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Phoenix: Complex Adaptive System of Systems (CASoS) Engineering Version 1.0

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Abstract

Complex Adaptive Systems of Systems, or CASoS, are vastly complex ecological, sociological, economic and/or 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 pervasive interdependencies and attendant vulnerabilities to cascades in associated systems. Phoenix was initiated to address this high-impact problem space as engineers. Our overarching goals are maximizing security, maximizing health, and minimizing risk. We design interventions, or problem solutions, that influence CASoS to achieve specific aspirations. Through application to real-world problems, Phoenix is evolving the principles and discipline of CASoS Engineering while growing a community of practice and the CASoS engineers to populate it. Both grounded in reality and working to extend our understanding and control of that reality, Phoenix is at the same time a solution within a CASoS and a CASoS itself.

ACKNOWLEDGEMENTS

Following the favorable reception of the 2008 *Sandia National Laboratories A Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative*, initial funding was provided in November 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, Phoenix, 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). While members of Phoenix have come and gone, all played critical roles in the Initiative's development and are acknowledged as authors.

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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
SMU	Strategic Management Unit
STE	Science, Technology, and Engineering
U.S.	United States
VHA	Veterans Health Administration
VP	Vice President

1. THE PHOENIX PILOT

Humans use a myriad of systems for the exchange of goods and services, for the generation of food and power, for the delivery of water and internet connectivity, for the execution of law, and many other transactions. Humanity's systems operate within the ecological and meteorological systems of the planet on which we live. All of these systems are complex, are adaptive to changing conditions, and depend on numerous other contributing systems. All of these systems include people, encompassing some of humanity's largest problems.

Examples of such systems include: ecological and agricultural systems; cities and megacities (and their network on the planet); interdependent infrastructures; government and political systems, educational systems, health care systems, financial systems, economic systems and their supply networks; and the global energy system which itself is a system within the global climate system.

We have used the terms that define the principal attributes of such systems to name them: Complex Adaptive Systems-of-Systems, or CASoS. Our objective is to engineer solutions to problems within CASoS with the overarching goals of maximizing security, maximizing health, and minimizing risk.

CASoS are *complex*, often complicated, large and irreducible. Their dynamics have a wide range of time scales so that interpretation, modification, and quantifying the impacts of modification are difficult. CASoS are *adaptive*, often hysteretic and/or recursive, so building understanding through testing is challenging because repeatable initial conditions are generally not achievable and simultaneous tests are often not independent. CASoS are *systems of systems*, composed of systems that cannot be replaced by a single entity, and may be enormously complicated. Perturbations/disruptions in CASoS can devastate systems, causing harm, deprivation, disease or other impacts on local, national and global scales.

Through their laboratory directed research and development (LDRD) program, Sandia National Laboratories provided three years of funding in 2008 for the Phoenix Pilot to evolve the CASoS engineering discipline that had been developing at the lab since 2003. In recent decades the vulnerabilities created by the high degrees of complexity and interdependency among the systems we rely on have drawn the attention of scientists and generated new fields of study in many domains addressing complex systems and complex adaptive systems (CAS). Phoenix combines the bottom up "complex systems" and "complex adaptive systems" view with the top down "systems engineering" and "system-of-systems" view to seek solutions that minimize the risks inherent in CASoS.

As engineers, we are interested in influencing (designing, controlling, manipulating) systems to solve a problem, exploit an opportunity, achieve a goal, and/or answer a question. Phoenix utilizes CASoS engineering approaches focused by principles of system definition, conceptual modeling and representation, uncertainty quantification, and integrated, recursive research, development, and application to support policy decisions with solutions that improve system resilience, avoid unintended consequences, and perform well under a wide range of uncertainties.

Like the mythical reincarnating bird for which it is named, we expect Phoenix to cycle through growth, death and rebirth as time proceeds. Phoenix has been designed as a CASoS solution, one which itself is a CASoS with all the potential for dynamic, adaptive, and cascading behaviors that implies. In many ways, Phoenix is well aligned with the New England Complex Systems Institute, the Santa Fe Institute, National Centers for Systems of Systems (SoS) Engineering and others that focus on Complex Systems and systems of systems, but Phoenix is distinguished by our focus on engineering robust solutions for CASoS problems.

To accomplish the goal of engineering solutions to problems within CASoS, Phoenix must develop, hone and apply the principles of CASoS engineering. Motivation for this development comes through a combination of critical need, ability, and opportunity. This motivation initiated the construction of the CASoS Engineering Initiative Roadmap in 2007-2008 at Sandia National Laboratories.

The Roadmap defines CASoS, CASoS engineering, and the path forward to build the discipline of CASoS engineering. The path intrinsically integrates research, development and application by developing CASoS engineering theory and principles within context of designing problem solutions through applications.

A set of applications connected through the Roadmap's principal authors, Glass and Ames, formed the initial basis of Phoenix's implementation of CASoS engineering. At the current stage of our development, "applications" of CASoS theory, methods, and philosophy are implemented within the bounds of what Sandia usually terms "projects." From this initial set of applications, an outwardly growing network of research, development, and application connections is creating a CASoS engineering community of theory, practice and culture. Phoenix's current CASoS applications cross internal Sandia organizational boundaries as well as many external federal agency funding boundaries (e.g., Department of Energy [DOE], Department of Defense [DOD], Department of Homeland Security [DHS], Department of Veterans Affairs [DVA], Health and Human Services [HHS]). Addressing many of critical problems requiring solutions, these applications have now begun to engage business, academia and other institutions in collaborative research, development and analysis.

The kernel of Phoenix (people, applications, approaches, methods and theory) takes its roots from the National Infrastructure Simulation and Analysis Center (NISAC) funded by DHS. In 2002, the Advanced Methods and Techniques Investigations (AMTI) effort group was created to identify and develop theories, methods, and analytical tools in the field of Complex Adaptive Systems (CAS) and apply them to understand the structure, function, and evolution of complex interdependent critical infrastructures. This work was documented in the 2003 report *Defining Research and Development Directions for Modeling and Simulation of Complex, Interdependent Adaptive Infrastructure*. Through AMTI, NISAC's analysis of social, economic and technical infrastructures, such as public health, energy, supply chains, banking, and finance, led to high impact solutions, some with national and international recognition. Our work to design interventions for pandemic influenza was particularly successful in both influencing public policy and confirming the significance of our approach.

The theoretical approach for CASoS engineering is outlined in the Roadmap. We follow the theoretical approach for CASoS engineering in our own organization, first by defining Phoenix as a CASoS (Section 2) and explicitly stating its aspirations (Section 3). As we proceed, we are developing and applying CASoS engineering principles recursively to other CASoS as well as Phoenix's organization, development, and growth. As the functional structure of Phoenix emerges and new applications/projects and people join the Pilot (Section 4), our understanding of CASoS evolves and our aspirations are refined.

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. (Section 4.1)
- **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. (Section 4.2)
- **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.

  Here, Development is creating the tools of CASoS engineering. (Section 4.3)

Through implementation within and across these components, we seek the next steps and episodic transformations whereby intrinsic connections between research, development, application, insights, and breakthroughs in any area can inform the others. Accelerating this process will allow Phoenix to develop and use CASoS engineering principles (e.g., simplicity, analogy, dimensional analysis and similitude, verification and validation) and methods (e.g., networks and adaptive networks, agents, hybrid approaches that blend discrete with the continuous, uncertainty analysis, experimental design and high performance computing) effectively and efficiently and thus more rapidly pose and provide innovative solutions to problems currently beyond our reach.

The definition and development of the CASoS Engineer has begun as the functional structure of Phoenix has emerged with the addition of new applications and people, (Section 5). Although coming from diverse classical disciplines, CASoS Engineers share a drive to solve cross disciplinary economic, social, ecological, and technical problems. These first-generation CASoS Engineers have taught themselves and each other through the initial applications. Each person adds to and evolves the Initiative's three functional components (Framework, Environment and Application): as each learns, they contribute back to the whole. Components created for an explicit educational process are in development: these include a short course, an orientation seminar series, and external website-based access to foundational documentation and bibliographies. Figure 1 diagrams components contributing to the Phoenix's structure.

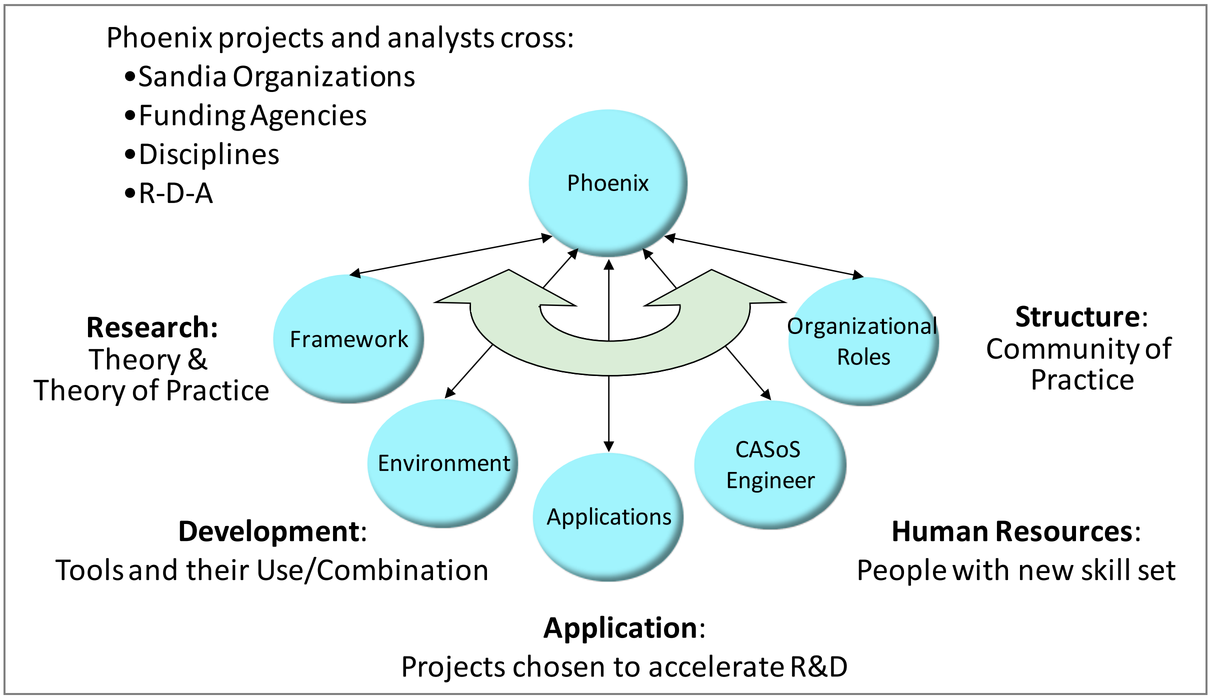

Figure 1. Phoenix contributing components

Organizational roles have emerged within Phoenix that mirror its functional structure (Section 6). The current set of roles has formed to integrate and coordinate applications to enable evolution of the tools and science of CASoS engineering. For the CASoS engineering Initiative to be successful, these roles must form a core, fundamental, and pervasive component of a growing number of projects (both within and outside of Sandia) and generate a community of practice for CASoS engineering. As the depth, breadth, and number of projects and people increases, the designated roles within Phoenix will necessarily change.

As we evaluate the past and anticipate our near future (Section 7), we recognize that our achievements have come through great effort and perseverance. Although Phoenix was initiated in the context of ongoing projects and management structures holding expectations not fully aligned with our aspirations, the enthusiastic involvement of team members has led to many successful developments. These achievements are reflected in the increasing external recognition of Phoenix in many forums, including invited talks given at NSF workshops in Complex Systems, Education, in MegaCities given at national and international conferences, and at universities (see Appendices A and B for complete listings of publications and plans). The coming year of the Phoenix Pilot will build upon this foundation and 1) add new applications/projects that are well aligned with our aspirations (total funding as of this writing ~$6M/year and growing), 2) better integrate new and existing applications/projects to build the Engineering Environment, 3) enhance our education and training components, and 4) enlist a Board of Advisors and Funders into active roles within Phoenix. Through these efforts, we will continue to grow our CASoS engineering community of theory, practice and culture.

