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Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions

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Complex Adaptive Systems of Systems, or *CASoS*, are vastly complex *eco-socio-economic-technical systems* which we must understand to design a secure future for the nation and the world. Perturbations/disruptions in CASoS bring with them the potential for far-reaching effects due to highly-saturated interdependencies and attendant vulnerabilities to cascades in associated systems. For example, the global effects of disruption within CASoS can be seen in the impacts of the Japanese earthquake/tsunami on not only the people and industry of Japan, but also on US car manufacturers, on global energy and financial markets, and on the future of nuclear power production around the world. We approach this sort of high-impact problem space as engineers, devising interventions or *problem solutions* that influence CASoS to achieve specific *aspirations*, an activity we call *CASoS Engineering*. Through application to real-world problems, the CASoS Engineering Initiative at Sandia National Laboratories is evolving CASoS Engineering principles while growing a community of practice and the CASoS engineers to populate it. The Initiative is both grounded in reality and works to extend our understanding and control of that reality; it is both a solution within a CASoS and a CASoS itself. We seek collaborators -engineers, problem holders, analysts, all those reaching for dynamic, adaptive solutions - to join in the evolution of the discipline of CASoS Engineering.

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1 Introduction

Our goal is to engineer solutions to problems within the vastly complex and critically important eco-socio-economic-technical systems that are all fundamentally *Complex Adaptive Systems of Systems (CASoS)* with influence spanning local to regional to national to global scales. Examples of CASoS include: eco and agro-eco 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. Example solutions include harvest/cultivation sequencing for agro-ecosystems under the pressure of climate change, adaptive intervention combinations for pandemic suppression, and "smart" grids to satisfy growing electrical energy requirements. All of these "system" solutions are potentially CASoS themselves, or what we call *CASoS solutions*.

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 eco-socio-economic-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 CASoS 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 classical scientific practice of exhaustively learning more and more about the details of individual CASoS: only those that are needed to achieve our aspirations must be understood and then only well enough for our purposes. Aspirations fall into a set of clearly identified engineering categories: *predict*; *prevent* or *cause*; *prepare*; *monitor*; *recover* or *change*; and most encompassing, *control*. Similar across all of these categories, three key components of aspiration must be defined: *decision* (what are the choices, what the consequences both intended and unintended?), *robustness of decision* (what are the uncertainties, how can they be reduced?), and *enabling resilience* (what conditions yield better end states?). In the context of CASoS, these definitions differentiate options to *inform policy*, the actions taken to influence the CASoS. Through such systemization, we argue that the requisite theories, technologies, tools, and approaches for aspiration-focused CASoS Engineering are similar across many CASoS domains and their integration forms an emerging discipline: mapping of aspirations to problem solutions within CASoS.

In this paper, we describe Sandia National Laboratories' evolving *Initiative in CASoS Engineering* which we call *Phoenix*. Like the mythical reincarnating bird for which it is named, we expect our Initiative to cycle through growth, death and rebirth as time proceeds. Phoenix has been designed as a CASoS solution (a solution which itself is a CASoS with all the potential for dynamic, adaptive, and cascading behaviors that implies). In many ways, it is well aligned with the New England Complex Systems Institute, the Santa Fe Institute and others that focus on Complex Systems but Phoenix is differentiated by our focus on Engineering: the design of solutions that influence, control, or manipulate CASoS behaviors. In other ways Phoenix is complementary to the National Centers for Systems of Systems (SoS) Engineering and others from Engineering as our focus is on the complex and adaptive nature of the systems (and solutions) of interest. Additionally, the ideas and conceptual basis of Phoenix are synergistic with many of those articulated in Bar-Yam's book *Making Things Work: Solving Complex Problems in a Complex World* [Bar-Yam 2005]. Given the brevity of this proceedings paper, we refer the reader to expanded works available on our CASoS Engineering website where a growing body of theory and application from across the Initiative are given in greater detail.

