CENTER FOR TRANSPORTATION RESEARCH

Developing Priority Index for Managing Utility Disruptions in Urban Areas with Focus on Cascading and Interdependent Effects

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Introduction

- Urban infrastructure consists of multiple components and assumes a "networked structure."
- A single infrastructure failure could trigger multiple failures in dependent systems due to the interdependencies in the urban network, causing widespread disruptions in utility services.
- During such events, urban communities are susceptible to the direct impacts of the event, as well as to prolonged utility disruptions.
- A methodological framework to assess and prioritize communities who are most vulnerable to such utility disruptions arising from disasters does not exist.

Methodology

- The direct and indirect impacts of the event on the performance of various utility systems in the infrastructure network are quantified using agent-based modeling (ABM) approach.
- The exposure of the initial event on the network depends on the structure of the infrastructure network, and the interdependent relationships existing among its various components.
- A sample of building footprint in the study area is obtained, and the utility service disruptions are mapped based on their geographic location.
- The social vulnerability characteristics of communities residing in the affected regions are evaluated using the generic social variables obtained from American Community Survey (ACS) data.
- The normalized exposure of communities to the utility disruptions is combined with the social vulnerability index to develop the priority index for immediate relief operations.

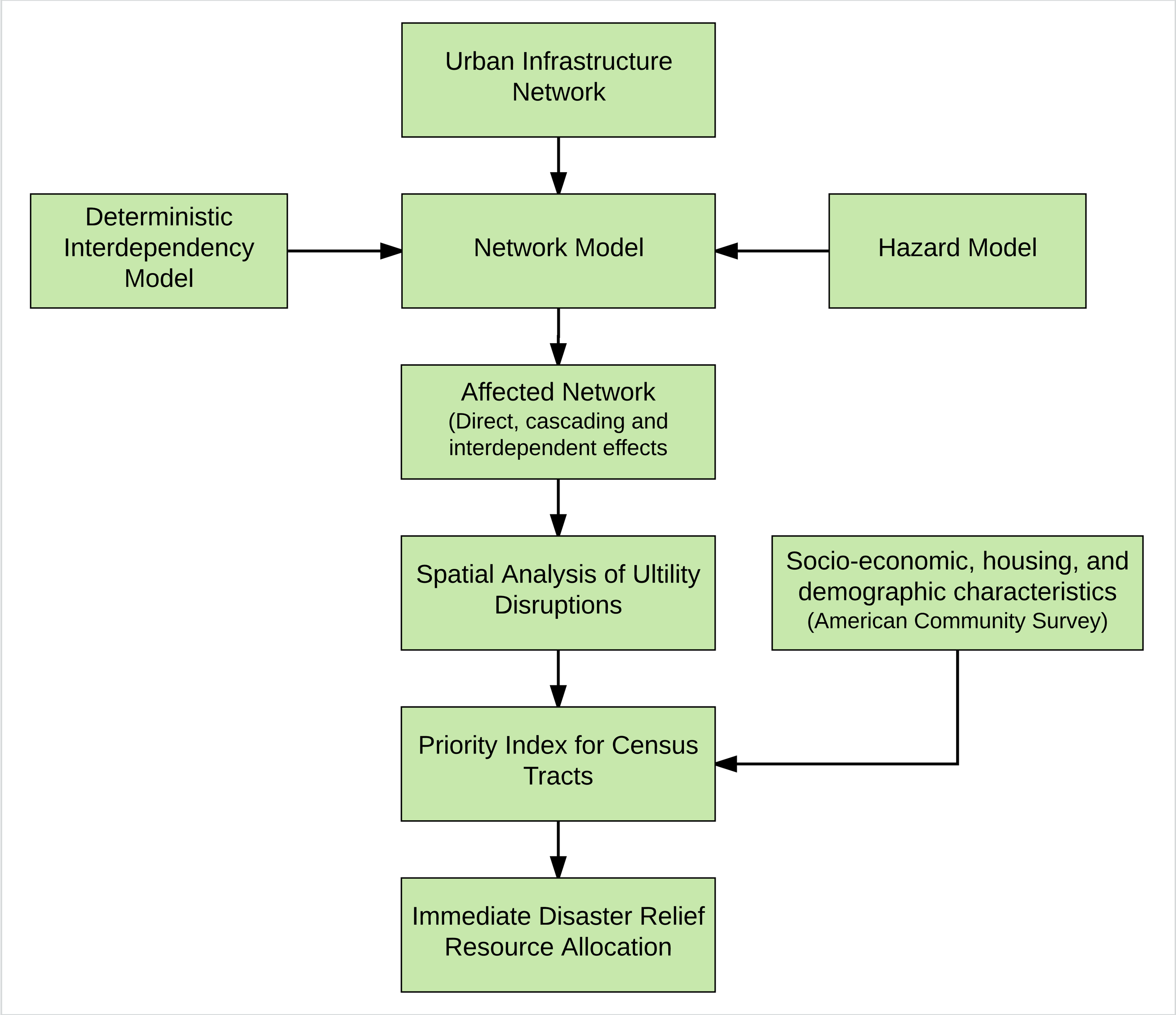

Fig 1. Methodological Framework for Developing Priority Index

