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Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0

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Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0

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Abstract

Complex Adaptive Systems of Systems, or *CASoS*, are vastly complex *eco-socio-economic-technical systems* which we must understand to design a secure future for the nation and the world. Perturbations/disruptions in CASoS have the potential for far-reaching effects due to highly-saturated interdependencies and allied vulnerabilities to cascades in associated systems. The Phoenix initiative approaches this high-impact problem space as engineers, devising interventions (problem solutions) that influence CASoS to achieve specific aspirations. CASoS embody the world's biggest problems and greatest opportunities: applications to real world problems are the driving force of our effort. We are developing engineering theory and practice together to create a discipline that is grounded in reality, extends our understanding of how CASoS behave, and allows us to better control those behaviors. Through application to real-world problems, Phoenix is evolving CASoS Engineering principles while growing a community of practice and the CASoS engineers to populate it.

PREFACE

This is a living manuscript documenting the evolving capability of CASoS Engineering from its beginnings within multiple programs at Sandia National Labs. One of four living documents, this report summarizes the current portfolio of Phoenix Applications; the others provide the history and guiding principles of Phoenix, and greater detail on the Phoenix theoretical Framework and engineering Environment.

Periodically, more concise documentation of Phoenix and its projects will be distilled, such as *Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions*, written for the New England Complex Systems Institute's 8th International Conference on Complex Systems, and also presented as the keynote at the 6th IEEE International Conference on Systems of Systems Engineering, both in June 2011.

ACKNOWLEDGEMENTS

Following the favorable reception of the *Sandia National Laboratories A Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative*, initial Phoenix funding was provided in 2008 through Sandia's Laboratory Directed Research and Development (LDRD) from the Energy Resources and Nonproliferation (ERN, reconfigured to be ECIS or Environment, Climate and Infrastructure Security in 2010) Strategic Management Unit (SMU) to develop a pilot for the initiative in context of analysis for the Global Energy System. Reported on in *A General Engineering Framework for the Definition, Design, Testing and Actualization of Solutions within Complex Adaptive Systems of Systems (CASoS) with Application to the Global Energy System (GES)*, this initial development has continued to evolve with additional contributions from Sandia LDRD within both ERN-ECIS and Homeland Security and Defense (HSD, reconfigured to be IHNS or International, Homeland and Nuclear Security in 2010) and from projects funded by a wide range of institutions:

- National Infrastructure Simulation and Analysis Center (NISAC), Department of Homeland Security (DHS)
- Science and Technology Division (S&T), DHS
- Public Health & Environmental Hazards (OPHEH), Veterans Health Administration (VHA), Department of Veterans Affairs (DVA)
- Center for Tobacco Products (CTP), U.S. Food and Drug Administration (FDA) Department of Health and Human Services (HHS)
- Department of Defense (DOD)
- Air Force Office of Scientific Research (AFOSR), DOD
- Office of the Secretary of Defense (OSD), Human Social Culture Behavior Modeling (HSCB) Program, DOD
- Center for International Security and Cooperation (CISAC), Stanford University
- New Mexico Small Business Administration (NMSBA), New Mexico Livestock Board (NMLB)

This work benefited greatly from the support of the following individuals within Sandia National Laboratories administration: Les Shephard (retired, previously 6000), Steve Roehrig (retired, previously 6300), Margie Tatro (6100), Rush Robinett (6110), Richard Griffith (6130), Pablo Garcia (6920), and Steve Kleban (6132).

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ACRONYMS, INITIALISMS, AND ABBREVIATIONS

AMTI	Advanced Methods and Techniques Investigations
CASoS	Complex Adaptive Systems of Systems
CDC	Centers of Disease Control and Prevention
DOE	Department of Energy
DOD	Department of Defense
DHS	Department of Homeland Security
DS&A	Defense Systems and Assessments
DVA	Department of Veterans Affairs
ECIS	Energy, Climate and Infrastructure Security
ECIS	Energy Climate and Infrastructure Security
ERN	Energy, Resources and Nonproliferation
FDA	Food and Drug Administration
GES	Global Energy System
HSD	Homeland Security and Defense
HHS	Health and Human Services
IHNS	International, Homeland and Nuclear Security
LDRD	Laboratory Directed Research and Development
MS&A	Modeling, Simulation, and Analysis
NISAC	National Infrastructure Simulation and Analysis Center
NMSBA	New Mexico Small Business Administration
NW	Nuclear Weapons
NSTS	National Security Technologies and Systems
PI	Principal Investigator
R&D&A	Research, Development, and Application
Sandia	Sandia National Laboratories
SMG	Strategic Management Group
STE	Science, Technology, and Engineering
U.S.	United States
VHA	Veterans Health Administration
VP	Vice President

1. INTRODUCTION TO COMPLEX ADAPTIVE SYSTEMS OF SYSTEMS ENGINEERING INITIATIVE (PHOENIX)

The concept of CASoS Engineering was first described at Sandia National Laboratories in the Roadmap for the CASoS Engineering Initiative[1] (2007-2008) to find ways to understand and solve the world's greatest problems. The Roadmap defines CASoS, CASoS Engineering, and the process for building the discipline of CASoS Engineering. The CASoS research, development and analysis framework for engineering solutions is an intrinsically integrated process that develops CASoS Engineering theory and principles in the context of solving high-impact (national and international) problems. The theoretical approach for CASoS Engineering outlined in the Roadmap emphasizes the importance of treating our engineering design and development initiative for CASoS solutions, called Phoenix, as a CASoS itself. This means that, as we proceed, we must apply the evolving CASoS Engineering principles to our organization, development and growth.

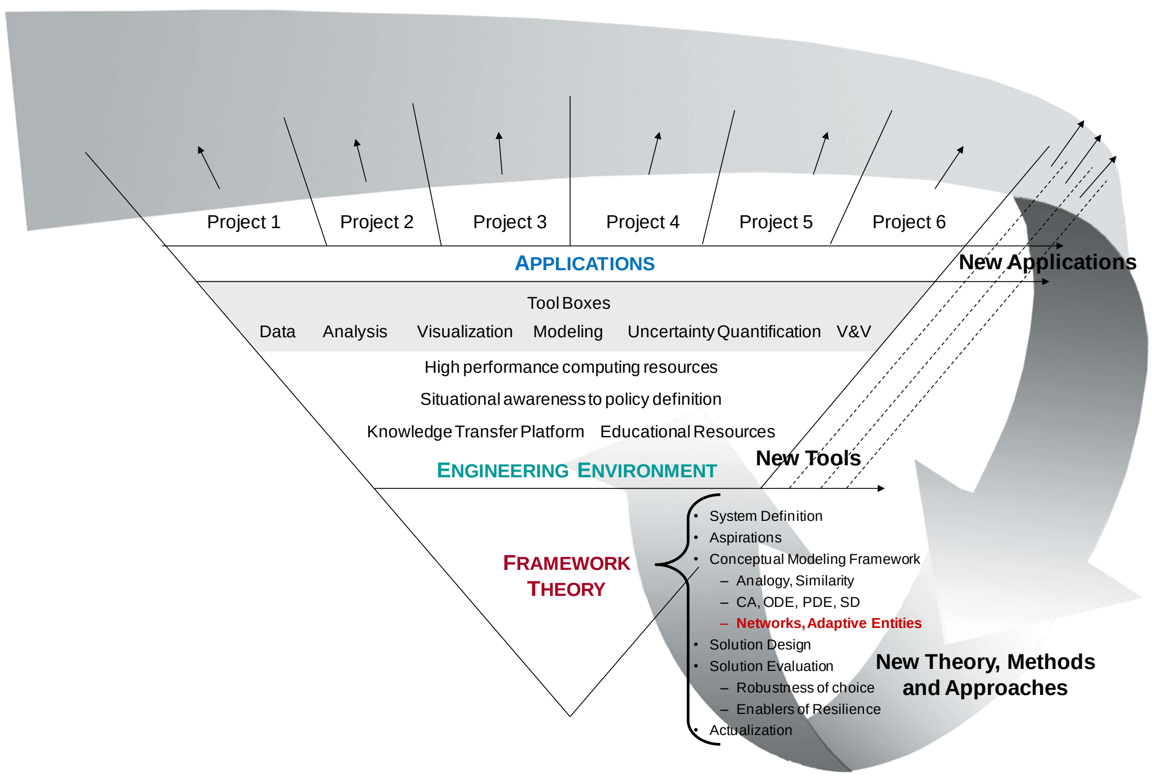

Figure 1. Integrated Research, Development and Applications Structure for the Phoenix CASoS Engineering Initiative

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[1] Glass, RJ, AL Ames, WA Stubblefield, SH Conrad , SL Maffitt, LA Malczynski, DG Wilson, JJ Carlson, GA Backus, MA Ehlen, KB Vanderveen, D Engi, 2008, "Sandia National Laboratories A Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative". Available from the AMTI External Web Site: http://www.sandia.gov/nisac/amti.html.

As illustrated in **Figure 1**, the functional structure of Phoenix has formed to fundamentally integrate Research, Development and Application:

- **Application**: High-impact CASoS Engineering Applications having problem and system orientation that meet CASoS criteria are chosen from the newly forming as well as established projects for which we have funding. The choice, sequence, and integration of applications are critical to the success of Phoenix and the growth of CASoS engineering research and development; we must learn to walk before we can run. Here, application drives the need for Research and Development and the requirements for CASoS engineering.
- **Research**: The ever-evolving CASoS Engineering Framework systematizes the theory and practice of CASoS engineering across wide ranging domains and diverse aspirations for affecting CASoS behavior. The Framework integrates three components:
  - Defining the CASoS, problem and approach
  - Designing and Testing solutions that are robust to uncertainty while identifying critical enablers of system resilience
  - Actualization of the solution within the CASoS.

  Here, Research is defining the science of CASoS engineering.
- **Development**: A CASoS Engineering Environment that supports the Framework by providing:
  - A modeling, simulation and analysis platform in which modular computational tools can be assembled in many ways and for many purposes
  - A knowledge facilitation platform for the capture, integration and evolution of the theory and practice of CASoS engineering, providing for the education and training of newly emerging CASoS Engineers.

CASoS Engineering is emerging as Applications are expanded and evolve. This document will be updated annually to address new Applications and changes in the theory or practice of Application due to changes in the Engineering Framework or Environment.

2. APPLICATIONS THEORY

The theory behind Phoenix's CASoS Engineering Initiative structure is that Applications drive the growth of the discipline and will sustain the community of practice. As illustrated in **Figure 2**, this structure is depicted as outwardly growing spiral in which each application adds knowledge to extend the core of Engineering Theory and Experiment within an expanding Environment of Data Analysis and Computational Simulation.