2. DEFINING PHOENIX AS A CASOS

As outlined in the CASoS Engineering Initiative Roadmap, the definition of the CASoS is the first step in the process of CASoS engineering. In Appendix D of the Roadmap this definition process is described and applied to 10 different ecological, social, economic, and technical systems of critical importance to the nation and indeed the world. The last of these defining examples is Sandia National Laboratories. Phoenix has been designed to achieve a set of aspirations within the Sandia CASoS, which itself is part of an expanding nested sequence of CASoS including the military-industrial complex, the United States, and the global environment (both physical and political). Evaluating Phoenix as a CASoS:

1. **System**: Phoenix is a system, whose functional components include Applications (projects), an Engineering Environment, and an Engineering Framework. These functional components are composed of people, many of whom are CASoS Engineers. Functional roles include: problem definer, subject matter expert, theorist, conceptual modeler, software developer, and knowledge manager/facilitator. Organizational roles include: Funder, Orchestrator, Framework architect, Environment architect, Engineering Applications architect, Conceptual Model architect, Communication Specialist, Application/Project leader, and Advisory Board member. In their various roles, people form a growing and changing network for the flow of information, influence, and funding

2. **Environment**: The environment within which Phoenix interacts, grows, and evolves includes Sandia components plus related personnel/organizations in the U.S. Government (e.g., DOE, DOD, DHS, DVA, HHS, etc), other funding sources, internal and external competitors, collaborators, academia, and the home environments of staff. Sandia components include its line-hierarchy (e.g. departments, groups, centers, etc), business units (e.g. Energy, Climate, and Infrastructure Security [ECIS], International Homeland and Nuclear Security [IHNS], Defense Systems & Assessments [DS&A], Nuclear Weapons [NW], Science, Technology, and Engineering [STE], Laboratory Directed Research and Development [LDRD]), non-Phoenix projects, subject-matter-oriented and functional groups (e.g. engineers, scientists, and managers), corporate incentives and regulations, and support systems (infrastructure).

3. **System of Systems**: The three CASoS engineering components (Framework, Environment, and Application) can each be considered interdependent systems. Work opportunities within each component can emerge independently, as can work products. Coordination across these work opportunities is intrinsically a system-of-systems effort, especially across the various Applications (often thought of as independent). The organizational and functional roles of people each form systems within which information, influence, and funds flow.

4. **Complex**: Phoenix is composed of a growing set of people and projects with connections to a growing number internal/external funders and groups. Many types of and motivations for interaction exist among these compositional entities: organizational,

functional, project/subject, funding, social, and spatial. Project constraints, funding changes, technical innovations, and conceptual breakthroughs all form perturbations that lead to a wide variety of dynamically changing interactions and the spontaneous emergence of sub-groups and new or reconfigured external connections to accomplish new goals. Complex behavior is a result of interactions among a number of entities. Such behavior is more likely to emerge in medium-sized organizations: small groups tend not to exhibit complex behavior due to inadequate numbers of interactions, while large organizations frequently dampen complex behaviors through command and control.

5. **Adaptive**: People conduct applications/projects in the context of the processes, theory, and philosophy of the Engineering Framework. People develop Engineering Environment capabilities and tools which will, in turn, change the definition and solution of problems within current and new Applications as well as the Framework and the Environment. Each of these components adapts to changes in the others, as well as to changes in personnel, funding, and the problem portfolio. Additionally, as Sandia adapts to changes in its environment, Phoenix must adapt as well: Sandia business area changes and re-assortments influence departments, groups, centers and directorates.

The definition of Phoenix as a CASoS will naturally evolve in the years ahead as we continue to grow and consider Phoenix more explicitly in context of the wider national and international realms.

3. ASPIRATIONS

In the design of the Initiative, we established aspirations as the basis from which we can engineer our CASoS (Phoenix) and solve problems within it as they arise. Our aspirations to create and grow the discipline of CASoS engineering include:

- Develop the science of CASoS engineering: the theories, methods, and approaches that enable the design of solutions for ecological, social, economic and technical problems, that are robust and resilient, and that can be applied such that their actualization within the CASoS is reflexive. By reflexive we mean that as the CASoS itself adapts to the solution, conditions are created that may require the solution to adapt.
- Develop an environment for CASoS engineering: the Environment enables the application of CASoS engineering to current and new applications and facilitates knowledge capture and transfer.
- Integrate and assemble individual Applications into a whole: the organization of applications emphasizes similarity such that solutions for one contribute to the foundation for all and foster the creation and growth of CASoS engineering as a discipline.
- Develop people to be CASoS Engineers: cultivate first generation CASoS Engineers to evolve the education and training needed for further generations, establishing an expanding community of practice that grows the new discipline.
- Create Organizational Roles for Phoenix members: roles must fit both the individual and the whole, be flexible and foster the growth of CASoS engineering.
- Apply CASoS engineering principles to Phoenix itself.

Maturing through the definition, design and testing of solutions for other CASoS, Phoenix has grown and adapted in its first years in ways that have built in robustness and resilience to some of the perturbations placed upon it by the internal and external environments.

In time, a definition, characterization, and measurement of the state of Phoenix must be made so that its robustness and resilience within its current and future environment may be quantitatively evaluated. This evaluation must include a characterization of Phoenix's internal structure, function, and health, a characterization of its interactions within Sandia and beyond, and an integration of measures into a combined index of systemic health.

4. FUNCTIONAL STRUCTURE

Technical objectives focused on overarching problems common to many applications are the primary drivers of the functional structure of Phoenix: research and development are fundamentally entwined with applications. Graphically, this structure was depicted in the Roadmap as an 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**). Expanding on Figure 1, this diagram illustrates the nautilus-like growth of the enterprise through the dynamic interactions among the theoretical Framework, the Environment, and the Applications.

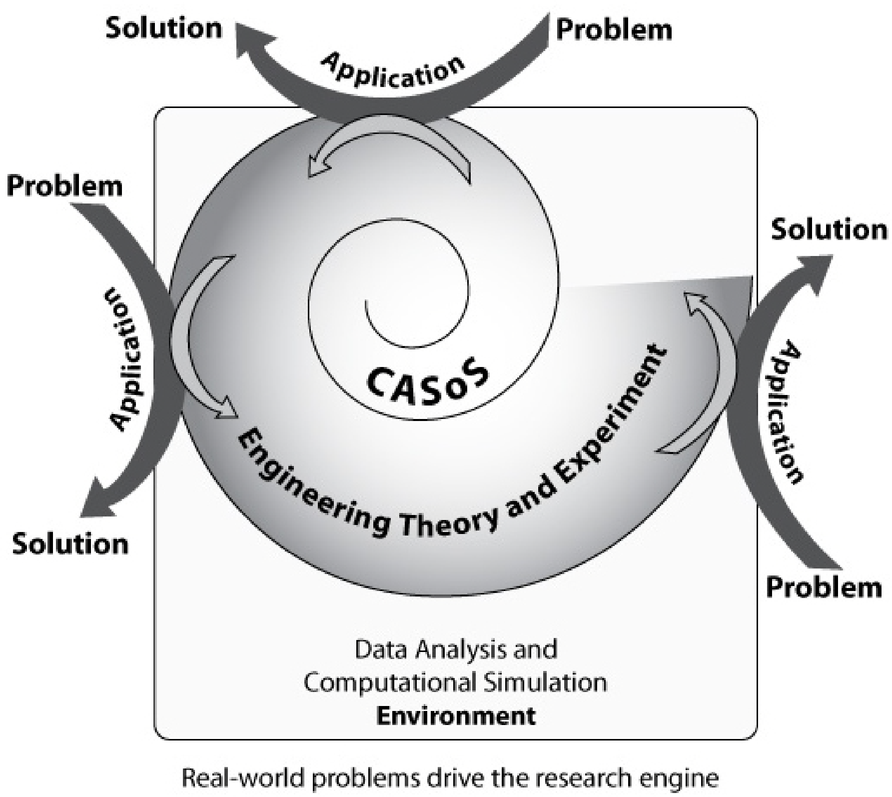

Figure 2. Diagram of CASoS Engineering Theory and Experiment Evolving through Application to Real-World Problems

Phoenix has instantiated this vision using both established and new applications. The CASoS Engineering Framework guides the development of the Engineering Environment within which the theory and practice of CASoS engineering are implemented through application development, simulation, and active knowledge transfer for education and training of both new and existing project teams and incoming CASoS Engineers.

Through the process of application, the functional structure of Phoenix has emerged in greater detail. As illustrated in **Figure 3,** knowledge and insight gained from applications in both established and frontier projects contribute to the advancement of CASoS engineering theory and principles, which in turn leads to the development of new tools and methods of application. These new capabilities and understandings are brought to bear on new projects as well as infused back into existing projects allowing them to continue to develop and transform over time. As applications advance core capabilities, more diverse applications can be supported.

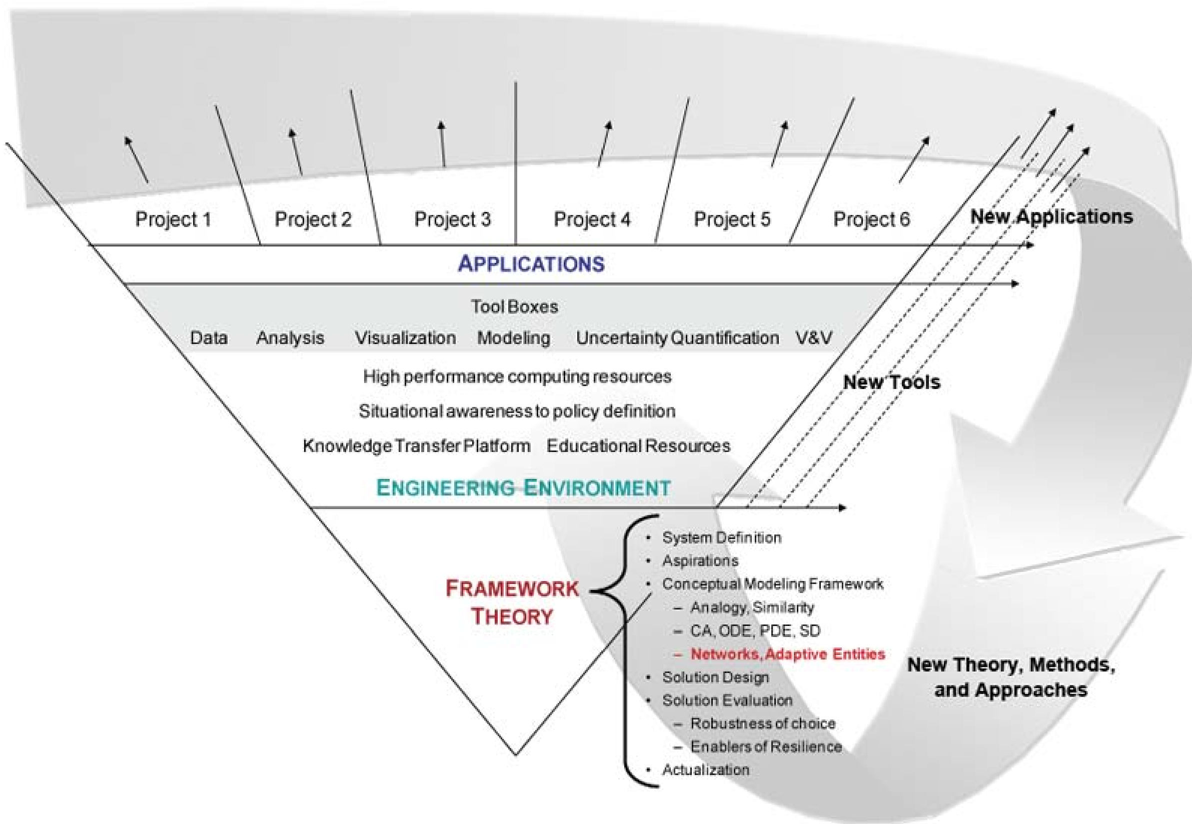

Figure 3. Diagram of Phoenix's Structural Integration of Theoretical Framework, Engineering Environment, and the Driving Reality of Real-World Applications

Both new and established projects are critical for this evolutionary model of the "whole" to grow and thrive: relationships and interactions within new problem spaces inform and amplify understanding within the entire "multi-cellular organism" or "ecosystem" that is Phoenix. Adoption and application of CASoS engineering capabilities in established projects extend project lifetimes to add greater stability to the whole. The link between new and established projects must be strong; this relationship enables the intrinsic integration of the individual applications into a whole.

The functional structure shown in **Figure 3** combines the advantages of both closed-loop and open-loop systems: while the closed-loop component of the structure exhibits goal-seeking behavior and stability, the open-loop element exhibits instability, divergence, and unbounded potential growth. The unbounded growth we are inviting through new applications is in knowledge and how we think about and understand problems. If we don't invite divergence in the form of new principles, new methods and new organization, our thinking and our approach to problems stagnate.

