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A Complexity Science-Based Framework for Global Joint Operations Analysis to Support Force Projection: LDRD Final Report

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Abstract

The military is undergoing a significant transformation as it modernizes for the information age and adapts to address an emerging asymmetric threat beyond traditional cold war era adversaries. Techniques such as traditional large-scale, joint services war gaming analysis are no longer adequate to support program evaluation activities and mission planning analysis at the enterprise level because the operating environment is evolving too quickly. New analytical capabilities are necessary to address modernization of the Department of Defense (DoD) enterprise. This presents significant opportunity to Sandia in supporting the nation at this transformational enterprise scale. Although Sandia has significant experience with engineering system of systems (SoS) and Complex Adaptive System of Systems (CASoS), significant fundamental research is required to develop modeling, simulation and analysis capabilities at the enterprise scale. This report documents an enterprise modeling framework which will enable senior level decision makers to better understand their enterprise and required future investments.

ACKNOWLEDGMENTS

The authors would like to thank Robert Glass, retired member of the team, whose application of complex adaptive systems of systems (CASoS) ideas to security was a motivating force and organizing idea for this project. Discussions with Captain Wayne Porter (USN) helped underscore the need to broaden our vision of security and security challenges if we are to successfully navigate an increasingly turbulent future.

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NOMENCLATURE

ACC	Air Combat Command
AFGSC	Air Force Global Strike Command
AFSOC	Air Force Special Operations Command
AFSPC	Air Force Space Command
AMC	Air Mobility Command
AOR	Area of Responsibility
AWACS	Airborne Warning and Control System
BIA	Behavioral Influence Assessment
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CASoS	Complex Adaptive System-of-Systems
COI	Country of Interest
CS&T	Cognitive Science & Technology
CVN	Nuclear Aircraft Carrier
CVW	Carrier Air Wing
DDG	Guided Missile Destroyer
DOD	Department of Defense
DOE	Department of Energy
EW	Electronic Warfare
GDP	Gross Domestic Product
ICBM	Inter-Continental Ballistic Missile
J6	Joint Chiefs of Staff Directorate 6
JFC	Joint Functional Capability
LCC	Amphibious Command Ship
LHD	Amphibious Assault Ship
LSD	Dock Landing Ship
MAJCOM	Major Combatant Command
MTTP	Multi-Service Tactics, Techniques, and Procedures
NAS	Naval Air Station
OPLAN	Operation Plan
OPORD	Operation Order
OSD	Office of the Secretary of Defense
PACAF	Pacific Air Force
PACFLT	Pacific Fleet
QDR	Quadrennial Defense Review
RFI	Request for Information
SIGINT	Signals Intelligence
SME	Subject Matter Expert
SNL	Sandia National Laboratories
SOF	Special Operations Forces
SoS	System-of-Systems
TTP	Tactics, Techniques, and Procedures
UAV	Unmanned Aerial Vehicle

UQ	Uncertainty Quantification
USNS	United States Naval Ship
USPACOM	United States Pacific Command
V&V	Verification and Validation
VRC	Vertical Resupply Corps refers to a Fleet Logistics Squadron

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1 INTRODUCTION

The national defense enterprise constitutes a complex adaptive system-of-systems (CASoS) which coordinates the acquisition, planning, development and deployment of national assets to accomplish effective global force projection. The military is undergoing a significant transformation as it modernizes for the information age and adapts to address an emerging asymmetric threat beyond traditional cold war era adversaries. This current and future operating environment will require us to cast global force projection in the broader context of a CASoS. Office of the Secretary of Defense (OSD) must coordinate countless factors, over a short period of time, including civilian leadership objectives, budget limitations, and adaptive adversaries to determine the optimal trade-offs of resources and capabilities to accomplish national security missions.

This is acknowledged internally within the DOD community (as seen below). This complexity has been exacerbated by an increasingly asymmetric threat and the exponential growth in information exchange and rate of flow. The operational effects of this are well characterized in the following quote from the Army Capstone Concept document "Operational Adaptability: Operating Under Conditions of Uncertainty and Complexity in an Era of Persistent Conflict" (United States Army Training & Doctrine Command, 21 December 2009):

"To operate effectively under conditions of uncertainty and complexity in an era of persistent conflict, future forces and leaders must strive to reduce uncertainty through understanding the situation in depth, developing the situation through action, fighting for information, and reassessing the situation to keep pace with the dynamic nature of conflict."

In other words, the challenge of projecting and sustaining force is becoming increasingly difficult to perform and manage. This is evidenced through the significant investment DOD is making in complexity science and complex system engineering. This is further acknowledged through request for information (RFI) solicitations for information planning tools that assist in managing and quantifying this complexity (see RFI NAICS Code 541512 dated March 11th 2011).

Management of this dynamic constrained system has for decades relied on theory and best practices of public policy and procurement to maximize force projection. Techniques such as traditional large-scale, joint services war gaming analysis is no longer adequate to support program evaluation activities and mission planning analysis at the enterprise level because the operating environment is evolving too quickly. New analytical capabilities are necessary to address modernization of the Department of Defense (DOD) enterprise.

This presents significant opportunity to Sandia in supporting the nation at this transformational enterprise scale. Although Sandia has significant experience with engineering system of systems (SoS) and CASoS, investment in the fundamental research required to develop a modeling, simulation and analysis framework to support OSD at the enterprise scale is necessary. Understanding what the proper investments are that improve the DOD enterprise – a large scale complex adaptive system-of-systems – and maximize the likelihood of successfully achieving its mission against an evolving uncertain future threat will require large scale enterprise modeling simulation and analysis capabilities. In fact, these opportunities can already be seen in the enterprise-scale set of questions Sandia is being asked to analyze by the DOD. However, no one (including Sandia) is yet prepared to respond to the enterprise scale of these questions – more research and development into the fundamental requirements of enterprise modeling is necessary. Analytical questions are no longer limited to single system-of-systems but collections of systems-of-systems operating together in a highly networked, interdependent, uncertain environment (a complex adaptive collection of systems-of-systems).

This LDRD leveraged the significant capability Sandia has developed in analyzing CASoS and SoS. Specifically, we have performed research to develop an enterprise modeling framework which will enable OSD-level decision makers to better understand their enterprise. We have used complex SoS engineering to develop an enterprise modeling framework. The Complex Adaptive System component of the hybrid modeling framework analyzes the structure and dynamics of OSD. The framework incorporates three main subsystems: (1) US military industrial complex model (conventional and nuclear), (2) Global threat model composed of a set of nation-states and non-state actors, (3) OSD decision analysis system. The global threat model provides integrated modeling capability of international military and political developments. The US military industrial base model represents national scale military industrial complex entities. The decision analysis system is designed to explore parameter spaces to derive the best performing, lowest uncertainty options.

Two examples, discussed in this report, will demonstrate and "validate" the utility of our framework and corresponding modeling constructs and analytical functions – the examples are notional and limited in scope only to the extent necessary to support the R&D. This demonstration includes characterization of the DOD enterprise (and associated inherent complexities), at the OSD level and an understanding of the required mission areas this enterprise supports. Figure 1-1 captures a top level representation of the DOD enterprise and mission set. The DOD is a highly complex system that itself is comprised of underlying complex systems and SoSs.

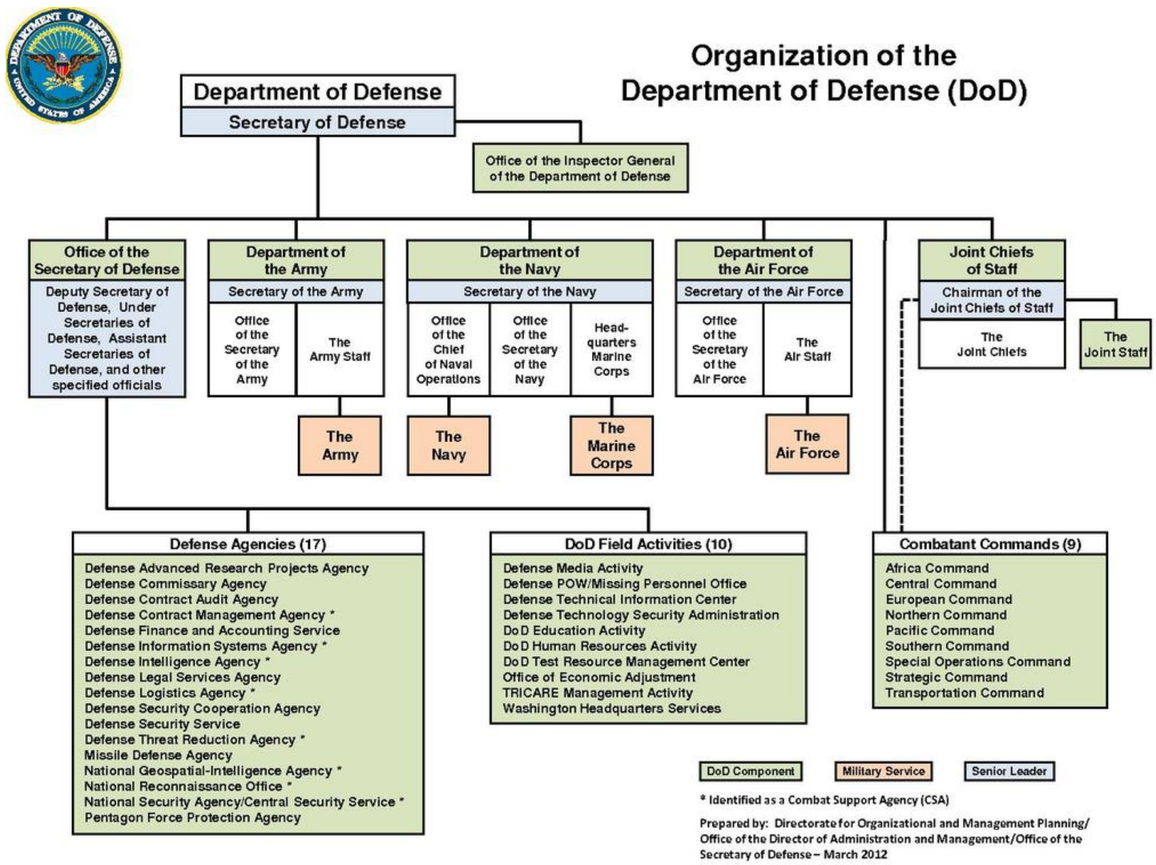


Figure 1-1 DOD Organization and Missions.

In addition to the inherent complexities of the military enterprise, DOD has identified numerous external sources of complexity in the environment in which they operate, specifically (from Future Operations in Complex Environments – Dr. Richard Hayes - Assistant Secretary of the Army (Network Information Integration) Mission Command CP Workshop, Oct. 2009):

- Changing social demographics
- Emerging patterns of globalization
- Shifting economic patterns
- Emerging energy technologies and demands
- Scarcity of food and water
- Emerging effects of climate change
- Natural disasters and pandemics
- Competition and conflict in the domains of cyber and space
- Hybrid enemies (state and non-state)
- Enemy adaptation (regular, irregular, terrorist tactics)

To demonstrate the applicability of our framework across the spectrum of these complexities within the mission sets listed in Figure 1-1 we have focused on two examples. These examples will demonstrate the flexibility and breadth of modeling and analysis of the DOD enterprise.

Our research of this enterprise-scale issue has uncovered some fundamental conclusions. The framework defines an approach for addressing this scale of problem. However, each problem will be unique to the fundamental architecture of its enterprise and therefore the framework provides an approach to addressing these problems. There is no single solution to cover each of these unique problem spaces. However, the intent of the framework is to provide analytical guidance to better define the problem and approach a set of solutions. Additionally, the performance model – which evaluates measures of performance for various investment alternatives for the enterprise – must be developed at an aggregate level while still capturing the relevant system details. This is not an easy endeavor and each problem will have a unique solution to this challenge. It is a difficult balance between detailed system performance and enterprise-level measures of performance. Finally it is important to understand that this scale of problem does not come with a simple set of solutions. There is so much uncertainty and so many factors that go into enterprise investment decisions that it would be irresponsible for any approach to claim a purely quantitative solution set. The framework that we have designed is intended to be used assuming various, uncertain environments and providing insights to decision makers. There is no intent for this framework to provide a single solution to this complex problem.

2 LITERATURE REVIEW

Several relevant papers and reports were reviewed at the start of the LDRD. Papers related to Force planning and Capabilities-Based framework and planning were a primary focus. The RAND Corporation, in particular Paul Davis, has performed extensive work in this area and developed numerous insightful papers and ideas. While the approaches described in the RAND papers described a similar framework similar to the one we propose here, they lacked modeling capabilities to support the steps within the framework. We felt that our research was still broaching on new ideas in terms of using a collection of modeling approaches to address the capability-based planning concepts. A bibliography of many of these useful references can be found in Appendix A: Bibliography.

In addition, we looked for economic perspectives on security investment. Because national security can be thought of as a public good, and because it can be pursued through a various kinds of government investment, including education, technological innovation, environmental protection, as well as improved military systems, we believed that the economic literature might contain helpful ideas about security broadly considered. Investment in military systems often creates broadly-useful technologies as well; the prospect of spin-off technologies providing innovation returns should be considered in valuing capability investments. In general, while we found that the inputs to military capability (labor, capital) were widely treated in economic models, the resulting outputs (security, technology) are uncommonly represented, and there is no well-accepted method for doing so. Some recent approaches are summarized below. The bibliography in Appendix A contains additional studies.

