MODELING AND SIMULATION TO SUPPORT RISK MANAGEMENT IN COMPLEX ENVIRONMENTS

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ABSTRACT

Critical infrastructure systems are complex and interdependent – they form networked "systems of systems". There are many risks to these systems associated with major disasters and disruptions. Risk can be considered the product of three complex and interrelated elements: threats, vulnerabilities, and consequences. In addition to disasters and disruptions, our world faces many "changes" such as a growing population, disruptive technological advances, and global climate changes. Due to the overall complexity, decision-support tools are essential for analyzing and actively managing risk. The Center for Understanding Change (C4UC) is a small non-profit organization that is developing a "supermodel" toolset that can be used to model and analyze a network of infrastructure sectors with regard to risk scenarios and policy options that might be considered to manage risks. In addition, C4UC "robust" decision-making processes can be integrated with models and simulations to explore prospective decisions "in vitro", in order to develop solutions, approaches, and actions that can optimize robustness and resiliency.

Keywords: risk, global change, decision making, modeling, simulation, analysis, software development

RISKS AND "CHANGES"

There are many organizations that try to peer into the future and examine what might happen to the world in terms of global trends, changes, and risks. For instance, The Global Risks 2014 Report (1) states that the *"ten global risks of highest concern are: fiscal crises in key economies; structurally high unemployment/underemployment; water crises; severe income disparity; failure of climate change mitigation and adaptation; greater incidence of extreme weather events (e.g. floods, storms, fires); global governance failure; food crises; failure of a major financial* *mechanism/institution; profound political and social instability."* It is also important to note that this report highlights *"how global risks are not only interconnected but also have systemic impacts. To manage global risks effectively and build resilience to their impacts, better efforts are needed to understand, measure and foresee the evolution of interdependencies between risks, supplementing traditional risk-management tools with new concepts designed for uncertain environments. … As international systems of finance, supply chains, health, energy, the Internet and the environment become more complex and interdependent, their level of resilience determines whether they become bulwarks of global stability or amplifiers of cascading shocks. Strengthening resilience requires overcoming collective action challenges through international cooperation among business, government and civil society."*

Global Trends 2030 (2) projects a "megatrend" involving the Food, Water, Energy Nexus – *"Demand for resources will increase owing to an increase in global population from 7.1billion today to about 8 billion by 2030. Demand for food set to rise 35 percent; energy 50 percent over the next 15-20 years. Nearly half of world population will live in areas with severe water stress. Fragile states most at risk, but China and India are vulnerable to volatility of key resources."*

The National Climate Assessment (3) states that: *"Climate change is already affecting the American people. Certain types of weather events have become more frequent and/or intense, including heat waves, heavy downpours, and, in some regions, floods and droughts. Sea level is rising, oceans are becoming more acidic, and glaciers and arctic sea ice are melting. Many impacts associated with these changes are important to Americans' health and livelihoods and the ecosystems that sustain us…While some changes will bring potential benefits, such as longer growing seasons, many will be disruptive to society because our institutions and infrastructure have been designed for the relatively stable climate of the past, not the changing one of the present and future. Similarly, the natural ecosystems that sustain us will be challenged by changing conditions. Using scientific information to prepare for these changes in advance provides economic opportunities, and proactively managing the risks will reduce costs over time."*

The 30-year update (4) to "Limits to Growth" points out that: *"For more than a century, the world has been experiencing exponential growth in a number of areas, including population and industrial production. Positive feedback loops can reinforce and sustain exponential growth. In 1650, the world's population had a doubling time of 240 years. By 1900, the doubling time was 100 years. When The Limits to Growth was published in 1972, there were under 4 billion people in the world. Today, there are more than 6 billion, and in 2000 we added the equivalent of nine New York cities."* The authors of the update have improved the World 3 systems dynamics model that simulates a number of important global concerns (Resources, Food, Population, Pollution, Industrial output, Human welfare index, and the Human ecological footprint).