2 Foundations

Phoenix has been designed to achieve a set of aspirations within a CASoS, Sandia National Laboratories (Sandia), which itself is part of an expanding sequence of CASoS including the military-industrial complex, the United States, and the global environment (both physical and political). From an initial set of applications, an outwardly growing network of Research, Development, and Application (R&D&A) connections is creating a CASoS Engineering community of theory, practice and culture. Phoenix's current CASoS applications cross internal organizational boundaries as well as many external federal agency funding boundaries (e.g., DOE, DOD, DHS, DVA, HHS). Addressing many of the problems critically requiring solution, these applications have now begun to engage business, academia and other institutions in collaborative development.

The kernel of the Initiative (people, applications, approaches, methods and theory) takes its roots from the National Infrastructure Simulation and Analysis Center (NISAC) funded by the Department of Homeland Security (DHS). In 2002, the Advanced Methods and Techniques Investigations (AMTI) 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 [Glass 2003]. Through AMTI, NISAC's analysis of socio-economic-technical infrastructures, such as public health, natural gas pipelines, petrochemical supply chains, and banking & finance, led to high-impact solutions, some with national and international recognition. In particular, our work to design interventions for pandemic influenza was particularly successful in both influencing public policy and confirming the significance of our approach [Glass 2006, 2008, 2009].

In response to this success, Sandia administration funded our development of a *Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering*

Initiative [Glass 2008] in which CASoS, CASoS Engineering, and a path forward to build the discipline of CASoS Engineering were defined. There we combined the fields of Systems, Complex Systems, Complex Adaptive Systems, and Systems of Systems and defined CASoS and CASoS Engineering through articulation of a set of 10 widely ranging Defining Examples of socio-economic-technical systems with critical importance to the nation and the world. The last of these defining examples was Sandia National Laboratories itself.

Our path forward rejects the classical linear compartmentalized progression from Research (R) to Development (D) to Application (A). Instead, it intrinsically integrates R&D&A by developing CASoS Engineering theory and principles in the context of solving problems for applications of consequence, i.e., those having the potential for high national and international impact. As illustrated in **Figure 1**, this path can be seen as an outwardly growing spiral in which each application adds knowledge to extend the core Engineering Theory and Experiment within an expanding Environment of Data Analysis and Computational Simulation.

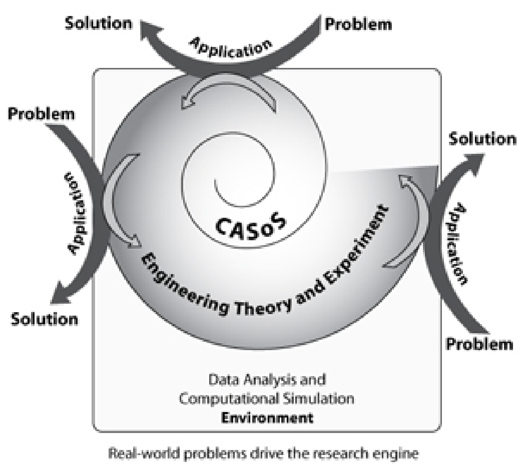

Figure 1: Diagram of CASoS Engineering Theory and Experiment evolving through application to real world problems

Hence, the functional structure of Phoenix (which we expand in Section 3) fundamentally integrates Application with Research and Development.

- **Application**: High-impact 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 3.1)
- **Research**: The ever-evolving CASoS Engineering Framework systematizes the theory & practice of CASoS Engineering across wide-ranging domains and

diverse aspirations for affecting CASoS behavior. The Framework integrates three components: 1) Defining the CASoS, problem, and approach; 2) Designing and Testing solutions that are robust to uncertainty while providing critical enablers of system resilience; and 3) Actualization of the solution within the CASoS. Here, Research is defining the science (principles and methods) of CASoS engineering. (Section 3.2)

- **Development**: A CASoS Engineering Environment supports the CASoS Engineering Framework by providing: 1) A modeling, simulation and analysis platform in which modular computational tools can be assembled in many ways and for many purposes, and 2) 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 3.3)

Within and across these components, through implementation and contemplation, we seek the next steps and episodic transformations in which intrinsic connections between R&D&A, insights, and breakthroughs in any area can cascade to the others. Accelerating this cascade 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.

Critically, Phoenix is a design solution which itself is a CASoS. Below we state its design aspirations (Section 2.1) and then define Phoenix itself as it currently exists as a CASoS (Section 2.2). Over time, CASoS Engineering principles are being applied reflexively to the Initiative's organization, development, and growth. We are finding that both our aspirations and thus the functional structure of Phoenix evolve as new applications/projects and people join the Initiative.