Dumas (1990) proposes an extension to a mathematized definition of security as some function of the ratio of own-to-other military strength to include (1) diminishing security as total strength increases (for example nuclear weapons) and explicit inclusion of economic output as a contributor to strength. Military expenditures are represented as drawing on economic resources but no other contribution to the economy is included.

Kalaitzidakis and Tzouvelekas (2011) use the notion of "public capital" to describe the (beneficial) effects of public spending. They model endogenous growth in a closed economy with N kinds of public capital. Public capital increases labor productivity, which increase production via a Cobb-Douglass formulation.

Dunne et al. (2005) provide a review of models relating military expenditures to growth. They organize the influence of military on the economy be demand effects, supply effects, and security. They find the Feder-Ram formulation, which treats the military as a separate productive sector, to have basic theoretical problems, and the augmented Solow model, which includes military capital as means of improving labor productivity (e.g., Kalatzidakis 2011) to be better grounded and to offer insights into dynamics, but find the mechanism of beneficial influence through technology to be unconvincing and incomplete.

Aizenman and Glick's (2006) modification of the Barro model, to include a cross-term relating expenditure and prevailing insecurity, is judged mechanistically more sensible. This empirical study finds a positive benefit for military spending when the environment is threatening, but a negative effect in other conditions.

Treverton, and. Jones (2005) defines three measures of power: resources/capabilities; conversion of that power (in the sense of being able to bring it to bear); and power in outcomes. The first two are measured using GDP, population, defense spending, and a technological index. Measures of the third are less specific, but suggestions seem to include level of corruption, degree of political accountability, and extent of community organization. An alternative to the distinction between hard and soft power is proposed: a spectrum ranging from ideal power (changing ideas) to worst-case power (military). Elsewhere the spectrum is described as spanning coercion to attraction.

3 DECISION EVALUATION FRAMEWORK

This study seeks to provide a framework for systematic, scientific, and explicit evaluation of strategic portfolios. A strategic portfolio consists of a set of systems that interact to accomplish missions that are important for maintaining security. The exact mix of those missions needed for a given security scenario depends on many complex external processes; often mission mix changes dynamically through the course of a scenario playing out. Conceptually, the evaluation of strategic portfolios entails attempting to find a set of decisions d, within a time-period t, controlling system structure that maximize utility u:

$$u = f(d(t))$$

Improving decision making does not require that we develop a complete mathematical expression for f, or to express all parts of the function in the same way. The practical goal is to formalize the function that connects decisions to utility to the extent that this formalization brings greater clarity and rigor to the process. For example, it may be relatively straightforward to estimate the material consequences of decisions c, such as their costs and the probability of their meeting each of a set of performance criteria, but difficult or impossible to develop a function that combines these quantities into an overall measure of utility:

$$u = f(d(t)) = v(c(t));\ c(t) = g(d(t))$$

In this case we concentrate on formalizing function g, which estimates the vector of objective measures, and we do not attempt to develop a model of the decision-makers' utility function v.

3.1 Functional Decomposition

A remaining challenge is to formalize the connection between the set of decisions to a set of relevant objective measures. Several complementary ways of breaking the function into components exist. Functional decomposition can be structured as evaluating a network of linkages connecting possible decisions to ultimate figures of merit through a set of intermediate measures, which indicate the system's ability to perform functions that are instrumental in accomplishing higher-level tasks (Figure 3-1).

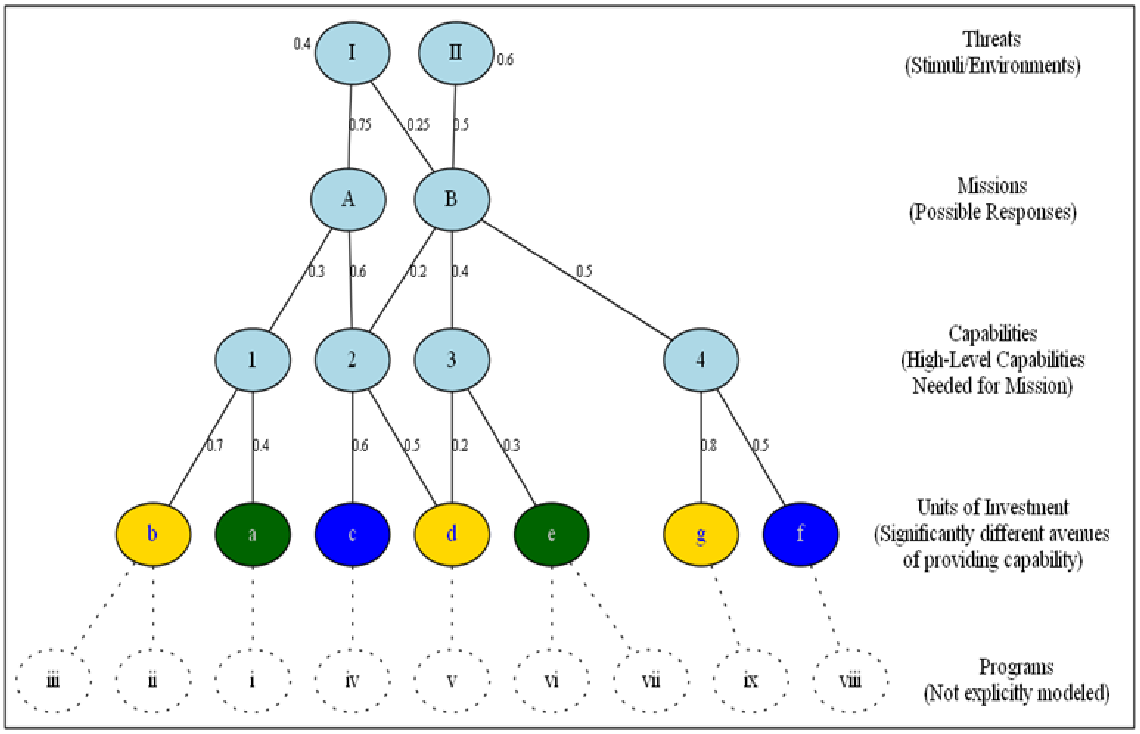
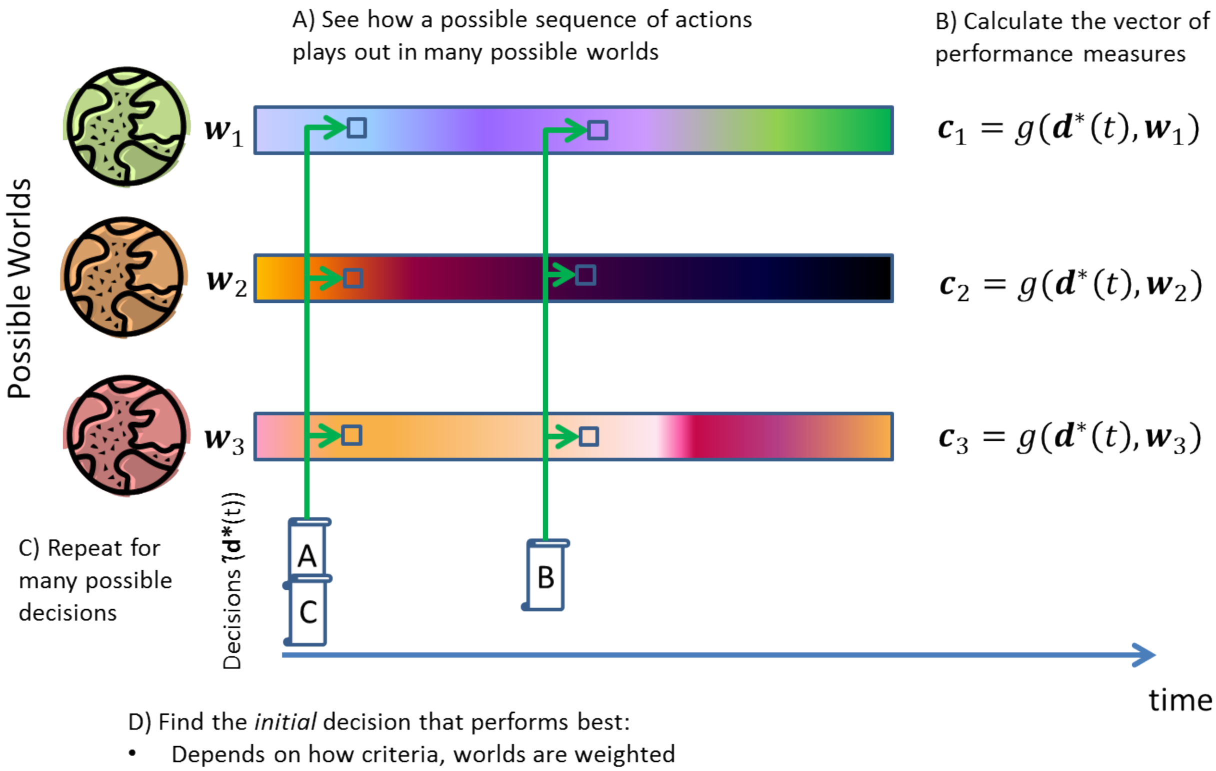


Figure 3-1 Evaluation Function as a Hierarchical Tree.

This structure decomposes system performance into layers of increasingly fine-grained components, and describes how components can act as complements or substitutes in performing higher-level functions. The level of detail can be tailored to the problem, and can vary among subsystems in the network. The network depicts functional dependencies among system state variables, but does not constrain the dimensionality of state variables, or the kinds of functions used to describe how changes in lower-level variables propagate upwards. For example, state variables might be scalar indicators of degree of performance, with higher-level variables being weighted combinations of components. Alternatively, a capability might itself be represented as a function that models the potential to act on some part of the system, with the units of investment creating a change in this function over time. Different formulations might be used in different areas of the network, for example with indicator variable weighting used to connect missions to threats and production system models used to connect units of investment to capabilities. The network diagram provides a clear decomposition of the evaluation function g, explicitly indicating dependencies among components and subsystems; however the underlying functions implementing these dependencies may be arbitrarily complicated. In general the function is dynamic, stochastic, and can have a high degree of uncertainty in both structure and parameters.

As a broad generalization, mathematical formulations for the more fine grained parts of the network, for example deriving performance measures for capabilities from descriptions of their implementing components, are well-developed in comparison to the upper parts of the network. There are no accepted formulations for the extent to which a specific mix of capabilities combines to improve the probability of accomplishing a mission, for example. Nor is there a systematic process for generating possible missions or describing their relative likelihood. We have therefore developed a framework for using simulation models to perform these functions. This framework emphasizes the importance of complex dynamics and uncertainty in defining the function g(d). Conceptually, a prospective set of decisions is evaluated by simulating their effects in a number of possible future operating environments or "worlds" (Figure 3-2).



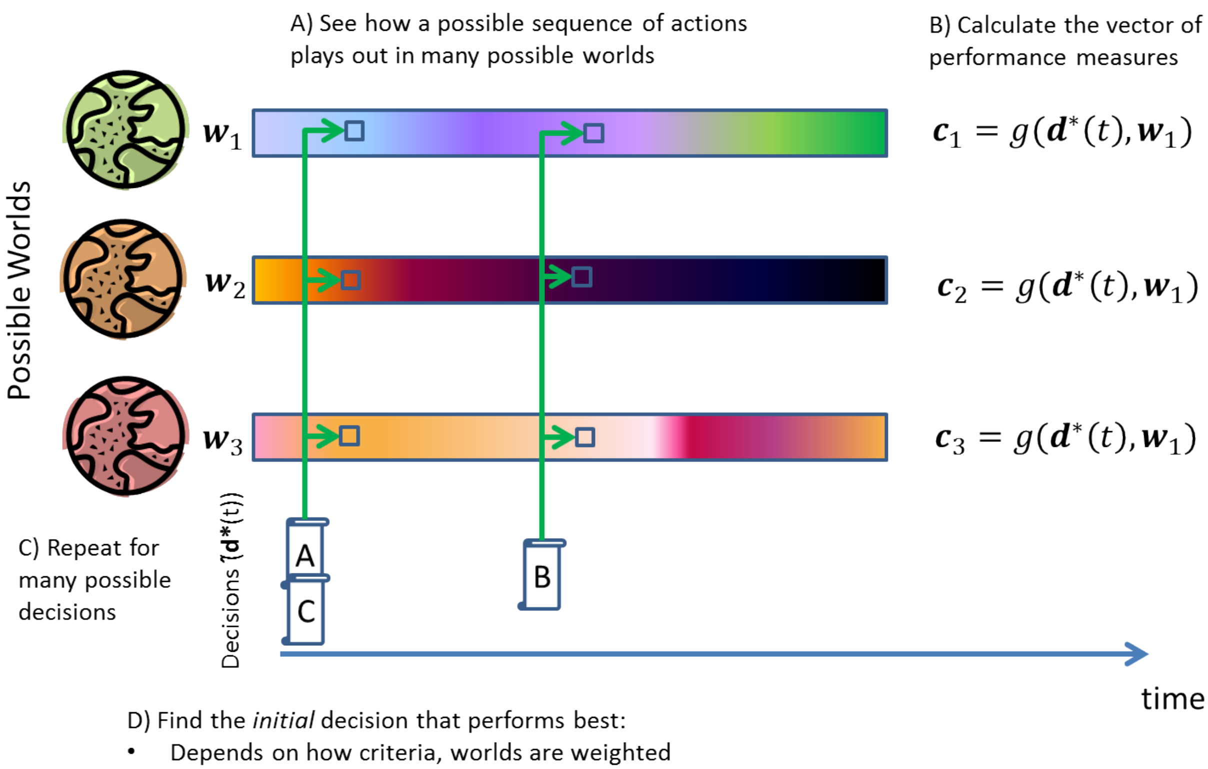


Figure 3-2 Evaluation of a Decision Sequence.

