UConn (in review)

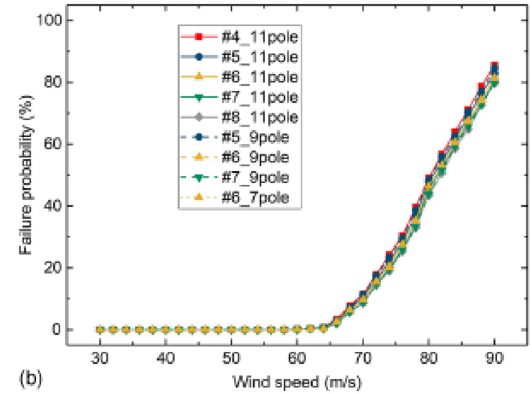
# Results (contd.)




Upstream Side poles 60º




Downstream Side poles 60º

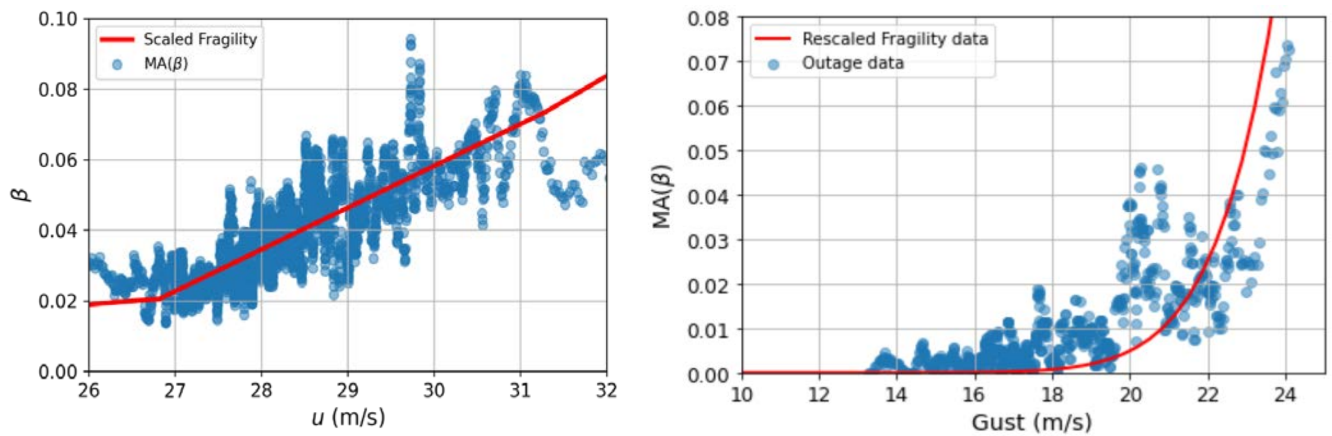



Inner pole 60º

Ma et al., 2021, “Local System Modeling Method for Resilience Assessment of Overhead Power Distribution System under Strong Winds”, *ASCE-ASME J. Risk Uncertainty Eng. Syst., Part A: Civ. Eng.*, 2021, 7(1): 04020053

# 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)

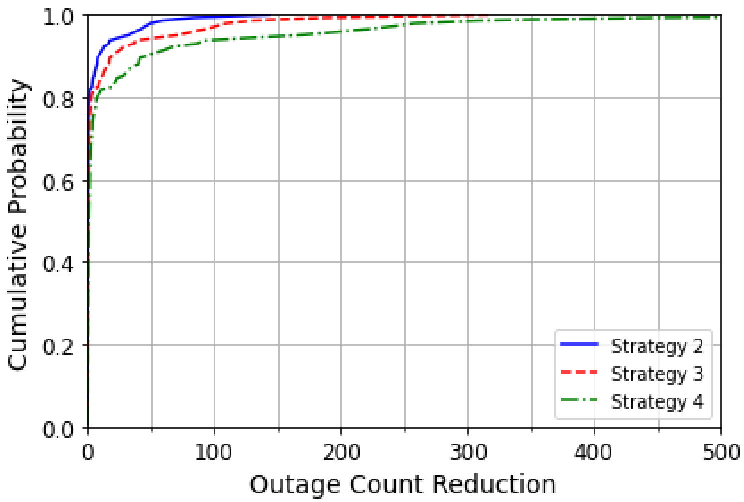
# Outage Prediction and Cost Analysis

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 ~25% of storms
- Total outages reduced annually: 47 (S2), 104 (S3), 246 (S4)

| Strategy | Description | Cost ($ Mil USD2019) |
|---|---|---|
| 1 | Do-nothing | 0 |
| 2 | 1 % Replacement | 19.2 |
| 3 | 2 % Replacement | 38.4 |
| 4 | 5 % Replacement | 96.0 |