Mathematical Formulation

Estimation of utility node-level performance

$$P_i(t) = \max\left(0, P_i(0) - \left[\sum_j (1 - P_j(t-\Delta t))\, w_{ij}\right] - \rho_i \iota_i^H\right)$$

$P_i(0)$ is the initial performance of node i, $P_i(t)$ is the performance at any time t, Δt is the simulation step size, J is set of all dependee nodes of i, and ρ is an indicator variable, ι_i^H is the direct impact of event on i, and w_{ij} is the dependency value of i on j.

Estimation of census tract-level exposure to utility disruptions

$$E_m = \sum_K (1 - P_K^m) \times w_K^m \;:\; 0 \leq E_m \leq 1,$$

E_m is the exposure in census tract, P_m^K is the expected performance of utility K in census tract m, and w_m^K is the corresponding weight.

Census-tract level social vulnerability to utility disruptions

$$mSVI_m = \frac{\sum_{s\in S} s_m}{15 \times 100};\; mSVI_{m,norm} = \frac{mSVI_m}{\max(mSVI_m)}$$

$mSVI$ is the modified social vulnerability index and $s \in S$ are the generic social factors (socio-economic factors, household composition and disability, minority status and language, and housing and transportation)

Calculation of census tract-level Priority Index values

$$PI_m = E_m \times mSVI_{m,norm}$$

Case Study

Infrastructure network, interdependencies and impact propagation

- A semi-realistic network in Austin, Texas consisting of power plants, electrical substations, electrical maintenance service, water treatment plants, hospitals and waste water treatment plants was chosen.
- A water treatment plant node was destroyed, and the interdependent impacts on other nodes in the network are simulated using Anylogic® software.

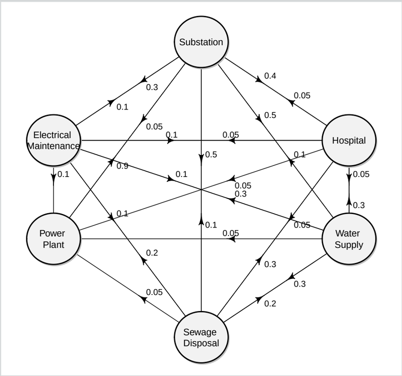

Fig 2. Interdependency Model (arrows represent direction of dependency; values represent the degree of dependency)

