Incorporating socio-economic impacts of infrastructure disruptions in resilience decision-making

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Infrastructure Monthly Meeting - QuakeCoRE

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Introduction

- Two Intra-CREATE projects
  - Disaster Resilience Assessment, Modeling, & Innovation Singapore (DREAMIN'SG).
  - Estimating Economic Losses from Cascading Infrastructure Disruptions (E2LCID)
- Motivation: Texas winter storm (2021)
  - Power blackouts and water supply disruptions due to extreme cold weather affected communities, and created ripple effects in global supply chains.
  - Economic impact in the range of $80bn - $130bn (Texas Comptroller of Public Accounts, 2021).
  - Low probability event combined with lack of preparedness among public and agencies

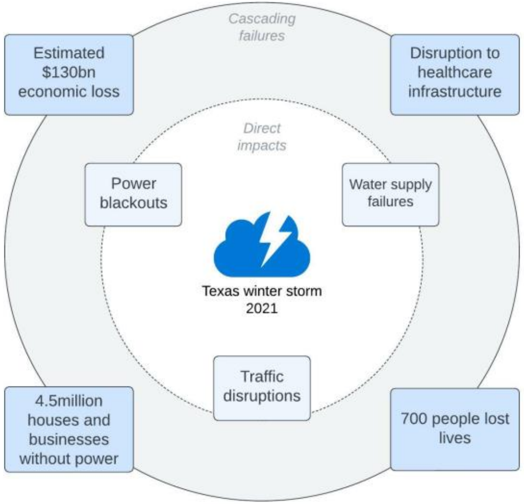
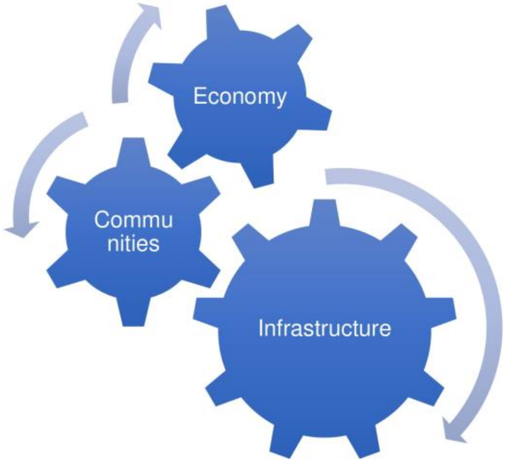


Photo credits: AP

Problem statement

- Any disruption to urban infrastructure could cause debilitating effects on the overall performance of cities (social, economic, health, and environmental).
- Interdependencies among infrastructure systems exacerbate the disaster impacts and slows down recovery if not properly managed.
- Can impacts to regional communities and economic sectors be the deciding factors for infrastructure resilience decision-making?



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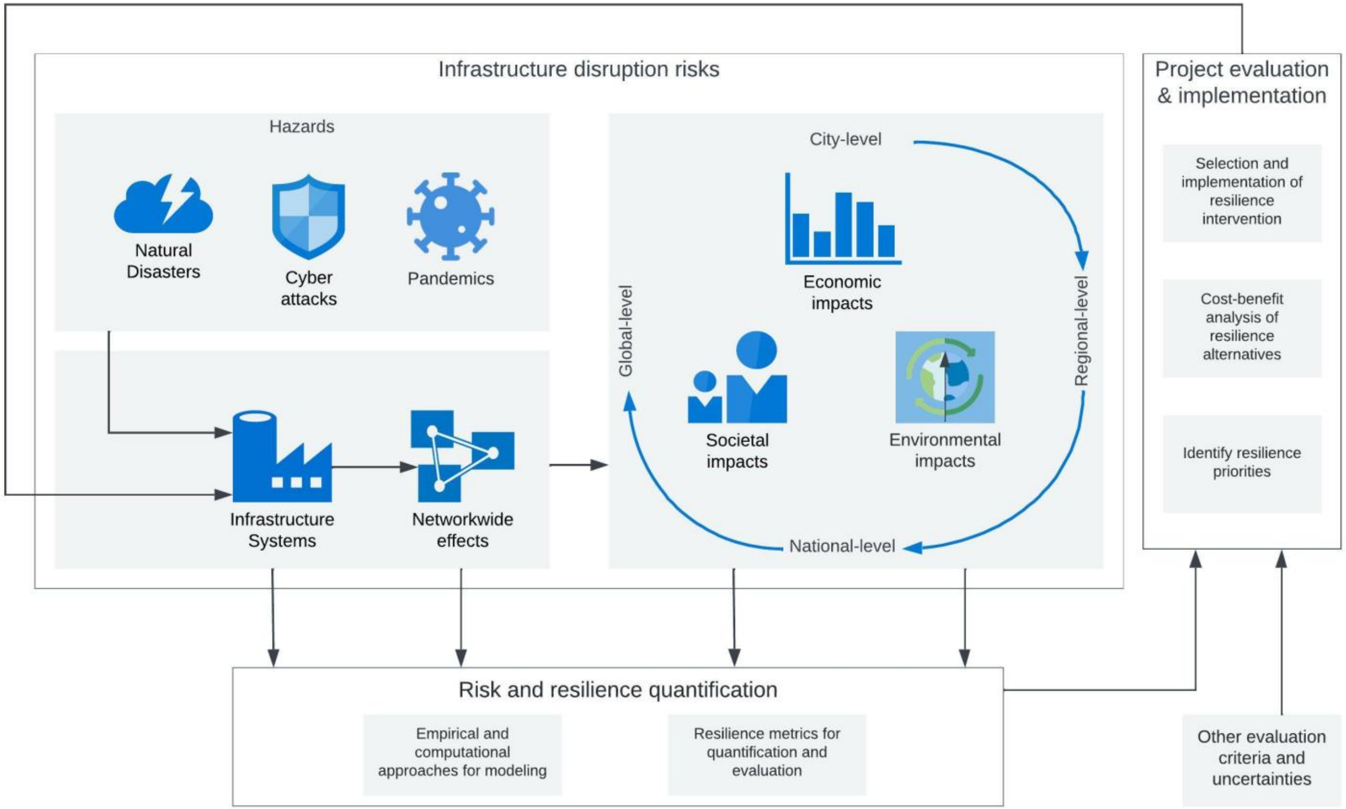
A Progressive Approach to Infrastructure Resilience



