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Complex Adaptive Systems Engineering - improving our understanding of complex systems and reducing their risk

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Abstract

Complex adaptive systems are central to many persistent problems locally and globally. Taking a longer and broader view of these systems and their dynamic interactions improves our ability to reduce the risks they face and create. This is particularly true with the risks due to climate change, economic crises, energy and food supply disruptions. Climate change and the challenge of addressing the global risks provides a common set of problems on which to build a global community of practice for engineering solutions to complex adaptive systems of systems problems. This paper presents general concepts and a few examples of successful applications of an engineering process for complex systems of systems.

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Complex Adaptive Systems-of-Systems (CASoS) Engineering: http://www.sandia.gov/CasosEngineering/

1 What are Complex Adaptive Systems (CAS) and why do we want to reduce their risks?

Many definitions for CAS exist, none are universal. Definitions sometimes emphasize system structure (e.g., composed of many interacting and self-organizing parts) or characteristics of system behaviour (e.g., emergent). From a scientific and engineering perspective it is important to have a definition that focuses on the process that creates these characteristic functional structures and enables emergence and other system behaviors. We define a CAS as one in which the structure modifies to enable success in its environment (Johnson et al. 2012). In this definition, a CAS's structure and behaviour are products of all the perturbations and modifications that it has experienced or implemented. Adaptive systems tend to exhibit certain structural characteristics, such as hierarchical and modular components, and they tend to have simple rules for interaction among the elements. These features allow us to design and modify CAS, and provide a guide for creating models to represent their behaviour. Many persistent, large-scale engineering challenges involve multiple interacting CAS or Complex Adaptive Systems of Systems (CASoS).

The class of problems for which we are applying CASoS Engineering approaches (Glass et al.,2011, Brown et al., 2011) include evaluation of what happens to CAS such as ecosystems, societies, infrastructures or economies when their environment changes and identifying strategies for reducing risks to CAS or increasing security through modifications that are robust to uncertainty (Figure 1). Climate change, and the impacts of climate change on the environment, population and engineered systems, is one of the problems that require a CAS approach for analysis and design of effective risk reduction actions.