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



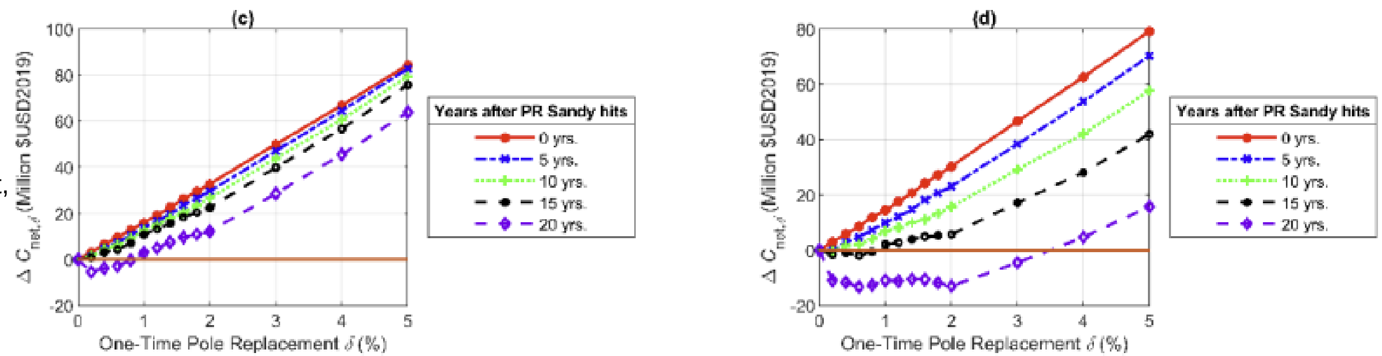

CDF outage reductions over storms

# Results (contd.)

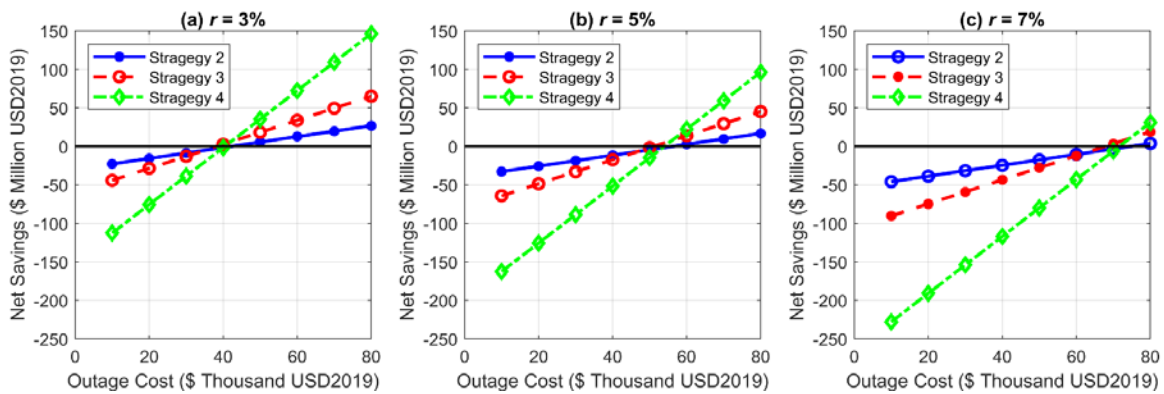
## Outage prediction and cost analysis

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

High replacement cost,
r=3%




Hughes et al., 2021, “Damage modeling framework for resilience hardening strategy for overhead power distribution systems ”, *Reliability Engineering and System Safety*, 207: 107367




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

| Weight | Most favorable strategy number | Strategy |
|---|---|---|
| $0 \le w_{FC} < 0.2$ | Strategy 11 | 40% poles being replaced with upgraded class ones |
| $0.2 \le w_{FC} < 0.42$ | Strategy 9 | 30% poles being replaced with upgraded class ones |
| $0.42 \le w_{FC} < 0.72$ | Strategy 7 | 20% poles being replaced with upgraded class ones |
| $0.72 \le w_{FC} \le 1$ | Strategy 5 | 10% poles being replaced with upgraded class ones |

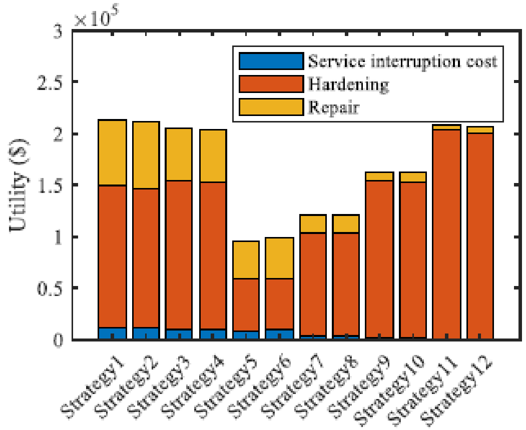
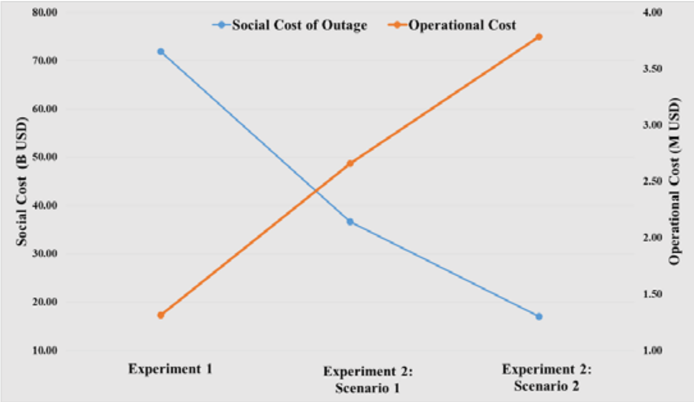



Fig. 8 Sectional cost of 12 hardening strategies

# 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

| Simulation Experiments | Restoration Prioritization Rule | Number of crew |
|---|---|---|
| Base Case | Same priority | 144 |
| Experiment 1 | Social-cost based priority | 144 |
| Experiment 2 | Social-cost based priority | 244/344 |



# 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)