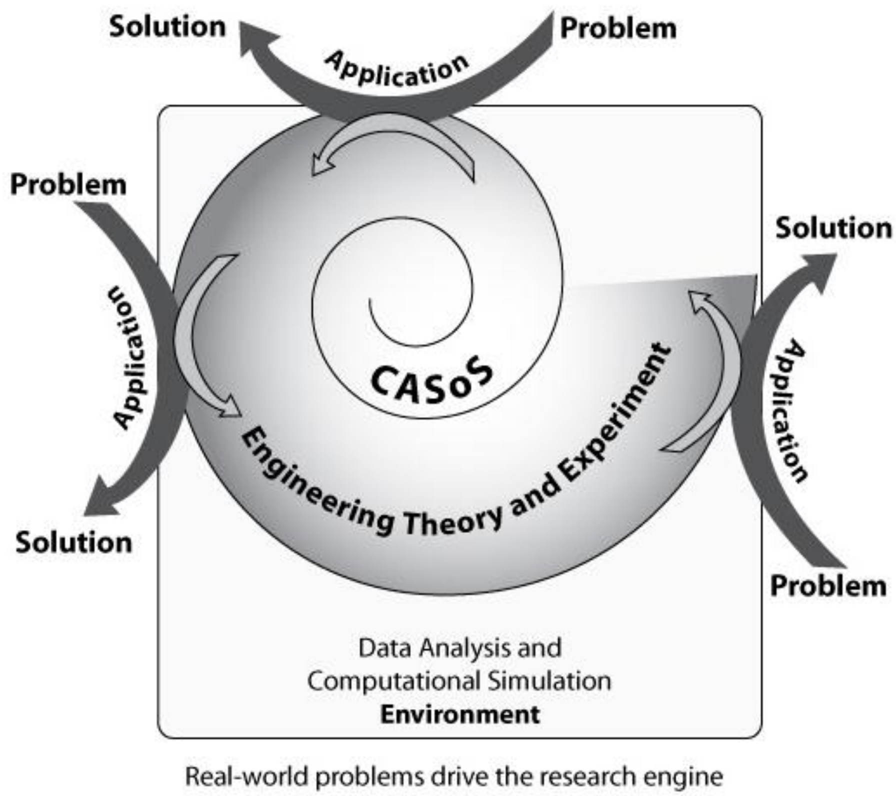


Figure 2. CASoS Engineering Initiative Development Structure

Two critical contributions are required for this evolutionary model of the "whole" to grow and thrive. First is the contribution of new frontier applications to the CASoS Engineering Framework and CASoS Engineering Environment: the relationships and interactions within new problem spaces inform and amplify understandings within the entire ecosystem. Second is adoption and use of the Framework and Environment in operational or established analysis projects. The link between the vanguard and the established must be strong; this relationship enables the intrinsic integration of the individual applications into a whole.

Applications are challenging because they require models that enhance our understanding of a particular situation or issue in CASoS; they depend on an integrated modeling and analysis environment in order to understand and communicate the key conditions, parameters and adaptive behaviors relative to the application goals; and they must allow for development and testing of theories about the vulnerabilities, strengths, and risks of particular CASoS. Applications that foster the growth of the discipline of CASoS Engineering are our goal, particularly in the initial stages of developing the discipline.

Applications chosen to foster the growth of the discipline require:

- model capability development that enhances our understanding of high impact situations or issues in particular CASoS of great interest to global security
- development and testing of theories about the vulnerabilities, strengths, and risks of general CASoS
- development of an integrated modeling and analysis environment to understand and communicate the key conditions, parameters and adaptive behaviors relative to the application goals

Applications are also chosen to balance the portfolio for diversity in scale (local, regional, national, or global) and subject domain so that cross disciplinary patterns can emerge. Ideally, applications should also cross internal organizational boundaries and external boundaries in order to form a cross-cutting kernel (both in terms of the domain and personnel) that is poised for growth. Outwardly-growing research, development and applications (RD&A) connections from this kernel will, if properly nurtured, ultimately form a CASoS Engineering community of theory, practice and culture that extends throughout the many fields where solutions to eco-socio-economic-technical problems are critically required.

The applications space is a function of the problems which would benefit from applying the CASoS Engineering Approach. **Figure 3** provides one view of the applications space as a network of perturbations, CASoS and aspirations; illustrating the breadth of problems that would benefit from integrated risk analysis and risk mitigation design.

There are significant gaps in what is done and what needs to be done to build the CASoS Engineering discipline. The history of Applications shows where we are.

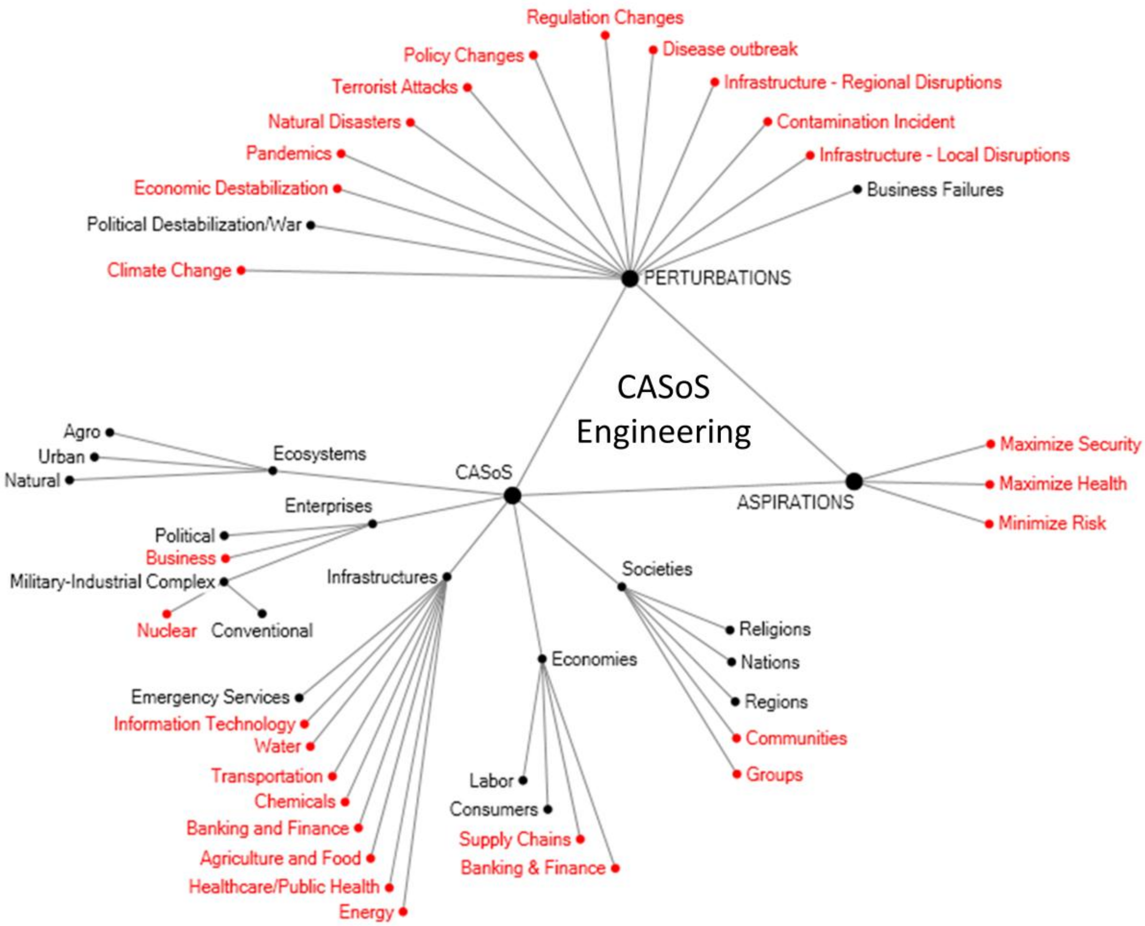


Figure 3. Applications Space as a Simplified Network of Aspirations, Perturbations and CASoS

Figure Note: Red indicates areas with artifacts, black are areas in development)

3. CASOS ENGINEERING APPLICATIONS HISTORY

As a matter of practicality, the initiative began with existing and newly formed projects in which we already have: domain expertise, application of a rudimentary form of the CASoS Engineering Framework, models and funding. These projects are also connected to people who were early adopters and founders of the CASoS Engineering concept. While the range of subject domains and funders is broad enough to satisfy our cross-cutting vision, the range of aspirations and organizational representation is not as developed. We must work to diversify these last two areas in the future.

Current Application subject domains include:

- Agriculture and Food Security
- Financial Security
- Chemical Security
- Energy Security
- Population Health
- Enterprise Security

With example perturbations:

- Regulation and Policy Changes
- Climate Change
- Economic Disruptions
- Pandemics and Disease Outbreaks
- Natural Disasters
- Terrorist Attacks
- Contamination
- Infrastructure Disruptions

Table 1 provides a brief summary of the Phoenix applications to date.

Table 1. Summary of Phoenix Applications

CASoS	Application Domain: approach, perturbation and aspiration	Phoenix Lead & Funder
Infrastructure: Agriculture and Food	Food Security: Analysis and design of interventions to reduce the consequences of food contamination using stochastic maps of food supply chains	SH Conrad: NISAC
Infrastructure: Agriculture and Food	Agricultural Security: Analysis and design of disease intervention policy within the livestock industry using stochastic mapping	RJ Glass: NMSBA-NMLB
Infrastructure: Banking & Finance	Financial Security: Evaluation of interbank payment system's transfer topology and monetary policy on congestion and cascades in payment systems	WE Beyeler: NISAC
Economies: Banking & Finance	Financial Security: Analysis of the global financial system to identify global financial risks and potential risk-mitigation measures	WE Beyeler: NISAC
Society: Extremist Groups	Societal Security: Analysis of self-organized extremist group formation, activation and dissipation to identify potential threat mitigation measures	RJ Glass: DHS S&T
Enterprise: Military Industrial Complex	Conventional Military Security: Field a means for predicting success of wide variety of socio/technical inventions within a military field of application.	AL Ames: DOD
Infrastructures: Chemicals and Energy	Chemical Security: Evaluation of petrochemical networks and their dependencies on energy to identify the risks due to dependencies and propagating disruptions	WE Beyeler: NISAC, DHS S&T

CASoS	Application Domain: approach, perturbation and aspiration	Phoenix Lead & Funder
Infrastructure: Water	Water Security: Review existing uncertainty quantification and validity of a combined hydrological and macroeconomic analysis of U.S. climate risks	TJ Brown: Sandia LDRD
Infrastructure: Energy	Energy Security: Analyze the electric power network to identify conditions that influence network congestion, potential for cascades and risks due to electric power disruptions.	RJ Glass: NISAC
Infrastructure: Energy	Energy Security: Develop the ability to evaluate global energy system disruption impacts on national security	WE Beyeler: Sandia LDRD
Infrastructure: Natural Gas	Energy Security: Analyze the risk to natural gas supplies due to earthquake hazards in the New Madrid Seismic Zone (NMSZ)	TF Corbet: NISAC
Infrastructure: Petroleum Fuels	Energy Security: Analyze the risk to petroleum supplies due to earthquake hazards in the New Madrid Seismic Zone (NMSZ)	TF Corbet: NISAC
Society: Community	Population Health: Develop a containment strategy to control the spread of a pandemic strain of influenza	RJ Glass: NISAC, VHA
Society: National	Population Health: Analyze the potential risks and benefits of Tobacco Control Policy and develop effective strategies for reducing population health impacts due to tobacco use.	NS Brodsky: HHS/FDA
Enterprise: Veterans Health Administration (VHA)	Operational Security: Evaluate threats and design risk mitigation strategies for the Veterans Health Administration	NS Brodsky: VHA
Society: Community	Population Health: Develop a methodology for evaluating and improving incident response and recovery prioritization to reduce population health risks	PD Finley: NISAC
Society: Nation	Population Health: Analyze and compare effects of possible policy interventions to reduce the public health impact of obesity and overweight through the identification of effective policies	T Moore: HHS
Enterprise: Corporation	Operational Security: Design measurement and detection methods for evaluation of the enterprise's internal network structure	RJ Glass: Sandia Corporate
Society: Group - Pashtun Tribal Leadership	Societal Security: Evaluate the dynamics of Pashtun leadership selection to support the design of social network interventions	JL Schubert: Sandia LDRD, DoD Fellowship
Society: Nation	National Security: Design social network interventions to provide improve defense against, and resilience to, attacks on social networks	AL Ames: DOD
Enterprise: Military Industrial Complex	Nuclear Security: Evaluate the global dynamics of nuclear weapon proliferation and assess the effects of different nonproliferation strategies to develop robust strategies for reducing nuclear risks	AL Pregenzer: DOE Sandia LDRD
Society: Global	Trans Spectrum Global Security: Evaluate the global geopolitical dynamics to improve understanding of global interdependency and promote international security	RJ Glass: Perry Fellowship, CISAC-Stanford, Sandia Division 6000
Society: Nation	National Security: Behavioral Impacts on Markets and Infrastructure Operations	MS Aamir: NISAC

Across this Phoenix application space, we have identified a number of capabilities (both theoretical and environmental, the domains of Framework and Environment respectively) required to evaluate and design solutions for CASoS. These capabilities are actively driving development in a wide range of topics.

