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Complex Adaptive Systems of Systems (CASoS) Engineering and Foundations for Global Design

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Abstract

Complex Adaptive Systems of Systems, or CASoS, are vastly complex ecological, sociological, economic and/or technical systems which must be recognized and reckoned with to design a secure future for the nation and the world. Design within CASoS requires the fostering of a new discipline, CASoS Engineering, and the building of capability to support it. Towards this primary objective, we created the Phoenix Pilot as a crucible from which systemization of the new discipline could emerge. Using a wide range of applications, Phoenix has begun building both theoretical foundations and capability for: the integration of Applications to continuously build common understanding and capability; a Framework for defining problems, designing and testing solutions, and actualizing these solutions within the CASoS of interest; and an engineering Environment required for "the doing" of CASoS Engineering. In a secondary objective, we applied CASoS Engineering principles to begin to build a foundation for design in context of Global CASoS.

ACKNOWLEDGMENTS

This work was funded by Sandia National Laboratories Directed Research and Development (LDRD) Program's Energy, Resources and Nonproliferation Investment Area (recently reorganized to Energy, Climate and Infrastructure Security). We thank 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) for making this work possible.

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ACRONYMS, INITIALISMS, AND ABBREVIATIONS

CASoS	Complex Adaptive Systems of Systems
CTP	Center for Tobacco Products
DOD	Department of Defense
DSA	Defense Systems and Assessments
DVA	Department of Veterans Affairs
ECIS	Energy, Climate and Infrastructure Security
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
NISAC	National Infrastructure Simulation and Analysis Center
NW	Nuclear Weapons
Sandia	Sandia National Laboratories
SMG	Strategic Management Group
SMU	Strategic Management Unit
U.S.	United States
VHA	Veterans Health Administration

1 OVERVIEW

Complex Adaptive System of Systems (CASoS) are ubiquitous, they include forests, farms, cities, infrastructure, government, armed forces, nations – in short, systems that are socio-economic-ecologic-technical in nature. As a national security laboratory with an engineering mandate, nearly every important problem which we confront is within a CASoS; problems include nuclear stockpile management, nonproliferation, energy surety, and critical infrastructure protection among many, many others. We must recognize (and reckon with) the CASoS context to properly pose and solve problems without producing unintended consequences: we design feasible solutions that are robust to uncertainties and enhance system resilience. Our overarching goal is to maximize security, maximize health, and minimize risk within the CASoS for which we design, understanding that achieving everything may not be possible and that each objective must be weighed against the others. This is the domain of the emerging discipline of CASoS Engineering.

The prime objective of this Laboratory Directed Research and Development (LDRD) project was to foster the development of the discipline of CASoS Engineering and to define and begin to build the capability required to apply it. We accomplished this through the intimate integration of Research, Development and Application within a group of projects that had CASoS Engineering at their hearts. As part of this effort we have created and developed:

- The Phoenix Pilot: a group of people and projects discovering, designing, using and evolving the discipline and tools of CASoS Engineering (human capital driven by high impact problems)
- A foundation for a set of integrated CASoS Engineering Applications that cross-cut diverse fields and funding (funding-driven real-world applications that integrate and direct overarching research)
- An expandable, general CASoS Engineering Framework for the definition, design, testing and actualization of solutions within CASoS (theory forged through diversity of application)
- The basis of a CASoS Engineering Environment for the implementation and dissemination of CASoS Engineering (re-assorting mixture of tools, platforms and frameworks that support CASoS Engineers)

All of these interacting components are ongoing, living, growing, and adapting. Together they are a CASoS solution which itself is a CASoS (the solution creates a complex adaptive system-of-systems) and which will continue to add additional components in coming years as it evolves.

As a secondary objective, we began to build a capability that could focus on the design of influence in Global CASoS. Such a capability would allow evaluation of the cost benefit for policies imposed at a variety of scales and thus the design of policy combinations to most effectively achieve high levels of individual and/or communal health. Many of these policies have to do with Security: land and boarder security, food security, water security, energy security, commerce security, etc. In this way, our effort lays the foundation to develop concepts for the design of Trans-spectrum (i.e., resource, entity, scale) Global Security.

1 BUILDING THE CAPABILITY OF CASOS ENGINEERING

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 interpreting and quantifying the impacts of modification is difficult; they are *adaptive*, often hysteretic and/or recursive, so building understanding through testing is difficult because repeatable initial conditions are generally not possible and simultaneous tests are often not independent. Additionally, many critically important CASoS are *socio-economic-ecologic-technical* in nature, so a wide range of "physics" apply that must address technical concerns, economic concerns, political concerns, and the interface among them. And because socio-economic-ecologic-technical CASoS most often embed people, experimentation within them is risky and costly. All these factors encourage widely different opinions on what the problems are, how big the problems are, and how to go about solving them.

To build the capability of CASoS Engineering, we must overcome this proliferation of opinion through critical thinking focused on systematic investigation often with the aid of explicit conceptual, mathematical and computational models and numerical experimentation. At this stage, theory, development and application must be intrinsically blended. Therefore, we created the Phoenix Pilot as a melting pot of people working on problems within CASoS. In context of Phoenix, a systemization of CASoS Engineering is emerging through the definition of three overlapping components: Applications and their interdependency in context of building capability, a theoretical Framework for defining and solving CASoS problems, and Environment where we do our work and communicate with others.

We summarize Phoenix, Applications, Framework and Environment below. Each of these components is documented in living evolving manuscripts used to guide our development in a thoughtful and explicit fashion now and into the future.

1.1 Phoenix Pilot

Initially using this LDRD as its kernel, Phoenix is designed as a cross-SMU, cross-SNL "pilot" experiment that organizes a set of projects which all do CASoS Engineering. Phoenix provides a human architecture for doing CASoS Engineering within Sandia that is growing and entraining new projects and groups of engineers. Phoenix is a solution within a CASoS and a CASoS itself. Its functional structure, shown in Figure 1**,** integrates Applications with Framework with Environment. New understanding found from integration of the set of Applications is distilled and incorporated into the Framework, which, over time, drives the development of new tools, connection and depth within the Environment.

While LDRD created the kernel, Phoenix will continue for many years to bring new applications, ideas and texts that continue building the capability of CASoS Engineering.

Currently, Phoenix has a core team of 10 researchers who are connected through the integration of over 20 projects to many other researchers across the lab. The core team spans a set of departments within two groups (6130, 6920) within two centers (6100, 6900) within one vice presidency (6000). In addition, over 20 undergraduate and graduate students from UNM and across the nation have been entrained.