Repeated simulation is used to capture the effects of uncertainty in model formulation, and stochasticity in system behavior, on the possible values of the performance measures. The complex dynamics of the system are reflected in the way each possible world is evaluated (Figure 3-3). Here the system model is formed from several interacting realms.

- A physics/economics model represents the flows of materials and wealth based on interactions among nations and economic sectors, environmental stresses, but particularly the decisions made in the other realms regarding capacity development and use. The vector of consequence measures c(t) might be based largely or entirely on state variables in this realm (GDP, population, aggregate mortality, etc.)
- Production models represent the translation of elements of the decision vector into distinct capabilities, which can then act on the physics/economics realm. This translation process is generally dynamic, stochastic, and may consume resources from the physics/economics realm. Capability availability governs the decision-making of the US and of all other strategic actors.
- Use models represent the decision-making processes of the US and of other relevant actors regarding the use of capabilities. There is an especially high degree of uncertainty in modeling this realm, and many development efforts devoted to improved models. Our approach has been to define a clear interface to facilitate interaction with current and future models that focus on these processes, but to use simple formulations for the purpose of testing and demonstrating the framework.

Many factors might influence decisions to use available capabilities, including the use decisions of other actors, apart from any effects those decisions have on the physical/economic system. These kinds of interactions depend on the specification of the decision-making models, which is not our primary focus. We do however need to represent the interactions between the physical/economic realm and the decision-making realm.

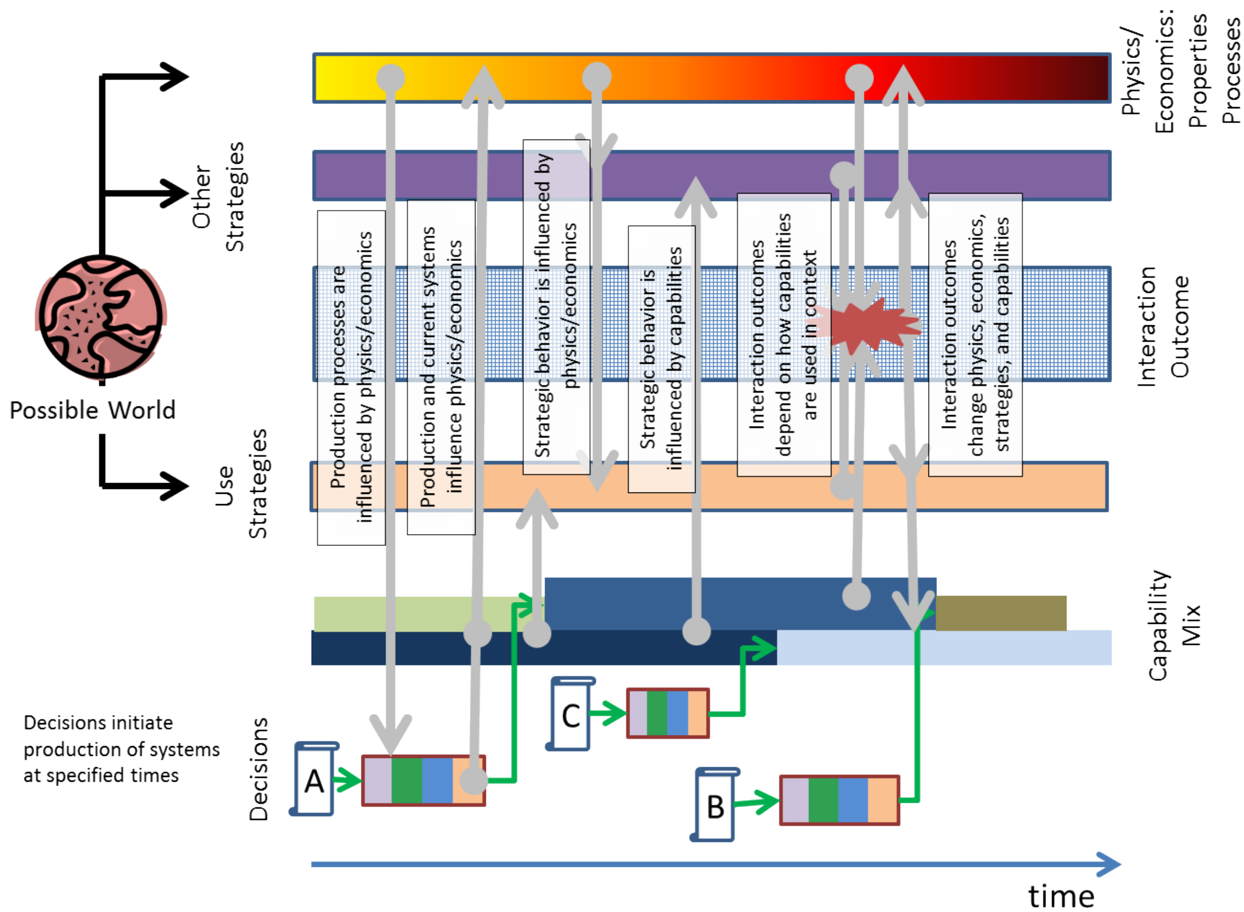


Figure 3-3 Model Realms used to Evaluate Decisions.

3.2 Physical/Economic System

The physical/economic realm is represented using the Exchange model[1], configured to simulate the interactions of economic sectors within nations through flows of resources and capital. Primary state variables include resource levels in all sectors and nations, as well as an integrated "health" state for each sector which depends on the recent availability of resources used by the sector. Individual capabilities can be represented by specific corresponding resources if it is useful to model the physical process of capability production. This approach effectively uses a part of the physical/economic model as the production model. Alternatively, the extent to which a capability is available may be some function of other resource levels. Most simply, an aggregate "security" resource can be produced through inputs of other goods and labor, and the specific capacity or combination of capacities represented by this resource can be determined by the way capability use is modeled.

[1] The Exchange model is an agent based simulation model intended to simulate multiple nation states interacting economically, militarily, etc. see [1] for a more detailed description.

All state variables of the physical/economic realm are potentially available as inputs to decision-making; however, a few of these seem especially salient influences on nations' decisions regarding capability use (Table 3-1).

Table 3-1 Role of Selected Exchange Model State Variables in Decision Making

State Variable	Possible Role in Decision-Making
Health level and rate of change in Households	Household health levels and changes plausibly drive domestic contentment or unrest. Unrest might in turn drive military aggression as a distraction.
Difference in Health vs. Peers	Comparative well-being may drive cross-border migration, or foster aggression to obtain resources.
"Security" resource	Levels or gradients of resource(s) representing offensive or defensive capacity may trigger actions by the resource owners, or by rivals and adversaries.
Strategic resource	Levels or gradients of certain commodity resources (e.g., oil) might trigger the use of offensive or defensive capabilities.
Comparative resource levels	Contrasts in resource levels may trigger acquisitive aggression or defense.

The Exchange model for the physical/economic realm is defined by the levels of resource controlled by the various entities in the model (nations, firms, households, etc.) and by the processes controlling the transformation and movement of these resources. Within this framework the effects of using a capability can be conveniently represented as either an abrupt change in one or more resource levels, a change in the parameters of a process in the model, or introduction of a new process into the model. The use (or attempt to use) a capability may entail consumption of some amount of resources, and may only succeed with some probability. Many kinds of military activities, especially aggressive activities, can be represented in this way. Table 3-2 describes some common kinds of tasks, and how their effects might be represented as perturbations to resource levels and parameters.

Table 3-2 Mapping of Tasks and Exchange Model Perturbations.

Military Task	**Representation as Perturbation to Resource or Process**
Destruction of assets	Removal of specific resources, including resource representing production capacity. Resources representing military capabilities, as well as the processes that produce them, would be likely targets.
Blockade or embargo	Interruption of (some fraction of) exchanges involving targeted entities.
Humanitarian relief	Transport of selected resources (food, water) or capacity (energy production) to selected areas.
Intelligence/Reconnaissance capabilities	Fast and accurate information on the state of the system.

Defensive capabilities can be represented by their effectiveness in blocking attempted use of offensive capabilities. Specifically a defensive capability changes the magnitude, probability of effectiveness, or both of an attempted use of an offensive capability in a particular location or circumstance. Deploying this capability may entail resource consumption, and its active use may consume additional resources or deplete the defensive capability itself.

The representation of the physical/economic consequences of basic elements of military actions is comparatively straightforward. While developing a general model of capability usage is outside the scope of this project, it is useful to define a structure of elemental tasks that combines basic elements into a coherent program of action. Such programs model operational plans that have been developed to achieve specific tactical goals. Successful execution, the time required for execution, and the material consequences of execution, depend on the capabilities available when the plan is instantiated. This construct provides a flexible interface between detailed specification of elemental actions in the physical/economic models and selection of missions to accomplish strategic objectives.

Action programs are defined by a sequence of elemental actions and simple control structures, such as conditional and iterative groupings. Free parameters may be used, so that a single program might be developed for, for example, blockading a port in general, with specific aspects of the operation made conditional on the properties of the specific port selected when the program is instantiated.

3.3 Framework Demonstration

Although the framework incorporates models of complex interactions among physical system, economic systems, and strategic actors, the overarching goal is simply to derive metrics for possible capability investments so that: 1) the benefits and costs of creating the capability are as comprehensive and systematically considered as possible; and 2) figures of merit may be compared across a wide range of alternative capability investments.

3.3.1 Algorithm

The algorithm can be expressed in the following pseudocode:

> For each capacity investment decision $\mathbf{d^*}(t)$ …
>
> > For a set of possible worlds $\boldsymbol{w}_i$ …
> >
> > > Derive the vector of consequences $g(\mathbf{d^*}(t), \boldsymbol{w}_i)$

In this representation of the algorithm each possible world includes use models for available capacities. In the case of the US these might be taken from existing operational plans. The use models of other actors may be highly uncertain, and so vary from one possible world to another.

3.3.2 Component Representations

Physical and economic processes define the context for the creation and use of capacities. For our demonstration applications we use a collection of national economies, each composed of a set of interacting sectors, to create this context.

Individual nations are defined by the relative sizes of their component sectors, the efficiency with which those sectors operate. This flexibility in assigning nation state actors in the model allows for: (1) Representing various possible future components of actual nations. (2) Rapid construction of thought experiments by designating notional nations whose constituent factors can be set by the investigator to illustrate a particular concept or sub-system currently under analysis.

3.4 Enterprise Framework

As part of the LDRD research, a more general framework was also developed which defines the process in which Enterprise-level decisions should be addressed. This framework is general and could apply to various types of DOD Enterprises. However, within each step of the framework, the approaches and models are unique to the problem being addressed. Figure 3-4 illustrates this framework.

The first step is defining the future operating environment. Traditionally for DOD applications, this information comes from official documentation such as the Quadrennial Defense Review (QDR). The official documentation has inputs from Military and Policy experts providing guidance regarding what future threats to consider as well as which priority (high level) capabilities should be considered. In this LDRD, we are proposing that modeling methods applied within this Enterprise Framework can be used to provide a distribution of possible future environments, considering a variety of economic and nation-state driving factors.

Once the distribution of future operating environments is constructed and evaluated, the next step in the framework development is to define the key mission objectives related to the future environments. This LDRD illustrates this approach with a decomposition of DOD missions defined per official documentation. This mission decomposition can be mapped to the key required capabilities to address the future threat operating environment.

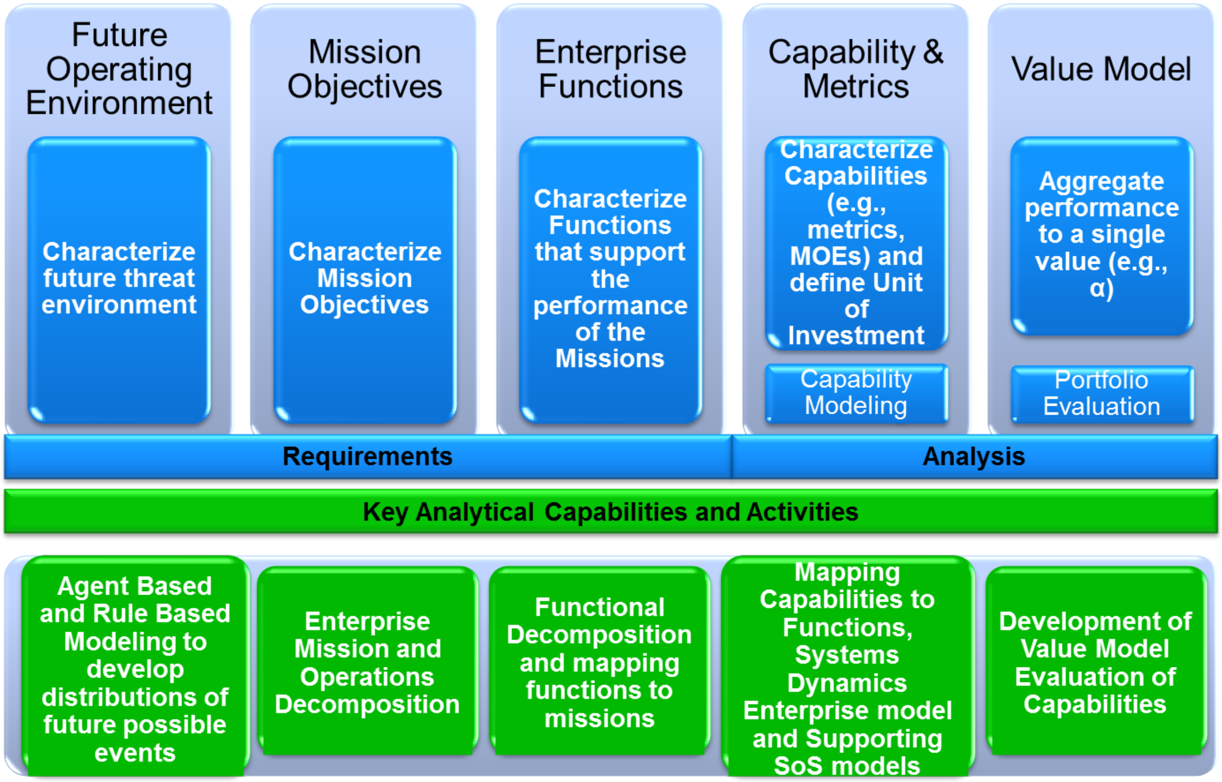


Figure 3-4 Enterprise Decision Model Framework.