Balakrishnan, S. (2020), Methods for Risk and Resilience Evaluation in Interdependent Infrastructure Networks, Ph.D. thesis, The University of Texas at Austin, Austin, Texas (adapted).

Research objectives

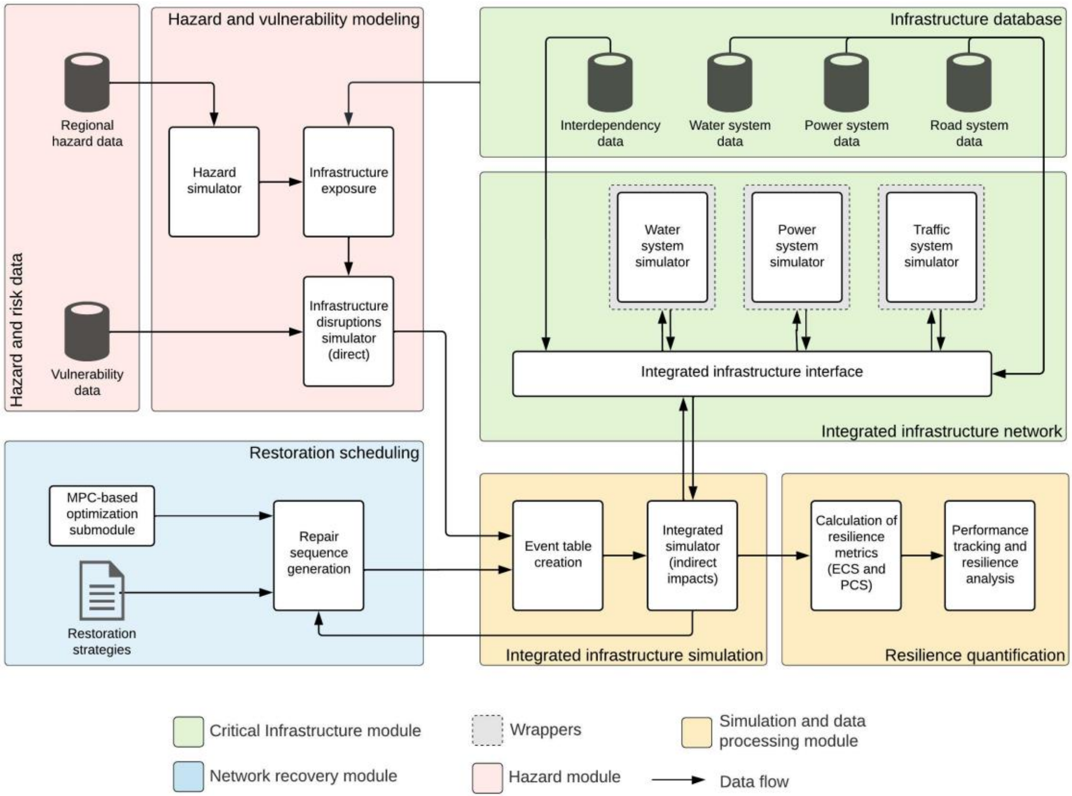
- The overall goal is to develop a framework and methodology to incorporate economic and societal risks of infrastructure disruptions and identify feasible resilience strategies that minimizes those risks.