Jeremy Grantham (5) summarizes his concern as: *"The world is using up its natural resources at an alarming rate, and this has caused a permanent shift in their value. We all need to adjust our behavior to this new environment. It would help if we did it quickly. The rise in population, the ten-fold increase in wealth in developed countries, and the current explosive growth in developing countries have eaten rapidly into our finite resources of hydrocarbons and metals, fertilizer, available land, and water. The fact is that no compound growth is sustainable. If we maintain our desperate focus on growth, we will run out of everything and crash. We must substitute qualitative growth for quantitative growth. From now on, price pressure and shortages of resources will be a permanent feature of our lives. This will increasingly slow down the growth rate of the developed and developing world and put a severe burden on poor countries. We all need to develop serious resource plans, particularly energy policies. There is little time to waste."*

We face another issue when managing risks and change: sometimes our actions can have "unintended consequences" that we never considered. A good example is Spain (6) which *"has served as both exemplar and scapegoat when it comes to renewable energy policy. Though power policy must necessarily accommodate specific national resources and goals, Spain's experience as an early and eager adopter of renewable energy technologies and subsidies is a cautionary tale of how the best intentions can have unintended consequences."*

MODELING AND SIMULATION

Sterman (7) states the issue we face when using computer models: *"Thoughtful leaders increasingly recognize that we are not only failing to solve the persistent problems we face, but are in fact causing them. System dynamics is designed to help avoid such policy resistance and identify high-leverage policies for sustained improvement. Understanding complex systems requires mastery of concepts such as feedback, stocks and flows, time delays, and nonlinearity. Research shows that these concepts are highly counterintuitive and poorly understood. … Most important, and most difficult to learn, systems thinking requires understanding that all models are wrong and humility about the limitations of our knowledge. Such humility is essential in creating an environment in which we can learn about the complex systems in which we are embedded and work effectively to create the world we truly desire. As the world changes ever faster, thoughtful leaders increasingly recognize that we are not only failing to solve the persistent problems we face, but are in fact causing them.* ***All too often, well-intentioned efforts to solve pressing problems create unanticipated 'side effects.' Our decisions provoke reactions we did not foresee. Today's solutions become tomorrow's problems. System dynamics helps us expand the boundaries of our mental models so that we become aware of and take responsibility for the feedbacks created by our decisions."***[bolded emphasis added]

The Center for Understanding Change (C4UC) was created in response to a challenge: to use the significant investment by the federal government in system dynamic models of our critical infrastructure, in a way that is proactive in the exploration of the public's interest. These models of critical infrastructures (energy, transportation, communications, food, water, etc.) and their interdependencies were developed for the Department of Homeland Security (DHS) primarily to protect our nation's infrastructure from natural and manmade disasters/crises. As stated by Bush et al (8): *"Critical infrastructures are increasingly automated and interlinked, subject to possibly cascading vulnerabilities due to equipment failure, natural disasters, and terrorist attacks. The system dynamics (SD) approach is particularly promising in understanding these complex systems, interactions, and issues. Problems in critical infrastructure protection are being investigated with a collection of SD models developed expressly for these concerns. The Critical Infrastructure Protection Decision Support System (CIPDSS) was created to provide fast, order-of-magnitude assessments of potential impacts of disruptions (9)."* The systems dynamics models of CIPDSS are the starting point for the C4UC analyses, but agent-based models and other numerical techniques will also be part of the approach.

The description of CIPDSS which follows comes from several detailed reports (10, 11). CIPDSS has demonstrated its capability to provide meaningful risk-informed decision support for several categories of threats that concern the DHS. As a system dynamics suite of simulations, it has confirmed the ability of system dynamics to support a wide range of analyses of interest to policy makers through aggregate-level simulation of multiple infrastructure systems. Combined with the flexibility and extensibility conferred by integrating software, the uncertainty and sensitivity analysis capability, the decision model, and the breadth of coverage (including all 12 critical infrastructures and 5 key resource categories), CIPDSS is a unique capability for investigating consequences of infrastructure disruption. CIPDSS incorporates a fully integrated risk assessment process, explicitly and rigorously accounting for uncertainties in threats, vulnerabilities, and the consequences of terrorist acts and natural disasters. CIPDSS goes beyond the sole calculation of first-order consequences in one or just a few infrastructures. CIPDSS models the primary interdependencies that link the 17 critical infrastructures and key resources together and calculates the impacts that cascade into these interdependent infrastructures and into the national economy. The project was developed in a system dynamics language (Vensim) to facilitate rapid development of capability. This decision-support system is designed to address various infrastructure- and risk-related questions, such as: What are the consequences of disruptions to infrastructure—including the consequences that propagate to other infrastructures? What are the highest risk sectors and assets? What investment strategies will have the most impact in reducing overall risk?

