Dynamic Resiliency Modeling and Planning for Interdependent Critical Infrastructures

Webinar, September 20, 2018
Introduction

• The increased connectivity of today’s critical infrastructure systems, such as power, transportation, telecommunication and banking, leads to a complex structure of interdependencies that are critical for our nation’s economy, security and health.

• Protection and prevention against disruptions are not always possible. Hence resilience of a system is critical for safeguarding against risks.

• Resilient infrastructure systems are those that can recover system performance in a desired time and/or with an acceptable cost after a disruptive event.
Research Questions

• How to make planning reduce the risk and improve the resilience of interdependent critical infrastructures?

• How to coordinate multiple infrastructures in the planning?

• How to integrate cyber, physical, and human elements into the planning?

• How to develop an integrated decision support tool that can automate resilience decisions?
Research Objectives

• Refinement and extension of results as demonstrations and initial tool frameworks for a **foundational understanding** of critical infrastructure system interdependencies.

• Development of **integrated and scalable risk assessment** and management approach for interdependent critical infrastructures.

• Development of **integrated decision support methods** and technologies to support secure and resilient infrastructures.

• Expanded **identification of end users** and expansion of assessments of end user needs and benefits as a basis for the development of an integrated situational awareness for the implications of actions.
Subway Station Location Relative to Floodplains, NYC, 2013


Note: PWMs are the FEMA “Preliminary Work Maps” released in 2013.
Provision of Electric Power to Subways, NYC

Power Outage Restoration by Storm

Figure 6. Comparison of Power Outage Restoration Percentages by Storm

Interdependent Critical Infrastructure

- Geographical dependency
- Cyber-Physical dependency (CC, CP, PP)
- Logical dependency
  - Human in the loop
  - Supply and demand
Cyber attacks on the power grid

- Loss of power
- Failures of water treatment facilities
- Contamination of the drinking water
- Epidemics among human networks
- Shortage of fuels for power plants
- Aggravation of the power systems.
Network of Networks

- Intra-network dependence
- Inter-network dependence
• Composed network indicates unforeseen interdependencies that can make the system vulnerable to faults and attacks.

• Coordinated resilience mechanism is needed for planning of each infrastructure networks.
Design for Resilience

- Static Resilience Planning
  - Contingencies
  - Investments
  - Network design: modularity and betweenness
  - Optimization problems with budget constraints
Cyber attacks on the power grid

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Mitigations:

- Backup power supply for the water treatment facilities
- Supply of bottled water in affected areas
- Hiring of part-time workers
Design for Resilience

- **Dynamic Resilience Planning**
  - System changes over time.
  - Real-time recovery strategies
  - Optimal control problems constrained by system dynamics and information structures

- **Risk-Adverse Resilience Planning**
  - Events can happen in a probabilistic manner.
  - Take into account uncertainties by studying risks
  - Design for the worst case
  - Stochastic and robust optimal control problems constrained by system dynamics and information structures
Design for Resilience

- Distributed Coordinated Resilience Planning
  - Coordination between networks is lacking.
  - Decentralized design of real-time recovery strategies.

  ➡️ Game-theoretic approach:
  
  How bad is the system resilience without coordination?
  Design a mechanism to improve the efficiency
Optimal Scheduling of Maintenance and Recovery

• Each node $i$ has a state of being normal $x_i = 1$ or faulty $x_i = 0$.

• Each node $i$ takes the action $a_i = 1$ or $a_i = 0$.

• Each node $i$ receives utility $R_i(x_i ; a_i) = R_i(x_i) - C_i(a_i)$.

• System state and action is a vector with exponential growth.

• Each node $i$ determines when and how to recover.
State Transition

- Transition probability $P(x' | x; a)$ to unify heterogeneous dependencies, e.g., logical, physical, geographical, etc.
- Local state of a node depends on others.
- Transition of the local state of a node depends on other nodes.
Optimal Scheduling of Maintenance and Recovery

- Markov Decision Process (X, A, P, R)
  - Stationary policy $\pi : X \rightarrow A$
  - Maximize Long-term payoff from now on, i.e., $V(x)$

- Dynamic programming (DP)
  - Bellman equation

$$V(x) = \max_{a \in A} R(x, a) + \gamma \sum_{x' \in X} P(x'|x, a) V(x')$$

Value Function  Current Utility  Discounted Future Expected Utility
Numerical Solutions

- Linear programming (LP) solves DP. → Curse of dimension
- Approximate LP (ALP) reduces the number of LP variables.
- Factored graph & variable elimination exploit the sparsity of dependencies.

\[
\begin{align*}
\min_{V(x)} & \quad \sum_{x \in \mathcal{X}} \alpha(x) V(x) \\
\text{s.t.} & \quad V(x) \geq R(x, a) + \gamma \sum_{x' \in \mathcal{X}} P(x'|x, a) V(x') \\
\forall x \in \mathcal{X}, \forall a \in \mathcal{A}.
\end{align*}
\]

\[
V(x) = \sum_{j=1}^{k} w_j h_j(x)
\]

\[
P(x'|x, a) = \prod_{i \in \mathcal{N}} P(x'_i|x, a) = \prod_{i \in \mathcal{N}} P(x'_i|x_i, x_{\Omega_i}, a_i)
\]
Acceptable Approximate Error

• Small absolute errors in green and red.