- The specific objectives are:
  1. To develop an integrated infrastructure-industry-community simulation model to estimate the societal and economic impacts of infrastructure disruptions.
  2. To apply the integrated model to conduct Cost-Benefit Analysis of potential pre-disaster and post-disaster resilience strategies considering their economic and societal benefits, and associated costs.

Integrated Simulation Model

Overview

- *InfraRisk*, an in-house integrated water-power-transport model developed as part of DREAMIN'SG project.
- Simulation model for the component-level and system-level analysis.
- Modules for:
  - Integration of existing individual infrastructure simulators
  - Disaster scenario generation
  - Recovery modelling
  - Resilience quantification



Balakrishnan, S., B. Cassottana. InfraRisk: An open-source simulation platform for resilience analysis in interconnected power-water-transport networks. *Sustainable Cities and Society*, 83, 103963.

Integrated Simulation Model (Contd.)

Infrastructure Simulation Model

- Existing Python-based packages for infrastructure modeling
  - Water network - *wntr* package based on EPANET
  - Power network - *pandapower* package
  - Transportation network - static traffic assignment package

- Created an interface to link individual infrastructure models through an interdependency submodule

- Interdependencies considered:
  - Power-water interdependencies including electric motor-water pump coupling and reservoir-generator coupling.
  - Road network - power and water dependencies (access to infrastructure assets during normal and stressed conditions).

Integrated Simulation Model (Contd.)

Hazard initiation and vulnerability model

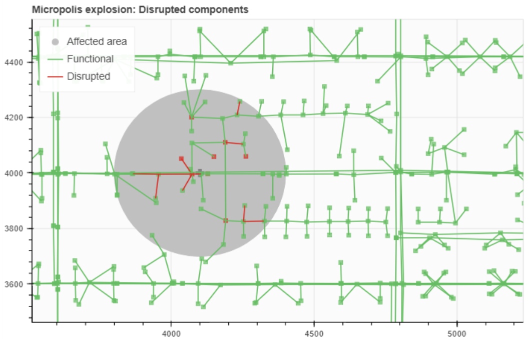
- Generates disaster scenarios and initializes disaster-induced infrastructure failures based on their vulnerability.

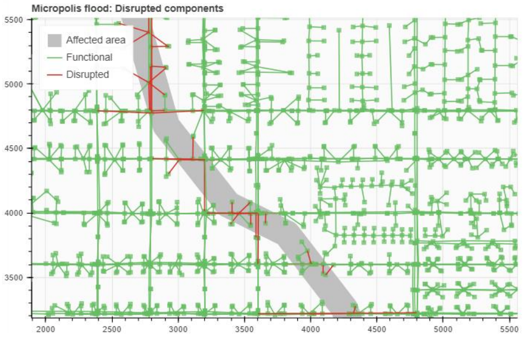
- Three types of disaster scenarios:
  - Random events - random failures.
  - Point events - explosions, targeted attacks, etc.
  - Track events - floods, hurricanes, tornadoes.
  - User defined events – coupling with other vulnerability models

- Probabilistic modeling of component failure.

$$P\left(\text{failure}_i\right) = P\left(\text{hazard}\right) \times P\left(\text{exposure}_i|\text{hazard}\right) \times P\left(\text{failure}_i|\text{exposure}_i\right)$$

  - Limitation: currently the vulnerability is based on distance criterion
  - Challenge: Fragility curves of different components subjected to different disasters





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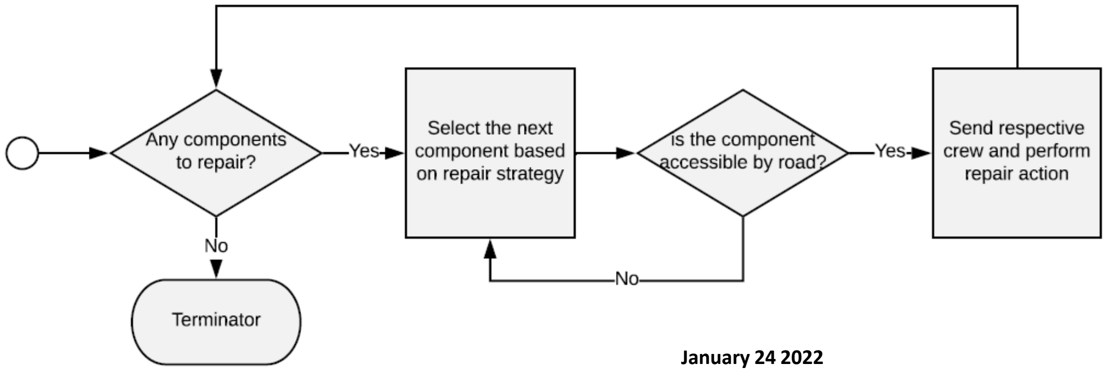
Integrated Simulation Model (Contd.)