As the third step, the framework next evaluates the Enterprise Functions that will support the performance of the missions defined in the second step. These functions should be defined in a manner which is applies to a range of systems and implementing organizations. The motivation for the strict hierarchical structure of the Enterprise Framework is to ensure that the process is not driven by bottom-up investment. The principal concept behind the Enterprise Framework is to promote more effective decision making by looking at what capabilities are actually required, rather than choosing from an existing set of capabilities and determining what missions and functions they can cover.

The fourth step in the framework involves characterization of the capabilities and performance measures of the actual units of investment. In this step, analysts begin directly comparing systems or performers for the capabilities required to meet the mission sets.

The final step is to assess the capabilities of alternatives in a value model. The value model takes into consideration a range of possible futures, and any other objectives beyond system performance to ensure that the investment decision is a good solution for a range of possible futures and not just an optimal solution for a small set of cases.

This framework provides the guiding principles for performing this complex, enterprise scale analysis. The realization through the research of this LDRD is that each of these steps in the framework could result in a significant effort. The goal is to illustrate the capability for the Use Cases we've chosen and provide examples that can be leveraged for future applications.

4 ANALYTICAL APPROACH

4.1 Exchange

The Exchange model (Beyeler et al. 2011) is designed to study the dynamics of complex systems composed of specialized consumers and producers of resources, which interact through resource exchange. The kinds of resources represented in the model, the kinds of entities that make up the system, and the patterns of interactions available to them can be defined to represent specific systems at a range of scales and with varying scope.

Two kinds of configuration are relevant for this framework. First, the complex production networks required to produce a chosen portfolio of military systems, including possible synergistic or competitive demands for resources or production facilities, can be modeled in order to represent the dynamics, contingencies, and secondary effects of production. Second, the national and sectoral economic dynamics that both enable weapons production and can influence their use can be modeled with the goal of delimiting possible scenarios and missions that might not otherwise be uncovered. We have not configured the Exchange model to represent production dynamics specifically for this framework, although patterns are available from other problem domains such as food production systems (Conrad et al., 2011).

Global economic dynamics, including the potential effects of disruptions to critical resource production and trade, were explored in considerable depth. The overarching aim was to discover possible future conditions that would create special challenges to US security. These challenges might arise because of the dynamics of economic growth and consequent resource flows, reactions to environmental shocks or trends, shifts in political alignment or military capabilities of other nations, or from an interaction of these processes. Security challenges might come from development of significant external threats, or through limitations on US economic and technological resources relative to adversaries.

In addition to using resource constraints and economic relationships to delimit possible security challenges, the Exchange Model can also represent the material ramifications of offensive and defensive military actions. Capturing these effects in the model allows their consequences to unfold through changes in industrial production capacity, resource availability, or other pathways that can feed back to influence security-seeking decisions. There are of course many other motivations for, and consequences of, the development and use of defense systems; these are represented in other parts of the framework The requirement for the Exchange model is that all of the relevant material processes, including those that can create the means and objectives for military actions, be captured.

The specific aims of this decision framework required additional concepts and processes to be added to the original Exchange model, as defined in Beyeler et al. 2011. To document the elaborated model, this section begins with an overview of the basic model components. A discussion of a set of security-related concepts and their representation using Exchange model constructs follows. We conclude with an overview of a configuration of a global model used to illustrate one role of Exchange in the framework.

4.1.1 Basic Model Concepts

Processes and Elements

Basic elements include *resources* of various kinds and *processes* that act on those resources. *Simple resources* are whatever basic material types are appropriate for the problem. *Continuous* and *discrete* subtypes distinguish resources whose quantities are measured by real numbers or integers. *Compound resources* are structures made of other resources. A *resource pool* is specific quantity of a resource of a particular type.

Processes act on resources by changing the quantities in specific resource pools according to some rule. Processes might operate continuously or instantaneously. Some processes require some material basis to carry them out, such as an oil refinery or a school. In this case a specific resource can be designated to represent this basis, and the amount of that resource corresponds to a capacity to conduct the process.

A *process instance* is a relationship among a process and a set of resource pools that match the connection requirements of the process. These pools define the inputs, outputs, and perhaps capacities for the process. In addition to these resource connections, the process instance might be modulated by a control signal from the *behavioral layer*.

Processes can model resource movement (between resource pools containing the same type of resource) as well as resource transformation. Processes can control other processes by changing the levels of their capacity resources. Figure 4-1 shows some uses of processes to describe resource flows.

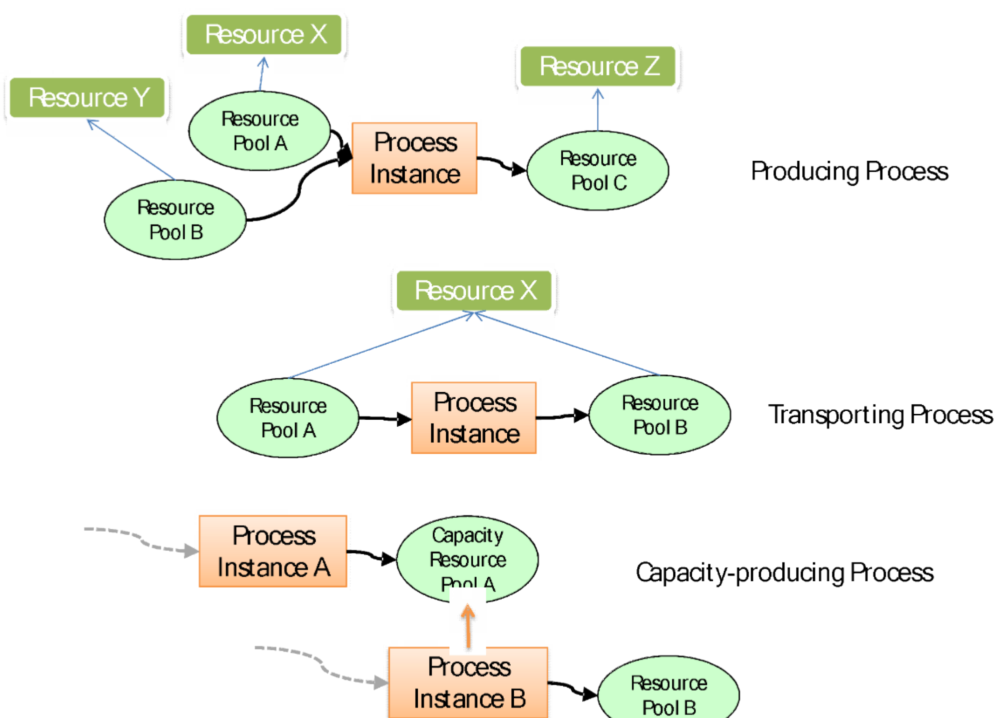


Figure 4-1 Some Process Types and their Effects on Resource Flows.

A *boundary* encloses a set of objects (resource pools, process instances, other boundaries) and controls the movement of objects across and within it. Because movement is represented by processes acting on objects, boundaries control movement by controlling how process instances are attached across and within them. A particular object might be enclosed by multiple boundaries, representing different kinds of regulation. For example, physical boundaries might constrain some kinds of processes, an ownership boundary might limit others, and political boundaries might impose other controls.

An *entity* is a compound object consisting of a set of resource pools and processes along with internal relationships among them, enclosed by a boundary. An entity is also an instance of a *compound* discrete resource. As a resource, processes can operate on entities to consume or produce them, or can have their processing capacity defined by the available amount (number) of the compound resource.

Markets are specialized entities that help manage the instantiation of exchange processes on behalf of other entities. Describing their operation in these terms is more complicated than their definition in the original model, but it avoids introducing a new basic type into the ontology, and it helps define the general requirements for controlling process interconnection.

An exchange process, depicted in figure 4-2, is a coordinated counter-movement of resources between entities:

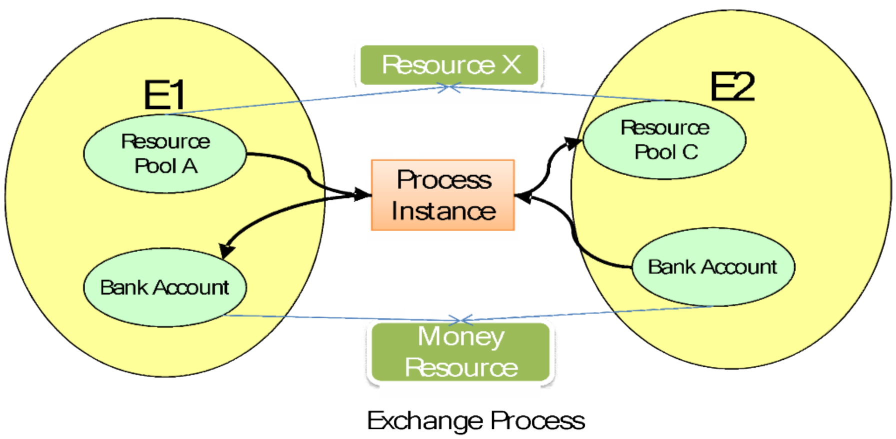
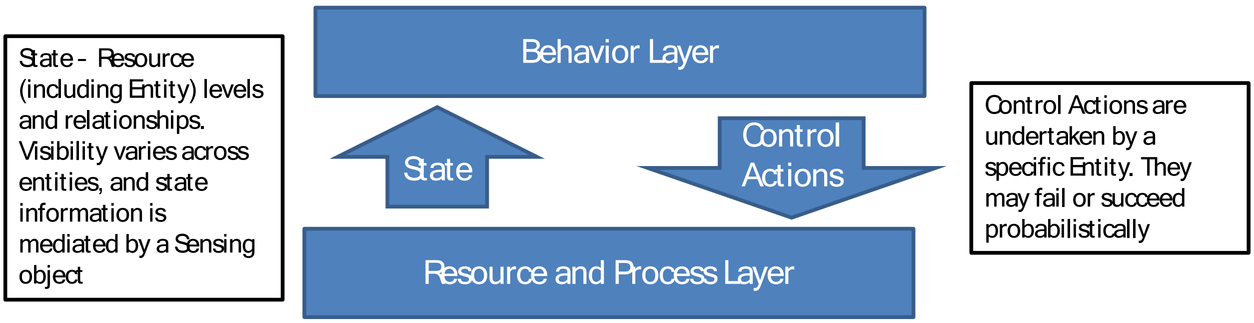


Figure 4-2 Exchange Model Process

Instantiating this process requires the consent of both the selling entity E1 and the buying entity E2. Both the seller and the buyer want to constrain the ratio of money amount to resource amount. They do this by communicating to the market entity the clauses (discussed below) defining an acceptable connection for an exchange process. The market processes can then be seen as a kind of resolution of the active clauses submitted by prospective sellers and buyers.

Behavior

Processes that operate on resources define the basic dynamics of the system. Process operation rates may be a function of resource levels and of random events, but processes are presumed to be local and reflexive, in the sense of depending only on the levels of resource pools to which they are connected. Decision-making by any cognitive and strategic actors in the system is represented in a separate behavioral layer. This layer receives state information (possibly partial, error-prone, and biased) from the material layer, and sends process controls into the material layer.



Kinds of Control Actions	
Concrete Description	*Abstract Description*
Instantiate a new process	
Connect to/Disconnect from a Market	Add/Delete a relationship between an Entity and a Market Entity
Instantiate Entities	Trigger a specific kind of production process
Adjust parameters on processes	
Join/Leave a compound Entity	Add/Delete a relationship
Set defense policy	Change boundary rules

Figure 4-3 Relationship between the Resource and Process Layer, which represents material flows, and the Behavior Layer, which represents decision-making and control logic.

Any aspect of the material layer is potentially available as state information to the rules in the behavioral layer. Control actions operate on processes in specified ways: adjusting operation rate or frequency, or triggering discrete processes, or connecting processes to resource pools. This architecture allows great flexibility in modeling behavior. Behavioral scripts can be defined so that the system enacts particular scenarios. Or cognitive or strategic models might be defined so that entities adapt their actions to achieve goals. A well-defined interface between the material layer and the behavioral layer allows the Exchange model to interact with a variety of models of strategic and political decision-making. Some possibilities are discussed subsequently.

