A Stochastic Model for Evaluating Interconnected Critical Infrastructure Decontamination and Recovery

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Background

- Critical infrastructure assets are vulnerable to the effects of natural disasters and CBRN terrorism events (e.g., a biological attack)
- The EPA has a need to evaluate and prioritize critical infrastructure remediation options for biological contamination events
- The complex and interconnected nature of critical infrastructure systems is vital to response planning
- Modeling these interactions as a system of systems can inform response activities such as decontamination, sampling, and waste management

Model Overview

- ***Model Objective***: Simulate the recovery of an interconnected system of infrastructure sectors in the aftermath of an adverse contamination event
- ***Model Inputs***:
  - Initial infrastructure sector operating efficiencies
  - Infrastructure sector interaction network
  - Remediation factors
- ***Model Approach***:
  - Gillespie Algorithm[1] – stochastic models dependent on component interactions
- ***Model Outputs***:
  - Time-dependent sector operating efficiency values used to inform decontamination strategies

Model Framework – Gillespie Algorithm

- Originally developed to stochastically model concentration profiles of coupled kinetic chemical reactions
- Extensible to any situation where species are converted from one to another via “reactions” of the form A + B → C
  - Ex: healthy person + sick person → 2 sick people, water + transportation + money → food
- Algorithm executes single, discrete interactions, randomly selecting which one occurs at each iteration
- Advantages over deterministic methods
  - Flexibility of applying discrete effects to the data (e.g., setting a maximum or minimum value of a component, using variable stoichiometric coefficients)
  - Ability to generate distributions and statistical conclusions on parameters and outcomes

Next Steps

- Use data from historical events to fit model parameters and validate model outputs
- Validate network of infrastructure sector interconnectivity with SMEs
- Apply results to prioritize infrastructure sector decontamination

Disclaimer

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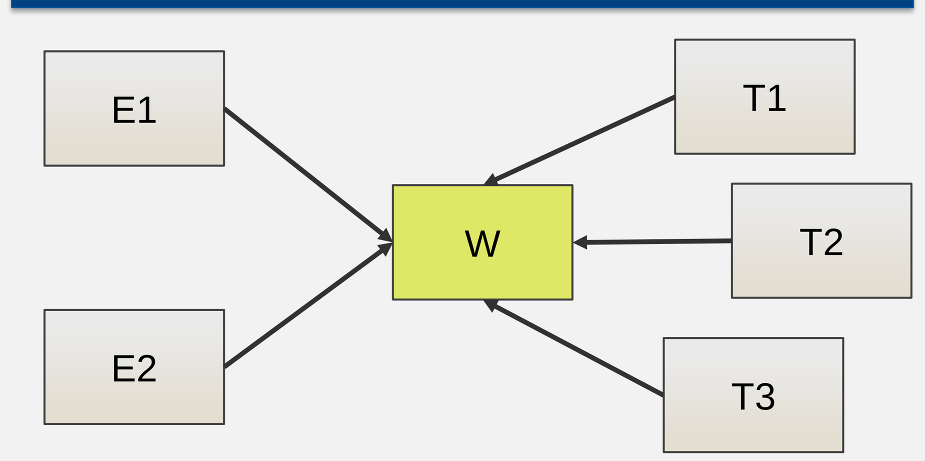
References

1. Gillespie, D.T. Exact stochastic simulation of coupled chemical reactions. *The journal of physical chemistry*, 81(25):2340–2361, 1977.
2. Knowlton, R.G., et al. “Quick Start Users Guide for the PATH/AWARE Decision Support System.” 2013, doi:10.2172/1090216.

Model Data – Infrastructure Interactions to System of Equations

- The model is based on the DHS list of critical infrastructure sectors, literature search, and operational feedback
- A network diagram of infrastructure sector interdependencies is used to develop the system of interaction equations
- Interaction diagram from PATH/AWARE[2] provides a large set of infrastructure dependencies between 70+ subsectors
- The number of defined “Parent → Child” relationships between each are used to determine the infrastructure sector interactions
  - Interaction coefficients are set as the number of child sub-sectors
- Remediation factors (RF) model the rate at which external resources (e.g., government) are used to provide remediation to a contaminated infrastructure sector