Infrastructure Recovery Model

- Two methods for repair sequence generation
  - Predefined strategies for component repair such as centrality measures, maximum flow, and land use.
  - Receding horizon-based optimization model to find optimal repair an iterative approach

- Dynamic modification to repair sequence based on transportation accessibility to damaged components

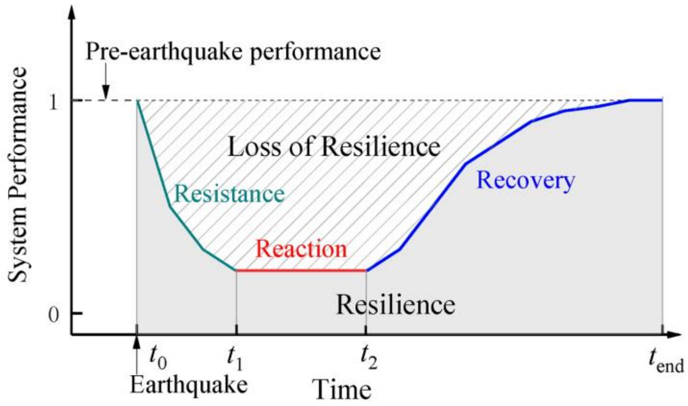


Integrated Simulation Model (Contd.)

Risk and Resilience Quantification

- The network simulation tracks the component-level, system-level and network-level performance using the following measures of performance (MOPs).
  - Prioritized component serviceability
  - Equitable component serviceability

- Resilience metrics are computed as the area under the curves profiled by MOPs.
- Can be used for evaluating both pre-disaster and post-disaster resilience interventions.

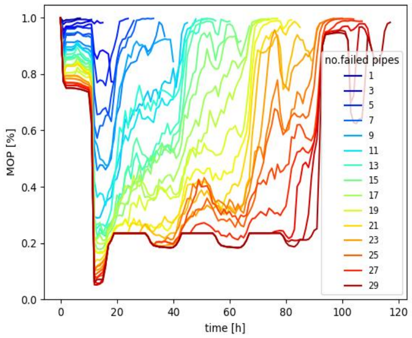


Integrated Simulation Model (Contd.)

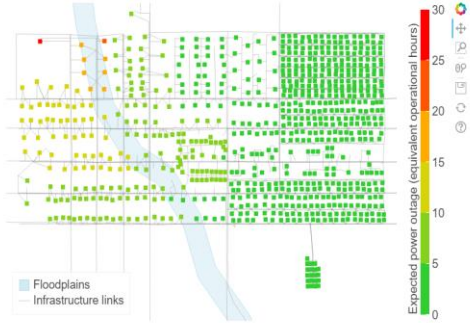
Industry and Community Layers

- *InfraRisk* is capable of simulating the building-level satisfied utility demand under normal and stressed conditions.

Direct flood impacts



Network performance



Building-level performance

- Point of Interest (POI) data and census data to develop industry layer and community layer.
- Input-Output methods to capture inter-sectorial relationships for economic analysis.

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Cost-Benefit Analysis of Resilience Strategies

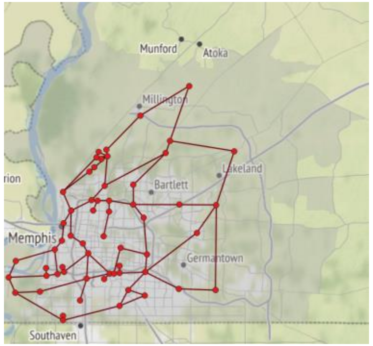
- Each resilience intervention involves costs, while resulting in system improvements in terms of reduced risks from specific disruptive events.

- Resilience interventions to be tested include:
  1. Pre-disaster measures: material changes and redundancy enhancements.
  2. Post-disaster measures: changes to repair strategies and resource mobilization.

- Cost-benefit analysis (CBA) in relation to status-quo or do-nothing strategy.
  1. Costs: upfront set-up costs, maintenance costs.
  2. Benefits: Expected reduction in physical, functional, and economic losses.