• Relative error in blue decreases as the network size increases.
Hurricane Sandy: Multiple Power and Transit Outages

Source of Map: Metropolitan Transportation Authority
Example

• Cost-saving policy for Wall St. Node 19, i.e., delay repairs because of low ridership.

• Precaution policy for WTC. Node 7, i.e., add redundancies to risky nodes before their failures.

• Value-oriented distributed policy is far-sighted and outweighs the rule-following policy.
Cascading Failure of a Large-Scale Infrastructure System

- 100 nodes + two layers.
- Nodes represent mixed components.
- Failure probabilities $P$ characterize state uncertainty.
- Lighter color means higher failure probability.
- Faulty state means $P=1$.
- One node failure increases the failure probability of its neighboring nodes.
Dynamic Recovery of a Large-Scale Infrastructure System

- Binary action: repair (a=1) or not (a=0).
- Repair single node.
- Nodes repaired are maintained for a few steps.
- First part: recover from disaster.
- Second part: maintain the healthy state.
- (Right y-axis) Node Utility.
- (Left y-axis) Edge connectivity.
Coordinated Resilience

![Diagram of communication and power networks with nodes connected]

- 1, 4, 5, 6, 7, 8
- A: Communication network
- B: Power network
- Formed by A: 
- Formed by B: 

![Graph showing algebraic connectivity against steps]

- Nash equilibrium network
- Constrained team network
- Algebraic connectivity $\lambda_2(G)$
Highlights

• Understand the **interdependencies** between energy and transportation.

• Establish a high-level probabilistic framework with high adaptivity to large complex systems.

• Handle **large-scale** problems with easy integration of heterogeneous systems.

• Design **value-oriented** distributed maintenance/recovery policy rather than rule-following myopic policy.
Where do we go from here?

• Integrate data sources and make the decision data-driven.
• Integrate human and socio-economic factors in the critical infrastructures.
• Validate and evaluate our approach with local utilities.
• Obtain useful direction and feedback for transitioning our research to practical uses.
• Develop software decision support tools that can automate analysis and decision-making of critical infrastructure planning based on mathematical foundations.
Where Do We Go From Here – Human Factors: Individual Transit User Behavior in Electric Power Related Transit Outage

Single Electric Power Outage → Transit Outage → Wait for service to resume t1

→ Switch modes, routes (rail) t2

→ Switch modes (road)* t3

→ Abandon trip** t4

Individual Transit User Behavior and Decisions

ROAD CONGESTION

People switch routes out of convenience and trying to complete the trip though the trip may take longer (suggested by Guo and Wilson 2011; Guo 2011)

People abandon the trip for fear that they cannot personally control the situation or perceived safety (suggested by Fischhoff et al. 2000 and Slovic 2000).

Notes:
*Options that increase use of roads include for-hire vehicles, carpooling, use of personal vehicles, bike-share options. The choice of behavior and decisions of users and workers can be time dependent, as indicated by “t” values, however, choices could occur simultaneously in time. **Abandon trip could be substituting trips with online shopping; telecommuting.

References:
Where Do We Go From Here – Human Factors: Community-Level Impacts and Decision-making in Electric Power Related Transit Outage

Economic and social impacts arise that are dependent on transit commuting:
- Increased household expenditures for alternative transport
- Jobs threatened
- Educational loss
- Business interruption
- Increased business costs

Pressure on Electric Power and Transit Agencies for Service Improvements
Pressure for Legal and Regulatory Action by Government Agencies
Demand for Government Infrastructure Investment Actions

Notes: The choice of behavior and decisions can be time dependent.
Multi-scale modeling
Concluding Remarks

• Cyber, physical, and human interconnections among critical infrastructure play an important role in the security and resilience.

• The multilayer network “system of systems” approach has been developed for (i) the pre-event planning, (ii) the post-event disaster response, and (iii) the coordination of efforts in the recovery process for a dynamic network.

• Decision support tools are developed to strengthen the security and resilience of critical infrastructures by analyzing and modeling the relationships of different infrastructure components.
Related Publications and References


Interdependency Frameworks


Cyber-Physical Infrastructure Connections


Acknowledgement

• We gratefully acknowledge funding support for the project “Dynamic Resiliency Modeling and Planning for Interdependent Critical Infrastructures,” from the Critical Infrastructure Resilience Institute (CIRI) at the University of Illinois, Urbana-Champaign, Homeland Security Center of Excellence, with funding from the U.S. Department of Homeland Security.
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