Sample Equation Development

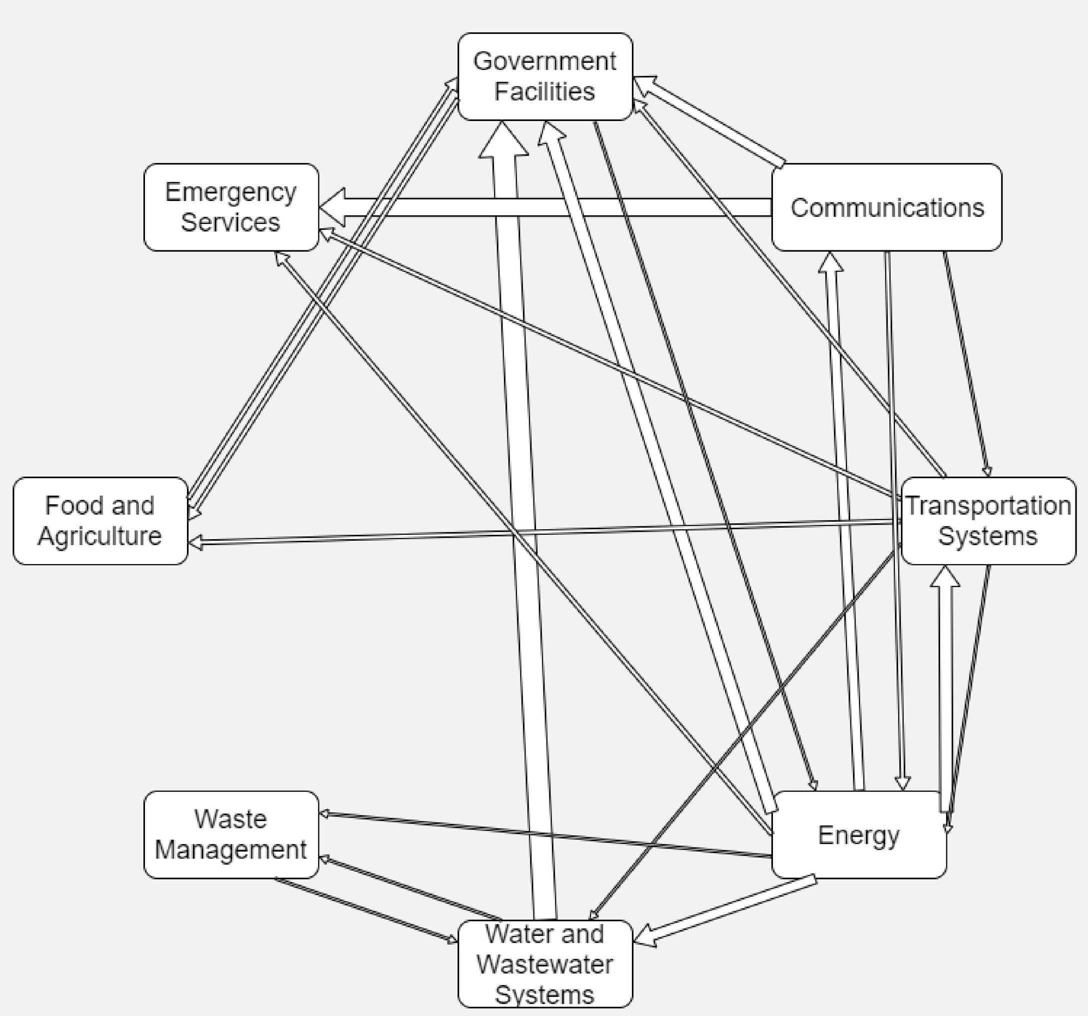


$$2E + 3T \rightarrow (5 + RF_w)W$$

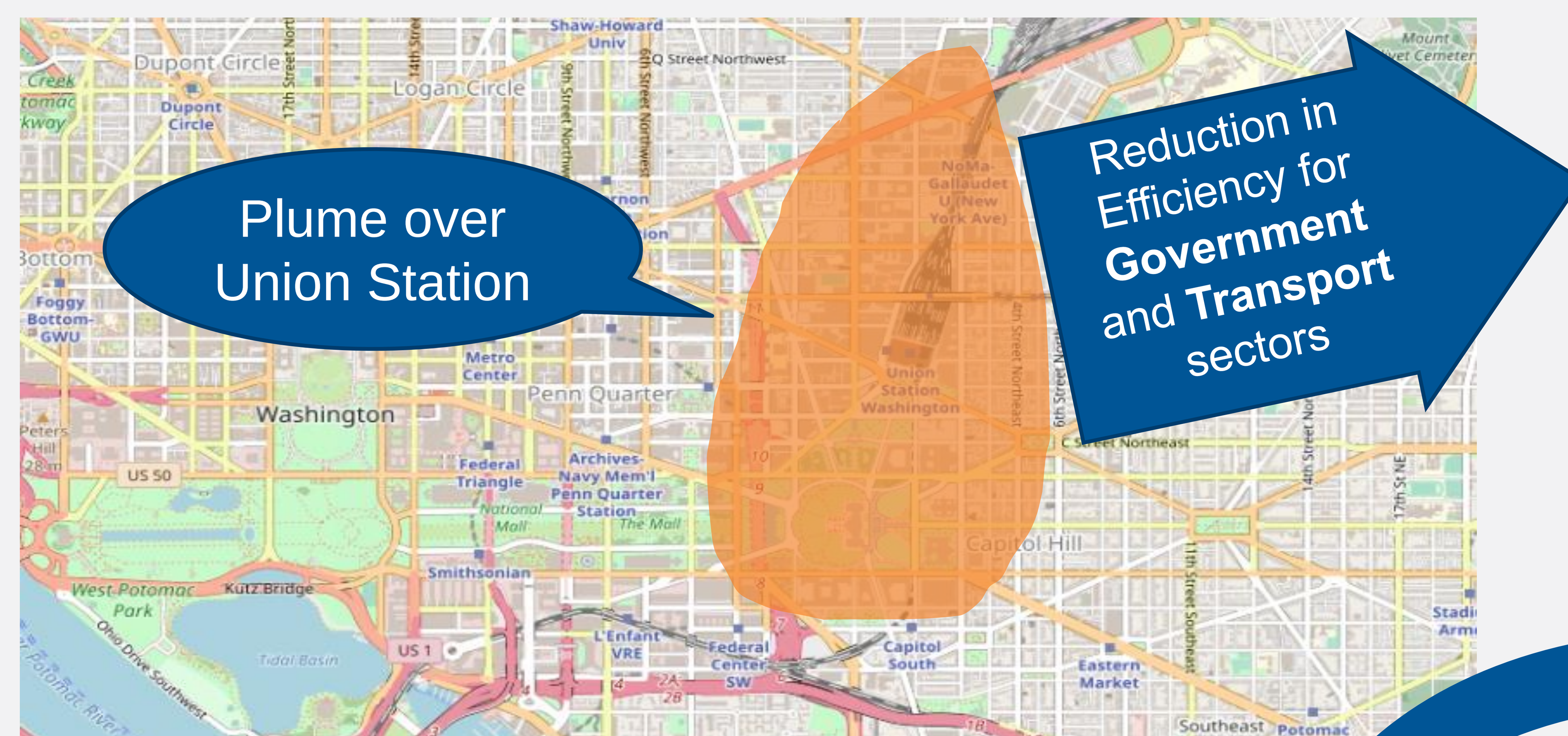
Developed Rate Laws for Sectors

Infrastructure Interactions	Rate
5E + T + M → (7+ARF)W	$r_0 = k_0*E^5*T*M/W$
T + 2C + G → (4+ARF)E	$r_1 = k_1*T*C^2*G/E$
C + 6E → (7+ARF)T	$r_2 = k_2*C*E^6/T$
5E → (5+ARF)C	$r_3 = k_3*E^5/C$
9W + 6E + 2T + 5C + 2A → (24+ARF)G	$r_4 = k_4*W^9*W^6*T^2*C^5*A^2/G$
W + E + T → (4+ARF)M	$r_5 = k_5*W*E*T/M$
2T + 2G → (4+ARF)A	$r_6 = k_6*T^2*G^2/A$
2E + 2T + 7C → (11+ARF)S	$r_7 = k_7*E^2*T^2*C^7/S$

Infrastructure Network Diagram



Model Algorithm Example



	Energy	Transportation	Government
Efficiency (%)	90	75	75
Remediation Factor	0.5	0.1	0.5