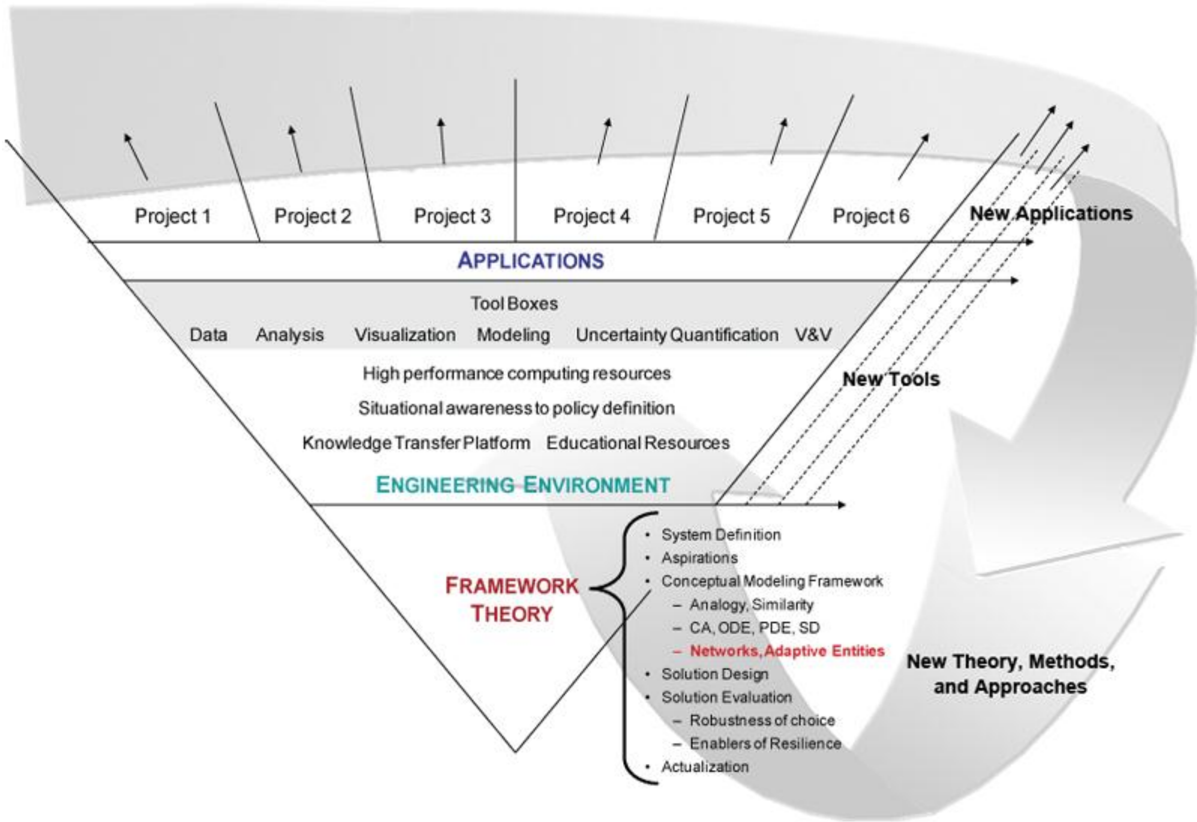

Figure 1. Diagram of Phoenix's Structural Integration of Theoretical Framework, Engineering Environment, and the Driving Reality of Real-World Applications

Phoenix is documented in our report *Phoenix: Complex Adaptive System of Systems (CASoS) Engineering Version 1.0* (Glass et al, 2011a). There, we also present our thinking on development of human capital for the capability (CASoS Engineers), give a set of current roles and responsibilities within the group, and an ongoing list of accomplishments and adaptable goals for the future.

Over the period of this LDRD (primarily in the final year) this group has produced:

- Book Chapters: 2
- Conference Papers: 14
- Journal Papers: 5
- Conference Presentations – Contributed: 17
- Conference Presentations – Plenary: 6
- Invited Seminar Presentations: 15
- Project Reports: 9
- Proposals for funding (external): 10
- Proposals for funding (internal LDRD): 26
- Short Course: 1
- Workshops: 2

These products have been presented/published at wide-ranging venues (for a complete listing see Appendix II of the Phoenix report, Glass et al., 2011a). Planned products for this next calendar year continue the upward trend, reflecting our focus on moving communication efforts from report to conference to journal publication within each project that is part of Phoenix (see Appendix III of Glass et al, 2011a).

The description of Phoenix in Glass et al. (2011a) is a snapshot of the living document: a distilled version (Glass et al. 2011b) was presented at the International Conference in Complex Systems in June 2011 and gives a more concise read (Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions).

1.2 CASoS Engineering Applications

In order to build the discipline of CASoS Engineering, Applications must push the evolution of the theoretical Framework and engineering Environment by transforming diverse forms of "energy" (funds, ideas, synergy between people and projects, and artifacts) into capability. Applications must also balance the portfolio for diversity in scale (local, regional, national, or global) and subject domain so that cross-disciplinary patterns can emerge. The current cross-cutting skill sets of CASoS domain experts and engineers must be maintained and extended to take advantage of the diversity of applications that are driving Phoenix. 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 beyond Sandia's walls to address ecological, sociological, economic, and technical problems of a complexity beyond the reach of conventional modeling/analysis methods.

Building from existing and newly formed projects in which we had domain expertise in 2008, the current integrated portfolio of Phoenix projects contains CASoS applications at a variety of states of maturity covering some of the problem space important to national and global security. In **Figure 2** we give a relational network view of our work that connects perturbations, a set of CASoS and our overarching engineering aspirations (to maximize security and health, to minimize risk). While not complete, this view shows the beginnings of a full taxonomy and our position within it: red indicates areas with artifacts, black indicates areas in development. We are poised for growth and impact within both traditional and new Sandia Application areas.

Within traditional Sandia application areas, CASoS Engineering supports infrastructure analysis within the National Infrastructure Simulation and Analysis Center (NISAC) for the International, Homeland and Nuclear Security (IHNS) Strategic Management Unit (SMU), and is growing to support nonproliferation and nuclear weapons (NP and NW), energy and climate (ECIS), and defense programs (DSA) in which a new upcoming LDRD project has been funded.