2.1 Aspirations

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

- Develop the science of CASoS Engineering: The Theories, Methods, and Approaches that allow the creation of solutions for eco-socio-economic-technical problems, that are robust and resilient, and that can be applied such that their actualization within the CASoS is reflexive (as the CASoS itself adapts to the solution, conditions are created that may require the solution to adapt as well).

- Develop an engineering 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: The first generation of CASoS Engineers, their backgrounds, education and training establishes an expanding community of practice that grows the 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: Phoenix's definition and development intrinsically and continuously emerges from application; our internal structure grows interactively and changes both Phoenix and the environment in which it exists, with extension to Sandia and the outside world.

2.2 Phoenix as a CASoS

The definition of the object of analysis or design as a CASoS is a critical step in the process of CASoS Engineering. Appendix D of the Roadmap [Glass 2008] describes this definition process and provides examples of its application. As mentioned above, our parent institution, Sandia, is the last of these Defining Examples and formed the context for designing Phoenix. Phoenix itself is a CASoS and a snapshot follows.

- **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 which 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, application integrator, framework architect, environment architect, conceptual model architect, communication specialist, application/project leader, application implementer, and advisory board member. In their various (frequently multiple) roles, people form a growing and changing network for the flow of information, influence, and funding.
- **Environment**: The environment within which Phoenix acts, grows, and evolves includes Sandia components plus related personnel/organizations in the U.S. Government (e.g., DOE, DOD, DHS, DVA, HHS), other funding sources, internal and external competitors or potential collaborators, academia, and the home environments of staff. Sandia components include its line-hierarchy (e.g. departments, groups, centers, etc.), business units, non-Phoenix projects, subject-matter-oriented and functional groups (e.g. engineers, scientists, managers), corporate incentives and regulations, and support systems (infrastructure).
- **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.

- **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, and is more likely to emerge in medium-sized organizations – small groups tend to not exhibit complex behavior due to inadequate numbers of interactions, while large organizations often try to dampen complex behaviors through command and control.
- **Adaptive**: People conduct applications/projects in the context of the processes/theory/philosophy of the Engineering Framework: they 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 application 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.

3 Functional Structure

Technical objectives focused on overarching problems across many applications are the primary drivers of the CASoS Initiative's functional structure: research and development are fundamentally entwined with applications.

Phoenix has instantiated the vision of outwardly growing spiral development integrating R&D&A (shown in **Figure 1**, above). **Figure 2** illustrates a refinement of this functional structure in which 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 vanguard projects as well as infused back into existing projects allowing them to continue to develop and transform over time.

Both vanguard 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 understandings within the entire "multi-cellular organism" or "ecosystem". Adoption, use, and application of CASoS Engineering capabilities in established projects extend project lifetimes to add greater stability to the whole. The link between the vanguard and the established must be strong; this relationship enables the intrinsic integration of the individual applications into a whole.