4.1. CASoS Engineering Applications

The applications that drive Phoenix 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 to understand and communicate 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. We seek applications that foster the growth of the discipline of CASoS engineering, particularly in the foundational stages of Phoenix.

Phoenix's intention is to blend research and capability development efforts to grow the Framework and Environment, respectively, in combination with high consequence Applications for funders who have real world problems that must be solved now. Research must address the entire space of applications, distill generality from what seem to be disparate independent problems, and promote understanding of the fundamental underlying similarity. This is the domain of the CASoS Engineering Framework. Capability development requires the implementation of various theories, algorithms, conceptualization tools, and approaches identified through the Framework process. Knowledge of concepts (foundational) and details (tools) must be transferred across sub-teams working on discrete projects in a manner that enhances each group's efforts. This dissemination is primarily the domain of the CASoS Engineering Environment.

Phoenix's Applications are chosen to most effectively both PUSH and PULL the evolution of the Framework and Environment by transferring energy (funds, ideas, synergy between people and projects) to develop the CASoS engineering discipline. 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 application 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 ecological, sociological, economic, and technical problems are critically required.

As a matter of practicality, Phoenix has been initiated with existing and newly formed projects in which we have domain expertise, have applied at least a rudimentary form of the CASoS Engineering Framework, and have existing models and funding. These projects are also connected to people who were early adopters and founders of Phoenix. **Figure 4** provides a diagram of the evolved CASoS engineering applications space as a simplified network connecting CASoS, their perturbations, and possible aspirations: existing applications are shown in red; areas where we are currently building are shown in black. This diagram is not a complete picture of the trans-spectrum global security problem space because it does not show all CASoS and perturbations, nor does it show the relationships among the individual elements. The diagram combines a classic categorization of subject areas (outer rim of elements) integrated by the CASoS engineering approach that evaluates problems and transcends individual subject areas to zero in, and maintain focus on, the overarching goal of developing solutions that maximize security, maximize health, and minimize risk to the CASoS.

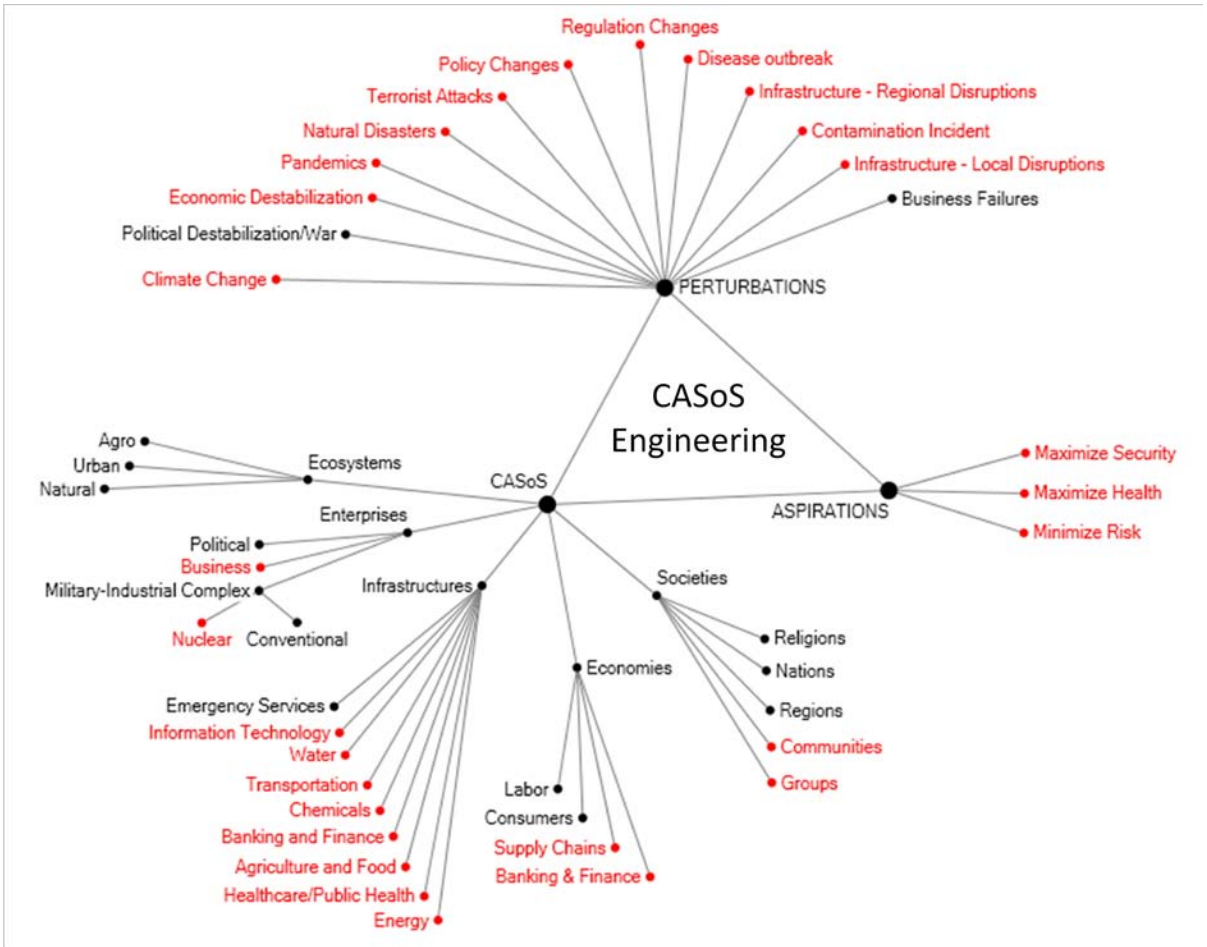

Figure 4. Integrated CASoS Engineering Applications Space as a Simplified Network of Aspirations, Perturbations and CASoS

Figure note: red indicates areas with artifacts, black indicates areas in development

CASoS include components from among broad classes of ecosystems, enterprises, infrastructures, economies, and societies and their sub groups such as urban ecosystems, energy infrastructure, or religious society.

The same rationale, identification of subject matter needs for analysis, applies to classification of perturbations. For example perturbations of concern for CASoS include:

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

Perturbation categories combine areas of subject domain expertise (e.g., climate, policy, terrorism) with actions that will cause the perturbation or series of perturbations (e.g., climate change, policy change, terrorist attack). This provides a description of the subject matter area and type of incident to be evaluated.

Supporting and refining Phoenix's overarching objectives of maximizing security, maximizing health, and minimizing risk, CASoS engineering aspirations are categorized by the goal of the analysis (see the Framework section for more detail on how aspiration categories were developed). Example aspirations include:

- Prevent or Cause
- Prepare
- Monitor
- Recover or Change
- Predict
- Control
- Design

Phoenix engineering domains combine the CASoS, perturbation(s), and aspiration(s). Examples include:

- Maximize population health through policy design
- Minimize Food Risks using stochastic mapping
- Promote global security and resilience to perturbation
- Minimize energy security risks

Note that this taxonomy of Phoenix applications is not static: it continues to evolve as we are presented with new opportunities to apply CASoS engineering.

The current portfolio of CASoS applications (see **Table 1**, below) are at a variety of states of maturity and cover only a portion of the problem space important to national and global security or for the development of a CASoS engineering discipline. Our most mature application area, in community health, began with a design for containing the spread of influenza to prevent a deadly pandemic and was eventually used to set the national planning policy. The public health and healthcare sector has many problems of similar scale and potential impact: here, our applications have expanded to include evaluation and design of tobacco control policies to improve population-level health as well as the modeling and analysis of healthcare systems operations to identify risks and effective risk mitigation measures. We are developing collaborative relationships to expand our work to other behavior-driven population health problems such as obesity, alcohol abuse and the combination of all these issues (tobacco use, obesity, alcohol abuse and drug abuse).

Although solutions can be devised based on an understanding of the system and how it will behave when perturbed, 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 consequences of disruption are severe. For CASoS problems in which the uncertainty is large and the potential consequences are great, the multi-objective of maximizing security and minimizing risk leads us to seek solutions most likely to reduce consequences sufficient to be a threat to national security.

The initial funding to create Phoenix and develop the CASoS Engineering Framework and Environment came from Sandia's ERN SMU through the LDRD project "Complex Adaptive Systems of Systems (CASoS) Engineering and Application to the Global Energy System (GES)." Recognizing that we needed more Applications to figure things out, we first expanded the initiative to include the LDRD Multiple Network Cascading project and then engaged funding partners explicitly in context of CASoS engineering (Veterans Health Administration [VA] and the Food and Drug Administration [FDA]). Current projects are mostly under the International, Homeland and Nuclear Security (IHNS) SMU and the Energy, Climate and Infrastructure Security (ECIS) SMU: funding across the set of projects is > $6M and growing.

Integrating these projects to build a whole has been a challenge: the corporate environment/culture does not naturally foster such integration and has been in transition through a major reorganization. Projects are considered independent, competing, and associated with a single SMU or organizational unit and persons such as Project Leads, Task Leads and Principal Investigators (PIs). Phoenix is outside of the SMU and organizational hierarchies, thus we have relied on ties among Project Leads, Task Leads, and PIs to accomplish the necessary integration. Phoenix has adapted and members have taken on roles to lead integration of applications with development, framework, and environment; however, more support from the corporate environment would improve the efficiency and successful establishment of the CASoS engineering discipline.

The project to design community containment strategies for pandemic influenza motivated the transition from CASoS modeling and analysis into CASoS engineering. We are actively working to engage funders with the understanding that their projects are building the discipline of CASoS engineering. Multi-year projects for the VHA and HHS/FDA are recent examples in which the external funder explicitly requires that CASoS engineering principles be applied. The current structure and state of Phoenix applications, including goals, development supported, and associated framework advances, are provided in the SAND report entitled *Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0* (currently in review).

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	WE Beyeler: NISAC, DHS

CASoS	Application Domain: approach, perturbation and aspiration	Phoenix Lead & Funder
	dependencies and propagating disruptions	S&T
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

CASoS	Application Domain: approach, perturbation and aspiration	Phoenix Lead & Funder
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

4.2. CASoS Engineering Framework

Engineering within CASoS spans a wide functional space. CASoS are *complex*, often complicated, large and irreducible. Their dynamics have a wide range of time scales so that interpretation, modification, and quantifying the impacts of modification are difficult. CASoS are *adaptive*, often hysteretic and/or recursive, so building understanding through testing is challenging because repeatable initial conditions are generally not achievable and simultaneous tests are often not independent. CASoS are *systems of systems*, composed of systems that cannot be replaced by a single entity, and may be enormously complicated. The ecological, sociological, economic, and/or technical nature of many critically important CASoS require a wide range of "physics" to address technical concerns, economic concerns, political concerns, and the interfaces among them. Because CASoS almost always embed people, experimentation within them is risky and costly, often leaving modeling as the only practical option for identifying potential solutions to detrimental conditions. All these factors encourage widely different opinions on what the problems are, how big the problems are, and how to go about solving them.

As engineers, our aspiration is to influence (design, control, manipulate) CASoS to solve problems, exploit opportunities, and/or achieve goals. A focus on aspirations breaks us out of the endless cycle of learning more and more about the details of individual CASoS. *Aspirations* fall into a set of clearly identified categories: Predict, Prevent or Cause, Prepare, Monitor, Control, and Recover or Change. Within each category, three sets of similar questions naturally emerge that encompass: *Decision*, determining *Robustness of Decision*, and *Enabling Resilience*. In the context of sociological, economic, technical CASoS, the answers to these questions *Inform Policy*. Through such systemization, we argue that the requisite theories, technologies, tools, and approaches for aspiration-focused CASoS engineering are similar across many CASoS and can be organized within a CASoS engineering Framework.

A general CASoS Engineering Framework must be wide and deep to cover the many potential opportunities for unexpected, nonlinear, interconnected behavior, and to find and make use of similarities across many disciplines. We envision the framework to be comprised of three phases applied primarily in succession but with some overlap, blending, and iteration to deliver CASoS engineered solutions (as diagrammed in **Figure 5**, below):

- **Defining** (blackboard to details):
    1. The CASoS of interest
    2. The Aspirations (Predict, Prevent or Cause, Prepare, Monitor, Control, and Recover or Change)
    3. Choice of aspirations based on constraints and impact
    4. Choice of appropriate methods and theories from the full space of those possible based on aspirations chosen
    5. Appropriate conceptual models
    6. Required data to support conceptual model development and validation

    Possible methods, theories and fields of contribution include analogy, dimensional analysis and similitude, experimental design, system dynamics, non-equilibrium thermodynamics, complex adaptive systems, game theory, percolation phenomena, agent-based modeling, networks, system optimization and control, and many others.