The system was designed to operate at two distinct scales of modeling: the national scale and the metropolitan scale. The national model represents the critical infrastructures at the national level, with resolution at a state level. The metropolitan model is intended to represent the functions of critical infrastructures at the local level, in urban landscapes with a population of 500,000 or more. Within these two modeling scales, many questions of critical infrastructure disruption can be addressed in a risk-informed framework. In general, both the models calculate the consequences of a disruption within the affected sector and in related sectors linked by primary interdependencies. For example, a disruption in telecommunications could have an effect on banking and finance, and even on traffic. Consequences are computed in the broad metric categories of human health and safety, environmental effects, economic costs, public confidence, and national security.

Each infrastructure sector is represented by a model of the system that is captured in a system dynamics representation. The most common form is a limited-capacity, resource-constrained model. In this generic representation, the infrastructure is a network of nodes, for example, variables that are linked by directed edges, or influences. The mathematical description (for example, a system of coupled ordinary differential equations) embedded in the syntax of the Vensim software defines the actual model. A key aspect of the CIPDSS infrastructure models is the capturing of the primary interdependencies between infrastructures. The dependencies are generically represented in the local availability of resources and materials and implicitly in the production operations. These functional dependencies are clearly called out in the infrastructure models. Because CIPDSS uses a high-level representation of operations, not all dependencies are modeled, just the primary dependencies. Also, to maintain a consistent model resolution level, the effect of the dependency is modeled rather than the detailed interactions. Each critical infrastructure sector is divided into a number of subsectors, for which one or more separate Vensim subsector models are developed. A Java-based program, the Conductor (12), is used to merge multiple system dynamics models, link variables that cross source code boundaries, and assemble a unified multisector model from individual sector model files. The Conductor identifies variables present in models with references to other source code files and resolves the references when the models are combined. As such, the program allows the models to be developed and tested at a modular level and enables simulation runs at the multisector level.

"SUPERMODELS"

CIPDSS introduced the concept of what we are referring to as "supermodels" – models composed of sets of smaller models. CIPDSS, simply put, is a set of coordinated models, all built with the same modeling tool, all with a common understanding of semantics, and designed to have the individual component models able to connect with one another on an "as needed" basis. The "Conductor" mentioned above is an integrating tool that can leverage this set to tie many models together as needed to explore problems. CIPDSS is used primarily in response to a major event such as a terrorist attack or natural disaster (hurricanes, earthquakes, pandemics, etc.). In such cases, the exploration of the range of proposed actions and potential consequences/impacts is by necessity limited in time and scope. Speed is of the essence and rapid results drive the process.

C4UC, as a small non-profit with limited resources, has set its sights on handling the other side – the proactive rather than reactive applications. At the outset, we were challenged to leverage the same asset, CIPDSS, but to use it to explore the implications of equally critical but less urgent decisions – those that are not by their nature in reaction to some immediate event. In exploring these important but less urgent decisions, it became clear that our exploration of the decision space would require models and data that were not part of CIPDSS. We would need to augment the CIPDSS resource with models and data held by others, including models and data held by the various stakeholders impacted by the issues we would be examining. This presented a significant challenge. System dynamic models, in general, cannot be just tied together. There are "order of operation" dependencies that need to be worked out. Typically what has to happen is that the content of one model needs to be built into the second model. CIPDSS itself was a major achievement – building a set of models that can work together. What we need is much more difficult to achieve: the ability to create a "supermodel" that can tie together models that were not originally designed to work together.