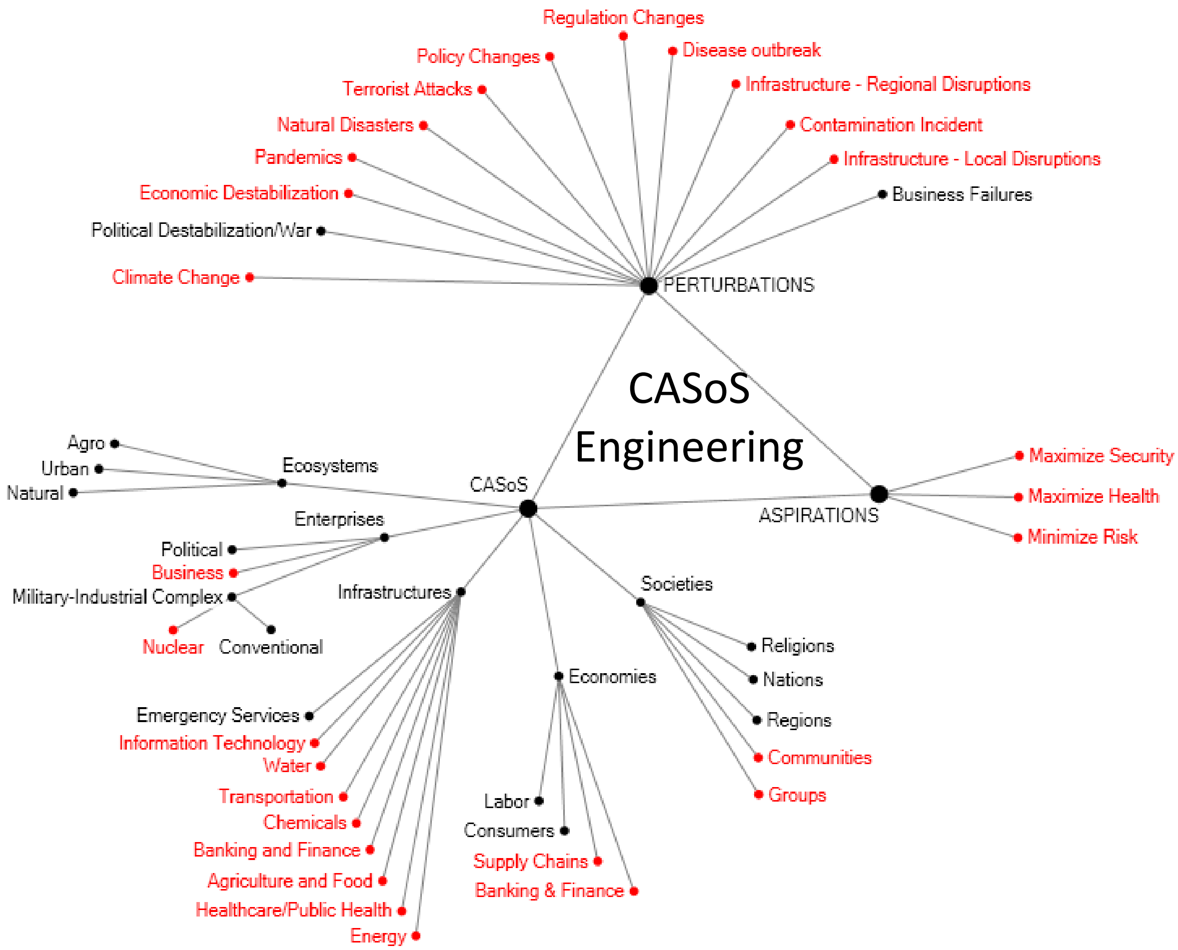

Figure 2. Integrated CASoS Engineering Applications Space as a Simplified Network of Aspirations, Perturbations and CASoS

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

Public health is an example of a new Sandia application area that we are growing. Evolving from a rapid analysis for NISAC in 2005 with a design for containing the spread of influenza to prevent a deadly pandemic, this work was eventually used to set the national planning policy in 2006. The public health and healthcare sector has many problems of similar scale and potential impact: our CASoS Engineering applications have grown to include evaluation and design of tobacco control policies to improve population-level health (for Health and Human Services/Food & Drug Administration [HHS/FDA]) as well as the modeling and analysis of healthcare systems operations to identify risks and effective risk mitigation measures (for the Department of Veterans Affairs/Veterans Health Administration [DVA/VHA]). Additionally, with Program Development funds from IHNS 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); we now have one National Institutes of Health (NIH) funded grant with the Prevention Research Center at the University of New Mexico that began in FY12 and several more submitted proposals pending in the funding review process.

In context of Security, our work in Global Financial Systems and Global Energy System (GES) applications (described later in this report) have generated a transcendent view, that of Trans-spectrum Global Security. Framing this view, a perspective that relies on the understanding gained across all our application space is being funded in FY12 by Division 6000 and Stanford University through the 2011-12 William J. Perry Fellowship in International Security at the Center for International Security and Cooperation at Stanford (awarded to R.J. Glass). Trans-spectrum Global Security has become a new and integrating current for CASoS Engineering.

In all our efforts, we are actively working to engage funding partners with the understanding that their projects are building the discipline of CASoS engineering in context of projects funded by others. Multi-year projects for the VHA and HHS/FDA are recent examples of work in which the external funder is fully engaged and explicitly requires that common CASoS engineering principles developed within Phoenix 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* (Brown et al. 2011). As with the other Phoenix reports, this is a living document used to guide our development in a thoughtful and explicit fashion.

1.3 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 be applicable to the incredibly diverse set of CASoS that we, as engineers, must design solutions within. Fundamentally, the framework depicted in **Figure 3**, contains three phases applied primarily in succession but with much overlap and blending to deliver CASoS engineered solutions:

1. **Defining** (blackboard to details) 1) the CASoS of interest, 2) the Aspirations, 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, and 6) Required data to support conceptual model development and validation. Possible methods include analogy, dimensional analysis and similitude, experimental design, system dynamics, non-equilibrium thermodynamics, complex adaptive systems, game theory, agent-based modeling, networks, system optimization and control, and many others.
2. **Designing and Testing Solutions** using computational models, data mining/integration, experiments, etc, within a common quantitative analysis environment. Designing and testing solutions will be problem-dependent; it will focus 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.
3. **Actualizing** the engineered solutions devised above 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.

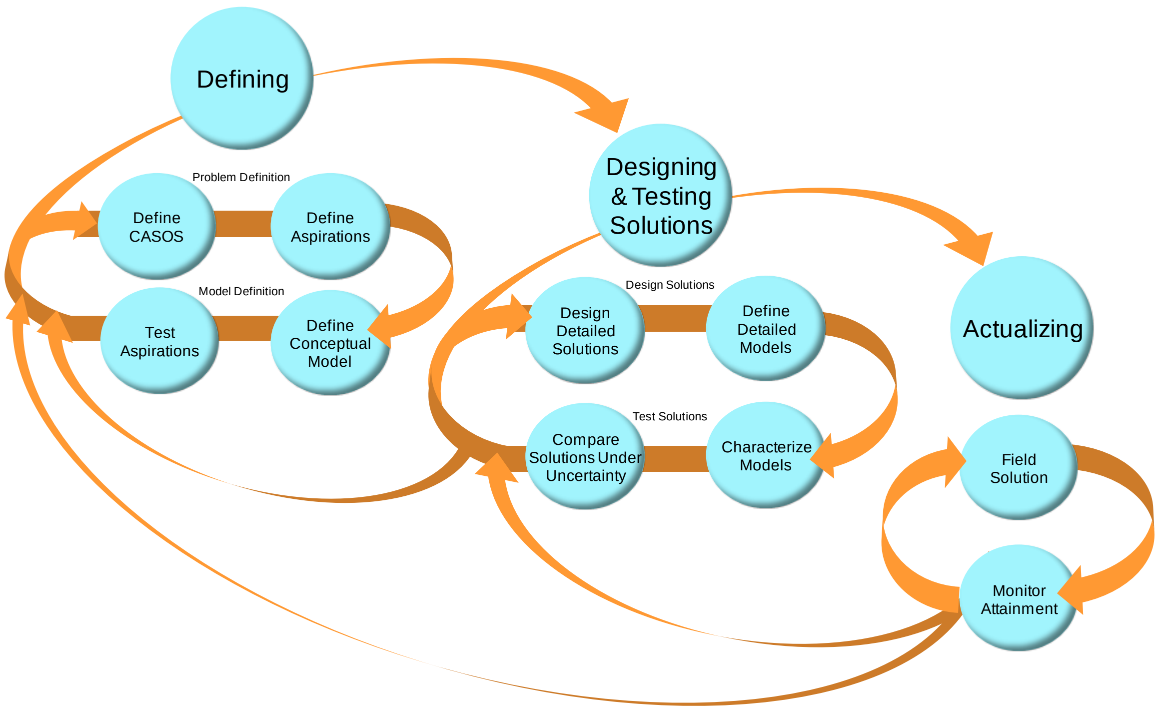

Figure 3. Diagram of CASoS Engineering Process and Components

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 reformulate our aspirations as the system changes.

Our Framework has evolved and expanded as we have learned from various Applications. It is not complete (and may never be). 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* (Ames et al., 2011). As with the other Phoenix documents, this is a living document used to guide our development in a thoughtful and explicit fashion.

1.4 CASoS Engineering Environment

The CASoS Engineering Environment supports all aspects of the CASoS engineering effort by providing integrated platforms for CASoS engineers to engage in conceptual design, modeling, simulation, analysis, education, training, communication, and collaboration. Computational and human resources are brought together through Framework principles and techniques, enabled by the Environment, to design, test, and implement solutions to CASoS problems.

The CASoS Engineering Environment (diagrammed in **Figure 4)** illustrates the overlapping platforms for Conceptualization, Analysis, and Design, Modeling and Simulation, and Knowledge Storage and Transfer.