Several kinds of control actions can be taken, as illustrated in Figure 4-2: control of an existing process instance by adjusting its parameters, instantiation of a new process instance; creating entities, connecting to markets; and defining rules governing the creation of new processes and relations. Many of these had been features of the original model which were used in constructing and configuring model instances. Making these features available *within* the model and exposing them to manipulation by a coupled model of behavior were technical advances motivated by this framework.

Process Parameters
Processes may define control parameters for specification or adjustment by behavior layer events. Continuous processes might expose a rate parameter, for example. Discrete processes might be explicitly triggered, or might be self-triggering according to a schedule whose parameters (such a frequency) can be set by signals from the behavior layer.

Instantiation
Instantiating a process involves creating a structure whose resource connection requirements can be satisfied through binding to resource pools. This is formally different from increasing the capacity to conduct the process by increasing an associated capacity resource. Capacity changes affect existing instances, and occur without direct intervention from the behavioral layer.

Resource Binding
Process instances become effective when their connection requirements are satisfied by becoming bound to resource pools of the appropriate type. Describing these connection requirements involves associating specific kinds of information with each of the processes resource pool connections. This information can by organized in such a way that it can be used both to define the possible bindings available to a decision-maker, and to support formal reasoning or planning for some implementations of decision-making logic.

Behavioral Layer Models
The behavioral layer receives state information and produces actions. There are many ways of mapping state information to actions, and many ways of classifying such mappings. For example, models might make different assumptions about the capacity of the behaving system to adapt over time, or to act using explicit anticipations of the consequences of actions. The exchange model architecture does not constrain the implementation of the behavioral layer. Some possible patterns, of increasing sophistication, are illustrated below in Figure 4-4. In this case the behavior can be defined by a simple set of rules.

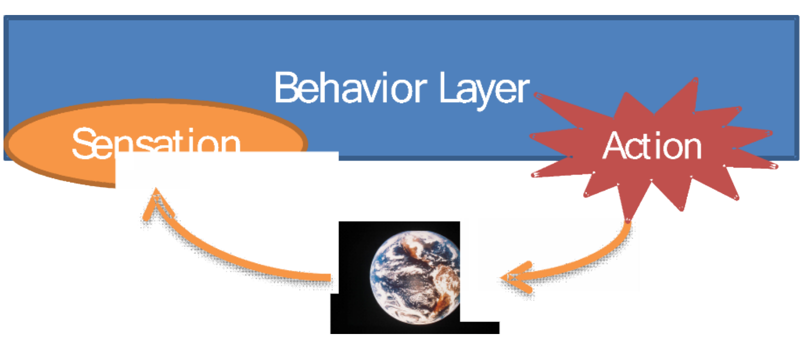


Figure 4-4 Behavior Layer

Figure 4-5 depicts behavior layers with internal state variables, and selections of responses from a set of capabilities that might develop over time, adds additional flexibility.

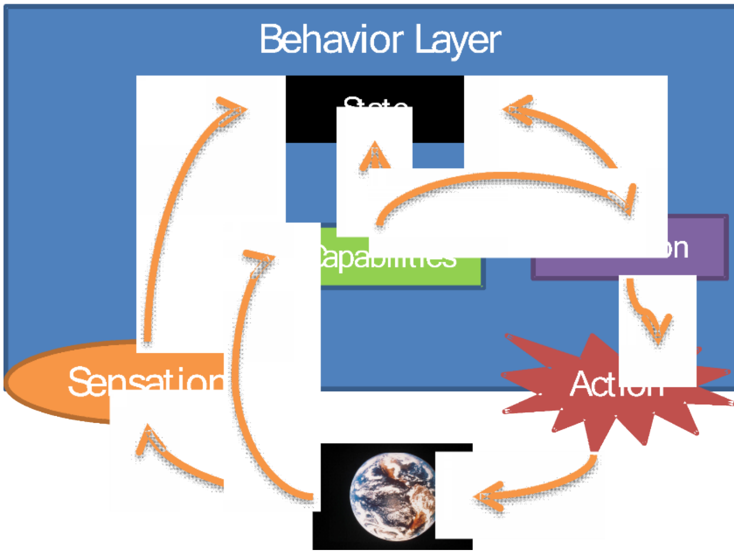


Figure 4-5 Behavior Layer with State Variables and Responses

Maintenance of an internal "World Model," and explicit anticipation and valuation of the future states that might result from alternative actions, as depicted in Figure 4-6, is a more sophisticated approach.

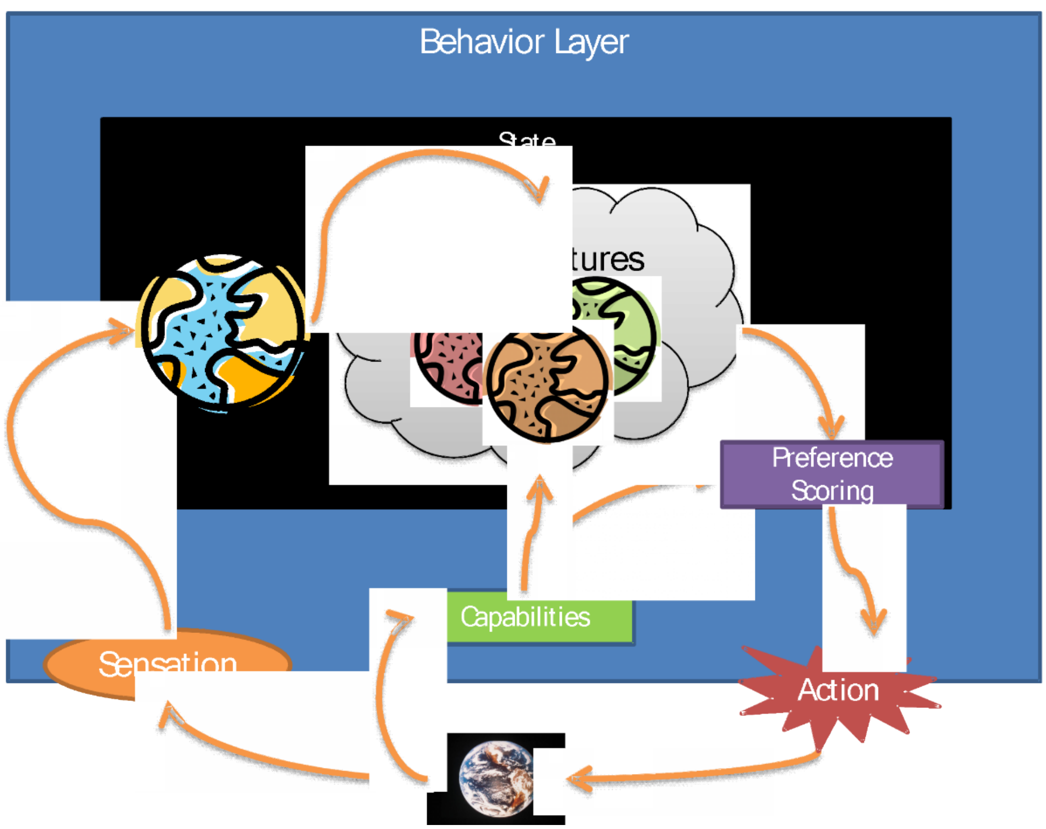


Figure 4-6 State Variables as Future Possible Worlds

4.1.2 Role in Evaluating Capability Investment

The resource flows and economic conditions represented in the Exchange model can help assess potential security decisions in three ways. First, future distributions of resources and wealth will create new political stresses within and between countries, which will in turn create security challenges. Delimiting the possible trends and patterns is helpful in understanding the kinds of missions that would be most helpful in maintaining security. Second, creating defense systems is a significant economic activity in itself, and so understanding the investments that may be required in producing and fielding systems, and the effects different decisions might have on other economic sectors, may be an important consideration in evaluating overall national security impact. Third, although the effects of specific systems in achieving mission outcomes cannot be assessed with this model, the effects of deploying capabilities in particular scenarios on resources, production capabilities, and the possibility and costs of trade can be studied.

To the extent that security involves protection of resources and trade, or the ability to interfere with adversaries' access to resources and trade, understanding how possible interventions may provoke unexpected reactions in the system is helpful for evaluating systems that enable these interventions. The Exchange model can represent certain functions that systems perform, and how the components contribute to that function. The specific systems that accomplish those functions will change as technology develops, but cost-per-unit capacity and cost-per-application parameters can be used to describe possibilities. Characterizing sub-systems in this way will also help identify areas with large return on performance gains.

From the overall measures of system health (GDP, employment, physical health, etc.) alternative investment policies by the DOD can be compared by their differential effects on these measures. The direct and indirect contribution of the military to these system properties has not been widely studied. The effect of military expenditures on the economy has been discussed as a source of stimulus and as an influence on labor supply, the effects of tax burdens required to support military expenditures are features of many macro-economic models, and the contribution of military technologies to civilian use (e.g., semi-conductors, the internet) is widely noted (Dunne et al. 2005).

There are examinations of the effect of military spending on growth that model military capital as a factor in production functions, usually Cobb-Douglass production functions (Pantelis Kalaitzidakis and Vangelis Tzouvelekas 2011). There are also several empirical studies of the connection of military spending on growth across various countries (Devarajan, S., Swaroop, V. and Zou, H. (1996))

Dunne et al. 2005 provide a review of models relating military expenditures to growth. They organize the influence of military on the economy by demand effects, supply effects, and security. They find the Feder-Ram formulation which treats the military as a separate productive sector to have basic theoretical problems, and the augmented Solow model, which includes military capital as means of improving labor productivity (e.g. Kalatzidakis 2011) to be better grounded and to offer insights into dynamics, but find the mechanism of beneficial influence through technology to be unconvincing and incomplete. Aizenman and Glick's (2006) modification of the Barro model, to include a cross-term relating expenditure and prevailing insecurity, is judged mechanistically more sensible. This empirical study finds a positive benefit for military spending when the environment is threatening, but a negative effect in other conditions.

There is evidently no model formulation that represents the role of the primary output of the military – the ability to inflict and deter damage of various kinds – on economic activity. By establishing or ensuring an environment in which actions can be controlled and therefore anticipated by legal arrangements, military defense presumably lowers transaction costs to a considerable degree. Controlling territory often leads to control of basic resources, lowering their costs to consumers under the protection of the military umbrella.

4.1.3 Global Model of National Interactions

A global model of interacting nations was developed by configuring the Exchange model as described below. This model was designed so that, through successive elaborations, it would include the three distinct connections to security investment evaluation: defining the distribution of futures to which security systems would need to respond; assessing the economic effects of the alternative configurations production networks configured to supply the materials and services corresponding to investment options; and representing the material effects of the use of military capabilities on resource access and trade. A model of strategic decision-making is important for judging the likelihood of capabilities being used in specific circumstances. Simple behavioral models can be defined for initial demonstration and testing; however in application a richer representation is needed. We have developed a behavioral-layer interface to the BIA model, described below in Section 4.2, for this purpose.

Formulating the model at the full global scope initially, rather than building it up by enlarging and combining models with narrower boundaries, is a necessary strategy for solving CASoS problems because: 1) solutions that assume isolation (at smaller scales) are often frustrated by feedbacks from outside the (narrowly) idealized system, and 2) a global scope forces parsimony in conceptualization and implementation as only appropriate detail can be included.

Although the initial model has global scope, processes are incrementally included so that the overall model behavior can be tested and understood. We developed a sequential approach to a comprehensive model, which includes the kinds of national actions and their motivations that seem necessary for producing plausible scenarios. Each stage introduces new processes or more refined models of processes captured roughly in earlier versions. The successive stages will give the entities' behavior-layer counterparts increasing capabilities to act on the system, and will use increasingly sophisticated decision-making logic to control those actions.

The initial model is a variant of nation-state models that have been analyzed for effects of energy policy (e.g., Mitchell et al. 2012). The system consists of a collection of nation entities, each composed of a collection of productive sectors. A definition of these sectors and their interdependencies is given in Table 4-1, and the associated dependencies among sectors are shown in Figure 4-7. Flows of Labor and Energy, which are used as inputs in all but the sectors that produce them, have been omitted for clarity.

