Wrangling with Uncertainty in Complex Adaptive Systems of Systems (CASoS) Engineering

or

“Why CASoS Engineering is both an Opportunity and Challenge for Uncertainty Quantification”

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Outline

- What is a CASoS?
- Where does uncertainty arise?
- Engineering within a CASoS: Example of Influenza Pandemic Mitigation Policy Design
- Towards a General CASoS Engineering Framework
What is a CASoS?

- **System**: A system is a set of entities, real or abstract, comprising a whole where each component interacts with or is related to at least one other component and that interact to accomplish some function. Individual components may pursue their own objectives, with or without the intention of contributing to the system function. Any object which has no relation with any other element of the system is not part of that system.

- **System of Systems**: The system is composed of other systems ("of systems"). The other systems are natural to think of as systems in their own right, can’t be replaced by a single entity, and may be enormously complicated.

- **Complex**: The system has behavior involving interrelationships among its elements and these interrelationships can yield emergent behavior that is nonlinear, of greater complexity than the sum of behaviors of its parts, not due to system complication.

- **Adaptive**: The system’s behavior changes in time. These changes may be within entities or their interaction, within sub-systems or their interaction, and may result in a change in the overall system’s behavior relative to its environment.
Many Examples

- Tropical Rain forest
- Agro-Eco system
- Cities and Megacities (and their network on the planet)
- Interdependent infrastructure (local to regional to national to global)
- Government and political systems, financial systems, economic systems, (local to regional to national to global)… Global Energy System
Core Economy within Global Energy System

Explanation
- Entity type
  - Broker
  - Power
  - Food
  - Consumer Goods
  - Industrial Goods
  - Minerals
  - Oil
  - Labor
  - Securities
  - Deposits
  - Emission Credits

Stuff
- Labor
- Finance
Global Energy System

Explanation:
- **Resources**
- **Information/Control**
- **Multiregional Entities**
- **Interregional Broker**
LOTS of Uncertainty

- Aspects of Complex systems can be unpredictable (e.g. BTW sandpile, …)
- Adaptation, Learning and Innovation
- Conceptual model uncertainty
  - Beyond parameters
  - Beyond IC/BC
Engineering within a CASoS: Example

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?
**Definition of the CASoS**

- **System**: Global transmission network composed of person to person interactions beginning from the point of origin (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

**HUGE UNCERTAINTY**
Analogy with other Complex Systems

Simple analog:

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

Aspirations:

- Could we target the social network within individual communities 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

Extended Family or Neighborhood

Social Networks for Teen 1

Household

Teen Random

School classes 6 per teen

Everyone Random

Disease manifestation (node and link behavior)

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

Children and teens form the Backbone of the Epidemic
Closing Schools and Keeping the Kids Home

ID Factor 1.0

1958-like

ID Factor 1.5

1918-like

Number infected vs. time (days)

- Unmitigated
- Closing schools
- 50% compliance
- 100% compliance
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 and uncertainty? (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.
Robustness of Choice to Uncertainty

Policies or Actions → Model → Measures of System Performance

Rank Policies by Performance measures while varying parameters within expected bounds

“Best” policies are those that always rank high, their choice is robust to uncertainty

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Finding the right model

- There is no general-purpose model of any system
- A model describes a system for a purpose

What to we care about?

What can we do?

Model

Additional structure and details added as needed
Pragmatic Detail: More can be less

1. Recognize the tradeoff
2. Characterize the uncertainty with every model
3. Buy detail when and where it's needed
Model development: an iterative process that uses uncertainty

Aspirations

Define Conceptual Model

Define Analysis

Evaluate Performance

Satisfactory?

Define and Evaluate Alternatives

Decision to refine the model Can be evaluated on the same Basis as other actions

Model uncertainty permits distinctions

Model uncertainty obscures important distinctions, and reducing uncertainty has value
CASoS Engineering: An Opportunity and Challenge for Uncertainty Quantification
EXTRA SLIDES
General CASoS Engineering Framework

**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**

An Opportunity and Challenge For Uncertainty Quantification
Evolving towards Resilience

Robustness of choice to uncertainty also shows _those factors that good system performance depends on_, in order:
- Implementation threshold
- Compliance
- Regional mitigation
- Rescinding threshold

**Planning and Training** required to push the system where it needs to be (carrots and sticks)

Because _eliciting appropriate behavior of humans is inherently uncertain_ (fatigue, hysteria, false positives), this policy is “interim”, meanwhile:
- Research to develop broad spectrum vaccine for influenza
- Resolving supply chain issues for antivirals
Extra NISAC Related
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
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

Source: Energy Information Administration, Office of Oil & Gas

Active Refinery Locations, Crude and Product Pipelines
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*”

**2003: Advanced Methods and Techniques Investigations (AMTI)**

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

Adapt & Rewire

Actors

Other Networks

Network Nodes Links

Tailored Interaction Rules

Drive

Dissipation
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.
Application: Congestion and Cascades in Payment Systems

Networked ABM

Payment system topology

Global interdependencies
Application: Industrial Disruptions

Disrupted Facilities $\rightarrow$ Reduced Production Capacity

Diminished Product Availability
Complexity Primer Slides
First Stylized Fact: Multi-component Systems often have power-laws & “heavy tails”

“Big” events are not rare in many such systems

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

log(Frequency)

log(Size)

normal

Power law

“heavy tail” region
Power Law - Critical behavior - Phase transitions

What keeps a non-equilibrium system at a phase boundary?

Equilibrium systems

Correlation

External Drive

Dissipation

Temperature

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

Drive

Relaxation

Cascade from Local Rules

‘Self-Organized Criticality’

power-laws

fractals in space and time

time series unpredictable
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