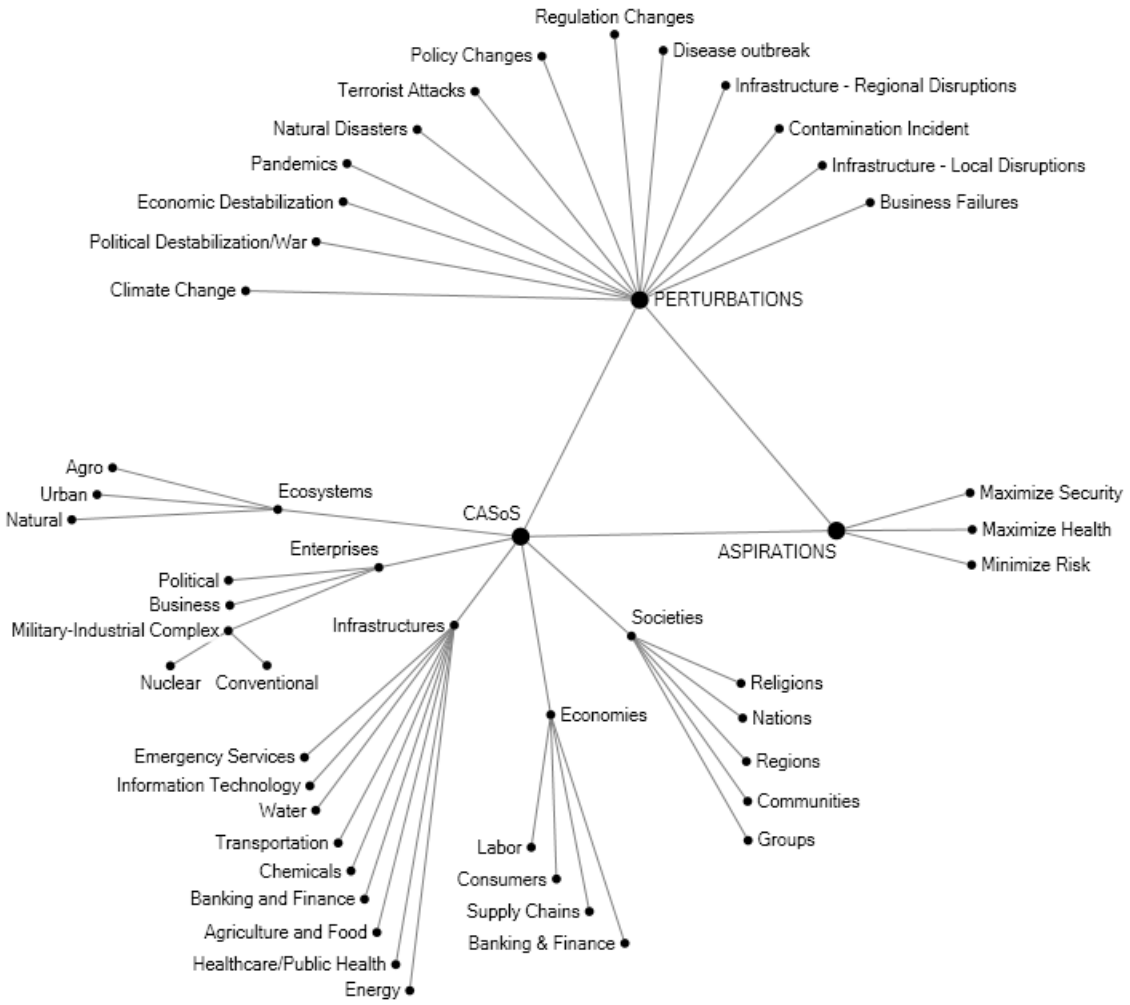

Figure 1CAS Problem Domains Represented by the CASoS, Perturbations and Engineering Aspirations.

2 What is needed for risk-informed decisions?

Modeling of coupled human, natural and technological systems provides a means for quantifying and testing theories about their dependencies, dynamics and response to different stresses. Analysis, using CAS models, provides information structured to support decision making and risk management within CAS. Such analyses provide a longer-term view of the potential consequences and benefits of actions than assessments based on a static system or network approach. Decisions are often made using a trial and error approach without identification of potential system level consequences; it happens in medicine, civil engineering, regulatory policy and many other aspects of our daily lives. Most of those decisions are not harmful and may fix a problem. In cases where the effects play out over longer time frames and propagate through interdependencies with other systems, the broader view and understanding gained from CAS analysis allow us to recognize the causal relationships and solve system-level issues.

Thanks to Malcolm Gladwell “tipping point” is a generally understood concept. Uncertainties, however, render tipping points difficult to predict and avoid. In CASoS such as infrastructures, system-spanning events like large-scale power outages are not frequent nor are they rare (Figure 2).

Network topology, control systems and innovations in processes and equipment influence the frequency of such events (Jensen, 1998; LaViolette et al., 2006; Beyeler et al., 2007); but, given the magnitude of the consequences, the risks are only slightly reduced by those measures. Adaptation can reduce the magnitude of events (Miller and Page, 2007). For critical services, redundant systems (e.g., back-up generators at hospitals, battery back-up for emergency communication systems, alternative fuels for power generators) are often used to reduce the impacts of disruption while the primary services are restored. Effective solutions require foresight. Back-up systems must be entirely independent, not impacted by the perturbation that caused the original system to fail or by the main system failure, and they need function until services can be restored.