Table 4-1 Structure of a Generic Nation: Sectors, Resources, and Input/Output Relationships

Sector	Produced Resource	Consumed Resources										
		Fuel	Transport	Metals	Industrial Goods	Military Goods	Military Capacity	Consumer Goods	Services	Food	Energy	Labor
Household	Labor		X					X	X	X	X	
Fuel Production	Fuel				X						X	X
Mining	Metals	X			X						X	X
Industry	Industrial Goods	X	X	X							X	X
Defense Industry	Military Goods	X	X	X							X	X
Military	Military Capacity	X	X		X	X				X	X	X
Manufacturing	Consumer Goods	X	X	X	X						X	X
Service Providing	Services	X	X		X						X	X
Farming	Food	X	X		X						X	X
Energy from Fuel	Energy	X			X							X
Energy from Other	Energy				X							X
Transportation	Transport	X			X						X	X
Government			X				X	X	X		X	X

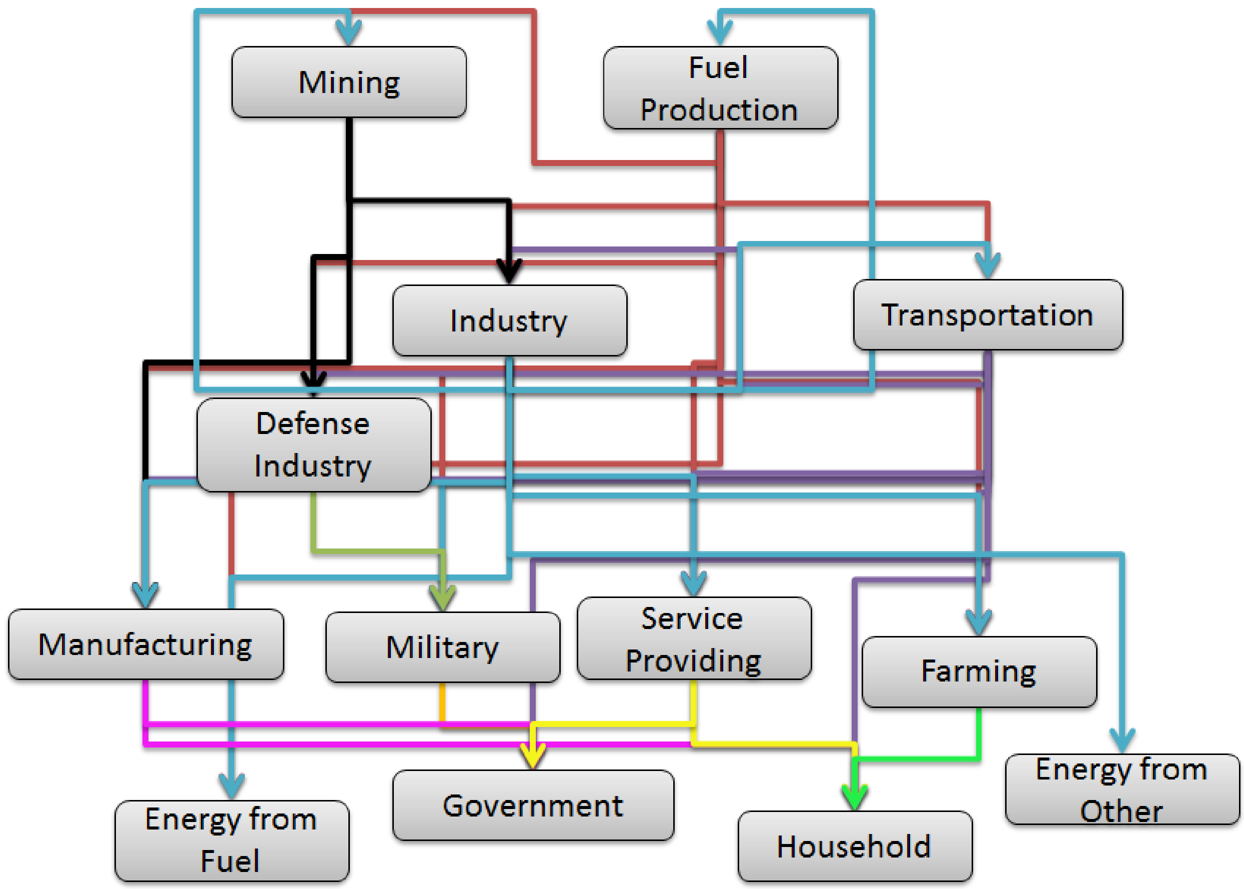


Figure 4-7 Sectors and Resource Flows within a Nation.

Each sector can be represented by a single entity, or by several entities with differing parameters. The use of multiple heterogeneous entities can be convenient for modeling some kinds of adaptation. The relevant parameters (consumption and production rates in each sector, sensitivities to resource availability, etc.) can be varied among nations to represent differences in natural resources, current technological development, and cultural dispositions. Different structures can be specified for some nations if important distinctions cannot be captured with parameter variations. Nations interact through international markets for resources. Multiple markets can be defined for each resource, differing in the participating nations and the terms of access (e.g., tariff levels).

The basic behavioral actions by governments are setting tax rates in the various domestic markets, setting tariffs on imports and exports, and allocating the "military capacity" resource to reduce the effects of random perturbations on domestic and international markets. This represents the most fundamental decision-making by nations. They adjust continuous variables to affect some optimal balance among the levels of critical resources. These resources minimally include Government money, military capacity, and household health.

In this example, twenty nation-states with the sectors and interactions shown in Figure 4-7 compose the world model. Stoichiometric coefficients and nation sizes will be sampled from distributions to create innate heterogeneities in the system. Random perturbations to internal markets and external markets represent a “state of nature” in which the environment is insecure and transaction costs are high.

The Government extracts taxes from internal markets, and can impose tariffs on transactions crossing its borders. It uses these resources to produce the “Security” resource, which it can expend on domestic or international markets or both. As a first step, we look at the simple decision problem of imposing taxes at different levels, and deploying security in different places. This first case presents nation’s decision-makers with a low-dimensional decision problem regarding where and how much money to extract, and how to allocate its security product. The decision problem is still quite complicated because the relevant processes have interacting dynamics with various time constants, and are influenced by the decisions of other nations.

Next we include households (in aggregate) as decision-makers. We add the prospect for conditions that effect households, especially their economic health, to increase or decrease the amount of civil unrest. Civil unrest is represented by perturbations to domestic markets and to resource stores. The macro effect is to increase the cost of transactions and to decrease the efficiency of production. Including this process brings in a new category of action (introduction of a perturbation process). The positive feedback between aggregate production and tax revenue for security creates the potential for two stable equilibria – one characterized by low civil unrest and high productivity and the other by high unrest and low productivity.

The third case includes multiple nations with randomly-sampled coefficients, linked through international markets which are subject to random perturbations, nominally more severe than those affecting un-buffered domestic markets. Governments may level tariffs on international trade through their boundaries, and may allocate some of their security resource to buffering international markets. This allows nations to create positive externalities by lowering trading costs for all nations through security expenditures. This may prove unsustainable, depending on whether the securing nation receives enough benefits from stabilization to offset their expenses.

The fourth case brings in the possibility of hostile international actions in the form of directed perturbations and attempts to block trade to or from other nations. Here the comparisons of resource level between pairs of nations can drive decisions to attack (or perhaps defend) other nations. Both strategic resource levels (oil for example) or Security levels may be important drivers for the decision.

The fifth case brings in alliance formation. Alliances are represented by composite entities that contain their members. These composites can also contain markets to which only their members belong, and with (presumably) lower transaction costs than general international markets. The composite may enforce security pacts by blocking perturbations between participating nations, creating a common pool of the Security resource to which all members contribute, or compelling joint response by all members if one is attacked.

This succession of process additions allows an increasingly sophisticated range of actions by strategic decision-makers, minimally governments and households. The final configuration is envisioned to include a sophisticated decision-making model such as BIA, coupled through the behavioral layer interface. Table 4-2 summarizes the sequence of configurations leading to the completed model, along with key triggers for, and actions by, the Government and Household decision makers. This completed model would enable a coherent evaluation of decision pathways leading to distinct capability mixes by modeling the material conditions associated with their production, availability, and use.

Table 4-2 Succession of Global Model configurations, with Associated Triggers and Actions

		Model Progression				
	Case	**Isolated nations managing internal security**	**Adding households as actors**	**Adding international linkages**	**Adding capability classes and enriched behavior by governments**	**Adding coalition formation**
	Description	Isolated nations with the sectors shown in Figure 4-3 and random perturbations to domestic markets. Government can set tax levels and deploy the Security resource it produces.	Isolated nations with prospect for civil unrest, meaning households create perturbations to markets and resources.	Nations with different sizes and economic coefficients. Governments can impose tariffs on int'l markets and domestic taxes. Governments can devote some of Security resource to buffering int'l markets.	Security resource disaggregated into specific capabilities; Nations can deploy those capabilities to defend or attack resources and markets.	Nations which can commit to reciprocal actions such as non-aggression, or mutual defense, or limiting tariffs.
Triggers monitored by Strategic Actors	Health level and rate of change in Households		Level or change triggers domestic perturbations			
	Difference in Health vs. Peers			Contrasts in health lead to domestic perturbations		
	Change in "aggression" threshold				Might be random, (e.g., representing change in gov't)	
	Internal resource levels:					
	Security resource	Used in all Security allocation decisions				
	Strategic resource			Possible input to tariff/tax decisions		
	Comparative resource levels:					
	Security				Input to selecting	

		Model Progression				
	Case	**Isolated nations managing internal security**	**Adding households as actors**	**Adding international linkages**	**Adding capability classes and enriched behavior by governments**	**Adding coalition formation**
	resource				targets (base as threat and as deterrence)	
	Strategic resource				Input to selecting attack targets and allocating Security as defensive buffer	
Household Action	Internal conflict		Perturbations to domestic markets and resource stores			
Government Action	External offensive act				Perturbation to int'l market or to resources in another nation	
	Alliance change					Join or leave compound entity that imposes constraints on interactions
	Build defensive buffer	Government allocates its Security resource over markets and component entities				
	Cut off resource flows				Selectively perturb inflows into/out of particular nations	
	Take or destroy resources				Selectively perturb international markets or other nations	
	Project force					Join mutual defense pact

4.2 Behavioral Influence Assessment Tool

4.2.1 Background

Behavioral Influence Assessment (BIA) is a theory-based, systems-level capability that is intended to enable analysts to better assess the effects of events, potential actions and counter-actions of governmental and non-governmental groups interacting within a country or countries of interest (COI). Specifically, BIA is designed to quantifiably address the social/political/military/economic dynamics between individuals, groups, and countries, as well as unanticipated, higher-order consequences of events or actions. This assessment tool can produce outcome distributions used to investigate attitudinal and behavioral reactions to U.S. and/or foreign policies and actions within a COI. Included in this assessment are considerations of the dynamics that drive stability and instability. BIA is the result of 10 years of Sandia cognitive modeling & simulation research and development (R&D) and 15-20 years in systems modeling and simulation R&D.

The foundation of the BIA system rests upon a synthesis of data-supported, psychological, social (psychosocial) and socioeconomic set of theories of decision-making and behavior. BIA integrates cognitive, social, and system dynamics approaches. Model information is refined by cultural and psychosocial data of the region up to specific knowledge of individuals— from Subject Matter Expert (SME) guidance, opinion polls, field reports, and social media. BIA intends to computationally represent the mindset of specific individuals and groups, comprising of beliefs, motivations, affective states, intentions, and potential behaviors. The actions of one modeled individual or group can affect the mindset and actions of others, including the society in which they are situated. This provides a, data-driven, analytical capability capable of assessing responses to events.

4.2.2 Overview of BIA Model Architecture

The BIA architecture is evolving and is being improved over time. In general, BIA consists of a psycho-social modeling framework, model simulators via software tools such as Vensim™, and an analysis and visualization engine, via tools such as Tableau™. The current BIA Modeling architecture provides for the storage of BIA Models, the execution of those models by compatible simulators, and the analysis of run results by various analysis engines. The integration with simulators and analysis engines leverages a plug-in architecture to convert data repository records into a compatible format for the external tools. Other arbitrary types of records that could represent source references or other supplemental information can be tied to models to provide deep traceability from a run or an analysis.

The current BIA architecture also includes a flexible database engine within the modeling framework to support organization of models (via Vensim™), runs, and references. In this LDRD, we have applied a progressively more complex BIA modeling architecture (Figure 4-8) to enable more efficient cross-modeling domain (i.e., different countries and groups), simulation and assessments, information sharing, knowledge structure development, and visualization.

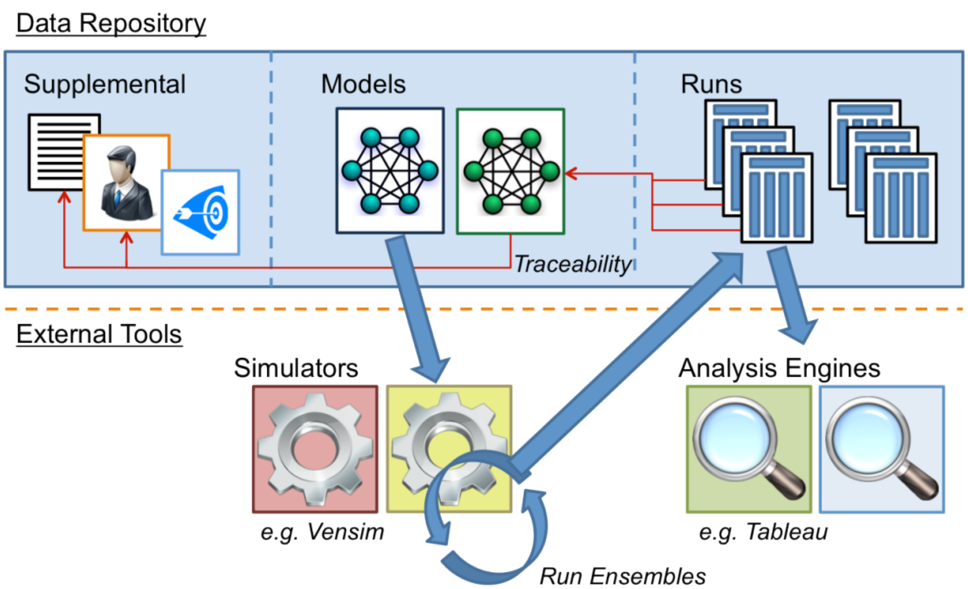


Figure 4-8 BIA Modeling Framework.

