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Complex Adaptive Systems Engineering and Risk Reduction

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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 those they create. This is particularly true with the risks due to climate change, economic crises, energy disruptions and food insecurity. The potential consequences of climate change for populations include reduced reliability of essential services (food, water, and electric power), economic losses, and geopolitical instabilities. When designing risk mitigation strategies it is critical to understand the uncertainty in the timing, magnitude, and nature of potential impacts. Climate impacts will vary regionally as a function of the differences in the current physical, geopolitical, and economic conditions and the nature, magnitude, and timing of the stresses in those locations. Climate change and the challenge of addressing the resulting global risks provides a common set of problems on which to build a global community of practice that utilizes earth systems engineering approaches and sustainability goals to understand and resolve complex adaptive systems of systems problems. This paper presents general concepts for infrastructure adaptation and examples of successful applications of an expanded engineering process for complex systems of systems.

Key Words: Dynamics; Sustainability; Infrastructure Planning

1 Introduction

What are Complex Adaptive Systems (CAS) and why care about their risks? While 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). For scientific and engineering purposes it is important to work from a definition that focuses on the process that creates these characteristic functional structures and enables emergence and other system behaviors. For this work, CAS are defined as systems in which the structure modifies to enable success in its environment (Johnson et al. 2011). 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). CASoS Engineering approaches were developed (Glass et al., 2011; Brown et al., 2011) to address this class of problems, including the evaluation of what happens to CAS such as ecosystems, societies, infrastructures or economies when their environment changes and the identification of strategies for reducing risks or increasing security through modifications that are robust to uncertainty (Figure 1). Climate change, and its impacts on the environment, population, and engineered systems, is one of the global challenges that will benefit from using a CAS approach for analysis and design of effective risk reduction actions.

The potential effects of climate changes on populations, such as reduced reliability of essential services (food, water, and electric power), economic losses, and geopolitical instabilities, are critical to understand when designing risk reduction strategies. The timing, magnitude, and nature of potential impacts will vary regionally as a function of the differences in the current physical, geopolitical, and economic conditions and the nature, magnitude, and timing of the climatic stresses in those locations. Temporal and spatial variability in environmental changes and the ability of populations to adapt to those stresses require us to look at this problem from multiple viewpoints in order to develop an understanding of the potential dynamics and identify the suite of risk reduction measures that may be needed. The CAS viewpoint provides a multi-domain perspective and long-term representation of the entities and processes as well as a means of aggregating and integrating the disparate changes in regional climates and their impacts on the environment, ecosystems, human populations, engineered environment and economies. Starting with identifying the entities and relationships that may be impacted by environmental changes and then mapping the stresses on engineered systems (Figure 2) begins the process of building the model design for this set of problems. The next stage of the problem-mapping process is representing the heterogeneity in the conditions and impacts.

For example, opening of Arctic transportation routes and access to natural resources resulting from warmer temperatures is a shock to the global economy (sudden structural change) and a stress on the geopolitical relationships between the countries with borders adjacent to those routes. Changes in climate will also impact agricultural productivity and lead to structural changes in global food supply and manufacturing networks that could have a greater extent of impact than opening Arctic transportation routes and resources, but put less stress on geopolitical relationships. Other impacts, such as reduced water supplies, will be regional in extent due to the inherently regional nature of water resources, but such impacts have the potential to cascade if the region involved is under another stress (geopolitical or economic).

To quantify regional or global risk, the probability of each potential consequence must be estimated, and the consequences made comparable. Probabilities are a function of the uncertainties in the stresses that will be experienced and the affected population's and the physical and engineered systems' vulnerability to those stresses. The severity of climate change is the primary source of parametric uncertainty in estimating stresses. Uncertainty in the vulnerability to the stresses is due to lack of knowledge about how the population will respond. It is assumed that the wealth of the population affected by those physical changes and the degrees of freedom those affected have to respond (migration, alternative resources) will have significant impacts on the population vulnerability.

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 diverse stressors. Analysis using CAS-based 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 decisions made in this way are not harmful and may fix a problem. In cases where the effects of decision play out over longer time frames and propagate through interdependencies with other systems, the broader view and understanding gained from CAS analyses allow us to recognize the causal relationships and solve persistent system-level issues.

Thanks to Malcolm Gladwell, “tipping point” is a generally understood concept defining the moment when change cascades into being. Uncertainties, however, render tipping points difficult to predict and avoid. In CASoS such as infrastructures, system-spanning events like large-scale power outages are neither frequent nor rare; frequency-magnitude plots of earthquakes, wars, power outages, forest fires, market crashes and other events have truncated, heavy-tailed distributions. 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 of system spanning events, 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 causes the original system to fail or by the main system failure, and they need function until services can be restored.