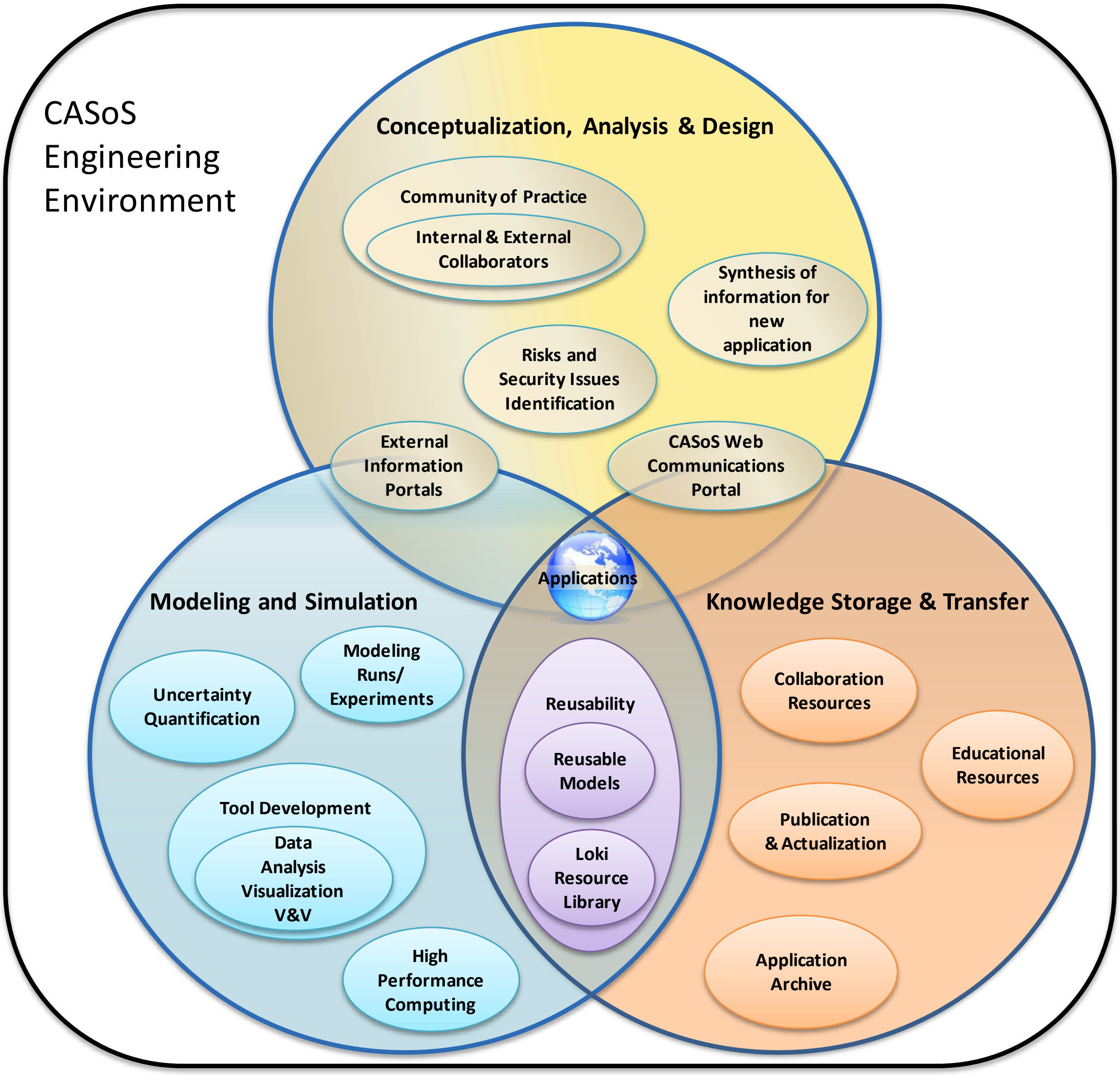

Figure 4. CASoS Engineering Environment Integrated Platforms

Conceptualization, Analysis, and Design (upper circle) focuses on CASoS Engineers and analytical processes. A community of practice is developed in which CASoS can be defined, researched, and analyzed. The process of CASoS Engineering, as described by the Framework, is implemented here. The Modeling and Simulation Environment (lower left circle) forms the cornerstone of computational capability required to implement the analysis process. Knowledge Storage and Transfer (lower right) organizes the information gained from analyses, captures the wisdom gained from Applications, and formulates it in ways that can be relevant to other problems. All elements of the Environment are connected through Applications which provide the opportunity to implement solutions and drive capability development.

This CASoS Engineering Environment supports the community of practice, communications, modeling resources, uncertainty quantification, and data analysis and visualization tools. Other modeling, simulation, visualization, and analysis capabilities, both internal and external to Sandia, continue to be explored for potential integration. The CASoS Engineering external, open website currently provides access to the growing body of theory and application from across Phoenix projects and the community. It is continuously evolving as an outreach mechanism, enabling us to more broadly engage with others working in complex adaptive systems-of-systems 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 Environment instantiates the core principles and processes defined by the Framework, supports the creation of Applications, and captures the knowledge and experiences gained for potential reuse. 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* (Linebarger et al., 2011). As with the other Phoenix documents, this is a living document used to guide our development and articulate progress.

2 GLOBAL CASOS

As a secondary objective, we aspired to begin building capability to focus on global CASoS. Tackling global problems directly (rather than building "up" to them) is important because: 1) solutions that assume isolation (at smaller scales) are often frustrated by feedbacks from outside the (narrowly) idealized system; 2) a global scope forces parsimony in conceptualization and implementation as only appropriate detail can be included; and 3) problems within Global CASoS are currently very difficult to define and solve, thus building such a capability would allow high impact.

Therefore, we built a conceptualization of Global CASoS that is:

- Multi scale
- Multi entity
- Multi resource

The critical dependent variable is Health. Entities are health seeking and health can be measured at a variety of scales. Such a conceptualization allows evaluation of the cost benefit for policies imposed at a variety of scales and thus the design of policy combinations to most effectively achieve high levels of individual and/or communal health. Many of these policies have to do with Security: land and boarder security, food security, water security, energy security, commerce security, etc. In this way, our effort lays the foundation to develop concepts for the design of Trans-spectrum (i.e., resource, entity, scale) Global Security.

2.1 Generalized Conceptual Lens for Modeling CASoS

Across the wide variety of applications Phoenix has considered while evolving our CASoS Engineering Framework, a generalized conceptual lens for modeling CASoS has emerged. This conceptual lens is similar to those used in physics, biology, economics, and other diverse areas in which Complexity Science has provided fruitful insights. As depicted in **Figure 5**, we render the system as entities (nodes) that interact via links to "neighbor" entities to form a network. Networks can be static or dynamic. The behavior of individual entities can be influenced by that of their neighbors and adjusted based on perceived performance either of themselves, others or the collective (up to the global scale). This influence can cause change in interactions or network connection and bring about growth, evolution or adaptation at a variety of scales. Networks created for one purpose are connected to networks created for another through individual entities that make use of both to form systems of systems with appropriate entity and interaction behaviors. Computational implementation of the conceptual model rendered by the lens can take a variety of mathematical forms including continuous to discrete, system dynamics to agent based with infinite to finite state machines, or approaches that hybridize these forms.