One way to tackle this supermodel problem is to treat this as just a step for building a bigger, single model – the brute force method. If the models and data can be shared, then someone can go through the exercise of actually building the contents of a second model into the existing first model. Another way is to predetermine the extent of the models to be used and build them all with a common framework so that they are designed from the beginning with the ability to interact. That is part of the beauty of the CIPDSS set of models. C4UC quickly realized, however, that another challenge would prevent us from using the brute forced method: The Stakeholder Problem. Simply put, the various models and data necessary to explore many problems are held by independent parties, whose interests are often conflicting. Also, for many, these models and data are considered proprietary or sensitive and the stakeholders are either unwilling or unable to expose them to other stakeholders, even when the models and data are critical to understanding the issues and actions these same stakeholders need explored. In April 2014, C4UC will show to the public for the first time its solution to both the supermodel problem AND the stakeholder problem (13).

What C4UC has done is to create a tool that allows system dynamic models to be connected to one another and to operate as a supermodel, getting the same results as if the models were combined in the brute-force, single model method mentioned above. The C4UC tool works, even when the each of the component models of the supermodel is residing on separate computers in different locations, regardless of any firewalls that these models might be sitting behind. In other words, the C4UC tool now allows system dynamic models to interact as if they were in a single, combined model, and it can do this even when the owners of those models are not willing to let their models outside their own firewalls. The software will allow models and data held securely by independent stakeholders at multiple sites to run in an integrated framework without the stakeholders having to "trust" one another. This ability to allow stakeholders with a large and complex joint challenge to work together even when they don't trust one another is likely to be a **"game changer"**. In the near future, the C4UC tool will also allow system dynamic models to interact with agent-based models, vastly increasing the ability to explore scenarios. What makes this possible is a revolutionary new software framework that is based on a complete rethinking of the assumptions of modern code. This message-centric, object-based (not object-oriented) software is highly encapsulated, extremely scalable, and inherently robust/resilient in itself. One side effect of building the C4UC tool on this framework is several orders of magnitude improvement in speed, as well as the ability to handle models at scales that are challenging to commercially available software.

C4UC solves the stakeholder problem by providing a mechanism with which the various stakeholders involved in an issue can engage their expertise, models, and data, without requiring that the models and data be exposed to others. Simply put, the C4UC solution engages each stakeholder's model and data from a position behind that stakeholder's existing firewall structures. While no system can ever be guaranteed to be 100% secure, what C4UC has done is to permit this activity without increasing any levels of risk to the stakeholder's intellectual property. The deployed system consists of supermodel software sitting on an isolated C4UC machine outside the stakeholder's firewall. The C4UC machine has a security filter and it has access to the external internet. The machine is NOT connected to any of the stakeholder's internal networks – it only requires access to the firewall. The stakeholder's models and data are loaded on their machine – behind their firewall. A communicator program manages receipt of requests for exercising parts of the stakeholder's model and passes the results back to the supermodel – this ensures that only data/results acceptable to the stakeholder are transferred.

In the spirit of "trust, but verify," there is a "Reagan Filter" under the control of each stakeholder. This filter has the capability to clamp down on the results of the model, either by limiting the number or names of variables that can be exercised, and/or by limiting the range, and/or precision, and/or time-granularity of the response. What crosses the Reagan Filter is plain text (XML formatted) and stakeholders may insert any type of additional functionality to that filter. Most of the models and data of critical infrastructure are considered "sensitive in aggregate" – that is, any single piece of data may be public knowledge but when combined with large quantities of similar data the aggregate may be considered sensitive. For those times where the nature of the data is sensitive regardless of the scales, C4UC has the ability to add an encryption function to the data passing between models.

Whenever a large, complex, system of systems challenge is addressed using sets of models like this, there are three key challenges: Science, Technology, and Stakeholders. CIPDSS represents a significant effort in critical thinking about infrastructure, in part because it set a domain and then built a solution for that domain that addressed the first two challenges and eliminated the need for involvement of the third. What C4UC has done is to provide a resolution for the latter two challenges (Technology and Stakeholders) while providing a mechanism for addressing the first challenge (Science) as part of the engagement process. When C4UC tackles an issue, there is one key step required to solve the Science challenge: scientists from all stakeholders must sit in a room together and build a common understanding of the larger issues, understand what data and models are available (and where they reside), and determine what needs to be acquired or built. Together, these scientists, facilitated by C4UC, build the picture of what the supermodel needs to look like, define what the ranges of exploration need to be, and identify which resources need to be engaged from behind firewalls. This supermodel "seed" becomes the master from which C4UC exercises the supermodel and it is this "seed" that starts and integrates the model and data exploration process.