Table 2 summarizes the cross-cutting, capabilities developed to support the CASoS engineering modeling and analysis environment for Phoenix applications.

Table 2. Cross-Cutting Capability Development Projects

Capability Area	Capability Development Project	Phoenix Lead & Funder
Networks	Networks, dynamic networks and inter-network cascading : design of multi-network models to evaluate vulnerabilities to perturbations	RJ Glass: Sandia LDRD, FDA/CTP, VHA
Exchange Physics	The conservative exchange of materials that can then be transformed or consumed through productive processes (e.g., resources exchanged for money by entities within an economy)	WE Beyeler: Sandia LDRD, NISAC
Transfer Physics	The movement or spread of non-conservative constituents (e.g., diseases, ideas) on reactive dynamic networks (e.g., epidemics on social networks, opinion on social networks)	RJ Glass: NISAC, FDA/CTP, VHA
Behavior	Representation of entity behavior by finite or infinite state mathematics	WE Beyeler: NISAC, Sandia LDRD
Behavior	Evaluation of learning and behavioral models for generic entities	WE Beyeler: Sandia LDRD; VHA; FDA/CTP
Uncertainty Quantification	Develop rigorous methods to evaluate and rank modeled policy effectiveness in context of model uncertainty, provide metrics and information to characterize risks.	P Finley: Sandia LDRD, VHA, FDA/CTP
Validation and Verification	Identifying the true dynamical content of large dynamical models	AL Ames: AFOSR, DOD
Validation and Verification	Human, Social, and Cultural Behavior (HSCB): Design of a Generalized Validation & Verification Methodology	AL Ames: AFOSR, DOD OSD HSCB
Design of Measurement and Detection	Analysis of Web-based Social Media for Detection	AL Ames: Sandia LDRD

A more complete summary of each Phoenix application is provided in the Appendix. The summary includes links to references on the application, application goals, development supported, framework enhancements, leadership, and relationships to other organizations.

Figure 4 illustrates the evolution of our theoretical understanding and capability development moving the discipline from systems to complex systems to systems-of-systems to complex adaptive systems and on to our ever-evolving discipline of CASoS Engineering (black text), with examples of projects that we integrated (green text), and the application's external influence (blue text). The project to design community containment strategies for pandemic influenza motivated the transition from CASoS modeling and analysis to CASoS Engineering.

We are actively working to engage problem holders who fund our analysis with the understanding that their projects are building the discipline of CASoS Engineering. To grow the discipline, we need applications like those conducted for the NISAC pandemic studies and, currently, for the FDA tobacco control policy analyses that involve CASoS, where the goal is to design solutions that are effective because they are a part of the CASoS, adaptive and dynamic, and utilize the attributes of systems-of-systems. The community containment strategy for pandemic influenza was adopted because it is designed for adaptation to the characteristics of the disease and to local/regional conditions, and because it utilizes knowledge of social network structures to target required changes to slow disease spread and stop a pandemic.

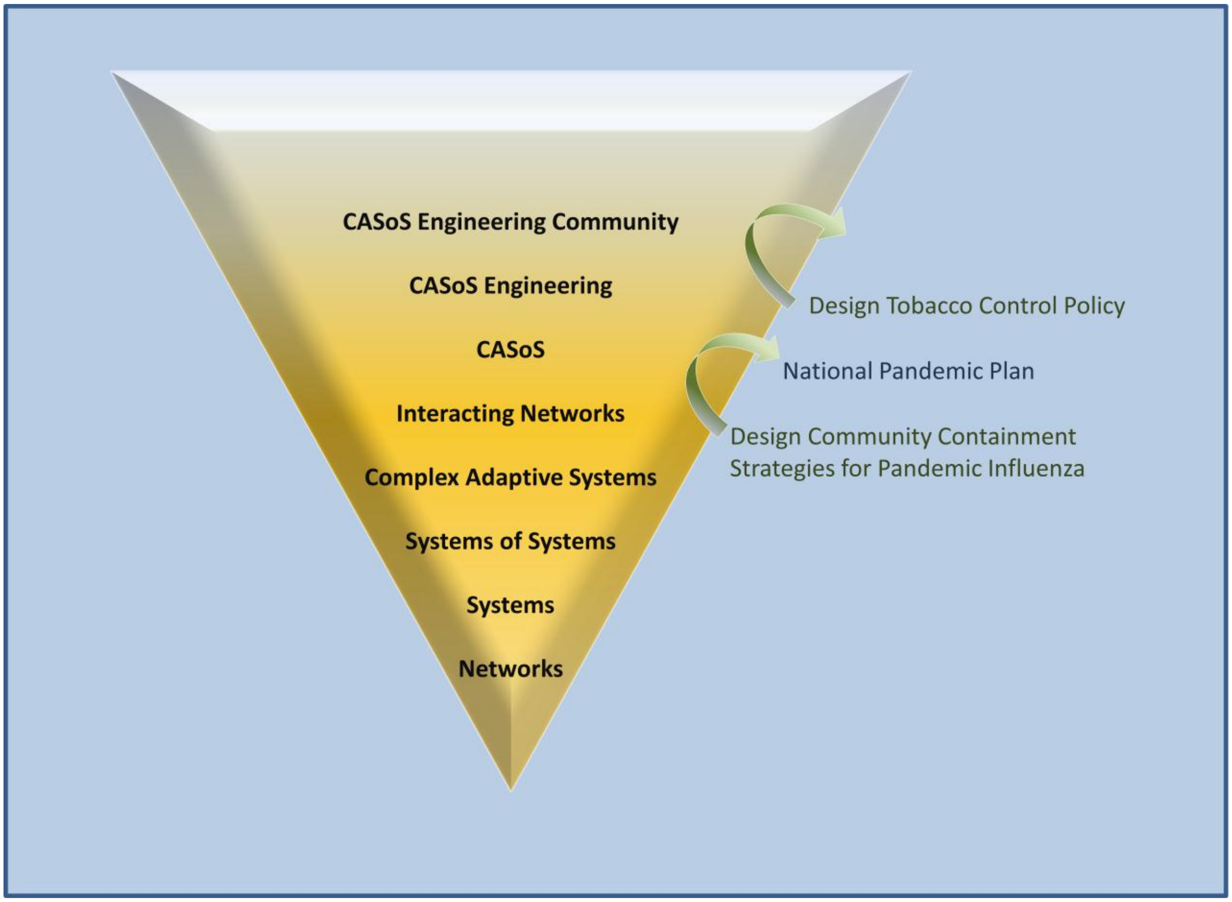


Figure 4. Evolution of Applications and Examples of Influence

Phoenix applications to date have touched on CASoS in a number of domains related to a diverse set of perturbations/disruptions (red nodes in **Figure 3**). The fact that an application has touched on a subject, provides a limited view of the Application gaps and a single problem analysis does not cover the entire range of the potential problem space.

4. CASOS APPLICATION DEVELOPMENT

Current CASoS applications are in various states of maturity and cover only a portion of the problem space important to national and global security. The development of a CASoS Engineering discipline also requires more complete understanding across the problem space. Applications necessary for optimal evolution of the discipline can be identified by evaluating the problem space from multiple perspectives including:

- partnerships with decision makers and experts (collaborators)
- the group of CASoS Engineers needed to solve this suite of national and global security problems
- the level of maturity in the understanding of key CASoS
- currently developed and deployed engineered solutions to national and global problems
- identification, development and testing of a fundamental set of models (such as exchange, infection, opinion dynamics) and performance metrics needed to solve CASoS problems

The next sections present CASoS engineering domain expertise development from the perspectives of people, systems, problems, and discipline. Tracking our developing capability and understanding helps us set priorities for new applications and target partnerships that will expand the knowledge base, create a community of practice and continue to mature the CASoS Engineering discipline.

4.1. People

Each of the CASoS of interest listed in **Table 3** is a very broad topical area with many decision makers and potential perturbations. The table only lists a few of the federal decision makers and broad categories of other levels of decision makers (e.g., states, industry). We have collaborations in most of the infrastructure categories, but there are key areas where we need to develop partnerships with decision making organization (e.g., NISAC is only one program within DHS). Blank cells in Table 1 represent gaps, where we have not yet established collaborative projects (Emergency Services, Government, Water, Enterprises).

Figure 5 depicts a network view of CASoS engineers, the infrastructures in which they have developed capabilities, the collaborations they have established with the funding agency, and relationships to experts within the field. The current areas of focus and CASoS Engineering capability development are in Agriculture supply chains, Healthcare and Public Health problems, Energy networks (electric power, petroleum and natural gas) perturbation impacts, Banking and Finance payment systems perturbations and policy impacts, Chemical supply chains, Transportation security and Information Technology perturbations. Healthcare is the most developed area as we are beginning to have multiple experts, funding sources and collaborations.

Table 3. Existing Partnerships, Engineers, and Gaps Showing Development Needs

Tie to Framework	Defining CASoS of Interest		People		
	Systems	Sub-Systems	Decision Makers	Collaborators	CASoS Engineers
Infrastructures		Agriculture and Food	USDA, FDA, DHS, States, Industry	NISAC, AON, FASD, NM	Conrad, Beyeler
		Banking and Finance	Treasury, Federal Reserve, Industry	NISAC, FRB-NY, Bank of Finland	Beyeler
		Chemicals	EPA, DHS	DOW, DHS S&T, NISAC	Downes, Beyeler
		Emergency Services	FEMA, States, Local		
		Energy	DOE, DHS, Industry, NRC,	NISAC, LDRD, RBAC Inc.	Glass, Corbet,
		Government	Federal, State and Local Agencies		
		Healthcare Public Health	HHS, CDC, NIH, DHS NBIC, State, Industry	VHA, FDA, UNM/PRC	Glass, Moore, Brodsky, Finley, Verzi
		Information Technology	FCC, DHS, Industry	Lucent	Kelic, Conrad
		Transportation	DOT, DOC, FAA, TSA, Industry	NISAC, TSA	Conrad
		Water	EPA, State, Local, Industry		
Enterprises		Businesses	DHS		
		Military Industrial Base - Nuclear	DOE, DoD		
		Military Industrial Base – Conventional	DoD		