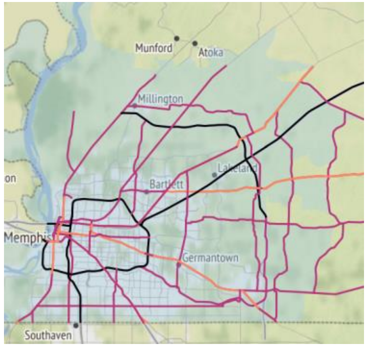
Case Study: Shelby County Network (Ongoing)

- The framework will be applied to the Shelby County interdependent power-water-road network and regional economy to analyse resilience interventions against earthquakes.
- The Shelby County network data is being developed.
- The Safegraph dataset (points of interest) and US Census data of the region to model the distribution of industrial sectors and communities.
- U.S. and OECD Input-Output tables for economic impact analysis.

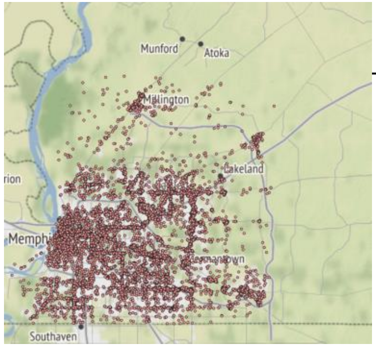


Power network

Water network



Road network



Points of interest

Case Study: Expected Outcomes

- The results of Cost-Benefit Analysis (CBA) and sensitivity analyses would provide insights into advantages and disadvantages of interventions at a system-level.
- Recommendations on resilience strategies based on trade-offs.
- Framework that integrates socio-economic aspects in infrastructure resilience decision-making.

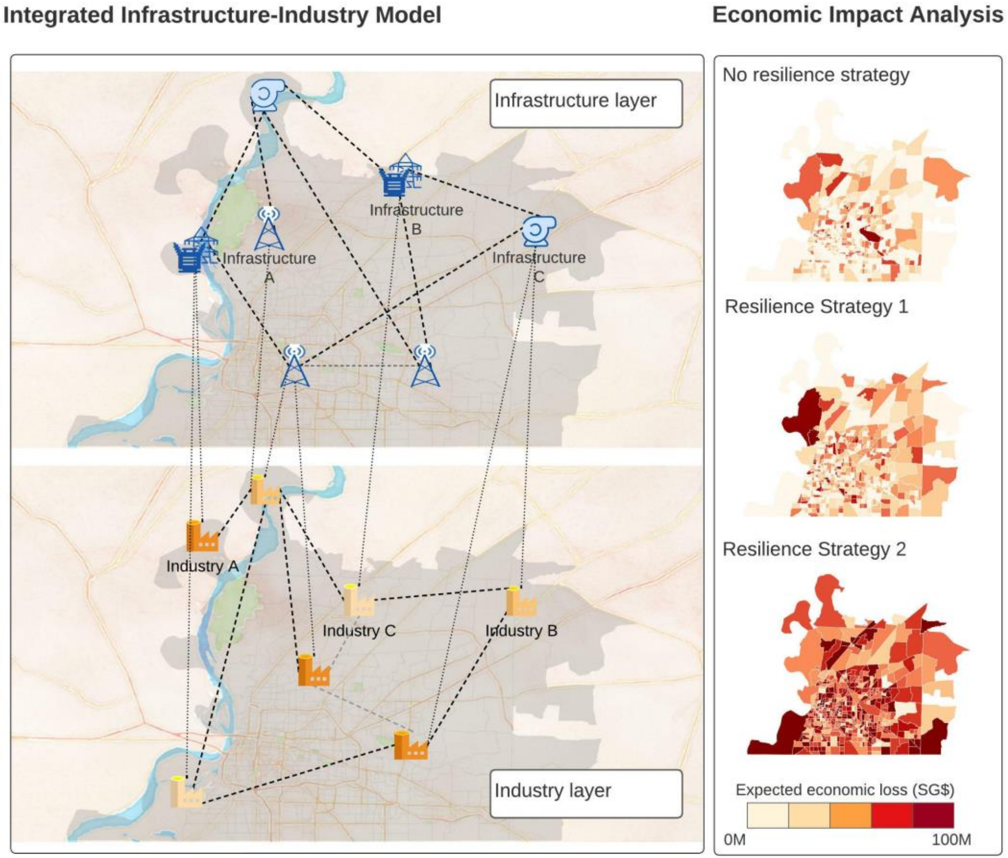


Figure: Expected outcomes

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