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Mapping Infrastructure Interdependencies for Improved Emergency Management and Resilience Investment Decisions

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Homeland Security Challenge


Aging Infrastructure

+


Vulnerability to Natural Disasters

+


Susceptibility to Organized Attacks

+


Increasing Connectivity of Critical Infrastructure

Cascading Failures

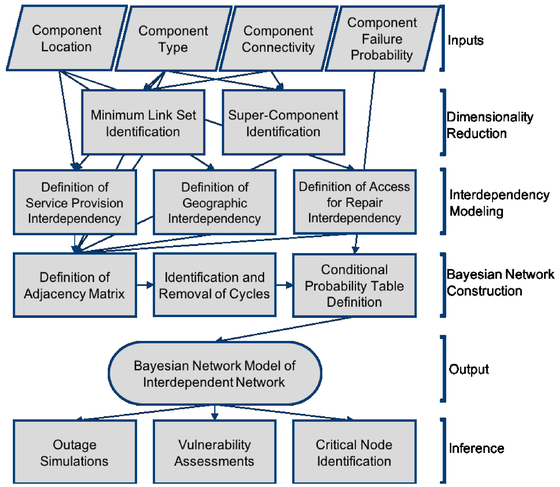
- Single infrastructure component causes outages in other components or infrastructure systems
- E.g., power substation outage causes outage in the water pump


Blackout in Chelsea from Southern Manhattan power outage
Credit: Dan Nguyen

Need to Assess Impacts of Interdependencies

- Enable comprehensive risk and vulnerability assessments accounting for interdependencies and cascading failures
- Tool to enable infrastructure owners and operators, and municipal managers and planners, to prioritize maintenance and investment decisions to increase resilience

Approach / Methodology



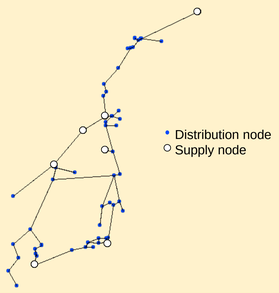
Inputs

Location
- Latitude-longitude pairs

Types
- Supply
- Distribution

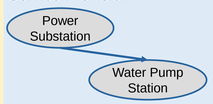
Connectivity
- List of links
  - E.g., water pipes

Failure Probability
- Empirical
- Estimated
- Obtained from owner

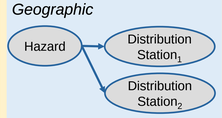


Interdependency Modeling

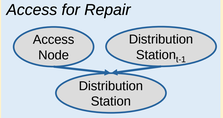
Service Provision



Geographic



Access for Repair



Dimensionality Reduction

Minimum Link Set Formulation
- MLS – minimum set of components that must be functional for supply to reach distribution point

Super-Components
- Defined when state is known given the failure of any one of constituent components

Make computation possible on large networks

Inference

Outage Simulations
- Input which node(s)
- Output
  - Change in failure probability of other nodes
  - Change in reliability of system nodes

Vulnerability Assessments
- Analyze which nodes may cause cascading outages
- Analyze susceptibility to or potential outages due to cyber attack

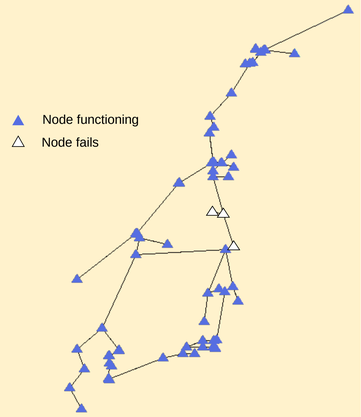
Critical Node Identification
- Prioritize components to focus on for repair, replacement, and reinforcement
- Help determine order of repair or investment actions to take

Demonstrate importance of considering interdependencies during each of these

Outcomes / Results

Model Validation

- Validate based on physical scenario that occurred in 2014 an 2017
- Water pump station lost power to both dual feeds, outages in Atlanta's downtown area
- To test scenario, simulated outage to power components supplying affected pump station



Component Importance

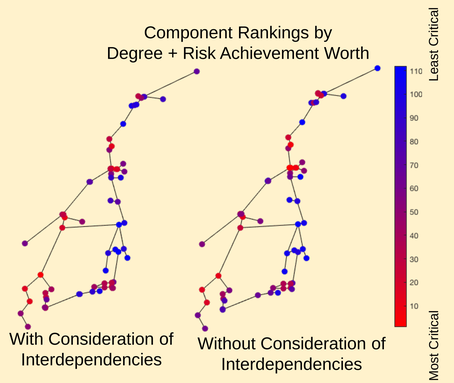
Centrality Metrics	*Reliability Metric*	*Combination Metrics*
Degree Centrality	Risk Achievement Worth: Increase in system reliability with perfectly reliable component	Degree Centrality + Risk Achievement Worth
MLS Appearances		MLS Appearances + Risk Achievement Worth

Effect of Interdependencies

Centrality Metrics
- Little change with and without consideration of interdependencies

Risk Achievement Worth
- Most components contribute to a larger decrease in system reliability when interdependencies are not considered compared with when they are considered
- Most water supply nodes decrease in importance

Combination Metrics
- Most components contribute to a larger decrease in reliability with consideration of interdependencies versus without consideration of interdependencies

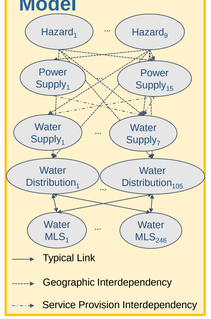


Conclusion

Algorithms to Build Bayesian Network Model

- Framework that maps interdependencies between infrastructures
- Can support comprehensive risk assessments across multiple systems
- Able to include hundreds of component nodes in a computationally efficient manner without approximating assumptions

Bayesian Network Model



Component Importance

- Determine where to invest resources to reinforce and recover infrastructure systems
- Assess centrality metrics and reliability metrics to rank component criticality
- Recommend combination metrics that account for topology of the network as well as individual component reliability

Effect of Interdependencies

- Component criticality changes for component importance measures applied to Atlanta water and power distribution networks
- Prioritize consideration of interdependencies to better understand infrastructure vulnerabilities

Decision Support Tool

- Can use this methodology to develop software tool for infrastructure decision-makers
- Tool will help utilities and municipalities prioritize maintenance decisions and inform infrastructure investment

Acknowledgements

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