- **Designing and Testing Solutions** using computational models, data mining/integration, experiments, etc, within a common quantitative analysis environment. The design and testing of solutions are problem dependent, focused on answering the three general sets of questions relevant to any aspiration: 1) What are *feasible choices* within the multi-objective space, 2) how *robust* are these choices to uncertainties in assumptions, and 3) what are the critical enablers that increase system *resilience*. Included in this process is the delineation of unintended consequences and their amelioration/mitigation.

- **Actualizing** the engineered solutions devised through application within the real system. The engineered solution may be a concept, a computational tool, a sensor, a control policy, etc. This activity involves working with decision makers (change the world), other researchers (change the field), and people affected by the change (understand the impact). This involvement requires a long term commitment: these are high-consequence systems that adapt to change. Any change makes us part of the system with concurrent obligation through a solution's lifecycle.

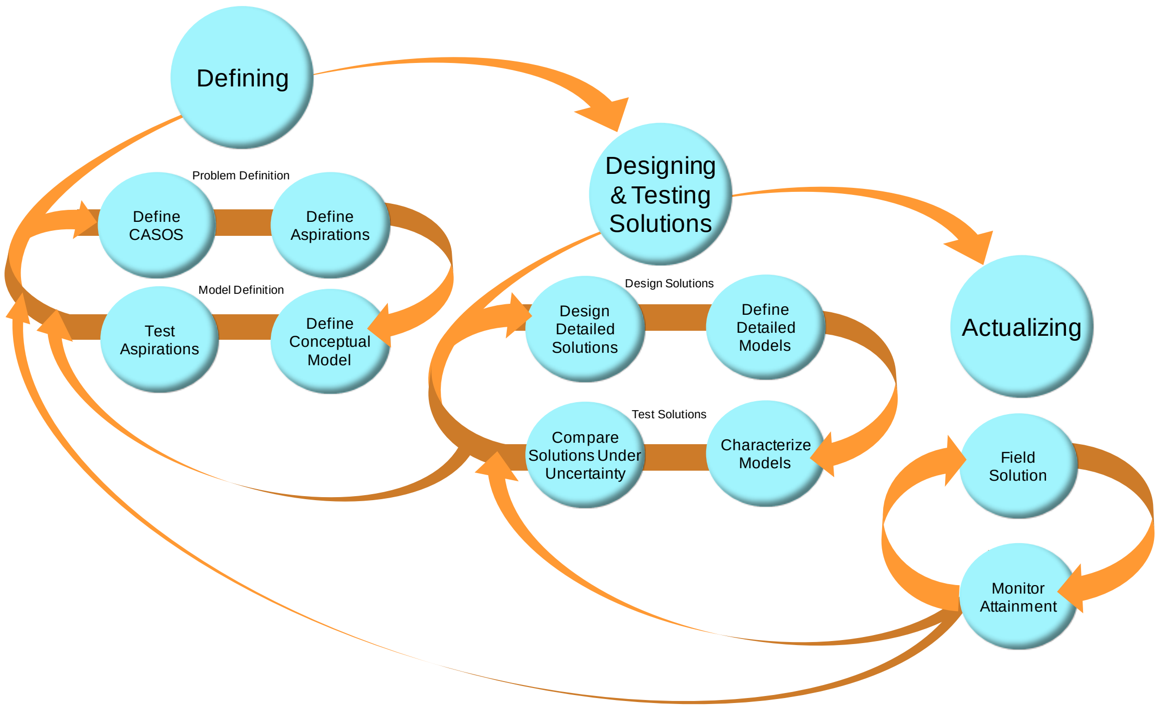

Figure 5. Diagram of CASoS Engineering Process and Components

As in classical engineering, iteration and blending among the phases is intrinsic. Actualization will require designing and testing to suggest future steps, and adaptations of the system might require us to return to fundamental thinking to understand the adaptations and possibly redefine the CASoS and our aspirations as the system changes.

Critical supporting efforts currently underway are Conceptual Modeling and Uncertainty Quantification.

- Conceptual modeling works inward from boundary conditions identified by problem definition and aspirations to develop a formal description of a system that allows us to derive the effects of actions on aspirations. The actions and observable properties related to the aspirations define essential "nodes" of the model. The model is developed by exploring and detailing the causal connections ("edges") among and between these nodes.

- Rigorous uncertainty analysis of model results provides a defensible basis for integrating CASoS modeling into policy design processes. We demonstrate the utility and limitations of experimental designs and statistical methods for extracting actionable information from model output. Parameter sweeps are useful for initial interpretation and to clarify basic model responses. Multivariate sensitivity analysis using space-filling experimental designs generate more-useful information on parameter interactions. Casting policy options as continuous rather than categorical variables permit the use of surrogate-based analysis to yield straightforward rankings of policy options that are robust to the identified aleatory and epistemic model uncertainties. These methods provide the additional advantage of requiring relatively few model runs to achieve a consistent and defensible ranking.

The current structure and state of the CASoS Engineering Framework are provided in the SAND report entitled *Complex Adaptive Systems of Systems (CASoS) Engineering Framework Version 1.0* (currently in review).

4.3. CASoS Engineering Environment

The CASoS Engineering Environment supports all aspects of the CASoS engineering effort by providing integrated platforms for modeling, simulation, analysis, education, training, and collaboration. Hardware, software, and people are combined to enable the consistent application of CASoS engineering principles and techniques to the solution of CASoS problems.

The CASoS Engineering Environment is currently comprised of two platforms, one computational and the other for knowledge management. This composite environment supports the Loki Network Modeling Resource Library, individual-based modeling, systems of systems modeling, uncertainty quantification, data analysis and visualization tools. Other modeling, simulation, visualization, and analysis capabilities, both internal and external to Sandia, will continue to be explored for potential integration into the Environment. An external, open website is being developed to more broadly engage with others working in CASoS engineering and related fields. Other components in active development include support for literature search, archive, retrieval, and exchange, both internally and with external partners; and the creation of a technology-enhanced collaboration space that facilitates group brainstorming and design activities and seamlessly captures the results.

The development of the CASoS Engineering Environment tracks the development of the CASoS Engineering Framework, and enables the development of applications using the Framework. The Environment instantiates the core principles and processes defined by the Framework, supports the creation of applications that are guided by the Framework, and captures the knowledge and experiences gained through the application of the Framework for potential reuse.

The overall goals of the CASoS Engineering Environment are to:

- Support the CASoS Engineering Framework with a computational environment that embodies its principles and techniques
- Facilitate computationally a multiple-model approach to modeling CASoS problems, either as independent perspectives of the same problem or as integrated models at different scales
- Support the creation of conceptual and computational models of CASoS problems

- Facilitate the reuse of knowledge, models, and code from previous CASoS efforts
- Create and support a robust software engineering process for the development and reuse of CASoS computational models
- Support a growing set of computational model categories (*e.g.*, Contagion, Exchange) with core modeling and implementation components.
- Foster the development of a CASoS engineering community of practice, and provide computational support for all of its critical activities, whether directly related to model development or not
- Support the education and training of new CASoS engineers, both inside and outside of Sandia
- Enhance the development of the discipline of CASoS engineering
- Recognize that the CASoS Engineering Environment is itself a complex adaptive system-of-systems and strike the right balance between expansion (exploration) and convergence (realization) in the evolution of the capabilities of the Environment.

High-level components of the Environment are illustrated in **Figure 6** below.

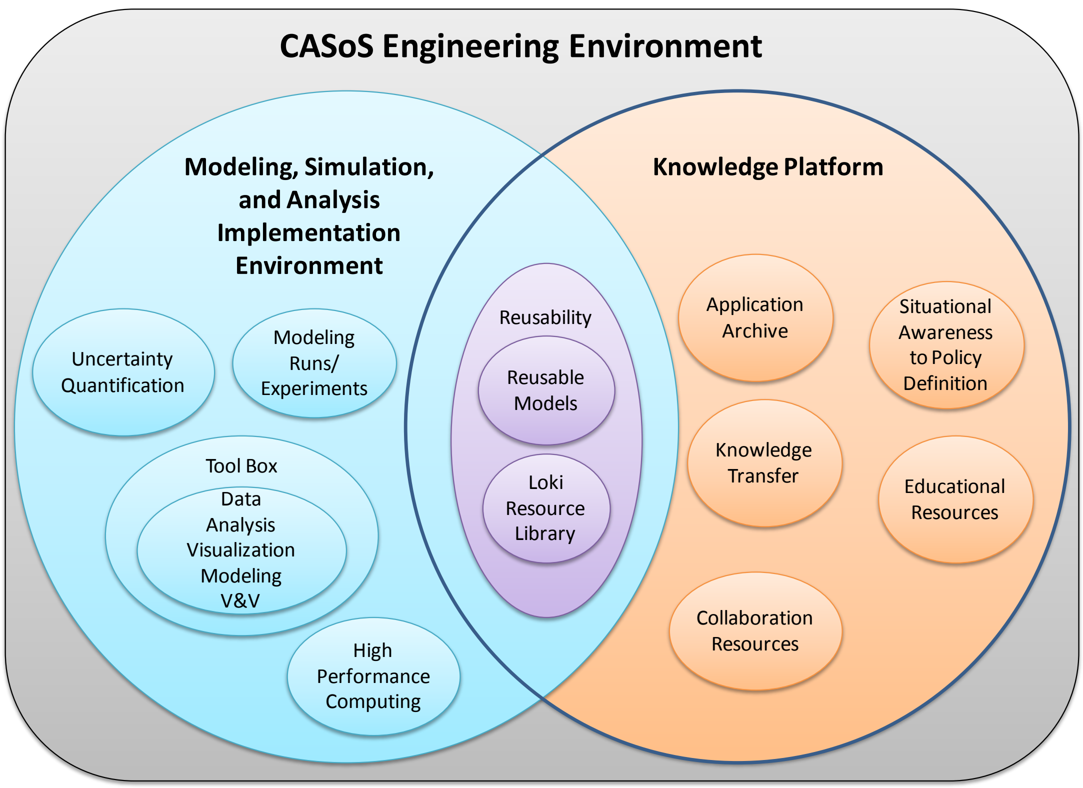

Figure 6. CASoS Engineering Environment Components

The current Modeling, Simulation, and Analysis (MS&A) Platform is composed of the Loki Network Modeling Resource Library and numerous tools and computing resources; it is specialized for the analysis and visualization of agent-based network simulations. Other modeling, simulation, visualization, and analysis capabilities, both internal and external to Sandia, will continue to be explored for potential integration into the Environment.

The Knowledge Platform currently consists of a Wiki site and a document repository site; the Wiki site is used to capture technical information that supports model creation and the development of the MS&A Platform, while the document repository site is focused more on the definition and documentation of models and on training materials for Phoenix. These two sites may be merged into a single team collaboration site in the near future. Other Knowledge Platform components in active development include support for literature search, archive, retrieval, and exchange, both internally and with external partners; and the creation of a technology-enhanced collaboration space that facilitates group brainstorming and design activities and seamlessly captures the results.

The current structure and state of the CASoS Engineering Environment are provided in the SAND report entitled *Complex Adaptive Systems-of-Systems (CASoS) Engineering Environment Version 1.0* (currently in review).

5. DEFINITION AND DEVELOPMENT OF CASOS ENGINEERS

CASoS engineers are practitioners of CASoS engineering. CASoS engineers do not widely exist at Sandia, nor are they being trained within academia or industry. Those that do exist have taught themselves and each other through the initial implementations of CASoS Framework theory, methods, and philosophy.

CASoS Engineers need skills that span CASoS engineering components: Framework, Environment, Applications. Generally, people come to the Initiative with the following backgrounds:

- complexity science
- basic and standard scientific and engineering fields
- computer science and engineering, software engineering and programming
- project management
- domain expertise

Engineers from each of these backgrounds could operate independently and their output be orchestrated into a whole. However, it is preferable to educate and train individuals to understand and practice the science and application of CASoS engineering. Specialists are needed but the whole of problem solution comes together much better if all the participants understand how and why to interact. **Figure 7** illustrates the interconnections necessary for effective evolution of CASoS engineering.

The CASoS Engineering Framework will evolve through new applications, implementations, and the new perspectives brought by those who join Phoenix. Our understanding of the process of CASoS Engineering and the hallmarks of good engineered solutions is growing; the Framework will of necessity evolve as we learn how to engineer in this new domain.