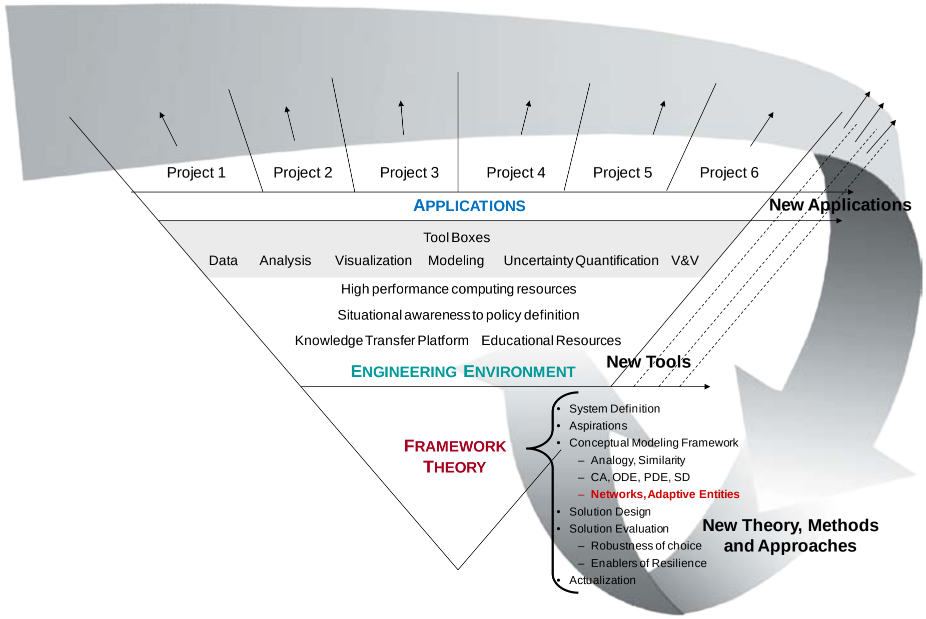

Figure 2: Diagram of CASoS Engineering Initiative's structural integration of theoretical framework, engineering environment, and the driving reality of real-world applications

The functional structure shown in **Figure 2** 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 that we are inviting through frontier applications is in knowledge, how we think about and understand problems. If we don't invite instability in the form of new principles, new methods, new organization, if we don't entertain the fate of the Phoenix, our thinking and our approach to problems stagnate. The current structure and state of Phoenix are provided in *Phoenix: Complex Adaptive System of Systems (CASoS) Engineering Initiative Version 1.0* [Glass 2011].

3.1 Applications

Applications are chosen to foster the growth of the discipline of CASoS Engineering, particularly in the initial stages of Phoenix, and require:

- model capability development that enhances our understanding of high impact situations or issues in particular CASoS of great interest to global security
- development and testing of theories about the vulnerabilities, strengths, and risks of general CASoS

- development of an integrated modeling and analysis environment to understand and communicate the key conditions, parameters and adaptive behaviors relative to the application goals

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

As a matter of practicality, Phoenix has been initiated with existing and newly formed projects in which we have domain expertise, have applied 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 3** shows the problem space encompassed by existing CASoS Engineering applications (red) along with areas where we are currently building (black).

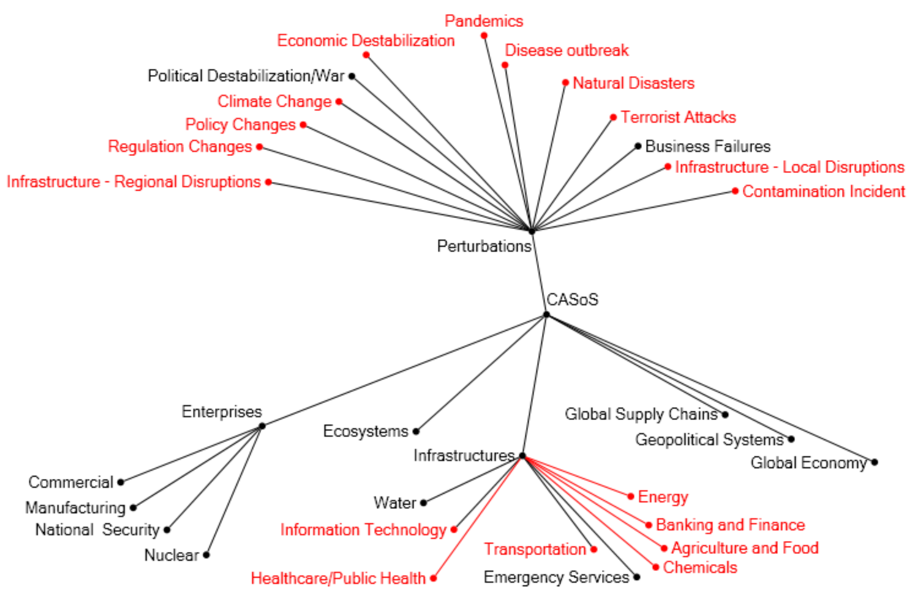

Figure 3: Diagram of Applications space as a simplified network of perturbations and CASoS

While the range of subject domains and funders is broad enough to satisfy our cross-cutting vision, the range of aspirations and organizational representation is less so. Phoenix must work to diversify these last two areas in the future. Example application subject domains include:

- Community Health
- Food Defense
- Banking and Finance
- Chemicals
- Energy
- Intelligence