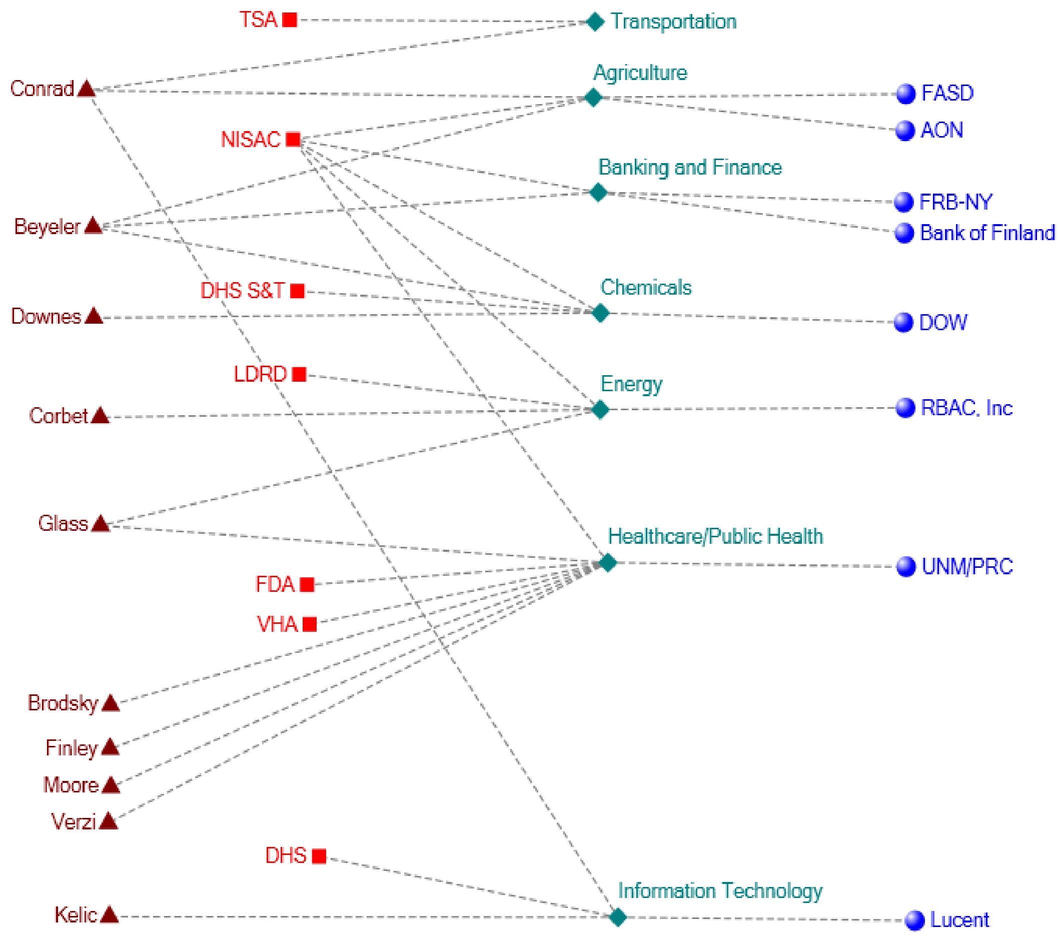


Figure 5. Network View of Existing Partnerships

Figure Note: Left to right: CASoS Engineers, Funding Entities, Infrastructures, and Industry Experts

4.2. Systems and Methodology Maturity

The CASoS Engineering Framework steps - identifying CASoS problems through system definition; defining aspirations; evaluating analytical needs (models, model design, scale of analysis, details of conditions and systems involved); and designing, fielding and evaluating solutions - represent different stages of maturity in our understanding and ability to reduce risks.

Table 4 provides a view into maturity through a comparative listing of infrastructures, the analytical capability developed, and any solutions designed using those capabilities. Our most mature capability, in population health, produced a design for containing the spread of influenza that was used to set the national planning policy. This is one of many problems within the public health and healthcare sector. Solutions can be devised based on an understanding of the system and how it will behave when perturbed, but solutions that are robust to uncertainty (those that produce better outcomes no matter the conditions) are the ones we strive to develop in cases where the consequences are severe.

The ability of systems to adapt can be part of problem solution as well as a risk factor. Adaptation has been handled in our models and analyses (up to now) by having condition-dependant behaviors, evaluating uncertainty through compliance with a particular rule or set of rules, or by allowing market forces to determine which entities receive resources. Model parameter uncertainties have been evaluated in our applications using Monte Carlo methods. Structural uncertainties and scaling issues have been treated using multiple modeling approaches. Including adaptation in behavioral models, developing statistics that are meaningful for evaluating CASoS and the development and testing of fundamental models are all areas where we need a concerted effort in order to evolve the discipline of CASoS engineering.

4.3. Problem Space

Table 5 provides a summary of applications in terms of the problem space and the metrics that are, or could be, used to evaluate system(s) performance. This table reveals more obvious gaps than the previous tables which focused on the existing capabilities; but is still an oversimplification of the problem space. For example, climate change will have impacts globally that could create national security, population health, supply chain and economic impacts. The impacts will be different due to heterogeneity in the climate, physical, economic and geopolitical conditions. The types of problems climate change could initiate span the problem space – natural disasters, geopolitical conflict, economic destabilization, changes in disease vectors and supply chain perturbations.

4.4. Discipline

We have begun to develop a set of fundamental models, such as resource exchanges, contagion spread, and opinion dynamics, which can be adapted and utilized for representing and solving a wide range of CASoS problems. As new applications are developed, we may identify and develop additional examples of these fundamental models. Each of the models matures through testing, applications, publication and peer review. **Table 6** lists the models and analytical capabilities identified through our existing Applications and the maturity of their development relative to the artifacts produced and confidence building to date. We are in the first iteration of confidence building for these models and in the early stages of development of the fundamental analytical capabilities.

Table 4. Existing Applications by CASoS of Interest Relative to Systems and Methodology Maturity

Tie to Framework	Defining														Designing	Testing	Evolve	People		
	CASoS of Interest		Aspiration	Methods																
			(Predict,	Methodology/Implementation State		Spatial Scale of CASoS Analysis Capability				Breadth of initial analysis capability					mitigation design	design	system	Decision		CASoS
	Systems	Sub-Systems	Prevent,	Conceptual Model	Models	Local	Regional	National	Global	disruption impacts	dependencies	adaptations	uncertainties	sensitivity		testing	evolution	Makers	Collaborators	Engineers
		Agriculture and Food	Predict	supply chains, production cycles (dynamics)	beef-dairy-corn cycle; sprout supply chain (stochastic)	for NM sprout supply	for sprout supply chain	yes	limited to conceptual models and boundary conditions (beef, sprouts)	yes - for beef cycle, limited application to feed supply and disease scenarios	yes for beef-corn-dairy interdependencies	alternative supplies and demand/pricing effects	stochastic mapping for sprouts	limited for beef cycle	for 1 threat to beef cycle			USDA, FDA, DHS, States, Industry	NISAC, AON, FASD, NM	Conrad, Beyeler
		Banking and Finance	Predict	global payment systems, monetary policy, exchanges	payment networks, monetary networks linked by currency exchanges	no	no	payment system	monetary	yes	no	loss of confidence, monetary policy implementation		of congestion in payment systems to parameters; of liquidity to policy making	elimination of competing monetary policy (simultaneous implementation), liquidity targets			Treasury, Federal Reserve, Industry	NISAC, FRB-NY, Bank of Finland	Beyeler
		Chemicals	Predict	supply chains, production cycles (dynamics)	supply chain network impacts	economic impacts	yes for a few supply chains	yes for a few supply chains	yes for a few supply chains	yes for a few supply chains (need updated list)	yes for petrochemical production dependencies on natural gas							EPA, DHS	DOW, DHS S&T, NISAC	Downes, Beyeler
		Emergency Services	Prepare															FEMA, States, Local		
	Infrastructures	Energy	Predict, Prepare, Control	global energy dynamics - nation states, national supply networks with storage and condition dependent demand	natural gas network, petroleum network	no	within the national	yes	as boundary conditions	yes, limited application to NMSZ earthquake planning and hurricanes		re-routing of flows			very limited, identification and quantification of the benefits of additional capacity/network changes			DOE, DHS, Industry, NRC,	NISAC, LDRD	Glass, Corbet,
		Government	Prepare	regulatory and policy impacts/role for selected problems														Federal, State and Local Agencies		
		Healthcare/Public Health	Predict, Prevent, Prepare	epidemics, VA operations, prevention (limited in scope)	social network models, discrete event model, SD model for contagions	yes with all 3 types of models	yes with all 3 types of models	yes with SD model	no	impacts on population health (all 3 types of models), impacts on healthcare (SD models), impacts on infrastructure capacities (SD models, analysis)	through analysis	behavioral responses (e.g., compliance with policy) impacts on epidemics (social network model)	for epidemics: disease parameters, population response	general capability under development; SA for 1918 like influenza completed for generic community (social network, SD) and national outcomes (SD)	community containment strategy, costs and benefit analyses	National Policy issued		HHS, CDC, NIH, DHS NBIC, State, Industry	VAH, FDA	Glass, Moore, Brodsky, Finley
		Information Technology		Cyber-Banking and Finance						loss of confidence due to cyber perturbaiton scenarios - conceptual model								FCC, DHS, Industry	Lucent	Kelic, Conrad
		Transportation	Predict	air security operations performance under policy changes	SD model of individual site operations	yes	no	no	no	changes in screening effectiveness, M&O costs		worker performance			staffing needs			DOT, DOC, FAA, TSA, Industry	NISAC, TSA	Conrad
		Water																EPA, State, Local, Industry		

Table 5. Identification of Application Gaps Relative to Integrated Risk Analysis Problems and Metrics

CASoS - Metric	CASoS Problem Space												
	Global Perturbations				Regional - National Perturbations						Local Perturbations		
	Climate Change	*Political Destabilization /War*	*Economic Destabilization*	*Pandemics*	*Regulation Changes*	*Natural Disasters*	*Terrorist Attacks*	*Policy Changes*	*Infrastructure - Regional Disruptions*	*Disease outbreak*	*Business Failures*	*Infrastructure - Local Disruptions*	*Contamination Incident*
Global Trade								beef embargos					
National Security								payment system congestion					food contamination stochastic mapping
Population Health				1918-like influenza impacts on US; mitigation design	tobacco - conceptual model; mathematical model development underway (multiple policy; multiple products; mitigation design)	earthquake scenarios, hurricanes	scenario analyses						
Enterprise Health										hoof and mouth impacts on beef supply			
Infrastructure Supply Shortages/Disruptions						earthquake scenarios, hurricanes	transportation adaptation and impacts; economic impacts						
Economic Impacts													

Table 6. Identification of Gaps in Development of CASoS Engineering as a Discipline

Tie to Framework:	Defining Stage									Designing Stage	Testing Stage
		Products: artifacts		Products: confidence building/iterative development							
Tie to Environment:	**Physics**	**Code**	**Application Space**	**Publication**	**Peer Review**	**Enhancement**	**Testing**	**Publication**	**Peer Review**		
Foundational Modeling	Disease Spread	Loki-Infect	Applied to community containment strategy design for 1918-like Influenza Pandemic	SAND Report, Multiple Journal Articles	Multiple by external groups and agencies during development and with journal articles	Contagion Model				Robust community containment strategy	National pandemic planning policy implemented
	Opinion Dynamics	Modified Contagion model	Applying it to tobacco smoking prevalence as a function of policies (business and government)	Conferences, Journal Articles in development	Limited to partners review, conferences						
	Financial Transactions	Loki-transact	Applied to FEDWIRE to evaluate conditions that lead to congestion in the payment system	Journal Article	Co-developed with FRB - NY, journal article	Exchange Model					
	Supply Chains	Exchange Model	Applied to petrochemical production capacities, natural gas network and petroleum products networks (crude oil and refined products). Identified need for additional foundation model for networks with seasonality and testing/comparison of models for supply chains with and without storage	SAND Reports							
	Contaminant Transport	Exchange Model with contaminant tracking	Applying it to sprout (fresh produce) supply chain and evaluating utility of stochastic mapping	SAND Report							
	Global Energy Dependencies	GES Model	Developed modeling framework	SAND Report		Nation State Model					
	Nation State Interactions/Dependencies	Nation State Model	Evaluating climate impacts, developing national health metrics								
Foundational Analysis	Sensitivity										
	Uncertainty										
	Mitigation Design										
	Dynamics										
	Network Capacities/Thresholds (phase-space)										

5. NEW APPLICATIONS

The process for generating new applications is based on the following principles:

- Clearly identify gaps (see Section 4)
- Prioritize the gaps based on immediacy of issues and ability to leverage existing capabilities
- Develop artifacts to focus plans
- Be ready to assemble team and address opportunities as they arise

The priorities, based on the immediacy and scope of problems, are: full-spectrum global security, engineered climate adaptation; design and dissemination of population health solutions to address obesity; and understanding cyber risks. There are problems that would benefit from our existing capabilities such as, evaluation of the potential effectiveness of new health policies, evaluation of global supply chain risks and design of risk mitigation strategies for population health and supply chain risks. There are capabilities that would benefit all applications, particularly development testing and automation of uncertainty quantification methods for classes of CASoS problems, statistics of failure for CASoS and testing and peer review of the foundational models and analyses.