4.2.3 Linking BIA with Exchange

BIA is well-suited as an implementation of the Exchange Model behavioral layer (described above in Section 4.1) for the purpose of model the possible behavior of strategic actors, such as governments and significant non-state organizations. The state variables of the Exchange model, when configured to represent economic actors within nations, provide key inputs for the decision-makers represented in BIA. Value of prices for key commodities, levels of employment, inventories of key resources, as well as rates of change in those variables, are natural cues for BIA decision-makers. BIA state variables, in turn, define the probability that specific actions will be taken, such as initiation of conflict or imposition of trade restrictions. The material consequences of these actions lead to secondary effects represented in Exchange, which in turn change cue values presented to the actors in BIA.

This close coupling between the processes represented in the two models requires co-simulation of a scenario using the two models, i.e., coordination of information flows and synchronization of state updates. Java classes implementing this coordination were accordingly implemented and tested as part of this framework development.

4.3 Mission and Functional Decomposition

General research was conducted relating to the range of military operations. This research sets the stage for whatever military units and capabilities we are considering. The information, found in Military Doctrine (documents such as "Joint Publication 3-0: Joint Operations" published by the Joint Chiefs of Staff), lays the foundation for mapping units and capabilities to missions.

THEMES				
Peacetime Military Operations	Limited Intervention	Peace Operations	Irregular Warfare	Major Combat Operations
Features				
Long term Non-doctrine Bilateral or multinational	End state clearly defined Limitations on supporting forces Limited size Limited phasing	Crisis response Contain conflict Limited contingency ops All instruments of national power Asymmetric threats Failing states Collapse of infrastructure Presence of dislocated civilians	State/nonstate actors struggle Irregular forces Warfare among/within people Indirect unconventional methods Special operations conduct most ops	General war Defeat enemy Sieze terrain Multinational interests Doctrine
OPERATIONS				
Multinational training excercises Security assistance Joint combined exchange training Recovery operations Arms control Counterdrug activities	Noncombatant evacuation Strike Raid Show of force Foreign humanitarian assistance Consequence management Sanction enforcement Elimination of WMD	Peacekeeping Peace building Peacemaking Conflict prevention	Foreign internal defense Support to insurgency Counterinsurgency Combating terrorism Unconventional warfare	Specific named operations Offensive joint operations Defensive joint operations Special operations

* Campaigns can involve multiple Themes

Figure 4-9 Military Themes, Features, and Operations.

Figure 4-9 shows a range of military operations defined in doctrine. In this table, themes are defined by general features (although multiple themes can share some features, the figure shows a general mapping). For example, Major Combat Operations is a theme describing major operations that are mapped to features like general war, defeating an enemy, seizing terrain, multinational interests, and doctrine. Operational themes are too general to be assigned as missions. Rather, they describe the major operation's general characteristics, not the details of its execution[2]. The themes are also tied to specific operations. In the case of the Major Combat Operations theme, typical operations include specific named operations, offensive or defensive joint operations, and special operations.

Operations are further defined by Joint functional capabilities (JFCs), multi-service tactics, techniques, and procedures (MTTPs), service specific OPLANs/OPORDs, and service specific TTPs as depicted in Figure 4-10.

[2] "Field Manual (FM) 3-0 Operations", Headquarters Department of the Army, Washington, DC, 27 February 2008.

<table>
<tr><td colspan="12">Example: Foreign humanitarian assistance</td></tr>
<tr><td colspan="12">Joint Functional Capabilities</td></tr>
<tr><td colspan="2">Command & Control</td><td colspan="2">Intelligence</td><td colspan="2">Fires</td><td colspan="2">Movement & Maneuver</td><td colspan="2">Protection</td><td colspan="2">Sustainment & Logistics</td></tr>
<tr><td colspan="12">Joint OPLAN/OPORD (How Organizations, People, and Equipment are used)</td></tr>
<tr><td colspan="12">Multi-service Tactics, Techniques, and Procedures (MTTPs)</td></tr>
<tr><td colspan="3">Army</td><td colspan="3">Navy</td><td colspan="3">Marine Corps</td><td colspan="3">Air Force</td></tr>
<tr><td colspan="12">Service Specific OPLANs/OPORDs</td></tr>
<tr><td colspan="12">Service Specific TTPs</td></tr>
</table>

Figure 4-10 Joint Functional Capabilities

Operations require a mixture of JFCs – units are organized by JFC. Joint OPLANs and OPORDS define how organizations, people, and equipment are orchestrated when conducting a joint operation. Multi-service TTPs detail the tasks associated specific elements of a joint operation. Service specific OPLANs/OPORDs and TTPs define specifics for each service involved in the operation.

As an aside, one can begin to see the hierarchical nature of the DOD operations and the interdependencies and relationships that exist, making it a highly complex problem in terms of planning and investing. The DOD example works well with our proposed framework in that we can identify these interdependencies and mappings and organize them from a capabilities perspective.

Continuing on, the JFCs can be mapped to specific actions and/or capabilities. Figure 4-11 shows a non-comprehensive example of how the JFCs are mapped. This level of detailed information that can be tied to an Enterprise of interest and its corresponding capabilities, which will be seen in the Use Case example of this report.

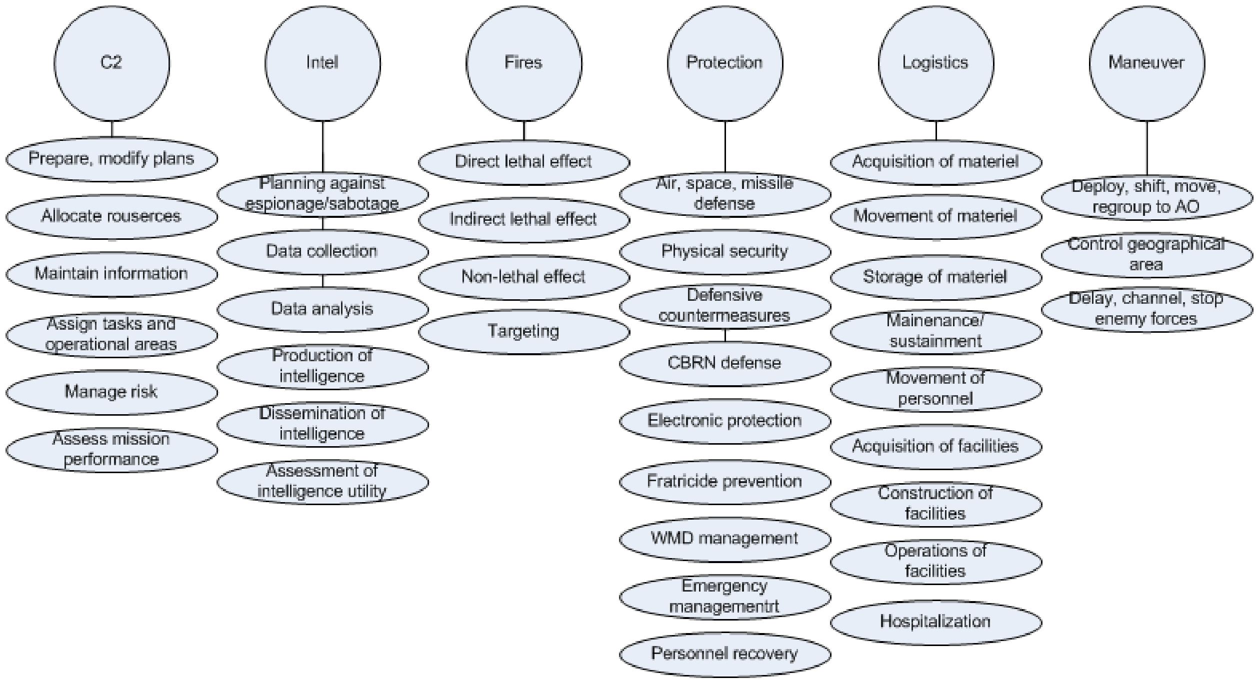


Figure 4-11 Capabilities Tied to JFCs.

5 USE CASES

5.1 PACOM

5.1.1 Background

As described on their web site, “The United States Pacific Command (USPACOM) Area of Responsibility (AOR) encompasses about half the earth's surface, stretching from the waters off the west coast of the U.S. to the western border of India, and from Antarctica to the North Pole. There are few regions as culturally, socially, economically, and geo-politically diverse as the Asia-Pacific. The 36 nations that comprising the Asia-Pacific region are home to more than 50% of the world's population, 3,000 different languages, several of the world's largest militaries, and five nations allied with the U.S. through mutual defense treaties. Two of the three largest economies are located in the Asia-Pacific along with 10 of the 14th smallest. The AOR includes the most populous nation in the world, the largest democracy, and the largest Muslim-majority nation. More than one third of Asia-Pacific nations are smaller, island nations that include the smallest republic in the world and the smallest nation in Asia.” [For more information on PACOM see www.pacom.mil]

Since PACOM is becoming more of a global focus, we chose to use PACOM as the use case to illustrate our capability framework concepts. The first step taken was a capability decomposition of PACOM given the current unit organizations, equipment, and missions. PACOM itself is support by four combatant commands: US Pacific Fleet (PACFLT), US Pacific Air Forces (PACAF), US Army Pacific, and US Marine Forces Pacific. Research was performed for each of the Air Force, Navy, and Army units which support PACOM. Air Force research produced information regarding the supporting units and the equipment available in each unit. Unit capability detail was not as available, but equipment capabilities were researched and mapped as part of the unit capability. Navy data was much more available and detailed mission and capability information was found at both the unit as well as equipment levels.

5.1.2 PACOM-specific unit capability description

For the Air Force, we started by looking at the component Air Forces of PACAF and the units beneath them, to get a sense of the capabilities provided. Capability descriptions for the units were generally not readily available; those that were available tended to be quite terse, or written almost solely in terms of platforms (e.g., “combat-ready F-16 wing”). It was straightforward, however, to find comprehensive information about which platforms the units owned, and then use information in the public domain to extract the key capabilities those platforms provide.

Through this process, it became clear that considering PACAF capabilities alone was insufficient, as the US would not be restricted to these capabilities in an actual conflict. First, there were important capabilities relevant to a potential conflict in the Pacific AOR that were wholly unrepresented within PACAF. Second, several airbases under PACAF’s command had a clear charter to be able to host aircraft from other commands – in fact, one such base has no aircraft natively assigned and solely supports rotational deployments from other commands. Some additional research elucidated that the following sister Major Combatant Commands (MAJCOMs) could augment PACAF with the following capabilities:

- Air Mobility Command (AMC) and Air Combat Command (ACC) logistics capabilities
- ACC air-to-air and ground attack/close air support capabilities
- ACC and Air Force Space Command (AFSPC) C4ISR capabilities

- ACC and Air Force Global Strike Command (AFGSC) conventional bombing capabilities
- AFGCS nuclear bombing and Inter-Continental Ballistic Missile (ICBM) capabilities
- AFSPC cyber capabilities
- Air Force Special Operations Command (AFSOC) Special Operations Forces (SOF) capabilities

Additional detail on these organizations and their missions can be found in Appendix C: Air Force Pacific Command Details.

Repeating the same process of studying these MAJCOMs' subordinate units, capabilities, and platforms led to the information in the table below.

Table 5-1 Mapping of AF MAJCOMs and Platforms to Capabilities

MAJOR COMMANDs	Platform	C. bomber	N. bomber	ICBM	Ground	Evacuation	Light utility	Refueling	Transport	Air drop	VIP	AWACS	C2	EW	Surveillance	SIGINT	Air	Stealth
ACC	B-1	X																
AFGSC	B-2	X	X															X
AFGSC	B-52	X	X															
AFGSC	ICBM			X														
PACAF, ACC	A-10				X X													
PACAF	C-12					X	X											
PACAF, ACC	HH-60					X	X											
PACAF	UH-1					X	X											
AMC	KC-10							X	X									
PACAF, AMC	KC-135							X X										
AMC	C-5								X X									
PACAF, AMC	C-130H				X	X		X	X X									
ACC	C-135								X X		X							
PACAF, AMC	C-17					X			X X	X X								
AMC	C-32										X							
PACAF, AMC	C-37										X							
PACAF, AMC	C-40										X		X					

MAJOR COMMANDs	Platform	C. bomber	N. bomber	ICBM	Ground	Evacuation	Light utility	Refueling	Transport	Air drop	VIP	AWACS	C2	EW	Surveillance	SIGINT	Air	Stealth
AMC	VC-25										X							
PACAF, ACC	E-3											X X	X	X		?		
ACC	E-4										X	X	X	X				
ACC	E-8											X	X	X	X			
ACC	MQ-9				X										X			
ACC	RQ-1				X										X			
ACC	RQ-170														X			X
ACC	U-2/TR-1														X X			
PACAF	RQ-4														X X	X		
PACAF	ground radar																	
PACAF, ACC	F-15																X	
PACAF, ACC	F-16																X	
PACAF, ACC	F-22				X									X		X	X X	X
AFSPC	satellites														X			
AFSPC	cyber capabilitie s																	
AFSOC	SOF																	

For the Navy data, research was conducted to determine which units supported PACOM as part of the PACFLT. The 3rd and 7th fleets were identified as the major units and thus detailed research on each of these units was performed. Information regarding the units, their missions, and their associated equipment was found. Additional research into the capabilities of the equipment (systems) was also performed. The result was a list of units and equipment in each of the fleets with detailed mission or capability descriptions. The next step was to take the detailed descriptions and parse out key phrases of capability or mission description to create keyword tags for each unit and equipment. Finally, these key phrases were consolidated and grouped according to similarity in an affinity diagram. Each of the groupings of similar phrases was labeled with a category description to match the associated key words. Thus resulting in a set of high level capabilities with each of the specifics (from unit and equipment details) mapped to a capability. The table below shows the final result of this process.