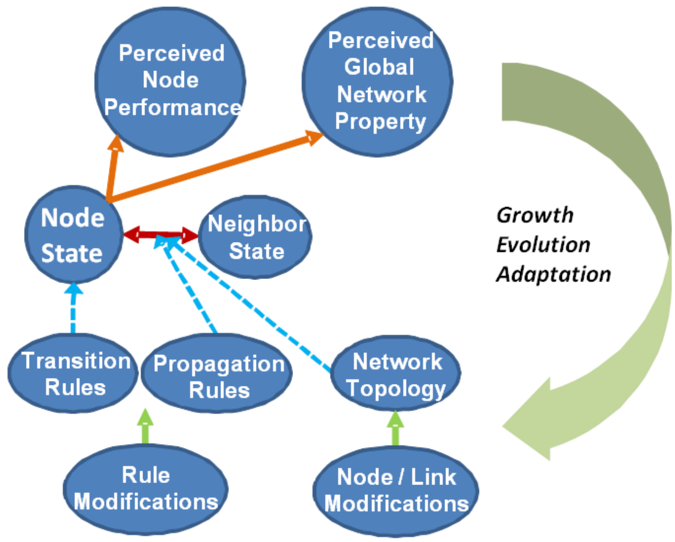

Figure 5. Conceptual Lens for CASoS Modeling

2.2 Conceptual Model for a Global System of Nation-States

We apply the general conceptual lens to first render a view of individual nations composed of a variety of entities representing the government, major economic sectors and internal markets that define domestic interactions among sectors (brokers for spot and contractual arrangements). An example of such rendering is shown in

Figure 6, each blue box represents a sector that is composed of a number of individual entities and interacts with other entities within other boxes through markets represented by yellow ovals. Arrows connecting sectors to markets show the direction of flow for goods, labor and finances. Each entity seeks health through consumption and production. If an entity can consume and produce as much as it desires, it is healthy. Though markets, one type of resource is exchanged using a common currency or "money". Within entities, a set of resources are consumed while others are produced, for instance, agriculture may consume water, labor and energy to produce food. The government sector can tax domestic markets to provide for national security and defense, or for other social and economic safety nets.

This single nation model can be extended to form a global system of nations. First, the national sub-sector flows (e.g., raw materials, industrial goods, services) are extended to the global scale. Nations differ in their resource endowments and in the capacity and efficiency of the production processes of their component sub-sector entities. International markets influenced by trade agreements define patterns of interconnection – for example water and labor markets might only connect bordering nations, while markets for goods and energy might be global. The efficiency of global markets can be modulated by imposing levies of varying amounts in each market to reflect trade agreements and the cost of transport. Secondly, security interactions among government entities are incorporated to form alliances. These alliances are conceived to reduce the influence of perturbations within member nations. A conceptual view of the global model is shown in **Figure 7** with regional trading and security agreements (brokers) connecting several nations that are likewise connected to others to define a global system of nested interdependencies.