Artifacts can be developed in several ways: through Laboratory Directed Research and Development (LDRD), through individual investment and through collaborative investment such as a workshop activity. The workshop concept is a proposed mechanism for applying CASoS Engineering in a new problem space and will be tested in 2012. The premise for this activity is that the workshop format will create an initial model and establish collaboration partnerships that are needed to initiate successful projects in new areas. The Phoenix group will hold a series of workshops with key partners (e.g., industry, government, academia and analysts) to identify common problems and begin developing modeling and analysis capabilities for engineering risk management strategies for specific CASoS.

One of the most obvious gaps in capability (see **Table 4** and **Table 5**) is in understanding Enterprise risks and the need for industry partnerships. One workshop will focus on a select set of corporate enterprises; a second will focus on a select set of government enterprises. The goals of each workshop are listed below.

Workshop Goals

1) Provide an introduction to CASoS Engineering and how it can be used to manage interdependency problems
2) Produce a conceptual model of interdependencies for each enterprise represented. The artifacts produced will include:
    a) an *influence diagram* of their CASoS
    b) a list of *critical system measures*
    c) a list of *threats* and how they might interact with the CASoS (add to conceptual diagram)
    d) a list of *mitigation/prevention policies* and how they might interact with the CASoS (draw on the diagram)

3) Conceptual models described in sufficient detail to allow a team to build an initial mathematical model

4) Partners' agreement to participate on a modeling and analysis team based on an defined path forward

5) Identify joint projects and appropriate funders

The Phoenix CASoS Engineering Initiative will continue to work on Applications as they arise including LDRDs, providing analysis of potential policies for the FDA CTP, developing capabilities and conducting operational analyses for the VHA and NISAC programs.

SUMMARY

Complex Adaptive Systems of Systems, or CASoS, are ubiquitous: they include people, organizations, cities, infrastructure, government, ecosystems, the Planet – in short, nearly everything that involves biological and social systems. Designing influence within CASoS, or CASoS Engineering, is the mapping of aspirations to problem solutions within this domain. The sheer complexity of CASoS, the subtlety of their adaptive behaviors, the difficulty of running experiments, and the problems of integrating the different analytic frameworks and representations required to understand their component systems underscores the need for new theory, methods and practice. Applications are the driving force of this effort.

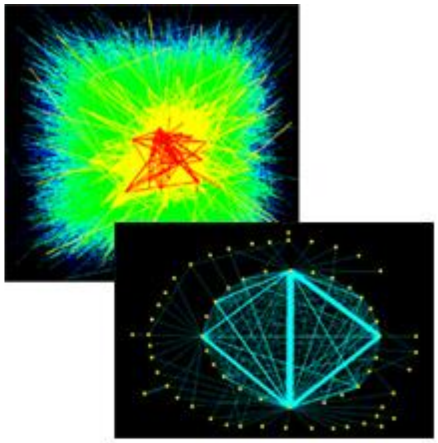
CASoS embody the world's biggest problems and opportunities. Engineering theory and practice must be developed together to create a discipline that is grounded in reality, extends our understanding of how CASoS behave and allows us to better control the outcomes. Applications provide an opportunity to engineer solutions to problems within CASoS while growing a community of practice and establishing the CASoS Engineering discipline. With the active collaboration of problem holders, Phoenix's structure is being driven using technical objectives focused on overarching problems across many applications and through recognition that the Initiative itself is a CASoS. As a CASoS, our definition and development intrinsically and continuously emerges from application; our internal structure grows and changes both the Initiative and the environment in which it exists.

This document will be updated periodically to reflect our growth.

APPENDIX: CONTRIBUTING APPLICATION PROJECT DESCRIPTIONS

Phoenix Applications are summarized briefly below. Additional information is available in the references listed for each project. The Phoenix website contains the most current application and publication information (http://www.sandia.gov/CasosEngineering/index.html).

A-1. Network Congestive Failure Risks



Problem Space: Network Congestion and Cascading Failures in Infrastructures

Cascading failure can occur with devastating results within and between infrastructures. The Advanced Modeling and Techniques Investigations (AMTI) group within the National Infrastructure Simulation and Analysis Center (NISAC) synthesized and extended the large variety of abstract cascade models developed in the field of complexity science and began applying them to specific infrastructures that might experience cascading failure to identify theories, methods, and analytical tools from the study of general complex adaptive systems that are useful for understanding the structure, function, and evolution of complex interdependent critical infrastructures.

For this problem area, the group developed a comprehensive model, Polynet, which simulates cascading failure over a wide range of network topologies, interaction rules, and adaptive responses as well as multiple interacting and growing networks. We applied this model to analyses of the electric power grid and of Fedwire, the US Federal Reserve's transaction network.

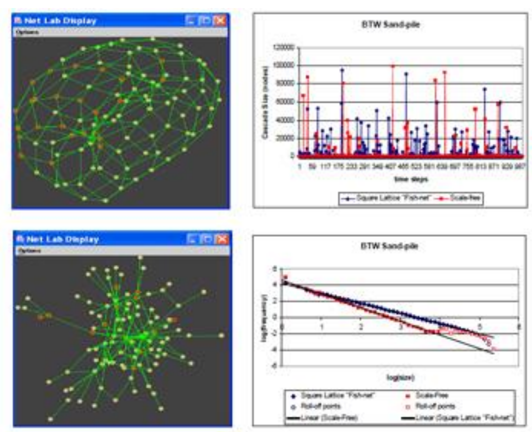
A-1.1 Cascading Failure In The Electric Power Grid

- Goal /Aspiration for Project

  Develop modeling and analysis capability for the U.S. electric power grid that will allow us to identify system conditions and perturbations that could lead to congestion in transmission, increasing the risk of regional power disruptions. Evaluate how congestion could be caused by deliberate attack or random failures and how controls influence the likelihood of congestion.

- Approach/Methods/Models

  Developed Loki Power, an abstract representation of the Western Electric Coordinating Council (WECC) high-voltage electric power transmission network, in 2004, and conducted experiments to identify conditions that increase the likelihood of congestion.



Example stylized network topologies (at left; fishnet above, scale-free below) and time series for cascade size (above) and cascade size distributions (below).

- Findings and Next Steps

  For the stylized electric power grid, our initial simulations demonstrate that the addition of geographically unrestricted random transactions can eventually push a grid to cascading failure, thus supporting the hypothesis that actions of unrestrained power markets (without proper security coordination on market actions) can undermine large scale system stability.

  We also find that network topology greatly influences system robustness. Homogeneous networks that are "fish-net" like can withstand many more transaction perturbations before cascading than can scale-free networks. Interestingly, when the homogeneous network finally cascades, it tends to fail in its entirety, while the scale-free tends to compartmentalize failure and thus leads to smaller, more restricted outages.

Other applications for this capability include design of network structures or controls that reduce the probability of congestion and limit the extent and duration of cascades; evaluation of robustness of new electric power grid topologies and characteristics (distributed generation, increased use of renewable power, increasing stored power); and evaluation of the robustness of other types of systems (financial, communication, transportation fuels, distribution networks).

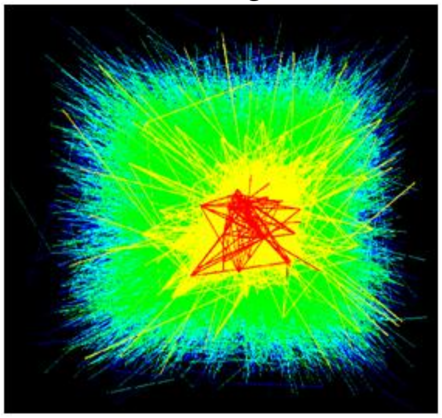
- New Capabilities
  - Loki-Power
  - Network topology and conditions effect on congestion risk.
- Publications
  - Advanced Simulation for Analysis of Critical Infrastructure: Abstract Cascades, the Electric power grid, and Fedwire
  - Sensitivity of the resilience of congested random networks to rolloff and offset in truncated power-law degree distributions

A-1.2 Cascading Failure in Fedwire

- Goal/Aspiration for Project:

  Develop modeling and analysis capability for Fedwire, the large transaction network in the U.S. financial system, which will allow us to identify system conditions and perturbations that could lead to network congestion. Identify conditions and network characteristics that lead to congestion and methods for reducing the likelihood and extent of congestion.

- Approach/Methods/Models:

  Working with the Federal Reserve Bank of New York, refined the problem description and designed the model and analysis. Developed a network model of Fedwire and conducted sensitivity analyses to identify conditions that increase the likelihood and extent of congestion in the payment system. Insights about the network topology and model sensitivity analysis used to identify actions that reduce congestion risks.

  For network congestion applications, the group developed a comprehensive model, Polynet, which simulates cascading failure over a wide range of network topologies, interaction rules, and adaptive responses as well as multiple interacting and growing networks. Polynet was tested by implementing the classical Bac, Tang, and Wiesenfeld (BTW) sand-pile in several network topologies and compared to the results from other models. The interaction rules in Polynet were tailored to represent Fedwire, a Federal Reserve network service for sending large-value payments between banks and other large financial institutions.

  The Fedwire network model is defined by Fedwire transaction data: payments among more than 6500 large commercial banks, with typical daily traffic of more than 350,000 payments totaling more than $1 trillion. The node degree and numbers of payments follow power-law distributions and bank behavior is controlled by system liquidity. Payment activity is funded by initial account balances, incoming payments, and market transactions; payments are queued pending funding; and queued payments are submitted promptly when funding becomes available.

- Findings and Next Steps:

  This set of studies found that payment flows follow a scale-free distribution and system performance is a function of both topology and behavior – neither alone can explain system robustness to disruptions (such as the loss of a bank). Liquidity limits can lead to congestion and limit throughput, but performance can be greatly improved by moving small amounts of liquidity to the places where it's needed. There are three time constants that control congestion: liquidity depletion time, net position return time and liquidity redistribution time through the market.

- New Capabilities
  - Polynet
  - Loki-Fedwire
  - Network topology and condition effects on congestion

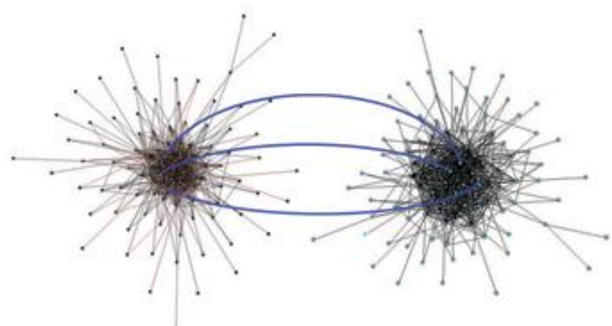
A-1.3 Payment Systems

Modern economies depend on efficient and reliable financial markets. Critical to the smooth functioning of these markets are a set of trading, payment, clearing and settlement infrastructures. Financial infrastructures are formed by a large number of technological and institutional components that interact within complex networks. Congestion in a payment system is both a cause and a consequence of reduced transfer capacity

We conducted a series of analyses with the goal of understanding how congestion arising from this stress is influenced by two control parameters: the global liquidity level and the conductance of a global liquidity market.