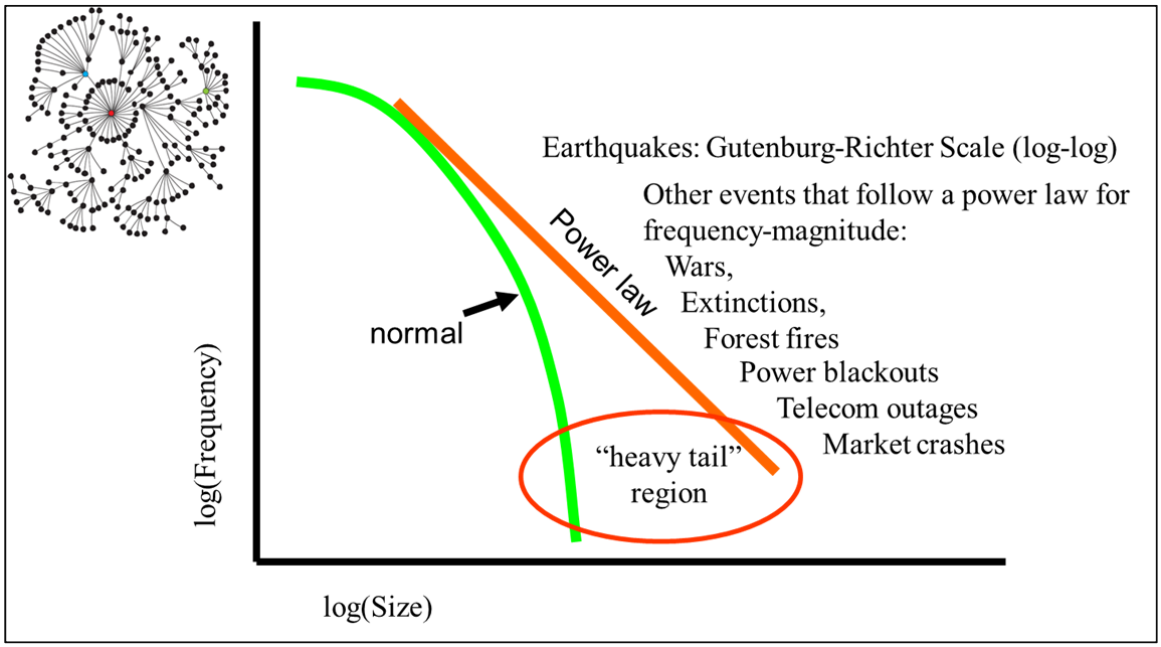

Figure 2 Truncated power-law verses normally distributed event sizes in CAS.

With climate change we are concerned about global cascades in supply chains that are critical to human life and prosperity. If we take a traditional economic view, individuals, companies and nations with sufficient resources will pay more or export fewer goods to offset their shortages; but this does not reduce risk at a global scale (Brown et al., 2010), and may increase risks over a longer time frame. There are tipping points for the behaviour of individuals and groups. We can't predict with any certainty what the final factor will be; we can only recognize the stresses that drive a system toward a tipping point and identify what it will take to keep conditions below the threshold with some certainty. Drought is the primary concern from an infrastructure and population perspective. Energy, manufacturing and agriculture are dependent on large quantities of fresh water. Countries that are economically dependent on agriculture (Figure 3), where long-term droughts are expected due to climate change, have less ability to adapt and are likely to be the first areas impacted. Providing food-aid would reduce some of the consequences but would not make the region more resilient or less vulnerable to climate impacts.

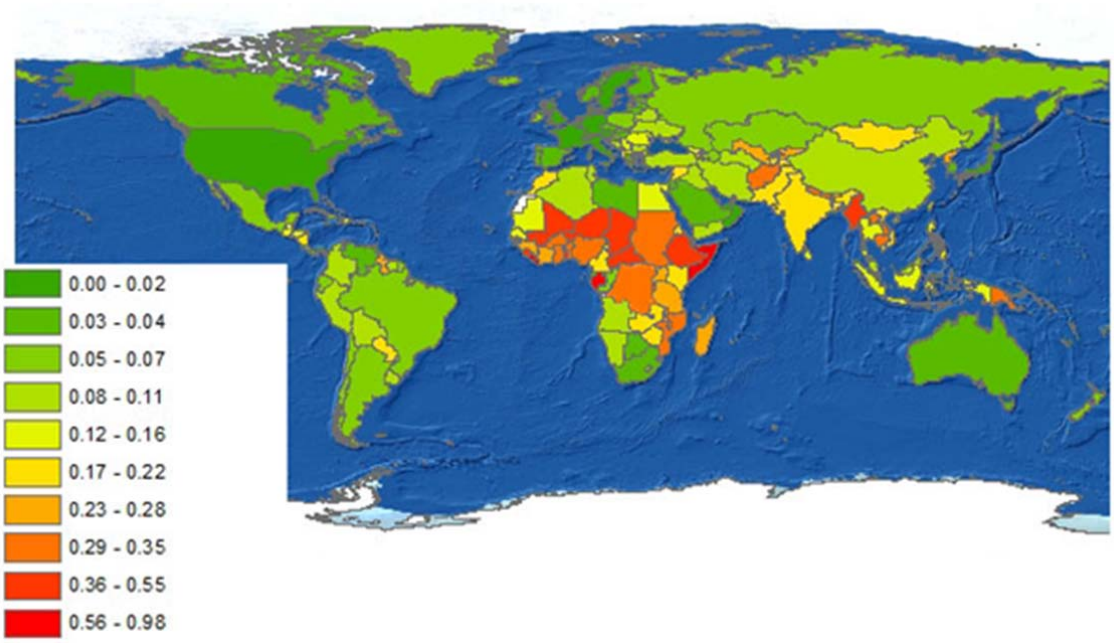

Figure 3 Fraction of Gross Domestic Product (GDP) from agriculture (U.S. CIA 2009) an indicator of risk due to climate change (agriculture vulnerability to drought and reduced economic capacity for adaptation).