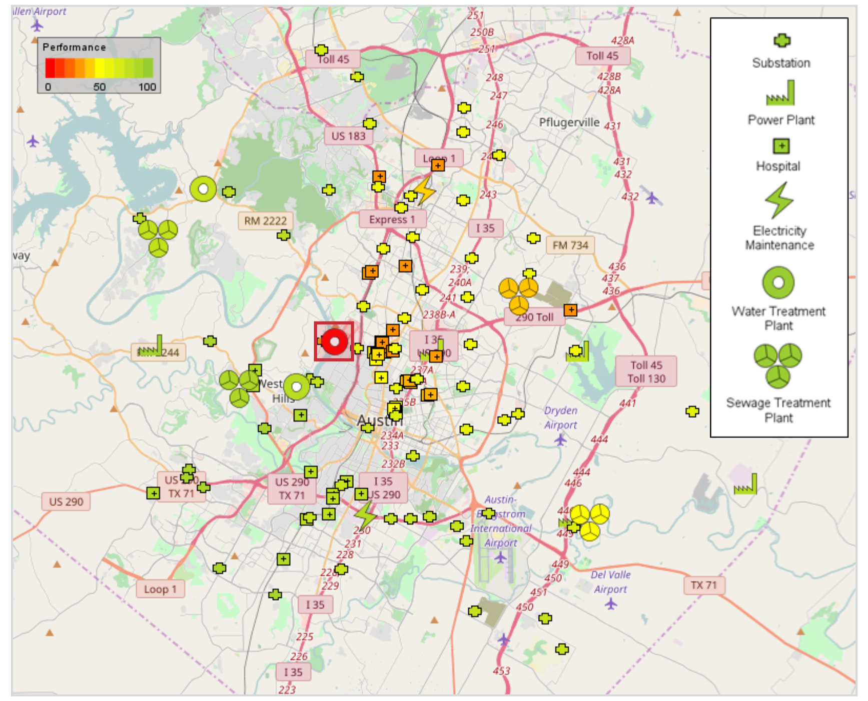

Fig 3. Semi-realistic Infrastructure Network (initial node failure is represented using red rectangle; the initial failure results in reduction in performance of other nodes due to (inter)dependencies.)

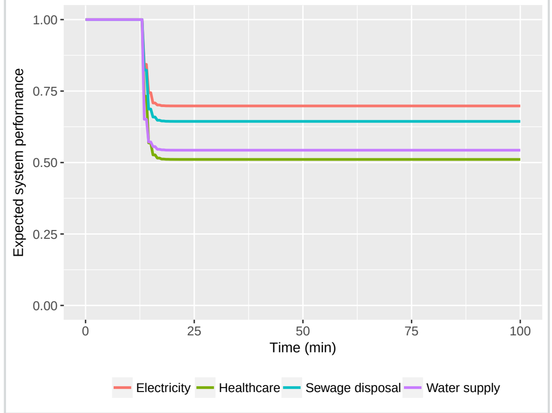

Fig 4. Simulated progression of impacts (when one node fails, the other nodes are also affected due to cascading and interdependent effects)

Spatial analysis of utility disruptions

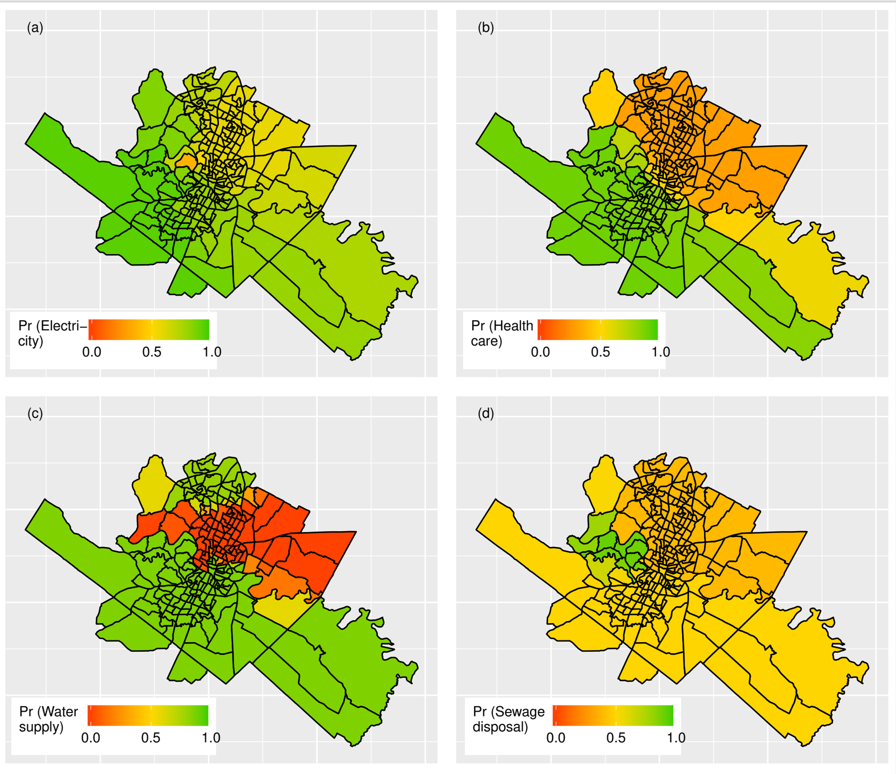

Fig 5. Spatial distribution of utility disruptions

- The performance reductions in utility nodes are mapped to corresponding service areas.
- The average reductions in each census tract under consideration are calculated.