Climate change raises concerns about global cascades in supply chains that are critical to human life and prosperity. In a traditional economic view, individuals, companies, and nations with sufficient resources will pay more or export fewer goods to offset their shortages: this response 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, but it is difficult to predict with any certainty what final factor will push the system over the threshold. Risk reduction solutions can be developed despite the uncertainties by recognizing the stresses that drive a system toward a tipping point and identifying what it will take to keep conditions below the critical threshold with some level of certainty.

Drought is the primary climate-related stress of 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 drought is expected due to climate change, have less ability to adapt and are likely to be the first areas impacted when a climate tipping point is realized. Providing food-aid would reduce some consequences but would not make the region more resilient or less vulnerable to climate impacts.

One strategy for managing climate risks, particularly for systems that provide services, is to engineer for resilience. Vugrin et al. (2011) provide a definition and mathematical framework for quantifying system resilience that allows comparison of options to support decision making through the explicit inclusion of costs. 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 to find 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 et al., 2008; Perlroth et al., 2010; Finley et al., 2011), identification of strategies for reducing counteracting monetary policies (Beyeler et al., 2007) and reducing uncertainty in forward and backward tracking of food contamination (Conrad et al., 2011).

The engineering goal for pandemic planning was to identify an intervention that would contain the spread of a novel strain of influenza, protecting the population until a strain-specific vaccine could be developed. Uncertainties included 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) changes the distribution of possible outcomes (Figure 4). The best-performing composite intervention strategies include school closure to effectively reduce the spread of disease by changing the structure of 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 and social distancing (e.g., wearing masks)) to reduce the mean and standard deviation in outcomes.

The consequences of economic perturbations are well understood given the on-going issues around the world. As with pandemics, the system interactions are global and interventions are 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 at a national level push the risk to the other participant in the exchange market, prompting a change in policy in the second system and promulgating a dynamic cycle of perturbations that may take many years to dampen. This highly-simplified abstract model indicates that prioritizing FX trades over normal payments can reduce exposures significantly in both systems and that differences in liquidity in the two systems can increase exposures. Low levels of liquidity in one system can negatively affect the other system even when it is operating with a higher level of liquidity.

Food supply chains are another type of global system that, when 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., although 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’ and the uncertainties in network connections provide a means for identifying more likely paths and prioritizing data needs (Conrad et al., 2011).

The applications synopsized above 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. Network and community builders are used to create models of single or multiple interacting networks (social, supply chain, transportation). Networks are used to simulate the transmission of infectious disease, exchange of goods, dynamics of opinion, and changes in population structure. The ability to represent the cascading effects of an environmental perturbation provides a means of understanding and designing network-based solutions. Infections and opinions propagate through multiple, interacting social networks; food contamination propagates through supply chains; behaviors spread as a function of opportunity, opinion and information through physical, social and communication networks; and functional disruptions spread through logical and physical system dependencies.

4 Conclusions

There are many challenges moving forward. Climate risks are global and will require an international community committed to reducing the risks. A strong international community of practice of CASoS Engineering working toward solutions will benefit all. Building such a community requires tremendous individual commitment and willingness to find ways to collaborate on common problems.

Confidence building in CAS-based models and analyses is needed and it will require new approaches to validation. CAS are inherently unpredictable, thus traditional validation methods based on predictability developed for physical models are not applicable. CAS analysis outcomes must demonstrate understanding of the potential dynamics, explicitly represent uncertainty, and lead to solutions that are robust to uncertainty. CAS models need to behave the same way that the real systems do, for the same reasons. Adaptation of system structure to maintain function under environmental stress, simple rules for entity interactions and condition-dependent behaviour are structural attributes that provide the means for creating models that behave the way the real system does and for the same reasons, improving understanding and design of robust, valid solutions.

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Figure Captions

Figure 1: Key aspects of the problem domains for complex adaptive systems and policy: systems, perturbations and engineered solutions

Figure 2: Climate processes, environmental changes and impacts on populations, infrastructure and perturbations to the global economy

Figure 3: Percentage of Gross Domestic Product (GDP) from agriculture (data from U.S. CIA, 2009) an indicator of risk due to climate change caused by agriculture vulnerability to drought, flooding, and sea level rise; and reduced economic capacity for adaptation

Figure 4: Uncertainty quantification for comparison of intervention effectiveness for a 1918-like pandemic influenza