One strategy for managing climate risks, particularly for systems that provide services, is to engineer for resilience. Vugrin et al. (2010) provide a definition and mathematical framework for quantifying system resilience that allows comparison of options and supports decision making because costs are explicitly included. They define system resilience as follows: Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is that system's ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels. Using resilience analysis to design and implement effective adaptation strategies for climate change adds the cost and reliability perspectives to the process needed for evaluating risk mitigation strategy options.

3 What are some successful examples of CASoS Engineering?

The goal of CASoS Engineering is finding realistic, risk-management solutions that are robust to uncertainty. This approach has been successfully applied to national planning for pandemics and other natural disasters (e.g., Davey, 2008, Perlroth, 2010, Finley, 2011), identification of strategies for reducing counteracting monetary policies (Beyeler et al., 2007) and reducing uncertainty in forward and backward tracking of food supply chain contamination (Conrad et al., 2011).

The engineering goal for pandemic planning was to find an intervention that would contain the spread of a novel strain of influenza, protecting the population until a strain-specific vaccine can be developed. The uncertainties include characteristics of the virus, effectiveness of existing vaccines, antiviral stockpile size and effectiveness, effectiveness of social-distancing measures, timing of interventions and compliance with each aspect of the intervention. A model of a representative population of 10,000 people, its social networks and disease spread was developed and used to evaluate the uncertainties, compare possible interventions and design a robust strategy. The uncertainty quantification results for a single pandemic strain, with characteristics similar to the

1918 pandemic, show how the number of aspects included in the intervention (expressed as a number of interventions) change the distribution of possible outcomes (Figure 4). The best-performing composite intervention strategies include school closure, effectively reducing the spread of disease by changing the structure of the social interactions until the strain dies out or a vaccine is developed. Quarantine and antiviral treatment appear to be effective in strategies reliant on few interventions, but require knowledge of who is infected and their close contacts. Prophylactic interventions (contact tracing-based antiviral prophylaxis) requires more interventions (such as school closure, social distancing (e.g., wearing masks)) to reduce the mean and standard deviation in outcomes.

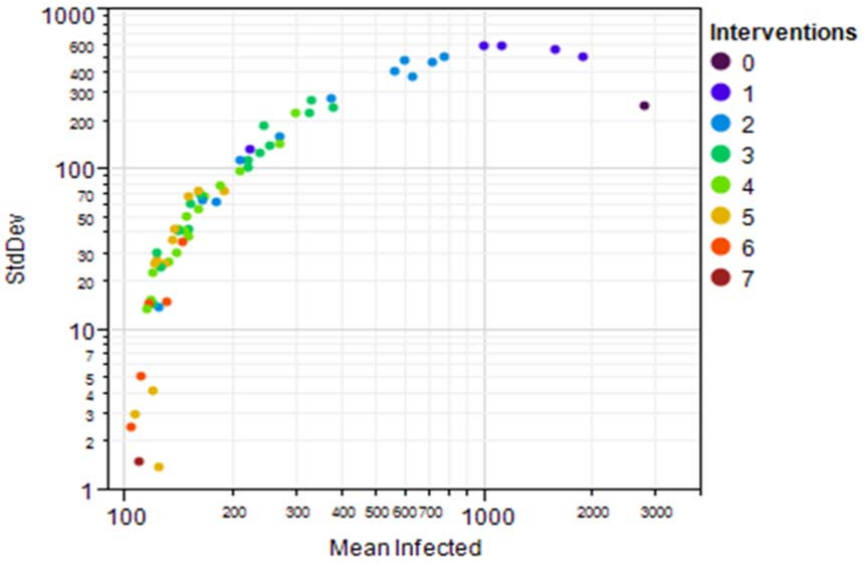

Figure 4 Uncertainty Quantification for comparison of intervention effectiveness for a 1918-like pandemic influenza.