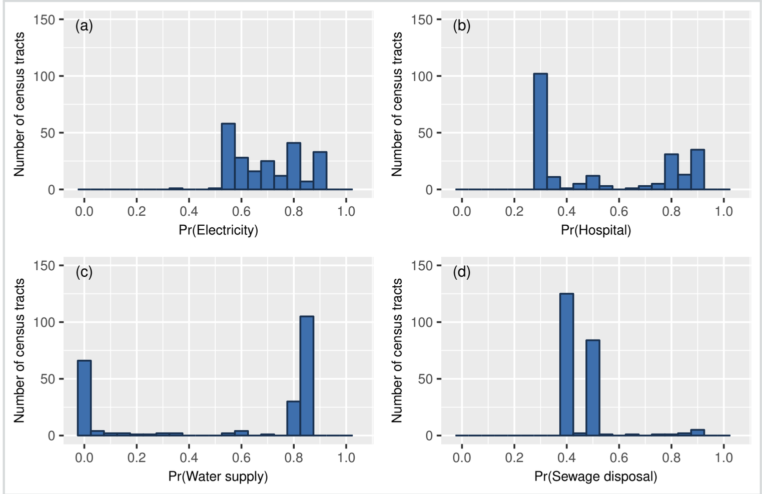

Fig 6. Overall distribution of utility disruptions

Normalized *mSVI* Values and Weighted Exposure of Census Tracts

- The vulnerability of communities in each census tract is mapped using generic social factors (ACS data).
- The weighted exposure denotes the overall impact of the infrastructure failures in a census tract.

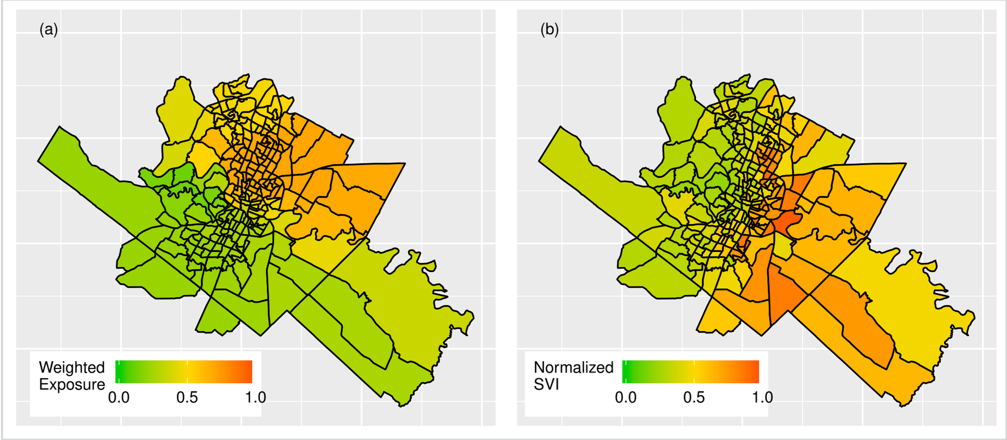

Fig 7. (a) Weighted exposure; (b) normalized social vulnerability

Priority Index Values of Census Tracts

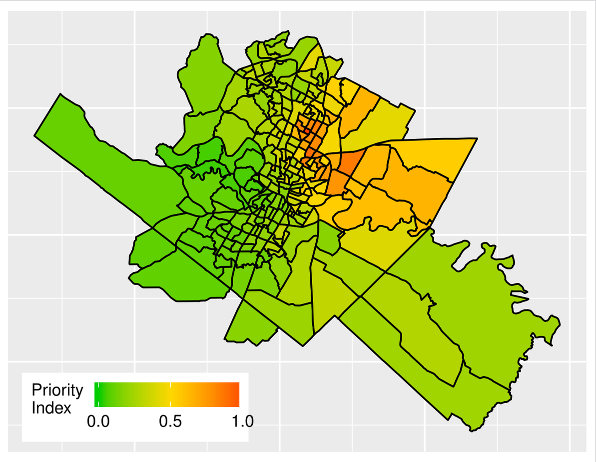

Fig 8. Priority Index of census tracts

- The Priority Index is calculated as the product of weighted exposure and normalized social vulnerability index.
- The higher the value of the index of a census tract, the higher the vulnerability of the communities will be to the given utility system failure.

Summary

- The methodology stresses upon the fact that utility disruptions happen not just due to direct impact of disasters, but also due to its cascading and interdependent effects.
- The framework could be employed for emergency planning, as well as for managing immediate relief operations, such as distribution of food, and water during disasters.
- The redundancy of the infrastructure network and the ability of individual infrastructure nodes to negate the impacts of utility service failures through backup systems are not considered in the current study.

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