The Engineering Environment evolves through the application of the Framework; the reuse of existing capabilities and the development of new capabilities to support CASoS applications; and through new people with fresh perspectives and innovative ideas. The CASoS Engineering Environment documents itself through the education and training platform.

New Applications bring new challenges for framework and environment and new people who are domain experts (collaborators), program managers, project leads.

People learn by doing and implementing and interacting with others. Their ideas also change and adapt the Framework, Environment in the process of Application. Those entrained into Phoenix become part of the ongoing process of research, development and application for the evolving science of CASoS engineering.

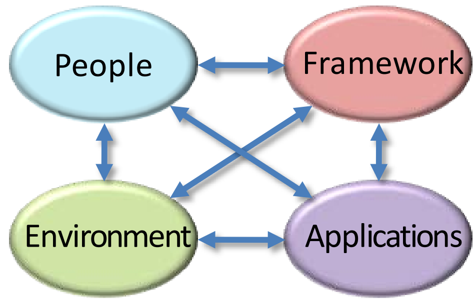

Figure 7. The Interrelations of People Produce the Integrated Evolution of all CASoS Engineering Components

We have found through our initial applications that an explicit training process must be designed and implemented for new CASoS Engineers. Just throwing people into the process of implementing CASoS analysis is not efficient. In the first year, a set of weekly meetings were instituted to provide this training. However, without accountability on the part of the learners to invest time doing homework this set of meetings was not as effective as we would have liked.

Current educational / training elements:

- **Short Course**: Developed in response to the request of Italian banking system representatives impressed by our published work in Payment Systems, our Short Course in Complex Adaptive Systems of Systems (CASoS) Modeling and Engineering was first given at Università di Roma in October 2010. A 4-day course of study, it includes advance readings and bibliography, introduction of CASoS engineering principles and process, in-depth lectures on two example applications, a demonstration problem to implement the process, and a follow-on independent project that extends or applies the concepts presented in the lectures. The course's generic structure allows it to serve as the basis for CASoS courses in any subject domain.
- **Orientation Course Summer 2011**: Now in review, a series of seminars prepared (and presented) for students will soon be available on the website for incoming CASoS engineers and others new to our projects.
- **Phoenix Wiki**: Currently used to capture information about the overall CASoS effort as well as detailed information about CASoS applications, the Wiki also supports the development of the modeling, simulation, and analysis platform to create CASoS applications. Application-specific Wiki pages can vary considerably in content, but there is common structure to help practitioners find similar information from within different application groups.
- **Students**: The program draws students from universities around the country: graduate and undergraduate, summer and year-round, short-term and multi-year. These student interns are mentored by experienced Phoenix staff.
- **Staff**: Staff members are encouraged to use their 32 hours of Sandia education time for independent reading or for classes at the Santa Fe Institute or the New England Complex Systems Institute. Staff is also supported for attending and presenting CASoS modeling and analysis results at conferences.

- **External Website**: The site summarizes the development and current state of Phoenix and the CASoS engineering discipline. It provides access to our complexity primer (with links to our initial course of study, foundational books, and visual maps of Complex Systems domains and history), short course, workshop presentations, a listing of conferences that address our fields of study, and links to other websites where work is being done across the field. The site is also an accessible repository for all unlimited release CASoS articles, documents, reports, and presentations.

A Version 1 report of our CASoS engineer education and training component that expands upon this synopsis in detail is scheduled to be written in the coming year.

6. ORGANIZATIONAL ROLES

Growing a capability in CASoS engineering requires an organizational structure that integrates "bottom up" initiative and creative forces with "top down" direction, cultivation, and support. In this combination, the top down force provides a path for facilitated growth but does not dictate the internal structure or the details of the growth process, allowing individuals to take responsibility and engage the CASoS discipline in ways most productive for themselves as well as for the whole.

The role of Sandia staff is to design, modify (as needed) and implement Phoenix as a CASoS. The role of Sandia management at Level 2 and higher is to guide, support and facilitate Phoenix as a unique experimental organizing structure within our research, development and analysis environment. Sandia Level 1 management's role is to incentivize, facilitate and support staff to institute Phoenix as a living CASoS.

Our goal is to learn from the Phoenix Pilot so that we can apply CASoS engineering through large single-customer programs such as NISAC, through large multi-customer groups such as ICE, and through Sandia and beyond as a multi-institutional network of collaborations that builds the community of practice and eventually the field of CASoS engineering.

The set of roles initially articulated in the Roadmap has since evolved to incorporate both the current membership and needed areas of growth for the future. Roles may change, new roles will be defined in time, and people will come and go. There may be advantages to making positions revolve (or be subsumed by emerging requirements). Natural inclination and individual enthusiasm must drive those who are in leadership positions.

- First and foremost, *ALL ARE CASoS ENGINEERS*. CASoS engineers are responsible for developing and implementing (development *through* implementation) the theory and practice of CASoS engineering. CASoS engineers also act as ambassadors for CASoS engineering.
- *Phoenix Conductor*. The Conductor (currently Bob Glass) has overall responsibility for the orchestration of Phoenix and is a primary contact for Phoenix and the application of CASoS principles. The conductor defines overall long-range goals and a vision that incorporates the essentials of CASoS engineering and also satisfies individual project programmatic and technical objectives.
- *Phoenix Engineering Framework Architect*. The Engineering Framework Architect (currently Arlo Ames) has responsibility to lead the development of the CASoS Engineering Framework. The Framework Architect maps the relationship between engineering and the unique requirements of Complex Adaptive Systems of Systems, devises engineering processes, ensures that processes support the needs of practitioners, tests the framework through application to real problems, works with practitioners to teach them, and integrates new understanding into the framework (including what works and what doesn't).
- *Phoenix Engineering Applications Architect.* The Applications Architect (currently Theresa Brown) works across individual applications to unify capability development, methodology testing and solutions engineering. Responsibilities include identifying application gaps and developing initiatives to fill those gaps to achieve the long-range

goals that build the essentials of CASoS engineering while also satisfying individual project programmatic and technical objectives.

- *Phoenix Engineering Environment Architect*. The Engineering Environment Architect (currently Walt Beyeler) has responsibility for leading and coordinating the design, development, and deployment of the CASoS Engineering Environment. The Environment Architect identifies needs and requirements across Phoenix and ensures that those needs and requirements are met by the Engineering Environment. Those holding this role also hold responsibility for organizing the efforts of the *Engineering Software Developers* when necessary.

- *Phoenix Experimental Design and Analysis Architect*. The Experimental Design and Analysis Architect (currently Patrick Finley) has responsibility to design and execute computational experiments to verify model design, validate model results, and quantitatively evaluate solution strategies. The Experimental Design and Analysis Architect executes studies to explore parameter and state spaces, quantify uncertainty of inputs and results, and distill model results into explicit and defensible policy and intervention recommendations.

- *Phoenix Conceptual Model Architect*. The Conceptual Model Architect (currently Walt Beyeler) has responsibility to define and describe the core modeling components and the specialization of these components for application in a variety of contexts. The Model Architect is also responsible to work with practitioners to teach them how to conceptualize their systems in context of CASoS Engineering.

- *Phoenix Communication Specialist*. The Communication Specialist (currently Louise Maffitt) has responsibility for the design, information architecture, and production of the CASoS external website, for the constructive review of texts to ensure that Phoenix documents are comprehensible by lay readers as well as by technical practitioners, for creating graphical representations of CASoS Engineering concepts and models, and for the integrated documentation of Phoenix project interactions.

- *Phoenix Analysis Environment Lead*. The Analysis Environment Lead (currently Nancy Brodsky) has responsibility for integrating staff efforts across multiple projects, managing workload, and influencing the team environment to facilitate the success of all members of Phoenix. The Analysis Environment Lead works toward establishing an appropriate balance of projects to sustain and improve individual and group capabilities and recognition.

- *Phoenix Application Leaders*. The individual Project leads whose applications are integrated within Phoenix have responsibility for achieving individual project goals while giving to and learning from the development of the CASoS Engineering Framework and Environments. Project leads are listed in Table 1 in this document and in the Appendix of *Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0*.

- *Phoenix Software Developers*. The Engineering Software developers have responsibility for adapting and expanding the engineering environment to meet evolving requirements of users and projects. The people in this role must be skilled developers (currently Java based) and have proven experience with creating functional systems that meet customer needs.

In the future, we need to emphasize and integrate the roles of:

- *Phoenix Funders*. Examples include Victoria J. Davey, PhD MPH RN, Chief Public Health & Environmental Hazards Officer, Veterans Health Administration; Brandon Wales, Director, Homeland Infrastructure Threat and Risk Analysis Center, Department of Homeland Security; Lawrence Deyton, MD MPH, Director Center for Tobacco Products, U.S. Food and Drug Administration, U.S. Department of Health and Human Services; and LDRD Strategic Business Unit leaders.
- *Phoenix Board of Advisors*. Responsibilities would include ideas/direction/advocacy. Examples could include Rush Robinett, Senior Manager, Grid Modernization and Military Energy Systems Group (6110), Margie Tatro, Director, Energy Technologies and System Solutions (6100), Terry Michalske (retired, now head of Savannah River National Laboratories), representation from 1000 and from outside of Sandia.

7. MATURING PHOENIX: STEPS TO BUILD A SUSTAINABLE FUTURE

This document describes the current state of the Phoenix Pilot after the first three years of the CASoS Engineering Initiative. Like its supporting reports on CASoS Engineering Applications, CASoS Engineering Framework, and CASoS Engineering Environment, this is a "living" document that will be revisited, revised, and updated as the science and discipline of CASoS Engineering evolves and Phoenix matures.

As in most endeavors, implementation of Phoenix is a double-edged sword of successes and setbacks. Fortunately, the cost of lessons learned has been more than balanced by our accomplishments and the tension has built a solid foundation for sustainable growth.

- Phoenix project funding now is greater than $6M and spans Sandia ECIS (reconfigured primarily from original ERN) and IHNS (reconfigured primarily from original HSD) business units and external customers in DHS, DOE, DOD, DVA, FDA, and the NMSBA. While Phoenix projects were chosen with CASoS Engineering explicitly at their core, including other projects from across the lab that are fundamentally CASoS Engineering projects could increase the tally of current funding for CASoS Engineering by as much as an order of magnitude, hugely increasing the possible leveraging of common understanding (framework) and development (environment) for the sake of individual projects (applications).
- Enthusiastic support by individuals within Sandia Management has been essential including Rush Robinett (6110), Steve Roehrig (6300, now retired), Les Shephard (6000, now retired and at the University of Texas, Austin), Terry Michalske (6300 now retired and head of Savannah River National Laboratories), Margie Tatro (6100), Richard Griffith (6130), Pablo Garcia (6930) and Steve Kleban (6132). Many others within management are beginning to take notice of Phoenix and we believe that interest in its continued sustainable growth is mounting.
- Enthusiastic Phoenix members including NISAC project leads (current and former), have spontaneously chosen to work together and forge a common future that crosses organizational boundaries, subject domains, and individual projects. The strength of the growing Phoenix team has weathered a wave of internal reorganization that has washed over Sandia in the past year and demonstrates the transcendent value of its foundation.
- External recognition through invited and contributed talks and papers is growing and "putting us on the map." Phoenix work products (18 project reports, 8 invited presentations, 27 contributed conference presentations [6 plenary], 20 conference papers, 5 journal articles, 2 SAND reports, 2 workshops, 1 short course, and 1 external website) are listed in tabular form in Appendix A. Beginning in year 3 and for the future our goal is for each project work product to generate at least one external conference presentation, conference paper, and journal paper. We are currently meeting and exceeding this goal.
- External recognition through research and advisory councils is also growing including:
    - Robert J. Glass has been named the 2011-12 William J. Perry International Security Fellow at the Center for International Security and Cooperation (CISAC) within Stanford University. His Research Prospectus focuses on applying CASoS

engineering to model global interdependency and design of policy that promotes international security.

- Theresa J. Brown, invited member of UK Infrastructure Transitions Research Consortium External Advisory Board, June 2011
- Theresa J. Brown, invited member of University of New Mexico (UNM) Prevention Research Center Community Advisory Committee
- Patrick D. Finley, invited member of National Operational Epidemiological Modeling Process Working Group (CDC, DoD)

- Phoenix's CASoS engineering external web site is building bridges to others by explaining what CASoS engineering is, how Phoenix is structured, our roots and our team, and giving educational material and full access to our papers and presentations (http://www.sandia.gov/CasosEngineering/)

We will build on this foundation to achieve our goal of a self sustaining CASoS engineering capability that is internally and externally recognized through its support of policy makers at the highest levels with the design of aspiration focused high impact solutions. To build this sustainable future, a series of steps must be embraced and supported in the coming years.