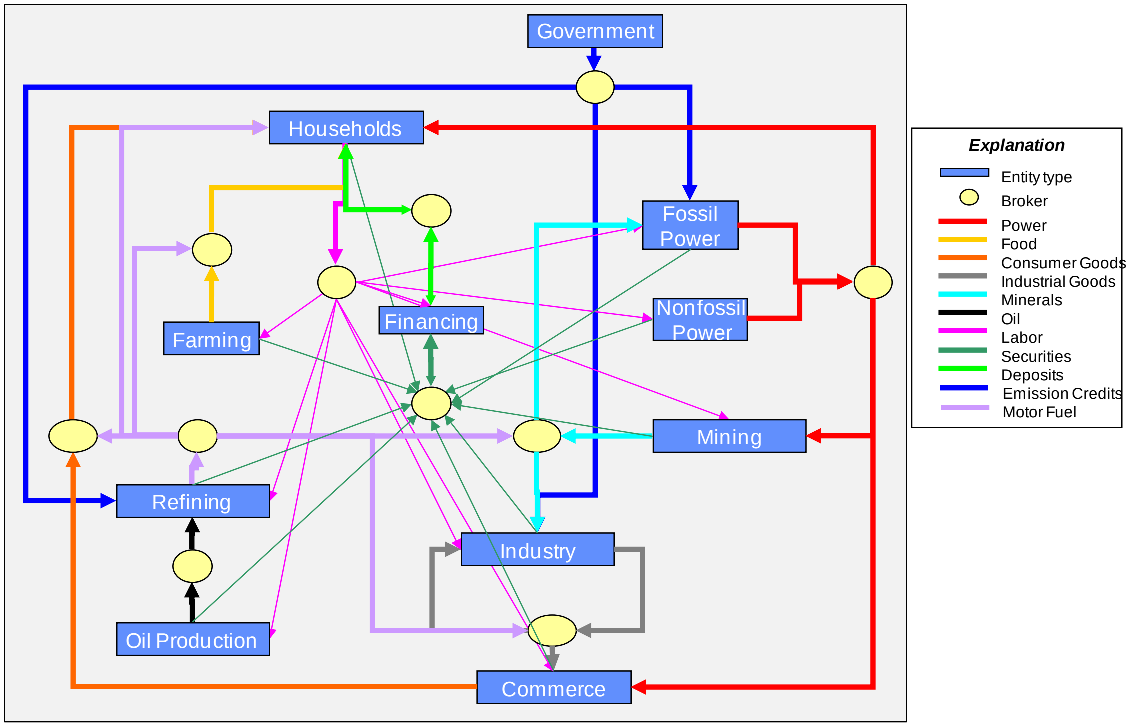

Figure 6. Example National Sector Interdependency Diagram

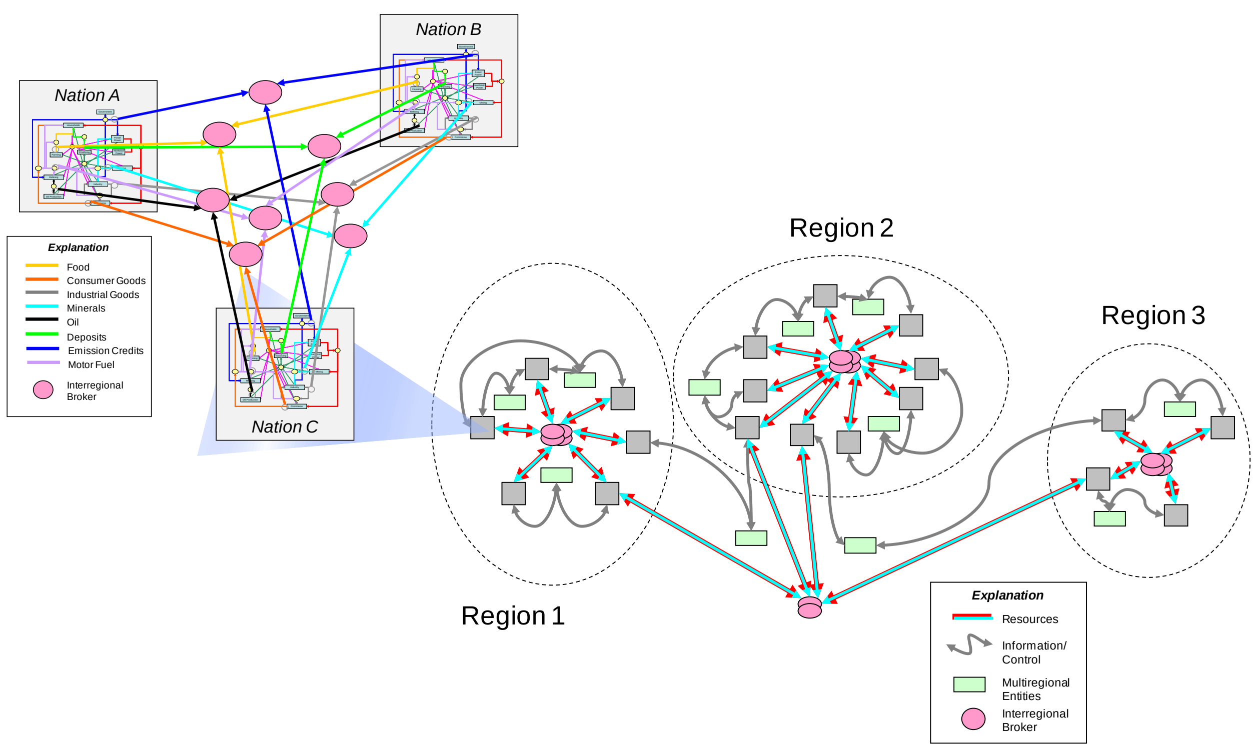

Figure 7. Example Global System of Nested Interdependencies

For a given set of nations, production/consumption parameter values, interconnecting markets, and trade and security agreements, numerical simulation will evolve the system to a dynamic equilibrium pattern of resource flows within and among nations. Perturbations can then be imposed relevant to the various focal areas of international security. A sudden change to the topology or efficiency of the international energy market, for example, can be used to represent embargoes or destruction of large terminals. As a simple illustration, conceptual results for an abstract problem with nine interacting nations are shown in **Figure 8**. In the left panel, the evolution to dynamic equilibrium is shown with three nations who primarily produce raw materials falling well below the health of the other six. In the middle panel, a small shock removes a portion of the raw materials within the system and the health of nations that produce the raw material goes up while those that require it goes down, followed by a resettling to the original dynamic equilibrium. In the panel to the right, the shock is large and causes disruption from which the system cannot recover (note the change in scale for this right panel).

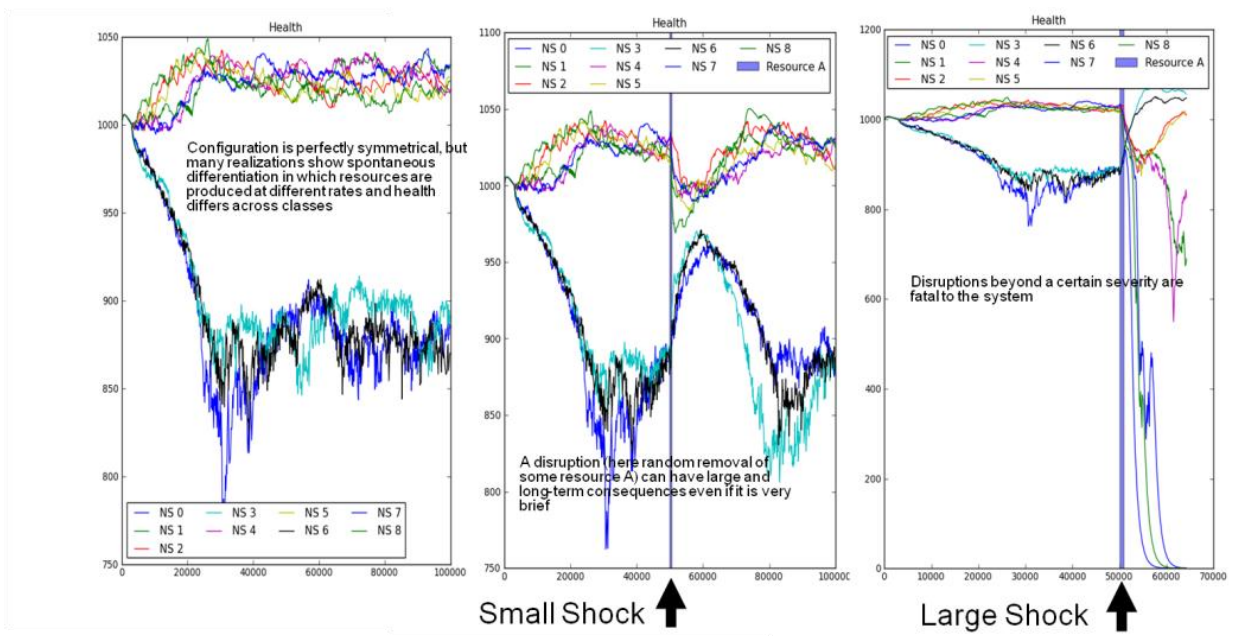

Figure 8. Example Conceptual Results: Entity Health in context of Perturbations to Resource

Using the principles and modeling approaches within the CASoS Engineering Framework, protective and/or mitigative policies may be evaluated (and designed) to increase the robustness and/or resilience of systems at scales from the individual national sector to the alliance or trading bloc to the global set of nations in the face of random or structured perturbations. Example policies such as used in today's world which could be considered include tariffs, embargos, loans, aid, and direct intervention. The design of potential new policy (or policy combinations) that may be more effective at achieving a given set of objectives is the ultimate goal.

2.3 Global Model Implementation

The global model has the flexibility to be implemented in a number of ways. We have done so in preliminary fashion using two different mathematical formulations each instantiated in two separate numerical codes.

The first formulation is described in Glass et al. (2008) and uses an artificial chemistry to describe the transformation processes implemented in model entities. This approach allows us to model processes that shape the behavior of entities over time, such as technological innovation, via mutation and recombination of the reactions that define entity dynamics. This flexibility allows the system to "discover" new resources and processes as part of its evolution.

An example problem for a single nation-state in which entities were configured to represent major economic sectors was used to explore endogenous dynamics of resource flows. **Figure 9** shows the inventories of goods at retailers and cash in households, along with activity in the market for goods. The system alternates between regimes of excess demand and excess supply due to inherent delays in inventory response and capacity adjustment.

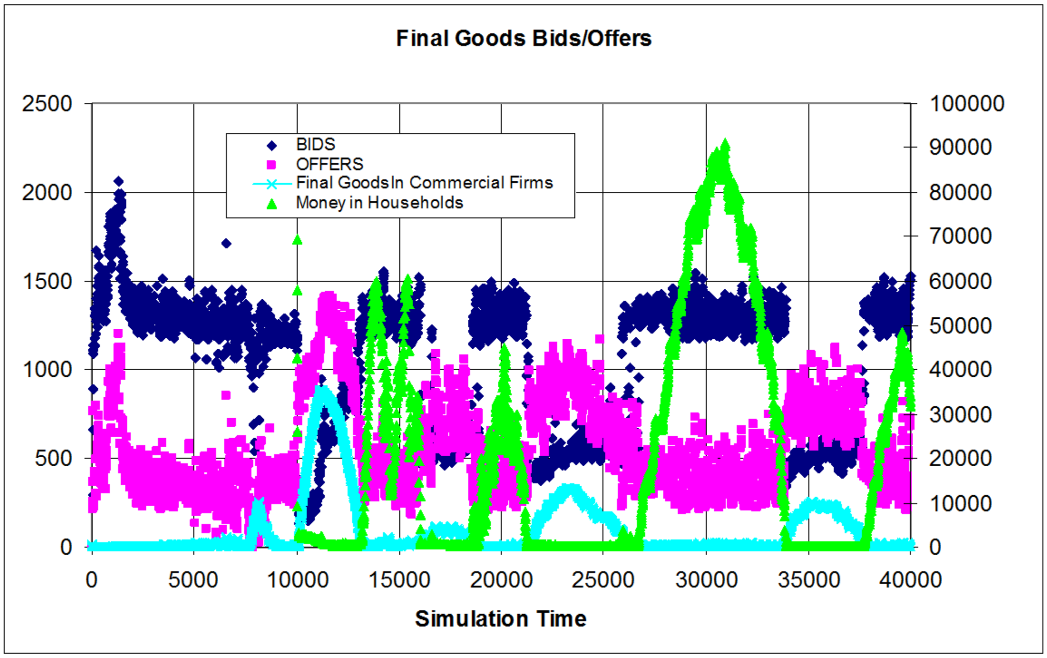

Figure 9. Bids and offers in the market for final goods, and household cash and retailers inventory, in a simple model of a national economy.