With example perturbations:

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

Cutting across these applications, we focus on a number of abstract/theoretical subject domains, for example:

- Networks, dynamic networks and inter-network cascading
- Learning and behavioral models for generic entities
- 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)
- 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)
- Representation of entity behavior by finite or infinite state mathematics
- Approaches to understanding, verifying and validating behavior of large systems

The current portfolio of CASoS applications 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, has produced a design for containing the spread of influenza to prevent a deadly pandemic. This design solution was used to set the national planning policy. The public health and healthcare sector has many problems of similar scale and potential impact. Solutions can be devised based on an understanding of the system and how it will behave when perturbed, but solutions that are robust to uncertainty (those that produce better outcomes no matter the conditions) are the ones we strive to develop in cases where consequences are severe. The current structure and state of CASoS Engineering Applications are provided in *Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0* [Brown 2011].

3.2 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. As illustrated in **Figure 4**, the framework is comprised of three phases applied primarily in succession but with some overlap, blending, and iteration (both between and within) to deliver CASoS engineered solutions.

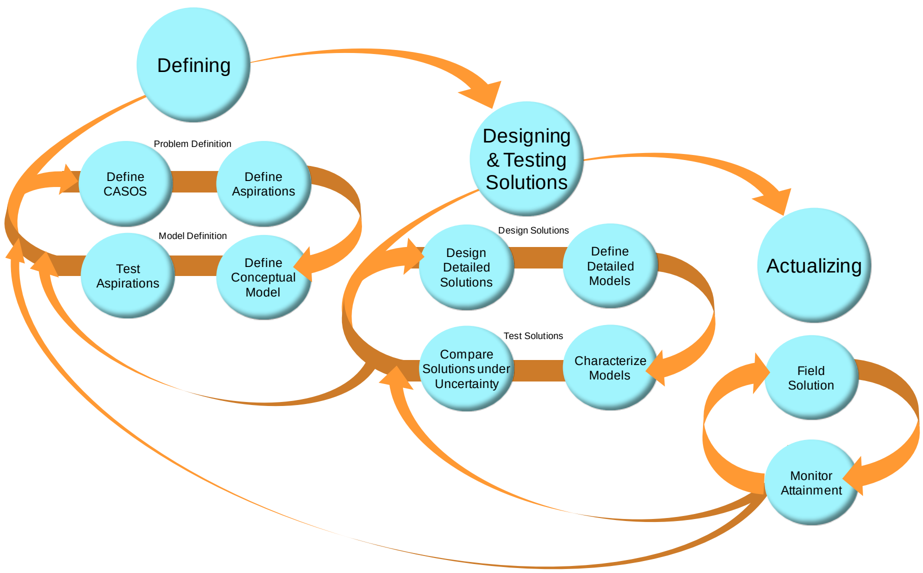

Figure 4: Diagram of the CASoS Engineering process

- **Defining** (blackboard to details) 1) the CASoS of interest, 2) the Aspirations (Predict, Prevent or Cause, Prepare, Monitor, Control, and Recover or Change), 3) Appropriate conceptual models (including required data), and 4) Testing to understand and compare aspirations. 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. A taxonomy of problems and approaches to their solutions is unfolding from this activity.

- **Designing and Testing Solutions** using computational models, data mining/integration, experiments, etc, within a common quantitative analysis environment. Designing and testing solutions are problem dependent, focused on answering questions relevant to any aspiration: 1) how might the aspiration be implemented and are there *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.

Integral to this process are Uncertainty Quantification and Verification and Validation efforts.

- **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, or a CASoS itself. 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. Monitoring of system response is required, which may trigger the redefinition, redesign, and retesting of solutions if found not to work.

Actualization will require designing and testing to suggest future steps: 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. The current structure and state of the CASoS Engineering Framework are provided in the *Complex Adaptive Systems of Systems (CASoS) Engineering Framework Version 1.0* [Ames 2011].

3.3 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 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. Additional goals of the CASoS Engineering Environment are to:

- facilitate computationally a multiple-model approach to modeling CASoS problems, either as independent perspectives of the same problem or as integrated ("docked") models at different scales
- support the creation of conceptual and computational models of CASoS problems
- enable uncertainty quantification for CASoS models
- facilitate the reuse of knowledge, models, and code from previous CASoS efforts
- 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.