- Define and implement incentives and processes such that applications are integrated more fully. So that projects actively contribute to the whole as they work to achieve individual project objectives, they are best defined at the outset with the whole in mind and with that whole fully supported by their funder. In this way, funders are pulled into Phoenix as active and critical members.
- Expand our Education and Training component and find new CASoS Engineers to join our ranks. Essential to this expansion is the leveraging of several summer student programs funded by DOE and DHS and the teaching of short courses at universities across the nation (e.g., Stanford is targeted for this next year, MIT should be added).
- Enlist a Board of Advisors and Funders into active roles within Phoenix. As described above, a sustainable effort requires that we build close ties with, on the one hand, those who can help us gain access to the policy makers who own the problems we wish to help them solve and on the other hand, those who are doing critical blue sky research that we can leverage into CASoS engineering practice. These are the areas from which we will draw our Advisory Board.
- Work to extend the web of staff that Phoenix is actively integrating and Sandia management that has CASoS engineering in their plans. Possibilities include: broadening the initiative within Energy Technologies and Systems Solutions (6100) and Geoscience, Climate, and Consequence Effects (6900), to Nonproliferation and Cooperative Threat Reduction (6800) and more broadly Energy, Nonproliferation, and High-Consequence Security (6000), entry Information and Cognitive Science (1460) and on to Computing Research (1400), entry into Systems Analysis and Engineering (8110), Information Security Sciences (8960), Computational Science and Analysis (8950) and more broadly into California Laboratory (8000), and entry into Information Systems and Analysis (5630) and more broadly into Information Systems Analysis Center (5600). In each of

these areas, current Phoenix members have active ties with collaborators but no direct common funded projects of appropriate size and fully aligned vision with Phoenix.

- Push to achieve our Work Products Accomplishment Plan (listed in tabular form in Appendix B) that includes an ambitious set of Project reports and presentations, Sand Reports, Conference presentations, Conference papers, and Journal Publications. Achieving this plan is foundational to create the strength and status required for sustainability.
- Integrate this and other Phoenix documents into the CASoS Engineering web site in such a manner that their content becomes truly "living" with the capability to use an automated selection of topics to publish new subject-specific treatises as snapshots. Update of this evolving content must be ongoing as we create the discipline of CASoS engineering.
- Work to obtain internal program development funds that can aid in building the Initiative and consolidate our emerging thrusts in 1) Community health and intervention and 2) Trans-spectrum global security
- Expand outreach via our web site to other sites and researchers across the world to instantiate the web of CASoS Engineers on the planet

8. CONCLUSION

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., CASoS engineering entails designing ways of influencing CASoS by mapping aspirations to problem solutions within this domain. The sheer complexity of these systems, 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. Phoenix at Sandia National Laboratories continues to evolve CASoS engineering principles and applying them to solve real world problems while developing a community of practice and the CASoS engineers to populate it.

This living document has described Phoenix, its development, current state and the critical future steps required to build it into a sustainable and growing capability. A summary, *Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions*, was presented both as the keynote at the 6th IEEE International Conference on Systems of Systems Engineering and at the 8th International Conference on Complex Systems in June 2011.

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 Phoenix itself is a CASoS. As a CASoS, our definition and development intrinsically and continuously emerge from application; our internal structure grows interactively and changes both the group and the environment in which it exists. With backgrounds in many classical disciplines, CASoS engineers are consistent in their attraction to cross disciplinary ecological, sociological, economic, and technical problems and to the pursuit of their solutions. We invite problem holders and people seeking their technical solutions to join Phoenix in the application and evolution of the discipline of CASoS engineering.

9. REFERENCES

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APPENDIX A: PHOENIX PUBLICATIONS

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Glass	Modeling Critical Infrastructures with Networked Agent-based Approaches	1/23/2008	Presentation: Invited	University of Southern California, Viterbi School of Engineering	2008-1806 P	NISAC
Glass	Engineering Solutions in an Interdependent World: The CASoS Roadmap	2/1/2008	Presentation	Sandia National Laboratories: An Invitation to the Roadmap for CASoS Engineering Initiative	2008-4651 (derived from)	SNL Corporate
Glass	Social contact networks for the spread of pandemic influenza in children and teenagers	2/14/2008	Journal Paper	BMC Public Health, 8:61, doi:10.1186/1471-2458-8-61, *highly accessed*	2007-5152 J	
Glass	Rescinding Community Mitigation Strategies in an Influenza Pandemic	3/1/2008	Journal Paper	Emerging Infectious Diseases, Volume 14, Number 3, March 2008	2007-4635 J	
Glass	Modeling Critical Infrastructures with Networked Agent-based Approaches	3/15/2008	Presentation: Invited	Lawrence Livermore National Laboratory	2008-1806 P	NISAC
Beyeler	Performance and Resilience to liquidity disruptions in interdependent RTGS payment systems	6/1/2008	Conference Paper	Joint Bank of France & European Central Bank Conference on Liquidity in Interdependent Transfer Systems, Paris	2007-5316 C, 2007-2930 P, and 2007-7271 C (derived from)	NISAC
Beyeler	Performance and Resilience to liquidity disruptions in interdependent RTGS payment systems	6/1/2008	Presentation: Conference	Joint Bank of France & European Central Bank Conference on Liquidity in Interdependent Transfer Systems, Paris	2007-5316 C, 2007-2930 P, and 2007-7271 C (derived from)	NISAC

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Corbet	Impact of a Large Earthquake on the New Madrid Seismic Zone on National Energy Infrastructure	6/18/2008	Project report	NISAC / DHS (may not be released per DHS)		NISAC
Brown	Dependency Indicators	6/30/2008	Book Chapter	Wiley Handbook of Science and Technology for Homeland Security		NISAC
Glass	Effective, Robust Design of Community Mitigation for Pandemic Influenza: A Systematic Examination of Proposed U.S. Guidance	7/2/2008	Journal Paper	PLoS ONE 3(7): e2606 doi:10.1371/journal.pone.0002606, *highly accessed*	2008-0561 J	
Glass	Sandia National Laboratories: A Roadmap for the Complex Adaptive Systems of Systems CASoS) Engineering Initiative	9/1/2008	SAND report	CASoS Engineering Initiative website	2008-4651	SNL Corporate
Downes	Chemical and Natural Gas Network Interdependencies	11/12/ 2008	Project Report	Report to DHS	2008-7948 C	
Downes	2008 Chemical Supply Chain Workshop	11/18/ 2008	Presentation: Conference	SNL/DHS/Industry Workshop, November 2008, Albuquerque, NM	2008-2598 P	NISAC
Glass	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)	12/1/2008	SAND report	CASoS Engineering Initiative website	2008-7952	NISAC

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Corbet	2008 New Madrid Seismic Zone Study: Projecting the Consequence of Disruption to Natural Gas Infrastructure: Analysis and Model Development	2/9/2009	Project report	NISAC / DHS (may not be released per DHS)		NISAC
Corbet	NISAC New Madrid Seismic Zone Study: Scenario Analysis of Earthquake Impacts to Infrastructures and the Economy	2/9/2009	Project report	NISAC / DHS (may not be released per DHS)		NISAC
Downes	Analysis of Petrochemical Supply Chain Impacts due to a Scenario Hurricane: Demonstration of Capabilities 2008	2/10/2009	Project Report	Report to DHS		
Downes	Chemical Industry Project: Capability Report 2008	2/17/2009	Project Report	Report to DHS	2009-1882	
Beyeler	Global Finance as a Complex Adaptive System	4/15/2009	Presentation: invited	Military Operations Research Society (MORS) Workshop on Risk-Informed Decision Making, Shirlington, VA	2007-5316 C, 2007-2930 P, and 2007-7271 C (derived from)	NISAC
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering	4/15/2009	Presentation: Invited	Military Operations Research Society (MORS) Workshop on Risk-Informed Decision Making, Shirlington, VA	2009-2145 P	
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering	4/17/2009	Presentation	Department of Homeland Security (DHS) Economic Roundtable, Washington DC	2009-2145 P (derived from)	

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Glass	Wrangling with Uncertainty in Complex Adaptive Systems of Systems (CASoS) Engineering or "Why CASoS Engineering is both an Opportunity and Challenge for Uncertainty Quantification"	4/19/2009	Presentation: invited	National Science Foundation Workshop "Opportunities and Challenges in Uncertainty Quantification for Complex Interacting Systems." Los Angeles, CA	2008-1806 P, 2008-7952, and 2009-2145 P (derived from)	
Conrad	Attack of the Killer Tomatoes: A Risk Assessment of a Directed Asymmetric Attack on the US Populace Using the Quick-Serve Restaurant Supply Chain	6/11/2009	Project Report	Report to DHS		NISAC
Glass	Pandemic Influenza and Complex Adaptive System of Systems (CASoS) Engineering	7/1/2009	Conference Paper	27th International System Dynamics Conference, Albuquerque, NM	2009-6117 C	
Glass	Megacities as Complex Adaptive Systems of Systems (CASoS) Engineering.	7/1/2009	Presentation: invited	George Mason University and NSF Headquarters Meeting on Megacities & Education	2008-1806 P, 2008-7952, and 2009-2145 P (derived from)	
Glass	Pandemic Influenza and Complex Adaptive System of Systems (CASoS) Engineering	7/1/2009	Presentation: Plenary	27th International System Dynamics Conference, Albuquerque, NM	2009-6117 P	
Glass	Infectious Disease Modeling and Military Readiness	9/1/2009	Journal Paper	Emerging Infectious Diseases, Volume 19, Number 9	2008-0561 J (our portion derived from)	

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Glass	Health Outcomes and Costs of Community Mitigation Strategies for an Influenza Pandemic in the U.S	10/19/2009	Presentation: Conference	Society for Medical Decision Making 31st Annual Meeting, Los Angeles, CA,	2010-8351 J (derived from)	
Beyeler	Chemical Supply Chains (Petrochemical-NG dependencies)	11/15/2009	Project Report	Report to DHS		NISAC
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering	12/4/2009	Presentation: Invited Seminar	Center for Simulation and Modeling, Center for National Preparedness, the Department of Industrial Engineering and the Graduate School of Public Health, University of Pittsburgh, Pittsburgh, PA	2008-1806 P and 2009-2145 P (derived from)	
Cannon	Effects of Healthcare Sites on Community Pandemic Influenza Transmission and Mitigation	1/1/2010	Presentation: Conference	Infectious Disease Modeling Meeting (IDMM), Armed Forces Health Surveillance Center, Department of Defense Global Emerging Infections Surveillance and Response System (DoD-GEIS) Operations, and Johns Hopkins University Applied Physics Laboratory, Laurel, MD	2010-8560 C	VHA
Corbet	Foundational Methodology to Support Infrastructure Decision Analysis: Methodology Development Extension for Earthquakes	1/15/2010	Project report	Report to DHS		NISAC
Glass	Health Outcomes and Costs of Community Mitigation Strategies for an Influenza Pandemic in the United States	1/15/2010	Journal Paper	Clinical Infectious Diseases, Containing a US Influenza Pandemic • CID 2010:50, expedited publication	2010-8351 J	VHA

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Beyeler	2008 Global Financial System Analysis Capability Development	1/31/2010	Project Report	Report to DHS		NISAC
Corbet	Impacts of a New Madrid Seismic Zone Earthquake on the U.S. Natural Gas Transmission System	2/15/2010	Project report	Report to DHS		NISAC
Beyeler	2009 Global Financial System Analysis Capability Development	2/28/2010	Project Report	Report to DHS		NISAC
Corbet	Modeling and Analysis: Impacts of a New Madrid Seismic Zone Earthquake on the U.S. Natural Gas Transmission System	2/28/2010	Project report	Report to DHS (may not be released per DHS)		NISAC
Corbet	Summary of Potential Infrastructure and Economic Impacts from Earthquakes: Southern California and the New Madrid Seismic Zone Scenarios	3/15/2010	Project report	Report to DHS		NISAC
Glass	Seminar in Complex Systems	4/1/2010	Presentation: Invited Seminar	University of New Mexico, Graduate Department of Computer Science		
Conrad	Scientific Meetings for Creating Interdisciplinary Research Teams	4/12/2010	Proposal: UNM Lead, SNL sub	National Institutes of Health FOA PA-10-106		NIH
Glass	Defining and Evaluating Threats and Designing Strategies for VA Healthcare	5/4/2010	Presentation: Conference	2010 VHA Comprehensive Emergency Management Program Evaluation and Research Conference	2010-8359 C	VHA