ROBUST DECISIONS

Decision making is not difficult. Just look at any "how to" web site and find five simple steps: 1) identify problem; 2) identify alternatives; 3) evaluate alternatives; 4) make decision; and 5) take action. But when applying these steps to socio-technical problems (such as those focused on energy, water, resource management and allocation) these simple steps become difficult to support. This is because: the systems are complex; evaluation of the alternatives is a mix of science/technology analysis and stakeholder input; the science/technology is uncertain; stakeholders have diverse and inconsistent knowledge, values, and agendas; and decisions are based on many variables. Regardless of these difficulties, the end goal is to choose policies (i.e. actions) that optimize the science/technology while building stakeholder buy-in.

The five "difficulties" itemized above will be refined using a recently developed system as an example. BASS (Bayesian Analysis for Spatial Siting) focuses on where to locate wave energy-generation devices off the Oregon coast (14). It integrates the best scientific models and data with stakeholder inputs in a Bayesian environment that manages information uncertainty to generate best estimates of technology impact at specific ocean sites. It not only includes geo-spatial analysis but a probabilistic basis on which to make decisions. The systems addressed in this paper are complex. They live at the intersection between people and science/technology - which is often poorly understood. In these problems there are many subsystems that interact in ways that cannot be understood by decision makers without analytical assistance and may be hard to model and analyze. To evaluate each alternative, the systems and subsystems must be modeled and their behavior simulated using the best information from past history, current assessments, and forecasts about the future. It is the results of these simulations that fuel the "make decision" and "take action" steps in the process. Additionally, in some cases, the number of alternatives to analyze is very high as will be seen in the BASS example.

BASS works in probability space analyzing the impacts of alternative technologies or policies on alternative locations. Specifically, BASS combines scientific models and data at specific ocean locations to estimate the impact of adding an energy-generation device at that location. The impact may be on a species of fish, whales, the coastline, shipping, fishing, tourism, or any number of other eco-resources. When looking for where to site a new technology, there are a very large number of alternatives to be considered (every patch of ocean off the coast of Oregon). Further, the system models at these locations are based on uncertain scientific algorithms and data. In some locations even the depth of the ocean is not very well known and it changes with the tides, seasons, and years. To accommodate the uncertainty, BASS makes use of Bayes Nets Modeling. To accommodate the spatial nature of the problem, a Bayes Net model is run at each location on a grid and then the results combined. In some cases the models are run at tens-of-thousands of locations. This is only possible in a near real-time environment because computer speeds are so fast and we reduce the sites considered by stakeholders to those that pass a scientific filtering.

While science and technology can be modeled as equations and rules, the inclusion of stakeholder values and qualitative estimates makes these systems much more difficult. In the ideal world of the scientist or engineer, all the information needed for a decision would be reducible to an analytic model. But real decision making doesn't happen this way. Virtually all decisions involve and revolve around people. Each of these people has a stake in the decision as they will be affected by the actions taken. Part of the decision-making process is to enfranchise these stakeholders and build decision buy-in. Efforts to base socio-technical decisions on science and technology alone are doomed. In fact, many decisions are made in spite of the science, as there is a lack of belief in the results of simulations and forecasts. Thus, one goal of the systems described in this paper is to integrate the science and technology with stakeholder values, beliefs, and opinions in such a way that the science is honored while stakeholder buy-in is developed. To gain buy-in, the stakeholders must feel that have been heard, their values (what is important to them) included in the evaluation, and they understand what went into the technical models (to a depth that makes them comfortable and accepting of the science).

In BASS we define two types of "measures" (the criteria by which the alternatives are evaluated). The first we call "Scientific Measures". For each of these we built a Bayes Net that combines all the science we know to estimate the impact at each alternative location. A Bayes Net is a probabilistic graphical model that represents the conditional dependencies among variables. For example, the impact on whales is a function of the depth of the sea, the bottom conditions, the noise caused by the addition of the technology, and many other factors. Each of these is uncertain and the combination of the uncertainties in the Bayes Net gives the probability (and its variance) of an impact on whales as a result of the analysis.