The second formulation is described in Beyeler et al. (2011a, b, c). This approach represents each entity as a set of ODEs governing the consumption and production of the entity's resources and the evolution of a scalar state variable (health) that defines the condition of whatever internal systems realize the entity's productive processes. This formulation gives some plasticity to entity's behavior, but it is not as open-ended as the implementation in Glass et al. (2008). By describing the entity's internal dynamics in this more restrictive way, however, the model's behavior is easier to control and understand, and certain analytical results can be derived, which aid verification and insight. In section 2.4 below, we use this second formulation to examine the implications of inter-regional trade in a very simple two nation-state configuration representative of one developed and one undeveloped country.

2.4 Example Application: Effects of Inter-Regional Trade

This application considers two economic regions or nation-states. Each is represented by a Compound Entity (shown in **Figure 10**). Each region has six component Entity types representing sectors of the regional economy: households, mining, manufacturing, water provision, agriculture, and energy production. These sectors exchange six kinds of resource: Labor, Food, Water, Energy, Raw Materials, and Goods. Each is produced by a specific sector using inputs from other sectors.

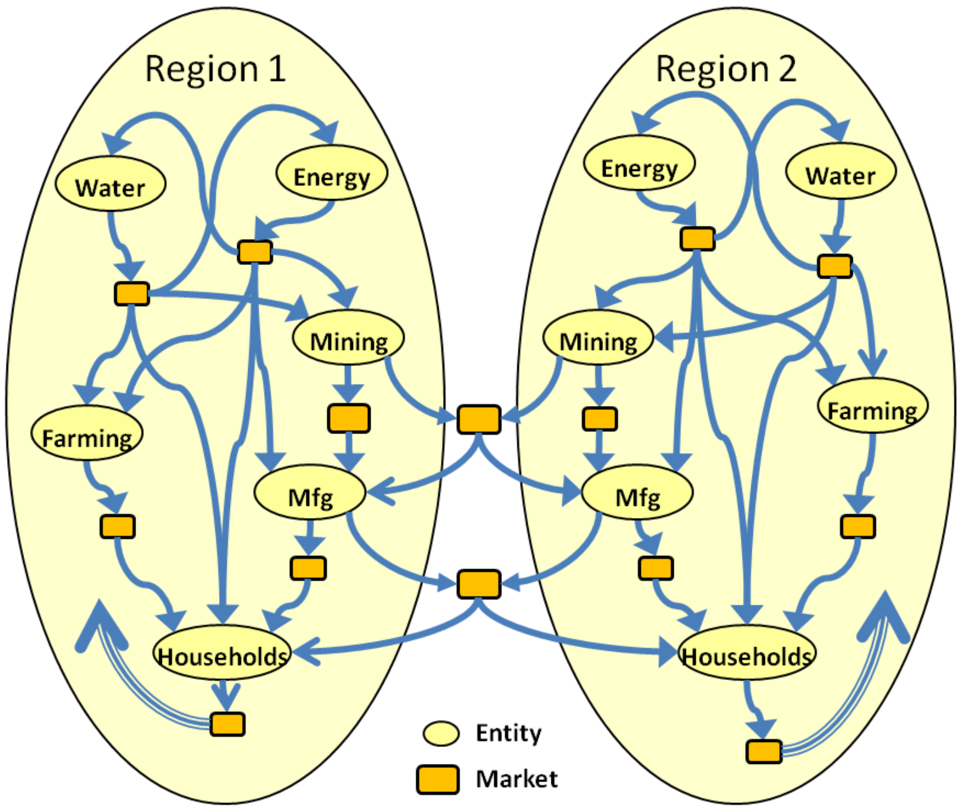

Figure 10. Example Trading Regions

The two regions differ in the relative efficiency with which resources can be produced. **Table 1** lists the nominal input and output coefficients for each sector-Entity type in the two regions. In Region 1 the processes tend to consume more energy and less labor than in Region 2, and household consumption of all resources is larger in Region 1 than Region 2.

In each of the two regions, we create three instances of each economic sector using the input and output coefficients in **Table 1**. Each region includes one market for each of the six resources, which connects all producers and consumers of the resource within the region. The nominal resource flow rates through these markets would be roughly three times the totals in **Table 1** if each Entity's demands could be feasibly satisfied. We first consider the resource flow rates and

Table 1: Nominal Input and Output Rates for Economic Sector Entities

Region 1 – More Energy Intensive, Higher Consumption by Households								
	Consumption Rate for Each Resource						*Produced Resource and Rate*	
Sector Entity Type	*Labor*	*Food*	*Water*	*Energy*	*Raw Materials*	*Goods*	*Production Rate`*	*Resource*
Household		3	3	3		3	0.8	Labor
Mining	0.1		0.5	0.5			1	Raw Materials
Farming	0.1		3	1			4	Food
Water Supply	0.1			0.5			8	Water
Manufacturing	0.4			3	1		3	Goods
Energy Production	0.1		0.5				8	Energy
Total	0.8	3	7	8	1	3		
Region 2 – More Labor Intensive, Less Consumption by Households								
	Consumption Rate for Each Resource						*Produced Resource and Rate*	
Sector	*Labor*	*Food*	*Water*	*Energy*	*Raw Materials*	*Goods*	*Production Rate`*	Resource
Household		1	1	1		0.5	1.2	Labor
Mining	0.2		0.5	0.2			1	Raw Materials
Farming	0.5		3	0.3			1	Food
Water Supply	0.2			0.2			7	Water
Manufacturing	0.5			1	1		0.7	Goods
Energy Production	0.1		0.5				2.7	Energy
Total	1.5	1	5	2.7	1	0.5		

sector health levels in the two regions without interregional communication. **Figure 11** illustrates the health trajectories in the two regions; resource flows rates are listed in the first column of

Table 2. Based on their nominal input and output rates from **Table 2**, the Farming and Water Supply sectors in Region 1 have production capacities somewhat in excess of the total nominal demand from the other sectors. The health of these sectors is therefore somewhat depressed relative to the health of other sectors, as the left half of **Figure 11** shows. Mining and manufacturing are relatively depressed in Region 2 owing to the spare capacity that they endure.

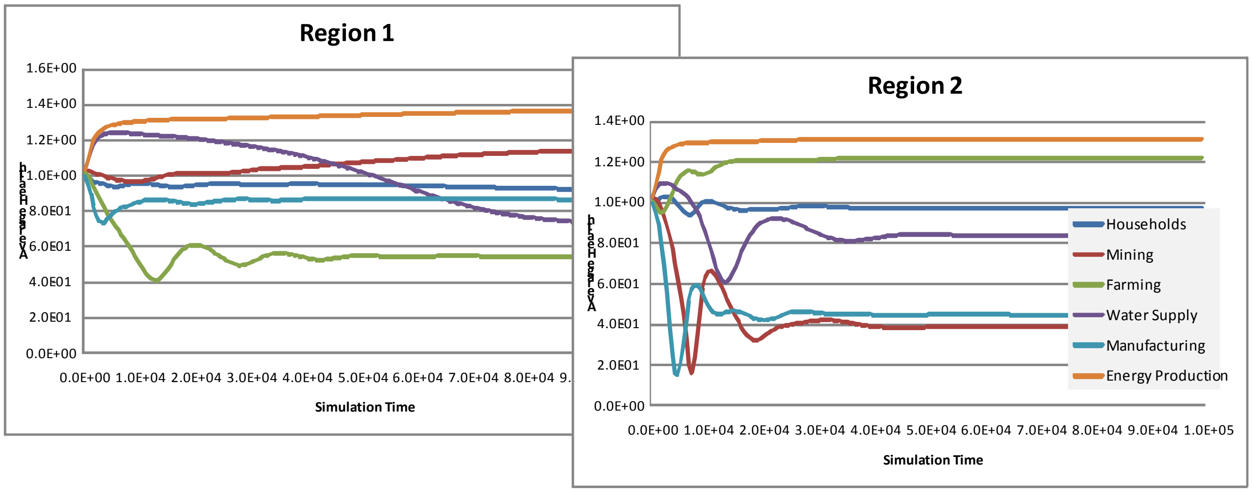

Figure 11. Average Health Values for Each Sector without Inter-regional Exchange

Table 2: Total Resource Flow Rates through Regional and Inter-Regional Markets for Three Cases of Inter-Regional Connection