- Goal /Aspiration for Project:

  Identify the basic parameters that control the quality of operation of payment systems, and characterize the problems that can arise when performance degrades; identify the effects of coupling among payment systems, and how different policies influence their performance.



- Approach/Methods/Models:

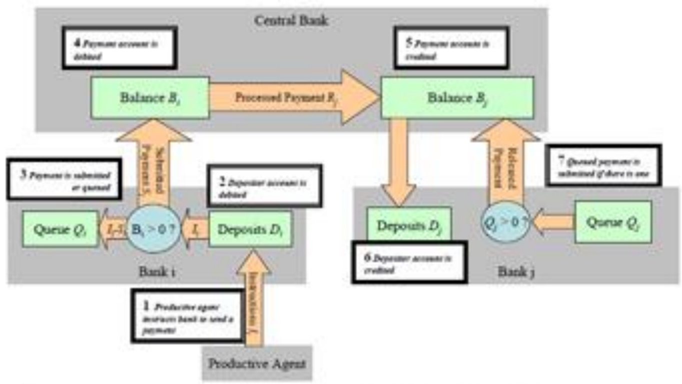
  Develop a parsimonious CAS model of the interbank payment system to study congestion and the role of liquidity markets in alleviating congestion. The model incorporates an endogenous instruction arrival process, scale-free topology of payments between banks, fixed total liquidity that limits banks' capacity to process arriving instructions, and a global market that distributes liquidity.

  Develop a model of multiple payment systems iterating through coupled transactions, such as foreign exchange transactions

- Findings and Next Steps

  We find that at low liquidity the system becomes congested and payment settlement loses correlate with payment instruction arrival delays. The onset of congestion is evidently related to the relative values of three characteristic times: the time for banks' net position to return to zero, the time for banks to exhaust their liquidity endowments, and the liquidity market relaxation time. In the congested regime, settlement takes place in cascades having a characteristic size. A global liquidity market substantially diminishes congestion, requiring only a small fraction of the payment-induced liquidity flow to achieve strong beneficial effects.

  Loki Transact allows us to evaluate liquidity and credit risks in the context of interdependent interbank payment systems interlinked through foreign exchange transactions. Further interdependence is created by a Payment versus Payment (PvP) constraint that links the two legs of the foreign exchange transactions. Using this model, the team identified conditions under which payment settlement in the two systems becomes correlated and showed that large credit exposures can be generated as the result of liquidity pressures in one of the two systems. PvP can eliminate this credit risk but creates a new interdependence by making settlement of payments in both systems dependent on the level of liquidity available in the other system.



Payment system components and state variables considered in the model, and their response to a payment instruction event

- CASoS Goals: General Capabilities
  - Loki-Transact
  - Interacting, adaptive networks
- Publications
  - Modeling Banks' Payment Submittal Decisions (2005)
  - Network relationships and network models in payment systems (BoF 2005 P)
  - Network Topology and Payment System Resilience - first results (BoF 2005)
  - The Topology of Interbank Payment Flows (2006)
  - Congestion and Cascades in Payment Systems (2006)
  - The Topology of Interbank Payment Flows (2007)
  - Congestion and Cascades in Payment Systems (2007)
  - New Approaches for Payment System Simulation Research (2007)
  - The Payments System and the Market of Interbank Funds (2007)

- Congestion and Cascades in Coupled Payment Systems (2007)
- Performance and resilience to liquidity disruptions in interdependent RTGS payment systems (Theme 4 2008)
- Congestion and Cascades in Interdependent Payment Systems (2009)

A-2. Population Health

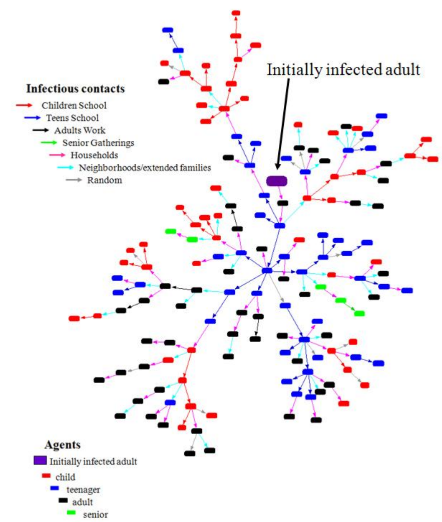
Problem Space:

Populations are vulnerable to novel strains of contagious diseases for which we have not developed immunity through exposure or pharmaceuticals (antiviral, vaccine, or antibiotic). Other “epidemics” such as smoking, obesity, alcoholism, caused by widespread, unhealthy behaviors have significant costs and damage the overall health of the society. For this problem area, we have developed social network models through which a contagion is propagated. This model has been utilized for evaluating the risks posed by diseases (e.g., pandemic influenza) and habitual behavior (e.g., smoking) and to engineer solutions.

A-2.1 Pandemic Influenza Containment Strategy

- Goal /Aspiration for Project

  Develop modeling and analysis capability that will allow us to identify methods for containing a 1918-like pandemic strain of influenza until a vaccine can be developed, distributed and administered. The goal of this analysis is to identify strategies that are robust to uncertainty (reduce the population health impacts without causing serious economic impacts when we have limited knowledge of the virus characteristics, what level of compliance will be attained with the policy and the population susceptibility).



- Approach/Methods/Models

  Developed a community-level model of disease spread at the individual level through multiple, linked social networks (individual-based, interacting social network model of disease spread and mitigation). Defined disease and intervention strategy scenarios to evaluate the uncertainties and identify and compare proposed intervention strategies. Evaluated network structure and model results for no-intervention cases that helped us identify additional intervention strategies. Ran a suite of scenario simulations to quantify uncertainty and evaluate the performance of the mitigation strategy under uncertainty. Analyzed the results and reviewed the outcomes with healthcare experts. Addressed experts review comments using additional simulations to build confidence in the recommended actions. Refined and submitted a community-based containment strategy design

- Findings and Next Steps

  Working with the National Security Council, this work was used to design the CDC’s policy for responding to potential pandemic strains of influenza.

- New Capabilities
  - Loki- Infect
  - Interacting, age-based (children, teen, adult, senior) social network models

- Publications

- Health Outcomes and Costs of Community Mitigation Strategies for an Influenza Pandemic in the United States, *expedited publication*, (2010) PubMed Summary

- Infectious Disease Modeling and Military Readiness (2009)

- Pandemic Influenza and Complex Adaptive System of Systems (CASoS) Engineering (2009)

- Robust Design of Community Mitigation for Pandemic Influenza: A Systematic Examination of Proposed U.S. Guidance (2008)

- Social Contact Networks for the spread of pandemic influenza in children and teenagers, *highly accessed*, (2008)

- Rescinding Community Mitigation Strategies in an Influenza Pandemic (2008)

- Design of Community Containment for Pandemic Influenza with Loki-Infect (2007)

- Targeted Social Distancing Design for Pandemic Influenza, *expedited publication*, (2006)

- Local Mitigation Strategies for Pandemic Influenza (2005)

A-2.2 Evaluating Threats and Designing Mitigation Strategies for the Veterans Health Administration

- Goal /Aspiration for Project

  Develop a model the health care system of the VHA as a complex adaptive system of systems, assess the effects of threat scenarios of consequence, and develop appropriate mitigation strategies to counter those threats.

- Approach/Methods/Models

  Decomposed the VA health care system into the fundamental building-blocks of medical physics, organizational physics, and social physics and developed a model that allows the investigation of how local policies affect the organization as a whole. Developed an analysis framework for quantifying organizational behaviors and identifying constraints within complex hierarchical networks

Three fundamental building blocks needed to model a healthcare system: medical physics, organizational physics, and social physics.

- Findings and Next Steps

  Successfully demonstrated initial model implementation of fundamental medical and organizational physics, both in steady-state and under perturbation (threat), for a single Medical Service Unit (MSU) and a network of MSUs

  Next steps are to generate results for a network of healthcare facilities subjected to two types of surges in demand: 1) a spike, representing a natural disaster which introduces patients with acute trauma requiring immediate treatment, and 2) a steady increase in demand imposed by the increasing prevalence of hepatitis C, which can result in a population with a significantly increased burden of end-stage liver disease and hepatocellular carcinoma. Policy actions to be evaluated include striking the right balance between medical center-level policies and network-level policies (issues of multi-level selection), cost-effective resource utilization, and mediating resource conflicts.

- New Capabilities

  - a general framework for public health action that uses medical physics, organizational physics, social physics, perturbations, and uncertainty quantification as fundamental components
  - a flexible timer-based simulation mechanism, that supports both stochastic and deterministic execution

- Publications

  - 8th International Conference on Complex Systems, June 2011, Quincy, MA (ICCS 2011 Proceedings available for download)

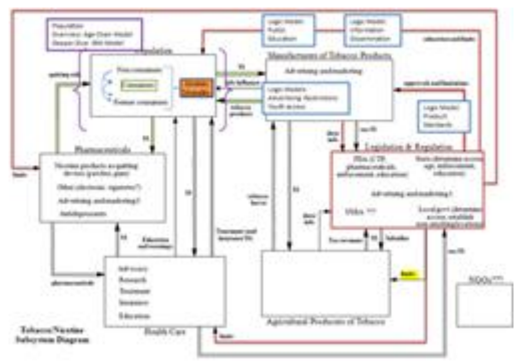
    - Analyzing Public Health Care as a Complex Adaptive System of Systems
    - Extending Opinion Dynamics to Model Public Health Problems and the Evaluation of Policy Interventions

A-2.3 Tobacco and Tobacco Control Policy Impacts on Population Health

- Goal /Aspiration for Project

  Develop the capability to fully analyze tobacco-related policies for the purpose of reducing the morbidity and mortality associated with tobacco use. This can include assessment of direct and cascading consequences of potential policies, generation of new and creative methods, and potential engineering of the CASoS.

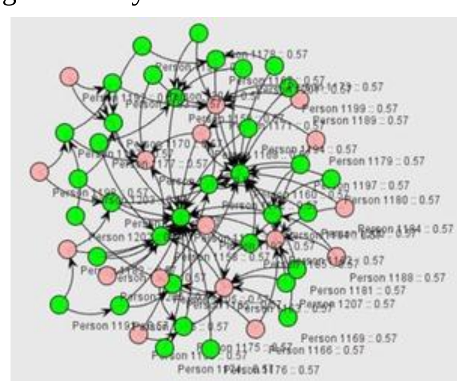
- Approach/Methods/Models

  The CASoS Engineering Framework guides the project, including identification of essential tobacco system components, processes, relationships, and interactions, and development of a flexible and dynamic modeling framework for analyzing the effects of potential tobacco-related policies on population health and mortality. This framework will simulate the complex systems involved in tobacco regulation, including:

  - tobacco product development and marketing
  - consumer initiation, use, cessation, and relapse
  - non-user perceptions and behaviors
  - morbidity and mortality associated with tobacco product use

  The relative efficacy of combinations of possible courses of action will be assessed with regard to population harm or benefit. Because the landscape of tobacco regulation will continue to evolve in coming years, the structure of the modeling framework is being developed to allow rapid adaptation and incorporation of new data as they become available. The modeling framework represents tobacco use behaviors (by, for example, age, socioeconomic group, and demographics), control policies, products, advertising, and possible adaptations. Multiple viewpoints, scales, and approaches are necessary for capturing various aspects of the problem space. We are using a multi-modeling approach for integrated analysis that includes:

  - System Dynamics stock and flow models
  - Individual-Based / Agent-Based models
  - Game Theoretic models
  - Models of Innovation

- Findings and Next Steps

  Work started on this project in May 2010 as part of a 5-year program. We have developed the conceptual model, initial models of opinion dynamics for smoking and a population simulation module for evaluating population health.