The CASoS Engineering Environment is currently comprised of two platforms, one computational and the other for knowledge management, that support 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 current structure and state of the CASoS Engineering Environment are provided in *Complex Adaptive Systems of Systems (CASoS) Engineering Environment Version 1.0* [Linebarger 2011].

4 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. Designing influence within CASoS, or CASoS Engineering, is the mapping of aspirations to problem solutions within this domain. The sheer complexity of CASoS, the subtlety of their adaptive behaviors, the difficulty of running experiments, and the problems of integrating the different analytic frameworks and representations required to understand their component systems underscores the need for new theory, methods and practice. The CASoS Engineering Initiative at Sandia National Laboratories is developing CASoS Engineering principles that are being applied to solve real world problems while developing a community of practice and the CASoS engineers to populate it. With the active collaboration of problem holders, the CASoS Initiative's structure is being driven using technical objectives focused on overarching problems across many applications and through recognition that the Initiative itself is a CASoS. As a CASoS, our definition and development intrinsically and continuously emerges from application; our internal structure grows interactively and changes both the Initiative and the environment in which it exists. With backgrounds in many classical disciplines, CASoS engineers are consistent in their attraction to cross disciplinary eco-socio-economic-technical problems and the pursuit of their solutions. We invite problem holders and people seeking their technical solutions to join in the application (and evolution!) of the discipline of CASoS Engineering.

Bibliography

[1] Ames, A.L., Glass, R.J., Brown, T.J., Linebarger, J.M., Beyeler, W.E., Detry, R.J., 2011, Complex Adaptive Systems of Systems (CASoS) Engineering Framework Version 1.0, Sandia National Laboratories SAND report.

[2] Bar-Yam, Y., 2005, Making Things Work: Solving Complex Problems in a Complex World, NECSI Knowledge Press.

[3] Brown, T.J., Glass, R.J., Beyeler, W.E., Ames, A.L., Linebarger, J.M., Maffitt, S.L., 2011, Complex Adaptive System of Systems (CASoS) Engineering Applications Version 1.0, Sandia National Laboratories SAND report.

[4] Davey, V.J., Glass, R.J., Min, H.J., Beyeler, W.E., and Glass, L.M., 2008, Effective, Robust Design of Community Mitigation for Pandemic Influenza: A Systematic Examination of Proposed U.S. Guidance, *PLoSOne*, 3(7): e2606, doi:10.1371/journal.pone.0002606.

[5] Glass, R.J., Beyeler, W.E., Conrad, S.H., Brodsky, N.S., Kaplan, P.G., Brown, T.J., 2003, Defining Research and Development Directions for Modeling and Simulation of Complex, Interdependent Adaptive Infrastructures, Sandia National Laboratories SAND 2003-1778.

[6] Glass, R.J., Glass, L.M., Beyeler, W.E., and Min, H.J., 2006, Targeted social distancing design for pandemic influenza, *Emerging Infectious Diseases*, Vol. 12, No. 11.

[7] Glass, R.J., Ames, A.L., Stubblefield, W.A., Conrad, S.H., Maffitt, S.L., et al., 2008, Sandia National Laboratories: A Roadmap for the Complex Adaptive Systems of Systems CASoS) Engineering Initiative, Sandia National Laboratories SAND 2008-4651.

[8] Glass, R.J., 2009, Pandemic Influenza and Complex Adaptive System of Systems (CASoS) Engineering, Proceedings of the 2009 International System Dynamics Conference, Albuquerque, New Mexico, July, 2009.

[9] Glass, R.J., Ames, A.L., Brown, T.J., Maffitt, S.L., Beyeler, Finley, P.D., et al., 2011, Phoenix: Complex Adaptive System of Systems (CASoS) Engineering Initiative Version 1.0, Sandia National Laboratories SAND report.

[10] Linebarger, J.M., Detry, R.J., Glass, R.J., Beyeler, W.E., Ames, A.L., Finley, P.D., Maffitt, S.L., 2011, Complex Adaptive Systems of Systems (CASoS) Engineering Environment Version 1.0, Sandia National Laboratories SAND report.