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Zagonel	Application of a System Dynamics Approach to Reduction of Tobacco-Related Health Issues	7/8/2010	Presentation: Invited	2010 Surgeon General Report Meeting regarding Mathematical and Statistical Modeling on Population Impact of Smoking, Washington DC	2010-4467C	FDA
Maffitt	Casos Engineering Initiative External Website	7/15/2010	Website	Sandia Open Network server	2010-7025W	
Brown	Uncertainty Quantification and Validation of Combined Hydrological and Macroeconomic Analyses	9/1/2010	Project report	CASoS Engineering Initiative website	2010-6266	LDRD
Beyeler	Motivating Information Sharing in Interdependent Networks	10/11/2010	Presentation: Invited Seminar	1st Workshop on Information Sharing for Financial IT Infrastructure: Barriers and Opportunities		NISAC
Glass	Engineering Change in Socio-Technical Systems	10/11/2010	Presentation: Invited Seminar	1st Workshop on Information Sharing for Financial IT Infrastructure: Barriers and Opportunities, Rome, Italy		
Glass	Complex Adaptive Systems of Systems (CASoS) Modeling and Engineering: Overview	10/18/2010	Presentation: Invited Seminar	Short Course in Complex Adaptive Systems of Systems (CASoS) Modeling and Engineering, Università di Roma "La Sapienza"		
Beyeler	Formulation of Models of Payment Systems	10/19/2010	Presentation: Invited Seminar	Short Course in Complex Adaptive Systems of Systems (CASoS) Modeling and Engineering, Università di Roma "La Sapienza"		NISAC

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Glass	Design of Community Containment for Pandemic Influenza	10/20/2010	Presentation: Invited	Short Course in Complex Adaptive Systems of Systems (CASoS) Modeling and Engineering, Università di Roma "La Sapienza"		
Beyeler	Applying the Process: Model Development	10/21/2010	Presentation: Invited Seminar	Short Course in Complex Adaptive Systems of Systems (CASoS) Modeling and Engineering, Università di Roma "La Sapienza"		NISAC
Cannon	The Effect of Healthcare Environments on a Pandemic Influenza Outbreak	12/10/2010	Presentation: Conference	2010 Conference on Modeling for Public Health Action: From Epidemiology to Operations, Centers for Disease Control & Preparedness, Atlanta, GA	2010-8560C (derived from)	VHA
Hobbs	Loki-Infect 3: A Portable Networked Agent Model for Designing Community-Level Containment Strategies	12/10/2010	Presentation: Conference	2010 Conference on Modeling for Public Health Action: From Epidemiology to Operations, Centers for Disease Control & Preparedness	2010-8575C	VHA
Moore	A Complex Adaptive Systems Modeling Framework for Public Health Action Exemplified by the Veterans Affairs Modeling Object Oriented Simulation Environment	12/10/2010	Presentation: Conference	2010 Conference on Modeling for Public Health Action: From Epidemiology to Operations, Centers for Disease Control & Preparedness	2010-8561C	VHA
Zagonel	Developing a theory of the societal lifecycle of cigarette smoking: Explaining and anticipating trends using information feedback	12/10/2010	Presentation: Conference	2010 Conference on Modeling for Public Health Action: From Epidemiology to Operations, Centers for Disease Control & Preparedness	2010-8563C	FDA

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Zagonel	Developing a Theory of the Societal Lifecycle of Cigarette Smoking: Explaining and Anticipating Trends Using Information Feedback	1/7/2011	Presentation: Conference	System Dynamics Winter Conference, McCombs School of Business at the University of Texas, Austin, TX	2010-8563 C	
Glass	Systems-oriented Analysis of Learning for Sustainable Actions (SALSA)	2/5/2011	Proposal: UNM Lead, SNL sub	NIH Grant Proposal: PAR-10-038		NIH
Glass	Population-based Research Optimizing Screening through Personalized Regimens (Prospr)(U54): Modeling Cost-Effective Colorectal Cancer Screening Strategies in Rural Clinics	2/9/2011	Proposal: UNM Lead, SNL sub	NIH Grant Proposal: NIH RFA-CA-11-003 RFA		NIH
Beyeler	2010 Global Financial System Analysis Capability Development	2/28/2011	Project Report	Report to DHS		NISAC
Beyeler	Banking and Finance Capability Development Report	2/28/2011	Project Report	Report to DHS		NISAC
Glass	Introduction to Complex Adaptive Systems-of-Systems (CASoS) Engineering	3/2/2011	Presentation: Invited Seminar (first of a series)	Seminar in Interdisciplinary Biological and Biomedical Sciences (SiBBs), University of New Mexico, Albuquerque, NM	2008-1806 P and 2009-2145 P (derived from)	
Linebarger	Introduction to Complex Adaptive Systems-of-Systems Engineering	3/2/2011	Presentation: Invited Seminar	University of New Mexico, Seminar in Interdisciplinary Biological and Biomedical Sciences	2011-1424 C	

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Corbet	New Madrid Seismic Zone (NMSZ) Capability Development: Impacts to Transportation Fuel and Electric Power Infrastructure	3/15/2011	Project Report	Report to DHS		NISAC
Beyeler	Limits of Predictability in Systems of Networked Interdependent Specialists Investment Area: Enable Predictive Simulation	3/30/2011	Idea Proposal: LDRD	TBD		
Brown	Developing and Testing a Model Classification System for Fundamental Complex Adaptive Systems of Systems Models	3/30/2011	Proposal: Pre	SNL LDRD		
Brown	Develop Modeling Analysis Capability Necessary to Understand Interdependent Climate, Water Economic and Infrastructure Impacts on Policy Effectiveness and Design Risk Reduction Measures	3/30/2011	Proposal: Pre	SNL LDRD		
Brown	Analysis and Modeling of International Food Insecurity	3/30/2011	Proposal: Pre	SNL LDRD		
Conrad	Explicit Cultivation of New Approaches to Enhance Innovation at TSA	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		TSA
Finley	Evolutionary and Speciation Dynamics in the Development of Models	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Finley	Exploring Uncertainty in Complex Adaptive System Models	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Glass	Decisions: Representing and Understanding Interdependencies of U.S. Nuclear Policies and Evaluating Alternatives	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Glass	Defining Full Spectrum Design Principles for Global Security	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories	N/A	
Kelic	Common Operating Environment for Response Activities	3/30/2011	Proposal	SNL LDRD		
Linebarger	A Complexity Science-Based Framework for Global Joint Operations Analysis to Support Force Projection	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Linebarger	A Social Physics Workbench for Multimodel Analysis and Prediction	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Linebarger	Characterization and Analysis of the Origin and Evolution of Network Topologies under Bottom-up and Top-down Selection Constraints and Environmental Perturbations	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Linebarger	Forecasting Information Propagation through a Social Network with Uncertainty Quantification	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Linebarger	Guidelines and Software Libraries for Heterogeneous Simulation Paradigm Integration	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Outkin	Self-Correcting Hybrid Causal-Learning Systems for Decisional Modeling	3/30/2011	Idea Proposal: LDRD	TBD		
Verzi	A Capability to Better Anticipate Attitude Formation and Emotion Contagion through the Integration of Cognitive and Social Network Models	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Verzi	Modeling Terrorist Networks to Anticipate Potential Domestic Threat Behaviors in the US for Homeland Threat Assessment	3/30/2011	Idea Proposal: LDRD	Sandia National Laboratories		
Beyeler	The Role of Interdependencies in Failure Statistics for Complex Systems	4/20/2011	Idea Proposal: Abstract	TBD		NISAC
Glass	Integrating Community-Based Investigation with Systems-Based Conceptual and Computational Modeling to Understand and Prevent Childhood Obesity: An Interdisciplinary Synthesis	5/11/2011	Proposal: SNL Lead, UNM sub	NIH FOA Social Network Analysis and Health PAR-10-146 R21		NIH
Beyeler	Modeling and Risk Analysis of Information Sharing in the Financial Infrastructure (Chapter 3)	5/30/2011	Book Chapter	Springer Verlag CoMiFin book		LDRD

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Beyeler	Modeling Systems of Interacting Specialists	6/26/2011	Conference paper	8th International Conference on Complex Systems, June 2011, Quincy, MA	2011-4204 C	LDRD
Beyeler	Modeling Systems of Interacting Specialists	6/26/2011	Presentation: Conference	8th International Conference on Complex Systems, June 2011, Quincy, MA	2011-4204 P	LDRD
Brodsky	Application of Complex Adaptive Systems of Systems Engineering to Tobacco Products	6/26/2011	Conference paper	8th International Conference on Complex Systems, June 2011, Quincy, MA	2011-3249 C	HHS/FDA
Brodsky	Application of Complex Adaptive Systems of Systems Engineering to Tobacco Products	6/26/2011	Presentation: Conference	8th International Conference on Complex Systems, June 2011, Quincy, MA	2011-3249 P	HHS/FDA
Finley	Integrating Uncertainty Analysis into Complex-System Modeling for Effective Public Policy I: Preliminary Findings	6/26/2011	Conference paper	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3422 C	ALL
Finley	Integrating Uncertainty Analysis into Complex-System Modeling for Effective Public Policy I: Preliminary Findings	6/26/2011	Presentation: Conference	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3422 P	ALL
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions	6/26/2011	Conference Paper	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3354 C	ALL
Moore	Analyzing Public Health Care as a Complex Adaptive System of Systems	6/26/2011	Conference paper	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3188 C	VHA

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Moore	Extending Opinion Dynamics to Model Public Health Problems and Analyze Public Policy Interventions	6/26/2011	Conference paper	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3189 C	FDA
Moore	Extending Opinion Dynamics to Model Public Health Problems and Analyze Public Policy Interventions	6/26/2011	Presentation: Conference	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3189 P	FDA
Moore	Analyzing Public Health Care as a Complex Adaptive System of Systems	6/26/2011	Presentation: Conference	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-3188 P	VHA
Outkin	Applications of Self-calibrating Hybrid Causal-Learning Systems to Opinion Dynamics Modeling	6/26/2011	Presentation: Conference	8th International Conference on Complex Systems, June 2011, Quincy MA	2011-1524 P	FDA
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions	6/28/2011	Conference Paper	SoS Engineering Conference	2011-3354 C	ALL
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions	6/28/2011	Presentation: Plenary	SoS Engineering Conference	2011-3354 P	ALL
Glass	A Systems Approach to Assessing Nonproliferation Strategies	7/16/2011	Conference paper	Institute of Nuclear Materials Management (INMM) Conference, Palm Desert, CA	2011-3768C	SNL LDRD
Glass	A Systems Approach to Assessing Nonproliferation Strategies	7/16/2011	Presentation: Plenary	Institute of Nuclear Materials Management (INMM) Conference, Palm Desert, CA	2011-3768C	SNL LDRD

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Moore	Extending Opinion Dynamics to Model Public Health Problems and the Evaluation of Public Policy Interventions	7/24/2011	Presentation: Conference	29th International Conference of the System Dynamics Society, Washington, DC	2011-3189 P	FDA
Zagonel	Development of an Agent Based Epidemiological Model of Beef Cattle	7/24/2011	Conference Paper	29th International Conference of the System Dynamics Society, Washington, DC	2011-4918 C	State of New Mexico Small Business Administration
Zagonel	Developing a theory of the societal lifecycle of cigarette smoking: Explaining and anticipating trends using information feedback	7/24/2011	Conference Paper	29th International Conference of the System Dynamics Society, Washington, DC	2011-2287 C	FDA
Zagonel	Development of an Agent Based Epidemiological Model of Beef Cattle	7/24/2011	Presentation: Conference	29th International Conference of the System Dynamics Society, Washington, DC		State of New Mexico Small Business Administration
Zagonel	Developing a theory of the societal lifecycle of cigarette smoking: Explaining and anticipating trends using information feedback	7/24/2011	Presentation: Plenary	29th International Conference of the System Dynamics Society, Washington, DC	2011-2287 P	FDA
Moore	A Multiscale Paradigm Combining Individual-Based Modeling and System Dynamics to Design Policy Options for Obesity Problem	8/18/2011	Conference Paper	29th International Conference of the System Dynamics Society, Washington, DC	2011-6146 C	FDA

