Designing Solutions in an Interdependent World: CASoS Engineering

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Resolving Infrastructure Issues Today

Each Critical Infrastructure Insures Its Own Integrity

Oil & Gas Communications Water Banking & Finance Continuity of Gov. Services Transportation Emergency Services Electric Power

NISAC’s Role:
Modeling, simulation, and analysis of critical infrastructures, their interdependencies, system complexities, disruption consequences
A Challenging if not Daunting Task

- Each individual infrastructure is complicated
- Interdependencies are extensive and poorly studied
- Infrastructure is largely privately owned, and data is difficult to acquire
- No single approach to analysis or simulation will address all of the issues
Example Natural Disaster Analysis: Hurricanes

Analyses:

- Damage areas, severity, duration, restoration maps
- Projected economic damage
  - Sectors, dollars
  - Direct, indirect, insured, uninsured
  - Economic restoration costs
- Affected population
- Affected critical infrastructures

Focus of research:

- Comprehensive evaluation of threat
- Design of Robust Mitigation
- Evolving Resilience
Critical Infrastructures:

- **Are Complex**: composed of many parts whose interaction via local rules yields *emergent structure (networks) and behavior (cascades)* at larger scales
- **Grow and adapt** in response to local-to-global *policy*
- **Contain people**
- Are interdependent “*systems of systems*”

Critical infrastructures are
Complex Adaptive Systems
of Systems: CASoS
Generalized Method: Networked Agent Modeling

Take any system and Abstract as:

- Nodes (with a variety of “types”)
- Links or “connections” to other nodes (with a variety of “modes”)
- Local rules for Nodal and Link behavior
- Local Adaptation of Behavioral Rules
- “Global” forcing from Policy

Connect nodes appropriately to form a system (network)
Connect systems appropriately to form a System of Systems

“Caricatures of reality” that embody well defined assumptions
Graphical Depiction: Networked Agent Modeling

- Actors
- Network Nodes
- Links
- Other Networks
- Tailored Interaction Rules
- Drive
- Dissipation

Adapt & Rewire
CASoS Engineering

Define
- CASoS of interest and Aspirations,
- Appropriate methods and theories (analogy, percolation, game theory, networks, agents…)
- Appropriate conceptual models and required data

Design and Test Solutions
- What are feasible choices within multi-objective space,
- How robust are these choices to uncertainties in assumptions, and
- Critical enablers that increase system resilience.

Actualize Solutions within the Real World
Example Application: Pandemic Influenza

Three years ago on Halloween NISAC got a call from DHS. Public health officials worldwide were afraid that the H5NI “avian flu” virus would jump species and become a pandemic like the one in 1918 that killed 50M people worldwide.

Pandemic now. No Vaccine, No antiviral. What could we do to avert the carnage?

Chickens being burned in Hanoi
This is a CASoS Problem

- **System**: Global transmission network composed of person to person interactions (within coughing distance, touching each other or surfaces...)

- **System of Systems**: People belong to and interact within many groups: Households, Schools, Workplaces, Transport (local to regional to global), etc., and health care systems, corporations and governments place controls on interactions at larger scales...

- **Complex**: many, many similar components (Billions of people on planet) and groups

- **Adaptive**: each culture has evolved different social interaction processes, each will react differently and adapt to the progress of the disease, this in turn causes the change in the pathway and even the genetic make-up of the virus
Analogy with other CASoS

Two Simple analogs:

- **Forest fires**: You can *build fire breaks* based on where people throw cigarettes... or you can *thin the forest* so no matter where a cigarette is thrown, a percolating fire (like an epidemic) will not burn.

- **Power grid blackouts**: The spread of a pandemic is a cascade that runs on the interactions among people, the social network, instead of the wires of a power-grid.