- New Capabilities
  - Snapdragon – an enhanced social network-based opinion dynamics model
  - Discrete Event Population Simulation Model (DE-PSM)
- Publications
  - 29th International Conference of the System Dynamics Society, July 2011, Washington, DC
    - Developing a theory of the societal lifecycle of cigarette smoking: Explaining and anticipating trends using information feedback
  - 8th International Conference on Complex Systems, June 2011, Quincy, MA (ICCS 2011 Proceedings available for download)
    - Extending Opinion Dynamics to Model Public Health Problems and the Evaluation of Policy Interventions
    - Integrating Uncertainty Analysis into Complex-System Modeling to Design Effective Public Policies
    - Application of a Complex Adaptive Systems of Systems Analysis Approach to Tobacco Products
    - Applications of Self-calibrating Causal-Learning Systems to Opinion Dynamics Modeling

A-3. Global Systems

Problem Space:

Global systems evolved to exchange resources between nations, businesses and people. These systems depend on financial transactions and reliable exchanges. Energy, Food, Transportation, Communication, Financial and Government systems form the basic infrastructure of global trade.

A-3.1 Global Energy Systems (GES)

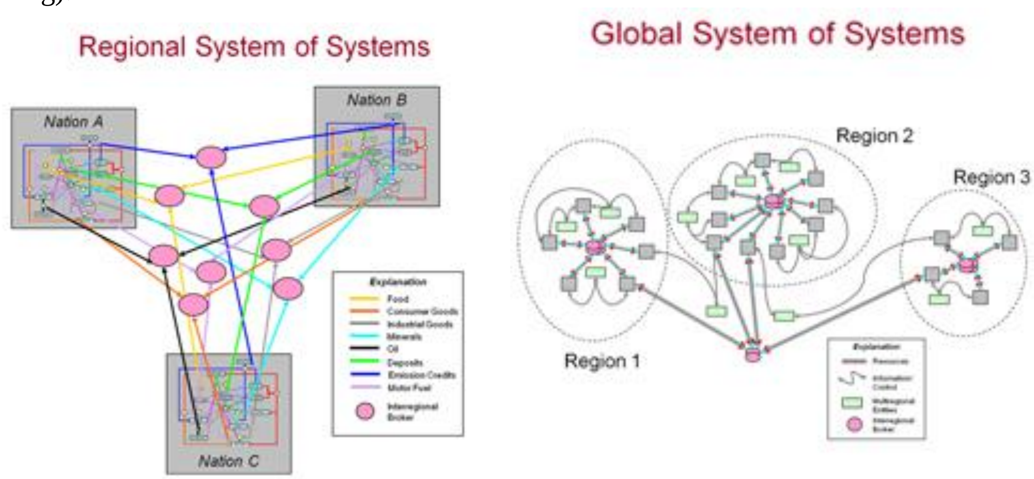
- Goal /Aspiration for Project

  Evaluate effective means of achieving energy security or surety while meeting global carbon goals. For the GES, we delineated a set of three nested Goals at increasing scale. The goal at each scale is to create a pattern of energy supply that supports essential activities and that is robust to disruptions that arise from human activities (such as shifting economic and political relationships) and from the physical system (changes in climate and encountering boundaries of resource supply).

  - National Transportation Energy Security: specific energy need at the scale of the nation
  - National Energy Surety: all energy needs appropriately interconnected with other sectors (e.g., agriculture, economic output) at the scale of the nation
  - Global Energy Surety: all energy needs appropriately interconnected with other sectors at the scale of the globe

- Approach/Methods/Models

  After defining the GES as a CASoS and an object of engineering, we formulated a conceptual model for multi-scale analysis of the GES to evaluate the effective means of achieving energy security or surety while meeting global carbon goals. The model represents interacting entities at a variety of scales (nations, industries, consumers) that have resources (material, funds, energy), technologies (transform resources, emit CO_2) and competing needs (energy surety, standard-of-living).



- Findings and Next Steps

  A simplified version of the model was implemented and preliminary analyses of two test cases were conducted. The limited purpose of these simulations was to test the model's ability to produce selected qualitative responses that would be expected in a real system that matched the model constraints: an overall increase in power price as a finite fuel resource is depleted, and an increase in power price and decrease in usage if carbon emissions associated with fossil fuel use are taxed. The behavior of the initial model conformed to important qualitative expectations about the real system.

As Next Steps to accomplish our objectives we will draw on and extend our new model constructed though this project. Three model extensions are required: a more complex and complete basic economy in a single region, multiple regions with varying endowments reflective of mature, emerging, and developing economies and a larger set of regions and a hierarchical structure of market interactions among them to reflect nations interconnected by trade agreements and common or readily convertible currencies.

Analysis using the extended model will evaluate the components of surety and economic performance on a global and entity level and can be used to evaluate the robustness of the policy and the critical enablers required to create system resilience.

- New Capabilities
  - GES model
- Publications
  - A General Engineering Framework for the Definition, Design, Testing and Actualization of Solutions within Complex Adaptive Systems of Systems (CASoS) with Application to the Global Energy System (GES

A-3.2 Global Financial System

- Goal /Aspiration for Project

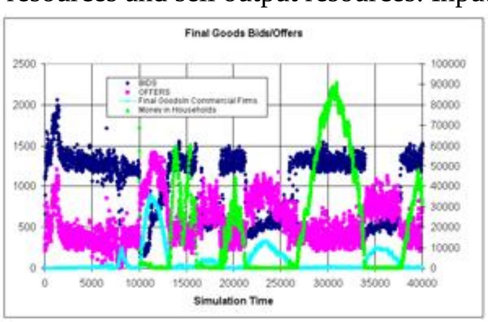
Identify system conditions and perturbations that could lead to disruptions in financial markets severe enough to degrade the national or global economy. Elucidate how large recurrent instabilities in financial systems arise, how they might be controlled and how controls influence economic growth.

- Approach/Methods/Models

Developed CAS models of interacting, large-transaction, financial and currency exchange networks interacting with economic production. Conducted sensitivity analyses to identify conditions that increase vulnerability and scenario analyses to evaluate potential consequences of policies on economic stability and growth.

- Findings and Next Steps

Developed an abstract model of entities that interact through markets in order to obtain input resources and sell output resources. Input and output resources for an entity are determined by its



productive process, which is modeled as a set of coupled chemical reactions. This formalism captures the behavior of economic firms as well as financial actors. The model accommodates innovation in production processes and the creation of novel resources including financial instruments: these processes are essential components of growth in both economic and financial systems. Exchange behavior is influenced by entities' forecasts about future conditions and their perception of the stability of those conditions. This process is an essential part of the model because changes in risk perception are a universal feature of financial crises.

The model has been implemented, and simple configurations have been explored to identify sensitivities.

- New Capabilities
  - Loki-Transact
  - Interacting, adaptive networks
- Publications
  - Analysis of the Global Financial System (GFS): Definition, Aspirations, Conceptual Model Development and Initial Phase Implementation (2008)
  - Global Financial System Analysis Capability Development (2009)

A-4. Supply Chains And Networks

Problem Space:

Supply chains depend on multiple systems and infrastructures (e.g., raw material production, energy, labor and transportation) and often represent a complex, globally distributed, multistage development chain. Understanding how these components work together under normal and disrupted conditions is critical for accomplishing the asset prioritization, consequence assessment, and policy guidance efforts.

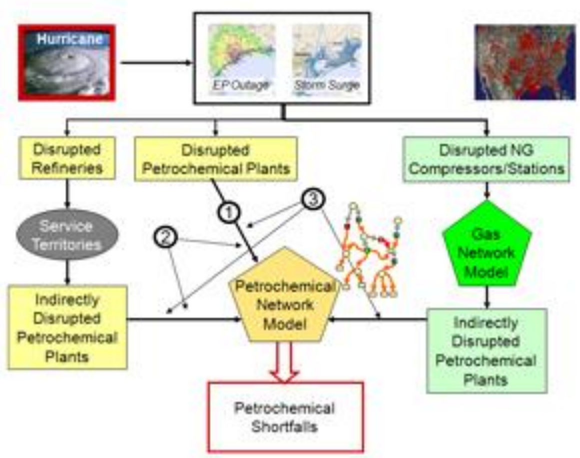
A-4.1 Petrochemicals

- Goal /Aspiration for Project

  Evaluate potential supply-chain impacts of disruptions in the petrochemical sector (steady-state) and develop a modeling, simulation, and analysis capability to assess sector vulnerabilities, its interdependencies with other critical infrastructures, its potential impacts from disruptive events (such as manmade and natural disasters), and its overall economic resilience.

- Approach/Methods/Models

  Developed a data-driven network model of the petrochemical supply chain then utilized several common measures of network topology to identify the processes and products that are "important" from the standpoint of the structure of this network. Definition of the edges connecting each process with its input and output materials creates a bipartite network of material-process-material-process chains.



- Findings and Next Steps

  LOKI-Network algorithms and techniques were used to analyze the petrochemical subsector to predict the nonlinear impact of the loss of typical and atypical production capacities on overall systemic throughput. The high-level view in this idealization of chemical supply chains were also used to identify problematic areas. For example, a network analysis reveals that propylene and styrene are connected to many other chemical products; such interconnectedness merits special attention from other higher fidelity modeling approaches.

- New Capabilities
  - Data driven network representation, identification of down-chain impacts
  - Capability to assess importance of a process by estimating the consequences of eliminating or curtailing that process for a network as a whole.
  - Dynamic network impacts, market effects and transient supply chain impacts

A-4.2 Natural Gas

- Goal /Aspiration for Project

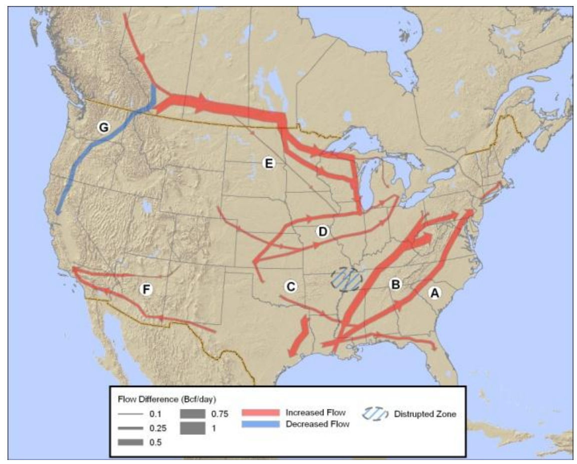
  Evaluate potential impacts of disruptions (due to earthquakes in NMSZ) on natural gas supplies (regionally to nationally)

- Approach/Methods/Models

  Developed a simple network flow model to estimate disruption consequences, and to place bounds on pipelines capacities using historical flow data. The network topology was derived directly from industry pipeline location data. The resulting model network was graphically overlaid on the pipeline network, and the locations and properties were reviewed and verified through GoogleEarth.