The consequences of economic perturbations are well understood given the on-going issues around the world. As with pandemics, the system interactions are global with the interventions applied at several levels (local, regional, national, multi-national). A highly abstracted model of two payment systems linked through a foreign exchange (FX) market provides a means to test and compare the effects of different monetary policies and how they are implemented (Renault et al., 2007). Monetary policies implemented to reduce risk exposure a national level push the risk to the other participant in the exchange market; prompting a change in policy in the second system and a dynamic cycle of perturbations that take many years to dampen. This highly simplified, abstract model indicates that prioritizing FX trades over normal payments can reduce exposures significantly and that differences in liquidity in the two systems can increase exposures. Low level of liquidity in one system can negatively affect the other system even though it is operating on higher level of liquidity.

Food supply chains are another type of global system that if contaminated, threatens population health. Recent events have highlighted the difficulties in identifying the source of contamination and eliminating it from the food supply. In the U.S. there are abundant data on the businesses involved in agriculture, food processing and retail sales. Information on the connections between entities in the food supply chain is not easily accessible. Tracing possible contaminant routes

through these supply chains is a labour intensive process. Accounting for the processes (growing regions and seasons, distributors, processors and products, retailers) general network characteristics such as big tends to sell to big; small sells to small (Figure 5) and the uncertainties in network connections provides a means for identifying more likely paths and prioritizing data needs (Conrad et al. 2011).

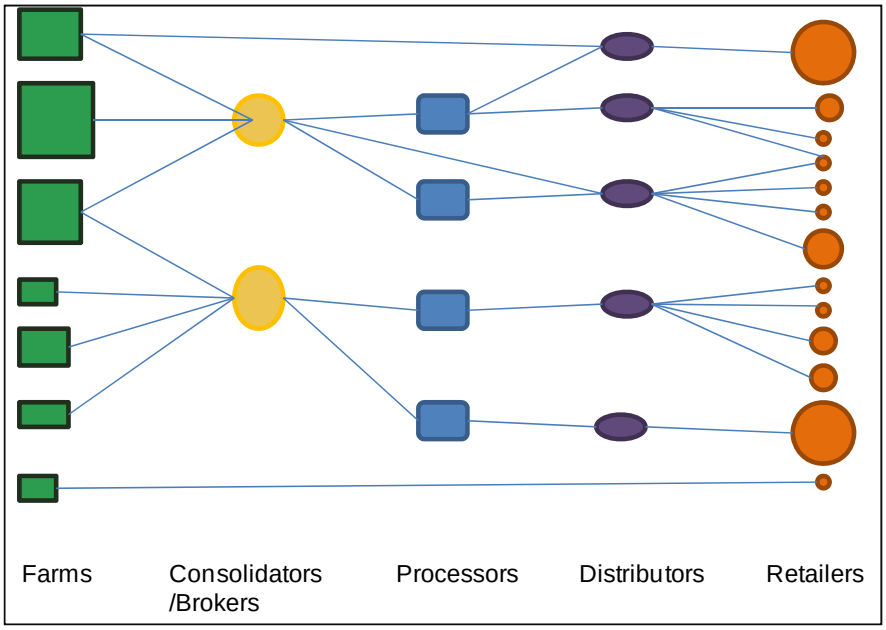

Figure 5 General network topology for food supply chains.

These applications produced a core set of general modelling and analysis modules that can be replicated, connected and populated with parameter values, then used to represent and evaluate a wide variety of CAS and perturbations to those systems. The core modelling components include: network and community builders for representing single or multiple interacting networks (social, supply chain and/or pipeline); and infectious disease, exchange, opinion dynamic and population structure models. Infections and opinions propagate through multiple, interacting social networks; food contamination propagates through supply chains; behaviors spread as a function of opinion and information through social and communication networks; and functional disruptions spread through logical and physical system dependencies.

4 Conclusions

We have many challenges moving forward. Climate risks are global and will require an international community committed to reducing the risks. We need to develop a strong international community of practice of CASoS Engineering to find solutions that will benefit us all. This requires tremendous commitment and willingness to find ways to work together on common problems.

We need to build confidence in CAS modelling and analyses. We need a different approach to validation for CAS modelling. CAS are inherently unpredictable, thus traditional validation methods based on predictability for physical models are not applicable. CAS analysis outcomes must demonstrate understanding of the potential dynamics, explicitly represent uncertainty in the analysis and validate the actions to be taken by designing solutions that are robust to uncertainty.

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