Phoenix Lead	Title	Publication Date	Product Type	Publication/Presentation Venue	SAND #	Funding
Moore	A Multiscale Paradigm Combining Individual-Based Modeling and System Dynamics to Design Policy Options for Obesity Problem	8/18/2011	Presentation: Conference	29th International Conference of the System Dynamics Society, Washington, DC	2011-6146 P	FDA
Moore	Extending Opinion Dynamics to Model Public Health Problems and the Evaluation of Public Policy Interventions	8/18/2011	Conference Paper	29th International Conference of the System Dynamics Society, Washington, DC	2011-3189 C	FDA

APPENDIX B: WORK PRODUCTS ACCOMPLISHMENT PLAN

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Conrad	Fresh Produce Market Topology: Modeling the Most Likely Contaminant Transport Pathways Through the Fresh Produce Market	3/31/2011	Project report	NISAC / DHS	NISAC
Conrad	The Value of Utilizing Stochastic Mapping of Food Distribution Networks for Understanding Risks and Tracing Contaminant Pathways	4/20/2011	Conference paper	4th Annual Conference on Infrastructure Systems: Challenges and Research For Next Generation Infrastructures in the 21st Century	NISAC
Schubert	Modeling Tribal Leadership Dynamics: An Opinion Dynamics Model of Pashtun Leadership Selection	6/1/2011	Conference Paper	Computational Social Science Society Conference	LDRD/ PostDoc Fellowship
Hobbs	Exchange 2 model and abstract problems	6/30/2011	SAND report, users manual, and executable code		VHA
Moore	Analyzing Public Health Care as a Complex Adaptive System of Systems	6/30/2011	Journal paper	TBD	VHA
Outkin	Applications of Self-calibrating Hybrid Causal-Learning Systems to Opinion Dynamics Modeling	6/30/2011	Journal paper	TBD	FDA
Brown	Earthquake warnings and event notification implications for infrastructure and population impact mitigation	7/28/2011	White Paper	SNL (SAND)	SNL PM
Hobbs	Loki-Infect 3: A Portable Networked Agent Model for Designing Community-Level Containment Strategies	7/30/2011	SAND report, users manual, and executable code		VHA
Finley	Disease Modeling for Global Biological Surveillance	8/1/2011	White Paper	DTRA (bio sciences Beth George)	SNL PD Salerno (IBTR)

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Brown	Modeling and Population Health - Step into Cuba/ CHILE	8/9/2011	Project Report	UNM/PRC	NIH Meetings Grant
Moore	Menthol scenario set analyses (Part of FDA Task 1)	8/28/2011	Project Report	HHS/FDA	FDA
Beyeler	Competitive Exclusion	8/30/2011	Journal paper	TBD	LDRD
Beyeler	Efficiency vs Robustness	8/30/2011	Journal paper	TBD	LDRD
Beyeler	Exchange2 Application to Global Insurance	8/30/2011	Journal paper	TBD	LDRD
Beyeler	Growth: Sizing Strategies	8/30/2011	Journal paper	TBD	LDRD
Glass	Exchange2 Application to National and Global Security	8/30/2011	Journal paper	TBD	LDRD
Glass	Phoenix: Complex Adaptive Systems of Systems (CASoS) Engineering Version 1.0 (LDRD Final SAND report)	8/30/2011	SAND report	CASoS Engineering Initiative website	SNL LDRD
Ames	Complex Adaptive Systems of Systems (CASoS) Engineering: Framework Version 1.0	8/31/2011	SAND report	SAND report	LDRD
Beyeler	Congestion & Cascades in Interdependent Payment Systems	8/31/2011	Journal Paper	International Journal of Central Banking (in review)	NISAC
Beyeler	Formulation of Exchange Model	8/31/2011	Journal paper	Possibly Physica A	LDRD
Brodsky	Application of Complex Adaptive Systems of Systems Engineering to Tobacco Products	8/31/2011	Journal paper	TBD	HHS/FDA

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Brodsky	Discrete-Event Population Structure Model with Applications to Population Health: Model Development and Preliminary Results (2011 FDA Task 1)	8/31/2011	Project report	CASoS Engineering Initiative website	HHS/FDA
Brodsky	Opinion Dynamics Model: Evaluating the effects of social networks and information on tobacco use and the effectiveness of public policy interventions (2011 FDA Task 1)	8/31/2011	Project report	TBD	HHS/FDA
Brodsky	Summary: Model Development and Testing to Support Tobacco-Control (2011 FDA Task 1)	8/31/2011	Project Report	CASoS Engineering Initiative website	HHS/FDA
Brown	Demonstration of modeling capability for tobacco prevalence and related mortality for 3 scenarios	8/31/2011	Project Report		FDA
Brown	Review industry guidance for reporting	8/31/2011	Project Report		FDA
Brown	Pathways Network Analysis Project	8/31/2011	Proposal	NIH - R21: Behavioral and Social Science Research on Understanding and Reducing Health Disparities (PAR-10-137)	
Brown	Complex Adaptive Systems of Systems (CASoS) Engineering: Applications Version 1.0	8/31/2011	SAND Report (Project report)	CASoS Engineering Initiative website	LDRD, other
Linebarger	Complex Adaptive Systems of Systems (CASoS) Engineering: Environment Version 1.0	8/31/2011	SAND report	CASoS Engineering Initiative website	SNL LDRD
Zagonel	Developing a theory of the societal lifecycle of cigarette smoking: Explaining and anticipating trends using information feedback	9/1/2011	Journal Paper	TBD	FDA
Brown	Tobacco community surveillance design recommendations	9/15/2011	Project Report		FDA

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Beyeler	Multi-network cascading LDRD Final SAND report	9/30/2011	SAND report	CASoS Engineering Initiative website	LDRD
Cannon	The Effect of Healthcare Environments on a Pandemic Influenza Outbreak Influence of Hospital Environments	9/30/2011	Journal paper	Public Health Journal (TBD)	VHA
Cannon	Biophysics model for Influenza	9/30/2011	Journal paper	Public Health Journal (TBD)	VHA
Finley	Integrating Uncertainty Analysis into Complex-System Modeling to Design Effective Public Policies (Applying UQ to Davey et al. 2008 PlosOne analysis using Infection3)	9/30/2011	Journal paper	UQ or Public Health or Math-Policy Journal	ALL
Moore	A Multiscale Paradigm Combining Individual-Based Modeling and System Dynamics to Design Policy Options for Obesity Problem	9/30/2011	Journal paper	TBD	FDA
Finley	Modeling Emergency Department Resource Allocation Policies	10/1/2011	Journal Paper	Leverage Art Kellermann for placement	VHA
Brown	Potential Impacts of Climate Change on Infrastructures	10/25/2011	Poster	WCRP Conference	LDRD
Brown	Phoenix Health Program Description (WHHSC, VA, FDA, UNM, others) umbrella initiative	10/30/2011	Project Report		FDA, VHA
Finley	Machine Learning Techniques Applied to Uncertainty Quantification of Complex Systems	10/31/2011	Journal Paper	Reliability Engineering and Safety Science (RESS)	FDA
Conrad	Stochastic mapping in support of food defense policy design	11/3/2011	Conference paper	Association for Public Policy Analysis & Management (APPAM) 33rd Fall Research Conference, Washington, DC	TBD

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Glass	Pandemic Influenza and Complex Adaptive System of Systems (CASoS) Engineering	11/3/2011	Presentation: Plenary	2011 Association for Public Policy Analysis and Management (APPAM) Fall Research Conference: Seeking Solutions to Complex Policy and Management Problems, Washington DC	
Brown	Infrastructure Interdependencies and CASoS Analysis	11/16/2011	Presentation: Plenary	3rd NSF Emerging Frontiers in Research Innovation (EFRI), Resilient and Sustainable Infrastructures (RESIN) Program workshop	
Brown	CASoS Engineering for policy design	11/30/2011	Journal	TBD	FDA, other
Moore	Extending Opinion Dynamics to Model Public Health Problems and the Evaluation of Public Policy Interventions	11/30/2011	Journal Paper	TBD	FDA
Schubert	Modeling Tribal Leadership Dynamics: An Opinion Dynamics Model of Pashtun Leadership Selection 2	12/9/2011	Journal Paper	Foreign policy, international relations journal of some sort	LDRD/ PostDoc Fellowship
Finley	Hepatitis C Analysis	12/15/2011	Journal Paper	Medical journal (to be lead by David Ross)	VHA
Finley	Agile Policy Design	12/15/2011	White Paper	DTRA	VHA, FDA
Moore	Semantic Characterization of multiple opinions in Opinion Dynamics (Part of FDA Task N)	12/15/2011	Project Report	HHS/FDA	FDA
Schubert	Modeling Tribal Leadership Dynamics: An Opinion Dynamics Model of Pashtun Leadership Selection 3	12/30/2011	Journal Paper	JASSS - Journal of Artificial Societies and Social Simulation	LDRD/ PostDoc Fellowship
Glass	Growth and defection in Hierarchical, Synergistic Networks	12/31/2011	Journal paper	TBD	

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Glass	Minimum social rules to build representative social nets	12/31/2011	Journal paper	TBD	FDA
Glass	Role of heterogeneous tolerance in meandering public opinion	12/31/2011	Journal paper	TBD	FDA
Glass	Initiating the Science of Engineering Corporate Excellence	12/31/2011	SAND Report	CASoS Engineering Initiative website	Sandia Corporate
Moore	Complexity approaches to population health problems (VA work + social network)	1/15/2012	Presentation: Conference	ECCS'12 - European Conference on Complex Systems	TBD/VHA
Finley	Spikes Analysis	2/15/2012	Project Report	TBD	VHA
Moore	Semantic Characterization of multiple opinions in Opinion Dynamics	2/15/2012	Journal Paper	TBD	FDA
Aamir	Value and limitations of data for anticipating and managing societal response to terror and natural incidents	2/28/2012	Conference Paper	Computational Social Science Society 2012 Conference	NISAC
Aamir	Condition-dependent maladaptive behavior scoping study (literature review and data assimilation for behavioral responses to terrorist attacks and natural disasters)	2/28/2012	Project Report	NISAC DHS project report Year 1	NISAC
Corbet	Validation of analyses in support of policy decisions and designs	2/28/2012	Project Report	NISAC / DHS	NISAC
Moore	Modified risk tobacco products scenario set analyses. draft results	2/28/2012	Project Report	HHS/FDA	FDA
Moore	Telemedicine Network Robustness for Healthcare Applications	2/28/2012	Project Report	VHA	VHA
Beyeler	Retail Payment System Capability Analysis	2/29/2012	Project Report	Report to DHS	NISAC

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Beyeler	Retail Payment System Capability Development	2/29/2012	Project Report	Report to DHS	NISAC
Brown	Networks and Population Health	3/20/2012	Journal	TBD	FDA, other
Corbet	Validation of analyses in support of policy decisions and designs	3/30/2012	Journal paper	TBD	NISAC
Finley	Spikes Analysis	4/15/2012	Journal Paper	tbd	VHA
Moore	Telemedicine Network Robustness for Healthcare Applications	4/28/2012	Journal paper	TBD	VHA
Brodsky	Overview on approach to a tobacco model	5/31/2012	Journal paper	TBD	HHS/FDA
Verzi	Population Structure Model with future projections for Morbidity and Mortality	5/31/2012	Journal paper	TBD	FDA
Brown	Infrastructures as CASoS	6/30/2012	Journal	TBD	NISAC, other
Conrad	Systems approach to implementing new technology in airport security systems	7/22/2012	Conference paper	30th International Conference of the System Dynamics Society, St. Gallen, Switzerland	TBD – Internat'l Travel
Moore	Modeling initiation, cessation, and prevalence using a social network model (incl examples of advertising, education, and addictiveness)	10/31/2012	Journal paper	TBD	FDA
Finley	Role of Uncertainty Quantification in Analysis of Complex Systems with Applications to Tobacco Control	9/31/2011	Journal paper	Support from Steve Marcus (NIH) for Journal placement	FDA
Corbet	Petroleum Fuels Networks	TBD	Project Report	NISAC / DHS	NISAC
Glass	Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions	TBD	Journal paper	Invited by new Central EU Engineering journal	ALL

Phoenix Lead	Title	Draft Date	Publication Type	Presentation/Presentation Venue	Funding
Glass	Water and CASoS Engineering	TBD	News Letter	Emerging and Innovative Technology Committee (EITC) column in the American Society of Civil Engineers (ASCE) Environmental and Water Resources Institute (EWRI) newsletter: Currents	ALL

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