- Findings and Next Steps

  Completed model testing and preliminary analysis of potential earthquake impacts on natural gas supply



- New Capabilities

  - Allocation model that spreads the shortages among the end users
  - Network flow model useful for analyzing other systems constrained by transmission capacity
  - Estimating patterns of service interruption arising from diverse causes, such as pipeline explosion or loss of storage

A-4.3 Petroleum Fuels

- Goal /Aspiration for Project

  Evaluate potential impacts of disruptions (e.g., due to earthquakes, hurricanes in the Gulf of Mexico) on transportation fuel supplies (regionally to nationally)

- Approach/Methods/Models

  The approach is to combine the process of specifying network elements and their associated parameters with the process of documenting data sources and interpretation. The intent is that multiple flow algorithms can be applied once a network is constructed. Currently three algorithms are implemented: a standard maximum flow algorithm, a balanced maximum flow algorithm (based on the Loki-Gas Allocation Method (GAM) algorithm), and a System-Dynamics-type inventory control algorithm.

- Findings and Next Steps

  Started model testing and conducted preliminary analyses of potential earthquake impacts on transportation fuel supply.

- New Capabilities
  - Rapidly define and visualize networks, document data sources and assumptions.
  - Various flow algorithms, some of which are specifically designed for the transportation fuels system.
  - Dynamic supply and demand model for materials flowing on a network that can adapt by re-routing shipments, drawing down storage, and utilizing excess process or transmission capacity.

- Publications
  - Chemical and Natural Gas Network Interdependencies (SAND2008-7948 C)
  - NISAC Chemical Industry Project Capability Report 2008 (SAND2009-1882 P)
  - NISAC Chemical Supply-Chain Analysis Demonstration (SAND2008-2598 P)

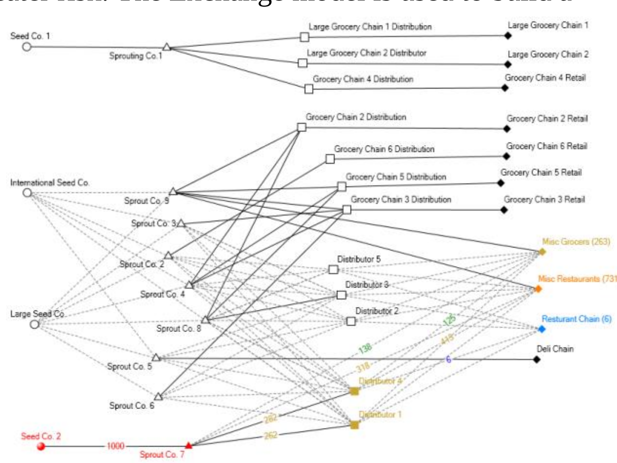
A-4.4 Detailed Topological Mapping and Modeling of Food Supply Chains

- Goal /Aspiration for Project

  Develop the analytical capability to deterministically/stochastically map food production and distribution supply chains for the purpose of supporting food defense and food safety risk assessments by improving the ability to: identify and prioritize vulnerabilities, identify actions that will reduce those vulnerabilities, respond to and reduce the consequences of food-pathogen incidents or attacks and improve the speed and reliability for tracing food pathogens as part of crisis response.

- Approach/Methods/Models

  Utilized a system-scale adversarial risk-assessment methodology that is iterative and dynamic to identify food supply chains that are at greater risk. The Exchange model is used to build a stochastic network representation. With this model, we explicitly incorporate, express, and visualize the uncertainties by producing probabilistic maps of the possible ways in which tainted food moves through its distribution network to the consumer. Map as completely as possible a single food marketing sector chosen from a short list of sectors identified as being particularly vulnerable to being appropriated as means for conducting a directed attack. Explicitly incorporate, express, and visualize uncertainties by

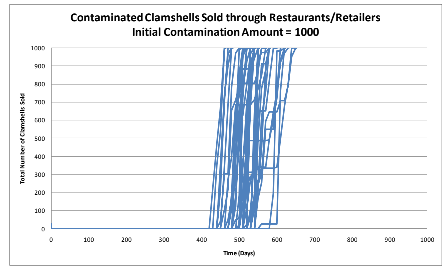


producing probabilistic maps of network topologies. We gathered information using literature search and interviews with food industry professionals.

- Findings and Next Steps

  Completed initial case study demonstrating the conditions under which stochastic mapping speeds contaminant tracing and the value of partial information on supply chain connections.

  The next steps are to publish the results and continue to utilize this risk assessment capability by working with our collaborators in business and in the federal and state agencies.



- New Capabilities

  - Stochastic mapping of contaminant pathways in produce supply chains

	Sprout Co 1	Sprout Co 7	Sprout Co 2	Sprout Co 4	Sprout Co 10	Sprout Co 8
Large Grocery Chain 1	1.00	0.00	0.00	0.00	0.00	0.00
Deli Chain	0.00	0.46	0.95	0.76	1.00	0.95
Sprout Co. 7 Customers	0.00	1.00	0.86	0.59	0.95	0.86
Grocery Chain 2 Retail	0.00	0.50	0.95	0.73	1.00	0.93
Misc. Grocers	0.00	0.51	0.93	0.70	0.98	0.91
Misc. Restaurants	0.00	0.51	0.93	0.70	0.98	0.91
Grocery Chain 3 Retail	0.00	0.47	0.95	0.68	1.00	0.92
Large Grocery Chain 2	1.00	0.00	0.00	0.00	0.00	0.00
Restaurant Chain	0.00	0.51	0.93	0.70	0.98	0.91
Grocery Chain 4 Retail	1.00	0.00	0.00	0.00	0.00	0.00
Distributor 5 Customers	0.00	0.50	0.95	0.71	1.00	0.93
Grocery Chain 6 Retail	0.00	0.48	1.00	0.73	1.00	0.93
Grocery Chain 5 Retail	0.00	0.50	0.95	0.71	1.00	0.93
Unconditional Probability	0.14	0.44	0.80	0.60	0.84	0.78

- Publications

  - White Paper on Food Defense Risk, PG Kaplan, October 2008

  - Total Risk Assessment Methodology, Wyss, G., et al., December 2008

  - Attack of the Killer Tomatoes: A Risk Assessment of a Directed Asymmetric Attack on the US Populace Using the Quick-Serve Restaurant Supply Chain, SH Conrad, PG Kaplan, and J Hardesty, June 2009

  - The Value of Utilizing Stochastic Mapping of Food Distribution Networks for Understanding Risks and Tracing Contaminant Pathways, SH Conrad, WE Beyeler, and TJ Brown (in press)

A-5. Full Spectrum Global Security

Problem Space:

Global systems share a common environment (the earth) and exchange resources through economic, humanitarian, diplomatic and adversarial transactions. The security of each nation depends on the ability of its populace to survive and prosper in the global environment despite the natural and anthropogenic perturbations it experiences.

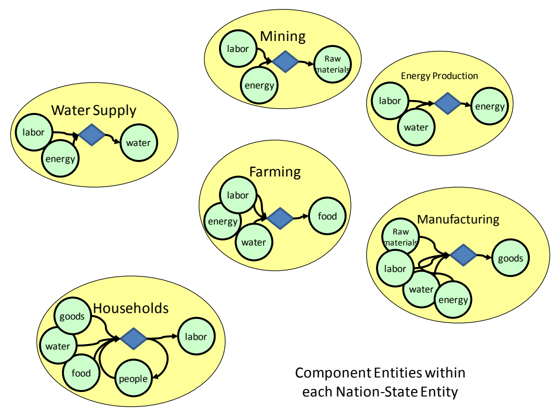
A-5.1 Nation State Transactions

- Goal /Aspiration for Project

  Develop fundamental models of nations and their interactions to identify potential risks to national security and system of system-based risk mitigation actions.

- Approach/Methods/Models

  Developing and testing initial model of 3 interacting nation states with different resources, capacities and efficiencies. We are using the Exchange model module to represent energy, food water, labor, raw materials, goods, people and money exchanges within and between the nations. Conducting numerical experiments to test the models and case studies to evaluate and refine the models for evaluating specific types of perturbations.

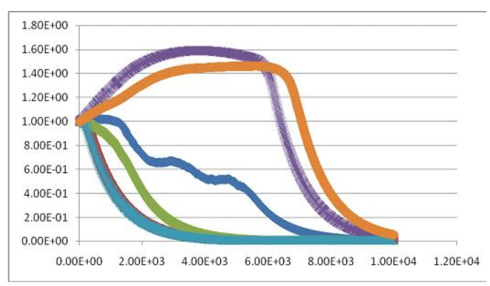


- Findings and Next Steps

  We are in the early model development and testing stage.

- New Capabilities

  - Interdependent Nation States Models



A-5.2 Climate Change

- Goal /Aspiration for Project

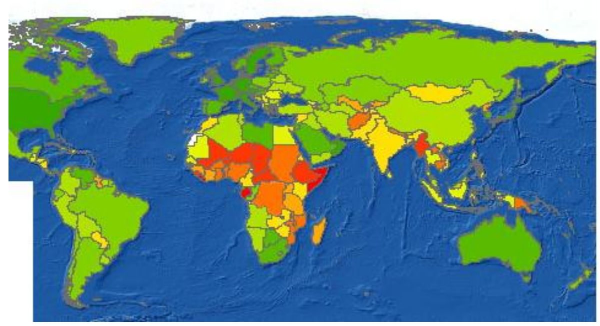
  Identify key uncertainties and dynamics in order to design and develop a CASoS engineering approach for reducing climate risks.

- Approach/Methods/Models

  Evaluate conceptual model design for linked/coupled hydrologic and economic models to develop a scientific-based risk analysis approach that accounts for the full range of potential outcomes and explicitly includes uncertainty, design validation strategy and identify modeling needs.

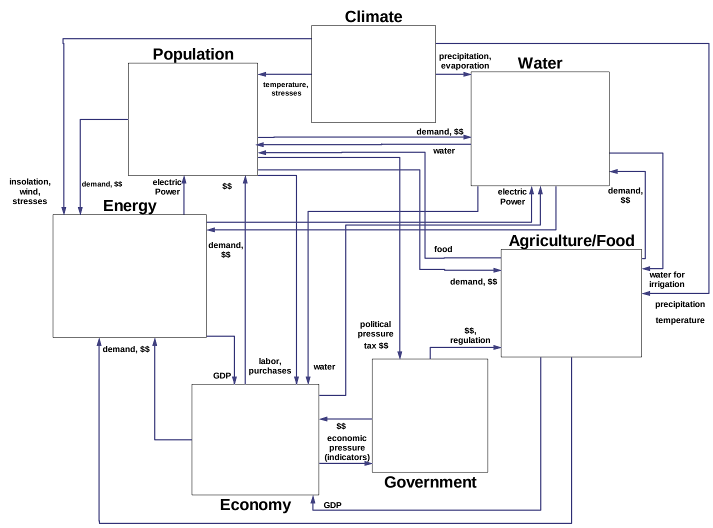
- Findings and Next Steps

Completed review of existing capabilities and proposed an approach that starts with an evaluation of global changes, then evaluates regional vulnerabilities to the changes and focuses on the impacts that could propagate to other regions and how the impacts could propagate. Analysts recommended a decision validation (robust to uncertainty) strategy due to the nature of the problem and the timeframe for decision making relative to the timeframe for conducting field experiments.



We are now working with climate, environmental, economic and risk modeling and analysis groups to develop proposals for developing the CASoS models and analysis capabilities needed to engineer climate risk reduction approach.

- New Capabilities
  - Enhanced the methodology for CASoS modeling validation.
  - Began conceptual model development for evaluating climate risks using a CASoS approach.
  - Conceptual model of global geopolitical condition impacts on US national security



- Publications
  - Uncertainty Quantification and Validation of Combined Hydrological and Macroeconomic Analyses

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