The second type of measure is a “Stakeholder Measure”, used to directly capture stakeholder evaluation of non-scientific measures at selected locations. This we capture by direct stakeholder input. For example, one Stakeholder Measure is “Impact on Sense of Place”. The BASS system allows the stakeholders to provide qualitative input about the impact of a technology at a specific site on their “sense of place”. The evaluations of both Scientific Measures and Stakeholder Measures are combined using a Bayesian analysis. The result of this analysis is a level of satisfaction.

BASS begins with the assumption that all models and data are uncertain – thus the choice of Bayesian methods for all the analyses. Scientists, especially oceanographers, are well aware of the uncertainty of their ecosystem models and BASS allows this uncertainty to be analyzed. Further, as mentioned before, the data analyzed by these models is usually uncertain, incomplete, and time varying. BASS allows these uncertainties to be reflected in the results.

For all decision problems there are many stakeholders who come with unique and diverse knowledge, values, opinions, and goals. This diversity is especially seen in the socio-technical problems addressed here. BASS engages them in an interactive environment where they can see the results of the analysis on the Scientific Measures as well provide input (both their evaluations of the Stakeholder Measures and the relative importance of all the measures). Specifically, stakeholders rank order the “importance of different impacts” which provides a measure of what each stakeholder really values. This accomplishes two things. First, the results are analyzed through the eyes of each stakeholder by weighting the analytical results with that stakeholder’s values. This gives the decision makers the ability to see the effect of different decisions on each stakeholder. Second, by separating what the stakeholders think is important from their evaluation of the Stakeholder Measures, disagreements among stakeholders are avoided.

The end goal, of course, is to make a decision and take action. BASS does not make a decision – it supports decision makers as they choose the best possible alternative by providing levels of satisfaction for each alternative. In many ways this is as important as making a choice. BASS provides the ability to view impacts a number of ways: one measure at a time, across all Science Measures fused into a single “satisfaction”, or across all measures as seen through the eyes of each stakeholder. Further, BASS is designed to be iterative and allow exploration of what-if questions and support deliberation. Finally, the Bayesian methods used in BASS can provide a Value-of-Information assessment. This is a uniquely Bayesian method that calculates what additional information may significantly change the result. This analysis aims decision makers at where to use scarce resources to obtain better science as well as where to work to resolve stakeholder issues. It helps reduce needless discussion about details that won't change the result and inter-stakeholder arguments about what is important.

COMBINING ROBUST DECISION MAKING WITH COMPUTER SIMULATIONS

The "robust" decision making process can be combined with real-time numerical model simulations to enhance the understanding and buy-in of disparate stakeholders. Passell et al (15) describe such an application as follows: "*The watersheds in which we live are comprised of a complex set of natural and social systems that interact over a range of spatial and temporal scales. These systems are continually evolving in response to changing climatic patterns, land use practices, and the increasing intervention of humans. Sustainable management of watersheds and their water resources benefits from the development and application of models that offer a comprehensive and integrated view of these complex systems and the demands placed upon them. The utility of these models is greatly enhanced if they are developed in a participatory process that incorporates the views and knowledge of decision-makers, resource managers, special interest groups, and the public.*"

C4UC PARTNERSHIPS

C4UC has established partnerships with a number of important organizations including government laboratories, academic institutions, and globally recognized institutes/organizations. Sandia and Argonne National Laboratories have signed Memoranda of Understanding with C4UC. Other organizations such as Old Dominion University, the Santa Fe Institute, MediaX at Stanford University, and Discern work more informally with C4UC. Our partnership model involves bringing together the "deep science knowledge" of our partners with integrating processes and software at C4UC.

SUMMARY

Critical infrastructure should be viewed as "systems of systems" – each infrastructure system is networked to other entities (e.g., suppliers and customers) via a series of complicated interdependencies. Risk (and, for that matter, global change) has three elements: threats, vulnerabilities, and consequences. Each element of risk is composed of a complex function of variables. Decision-support tools are essential in the active management of risk due to the complexity of networked systems today. C4UC is developing a "supermodel" toolset that can be used to model and analyze a network of infrastructure sectors with regard to "risk scenarios" and "policy options" that might be considered to manage risks. Robust decision-making processes can be integrated with models and simulations to enhance stakeholder understanding/support and avoid unintended consequences.

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