Resource	Inter-Regional Markets							
	None		**Goods**			**Goods and Raw Materials**		
	Region 1	Region 2	Region 1	Region 2	Inter Regional	Region 1	Region 2	Inter Regional
Labor	2.03	3.14	2.04	2.69		1.91	3.14	
Food	8.53	2.70	8.28	2.50		8.96	2.71	
Water	18.45	17.25	17.89	16.78		19.02	18.11	
Energy	21.32	7.24	21.48	6.11		20.50	6.41	
Raw Materials	2.60	1.89	2.65	0.00		0.00	0.00	2.18
Goods	7.48	1.43	6.56	0.00	1.07	4.80	0.00	2.42

We next add an inter-regional market for Goods, which enables Households in both regions to buy Goods from Manufacturers in either region. No tariffs or transportation costs were imposed on inter-regional exchange (although the model allows them). **Figure 12** shows the trajectories of health, and the resource flow rates are given in the central columns of **Table 2**. The manufacturing sector in Region 2 is extinguished, and because there is no other consumer of Raw Materials the Mining sector collapses as well. All goods are now produced in Region 1, and although the total flow of Goods from Region 1 is somewhat larger than in the case of no inter-regional exchange (6.56+1.07 vs. 7.48) this total flow is *smaller* than in the case of no inter-regional exchange. Region 1 shows a slight increase in labor use, while Region 2 sees a comparatively large decline. This decline in labor underlies the decline in total goods consumed.

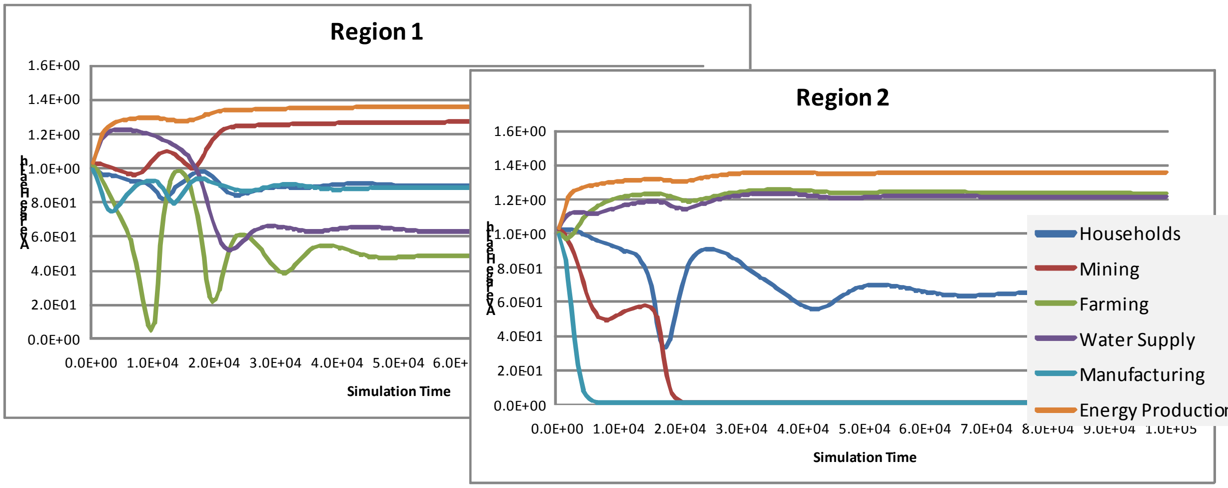

Figure 12. Average Health Values for Each Sector with Inter-regional Exchange of Goods

Finally, we include an inter-regional market for Raw Materials as well as Goods. **Figure 13** shows the trajectories of health in the two Regions: the last columns of **Table 2** list resource flow rates at the end of the simulation period.

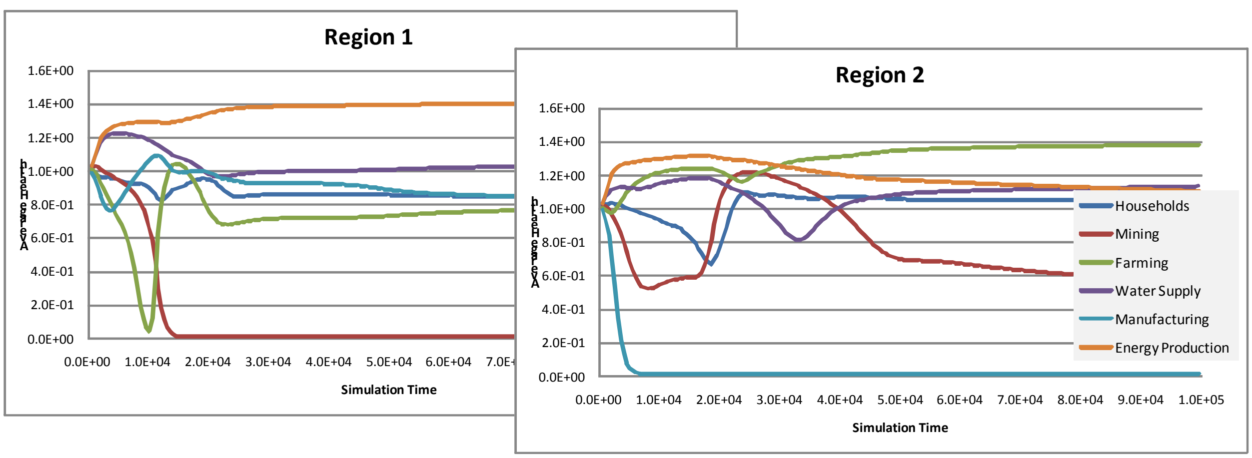

Figure 13. Average Health Values for Each Sector with Inter-regional Exchange of Goods and Raw Materials

Here we see a different pattern of specialization in which all Raw Materials are being produced in Region 2 and sold to the Region 1 Manufacturing sector, which is still the exclusive producer of Goods for both regions. The total production rate of Goods is again lower than in the case without inter-regional exchange, and the flow of Raw Materials is substantially lower. This is last reduction is largely due to the diversion of Raw Materials into the more-efficient Manufacturing sector in Region 1.

The definitions of economic sectors, and the coefficients used to describe them, were arbitrarily chosen for illustration. Models composed of hierarchical Entities managing populations of specialized producers can clearly give insights about possible consequences of international trade patterns; this configuration is a start toward such applications.

3 NEXT STEPS

Initiated by this LDRD, ongoing development of a CASoS Engineering capability continues through the efforts of staff members who are part of Phoenix, an evolving creation of this LDRD.

All of the following steps are underway:

- Evolve Phoenix and each of its supporting components (Applications, Framework, Environment) with a slow increase in people and projects picked to effectively PUSH and PULL capability development
- Develop projects within the core of each of Sandia's business areas (NW, ECIS, IHNS, DSA) and with critical external partners that explicitly use and develop CASoS Engineering
- Develop projects within the core of S&T that work explicitly with applications to develop underlying theory and methods
- Develop projects with groups of partners who own problems within Trans-spectrum Global Security
- Entrain critical members of the external research community through conferences and publication

The success of these steps and the continued development of a CASoS Engineering capability can be enhanced by Sandia Administration through their continued support.

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