Could we target the social network and thin it?
Could we thin it intelligently so as to minimize impact and keep the economy rolling?
Application of Networked Agent Method to Influenza

Example Teen

Social Networks for Teen 1

Extended Family or Neighborhood

Household

Teen Random

School classes 6 per teen

Stylized Social Network (nodes, links, frequency of interaction)

Disease manifestation (node and link behavior)

Latent
Mean duration 1.25 days
\(\lambda = 0.25\)

Infectious presymptomatic
Mean duration 0.5 days
\(\lambda = 0.25\)

Infectious symptomatic
Circulate
Mean duration 1.5 days
\(\lambda = 1.0\) for first 0.5 day, then reduced to 0.375 for final day

Infectious symptomatic
Stay home
Mean duration 1.5 days
\(\lambda = 1.0\) for first 0.5 day, then reduced to 0.375 for final day

Infectious asymptomatic
Mean duration 2 days
\(\lambda = 0.25\)

Immune

Dead

Transition Probabilities
\(p_S = 0.5\)
\(p_H = 0.5\)
\(p_M = 0\)
Network of Infectious Contacts

Adults (black)
Children (red)
Teens (blue)
Seniors (green)

Children and teens form the Backbone of the Epidemic
Tracing the spread of the disease: From the initial seed, two household contacts (light purple arrows) brings influenza to the *High School* (blue arrows) *where it spreads like wildfire.*
Closing Schools and Keeping the Kids Home

ID Factor 1.0

ID Factor 1.5

- unmitigated
- closing schools
- 50% compliance
- 100% compliance

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They identified critical questions/issues and worked with us to answer/resolve them
- How sensitive were results to the social net? Disease manifestation?
- How sensitive to compliance? Implementation threshold? Disease infectivity?
- How did the model results compare to past epidemics and results from the models of others?
- Is there any evidence from past pandemics that these strategies worked?
- What about adding or “layering” additional strategies including home quarantine, antiviral treatment and prophylaxis, and pre-pandemic vaccine?

We extended the model and put it on Tbird… 10’s of millions of runs later we had the answers to:
- What is the best mitigation strategy combination? *(choice)*
- How robust is the combination to model assumptions? *(robustness of choice)*
- What is required for the choice to be most effective? *(evolving towards resilience)*

These answers guided the formulation of national pandemic policy, Actualization is still in progress.
Application: Congestion and Cascades in Payment Systems

Networked ABM

Payment system topology

Global interdependencies
Application: Industrial Disruptions

**Disrupted Facilities** → **Reduced Production Capacity**

Diminished Product Availability
MEGACITIES

- Megacities are CASoS with many interdependent Systems… and CASoS Engineering can be applied
  - Design sub-systems
  - Design policy
- Networked Agent Conceptualization should be a powerful method
- Specific examples we have worked on could be adapted to Megacity Engineering
Two Thoughts for MEGACITIES

**Global view:** Megacities as a set of entities that interact locally and within global context, set goals, develop niches, form alliances, etc… research towards understanding the global ecology of cities.

**Local View:** Evolving land, energy, and water use into the future as a function of policy using ABMs, example: John Bolte’s work that considered Alternative Futures for the Willamette River Basin (Oregon State).
Complexity Primer Slides
"Big" events are *not* rare in many such systems

- Earthquakes: Gutenberg-Richter
- Wars, Extinctions, Forest fires
- Power Blackouts?
- Telecom outages?
- Traffic jams?
- Market crashes?
- … ???

First Stylized Fact: Multi-component Systems often have power-laws & “heavy tails”
What keeps a non-equilibrium system at a phase boundary?

Equilibrium systems

External Drive

Dissipation

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Temperature
1987 Bak, Tang, Wiesenfeld’s “Sand-pile” or “Cascade” Model

Lattice

Drive

Relaxation

Cascade from Local Rules

“Self-Organized Criticality” power-laws
fractals in space and time
time series unpredictable
Second Stylized Fact: Networks are Ubiquitous in Nature and Infrastructure

Illustrations of natural and constructed network systems from Strogatz [2001].
1999 Barabasi and Albert’s “Scale-free” network

Simple Preferential attachment model: “rich get richer” yields Hierarchical structure with “King-pin” nodes

Properties: tolerant to random failure… vulnerable to informed attack