Table 5-2 PACFLT Capability Categories

Capability Category	Capabilities and Mission Areas of Navy PACFLT
OPERATIONS	Deter crisis
	Forward postured and immediately employable force
NON-COMBAT OPERATIONS	Vertical lift Search and Rescue
	Conduct search and rescue
	Humanitarian assistance or disaster relief
	Security cooperation agent
SPECIAL OPERATIONS	Special warfare support
	Special Operations Forces Support
	Covert insertion of special forces
	Naval special warfare
DEFENSE	Fleet air defense
	Ballistic missile defense
SUBSURFACE WARFARE	Short range anti-air and anti-submarine warfare
	Persistent undersea warfare
	Anti-submarine warfare
SURFACE WARFARE	Counter-piracy
	Hosting helicopters to support forces ashore
	Surface combat
	Combat strike element
	Maritime patrol
	Attacking surface ships
	Carrier Strike
	Anti-Surface Warfare
	Assault under combat conditions
	Blockade running
	Conventional land attack
	Time critical strike coordination
	Torpedo
AIR COMBAT	Air-to-air
	Attack air surface and subsurface targets
	Enables air power projection
	Air-to-surface
	Air interdiction
	Close and deep air support
	Offensive and defensive counter air control
	Drone
MARITIME ESCORT/TRANSPORT	Escort large vessels

Capability Category	Capabilities and Mission Areas of Navy PACFLT
	Transport and launch landing craft and amphibious vehicles
	Fighter escort
	Amphibious transports
	Lands elements of landing force for expeditionary warfare
	Support Marine landing operations
	Defends against short-range attackers
	Raiding or commerce protection
	Aircraft carrier protection
	Maritime security
MARITIME LOG/MAINT	Carry supplies and mail
	Combat ready fleet logistics
	Logistic support to guided missile and fast attack subs and deployed surface combat ships
	Assist ships in maintaining highest level of materiel
	Vertical replenishment
	Conduct in-flight fueling operations
	Recovering aircraft
	Amphibious cargo ships
	Materiel readiness for ships and aviation squadrons
	Submarine maintenance
	Sustained operations at sea
	Hotel service
	Carrier onboard delivery
	Vertical on-board delivery
	Expeditionary intermediate level maintenance
TRAIN	Coordinate offensive and defensive ops
	Plans and conducts operations in surface
	Maintenance and training of surface ships
	Personnel readiness
	Unit-level training
	Integrated training
	Plan and execute amphibious operations
WARNING/DETECTION	Scouting
	Tactical airborne early warning
	Sensors
	Locate identify render safe and remove CBRN explosive hazards
	Command and control

Capability Category	Capabilities and Mission Areas of Navy PACFLT
	Suppression of enemy air defenses (SEAD)
	Airborne battle management and C2
	Obtaining tactical electronic intelligence
	Escort/standoff jamming
	Aerial reconnaissance
	Perform all-weather mining operations
	Airborne mine countermeasures
	Surface surveillance
	Explosive ordinance disposal mobile units
ELEC ATTACK	Electronic attack
	Electronic warfare
	Provide airborne electronic countermeasures

Using the high level capabilities list from each Air Force and Navy research effort, a single combined list was created. Similar categories were consolidated and sub-categories were captured where appropriate. For example, the original Navy category of Air Combat/Support is general enough to include several things. In this case, those sub-categories (some of which were originally Air Force categories) were defined as part of the overall Air Combat/Support category. This combined approach resulted in a hierarchy of capabilities rather than a one-dimensional array of top level categories. The team believes that this best captures the set of capabilities that currently support PACOM operations.

Table 5-3 PACAF and PACFLT Combined Capability Categories

Capability	Sub-Capability	Description
Non-Combat Operations		Includes search and rescue, humanitarian assistance, disaster relief, and security cooperation agent.
Special Operations		Includes all special operation activities.
Subsurface Warfare		Persistent undersea warfare and anti-submarine warfare.
Surface Warfare		Surface combat and related activities as well as support to forces ashore.
	Ballistic missile defense	Destroyers have some ballistic missile defense capability.
	Carrier and Combat Strike	Units and equipment specifically supporting strike elements.
	Maritime patrol	Monitoring areas of water.
	Anti-surface warfare	Suppression of surface combatants.
Air Combat/ Support		
	Air superiority	
	Ground attack	
	Fleet air defense	Defending Naval fleet from air attack.

Capability	Sub-Capability	Description
Maritime Escort/ Transport		Escorting large vessels, amphibious transports, supporting of Marine landing operations, maritime security and commerce protection.
Maritime Logistics / Maintenance		Includes carrying supplies, logistics support to subs and surface combat ships, in-flight refueling, recovering aircraft, carrier and vehicle on-board delivery, and maintenance.
Training		Coordinate offensive and defensive ops, maintenance and training of surface ships, unit-level and integrated training, personnel readiness.
Warning/ Detection		Includes tactical airborne early warning, command and control, suppression of enemy air defenses, escort/standoff jamming, airborne reconnaissance and mine countermeasures, surface surveillance.
	AWACS	
	C2	
	Surveillance	
	Ground radar	
	Satellites	
Electronic Attack		
Conventional Bomber		
Air/ Ground Sustainment		
	Light lift	
	Heavy lift	
	Refueling	
	Transport	
	Air drop	
VIP		
SIGINT		
Stealth		
Cyber Capabilities		

5.1.3 PACOM Capabilities Database

The information gathered during the research of PACOM and its units and capabilities was put into a database. The database captures the data in a relational manner which facilitates mapping, linking, and searching through the PACOM capabilities data. Figure 5-1 shows the database schema developed for the PACOM Use Case example.

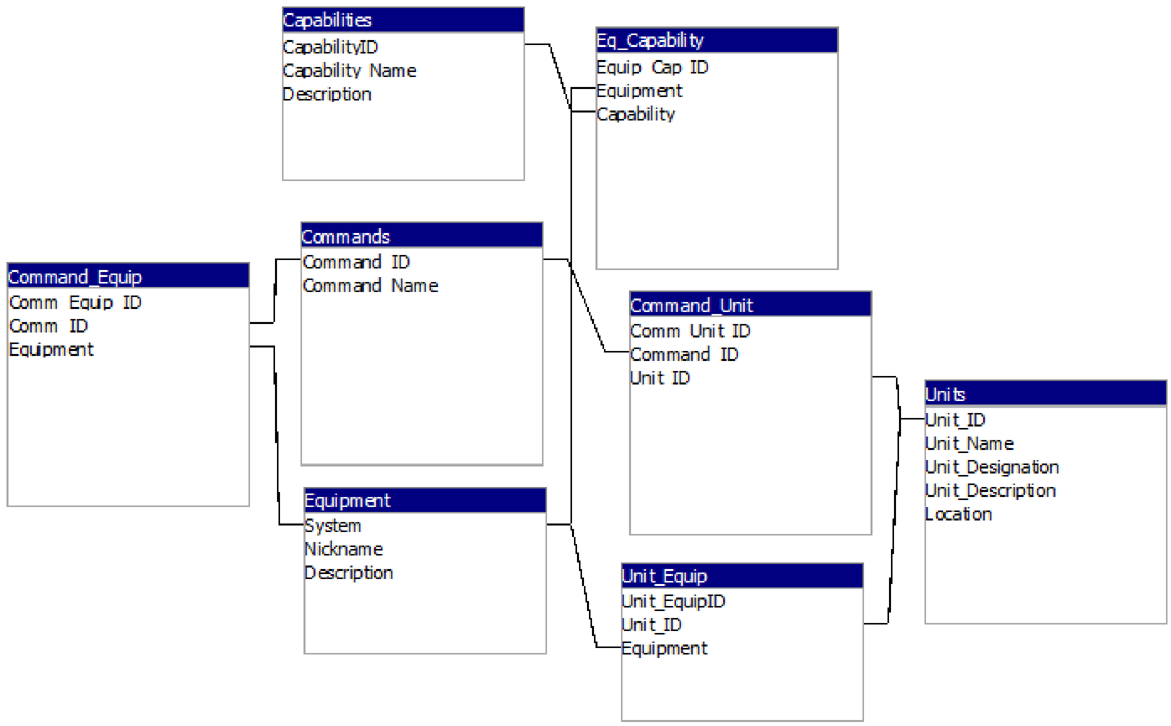


Figure 5-1 Database Relationship Schema for PACOM Capability Data.

The database organization is set up such that one could search for capabilities and determine which units and equipment contribute to those capabilities. Thus, in the framework approach we can focus on capability and drill down to specific options which contribute to the capability and do a performance evaluation of those alternatives. At an Enterprise level, this allows for a top-down approach to determining what is required to meet future capability needs.

5.1.4 Mapping Units to Joint Functional Capabilities

In the description of the analytical approach, we described the DOD enterprise mission and functional decomposition. The Joint Functional Capabilities, which tied to the more detailed actions and capabilities, can be mapped to the capabilities defined for PACOM. An example of this mapping for Navy and supporting PACOM units is shown in Figure 5-2.

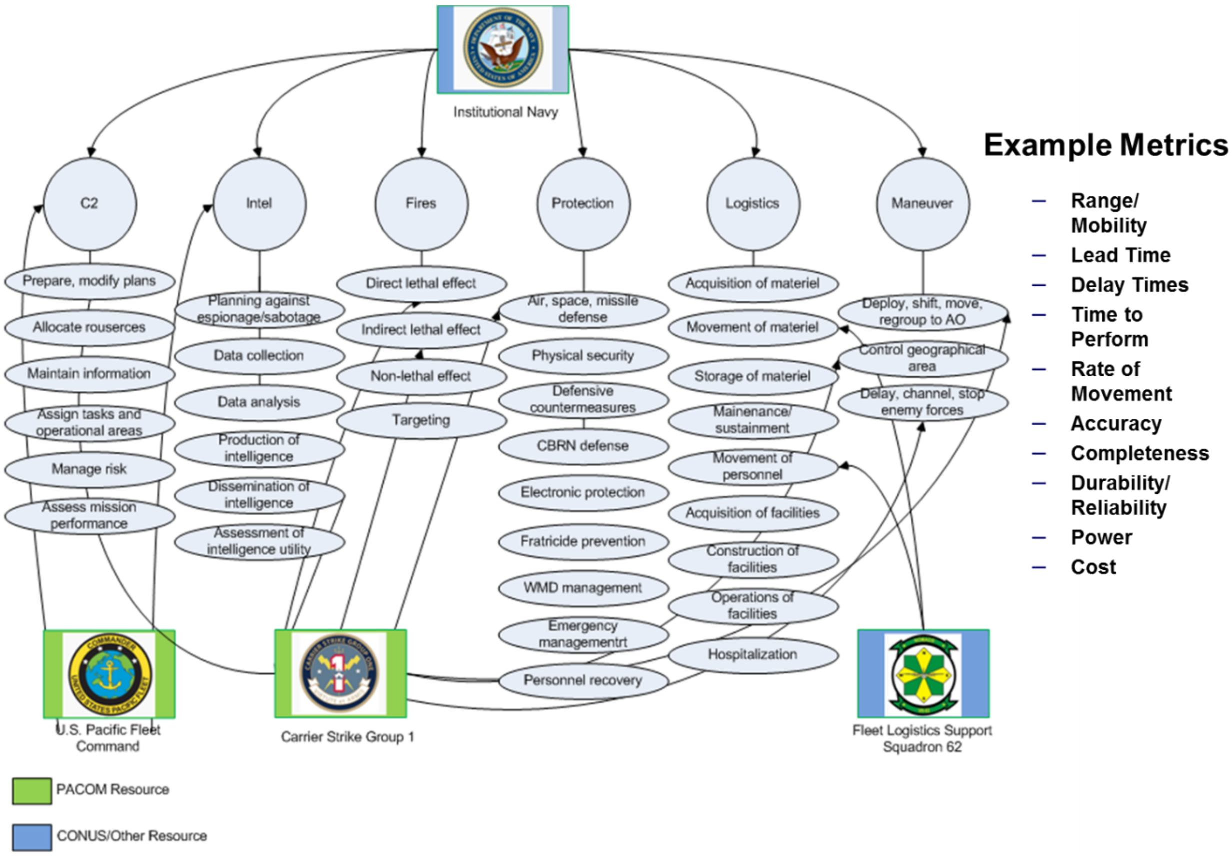


Figure 5-2 Mapping PACOM Units to Mission Decomposition Capabilities.

This information is also captured in the database developed for the PACOM Use Case. The idea is to develop this mapping for several different operation types to create a portfolio of operations, their respective JFCs and capabilities, and the current and potential future units and capabilities that are part of PACOM. For this LDRD, we focused on two specific operations which are discussed in the next two sections.

5.1.5 Humanitarian Assistance Disaster Relief Use Case: Operation Tomodachi

There is a natural dichotomy that exists in military operations and underlying military capabilities that is exemplified by PACOM. Specifically, most military systems, doctrine and force structures are designed with major military combat operations in mind. However, most of the application and use of this military equipment is often for other, non-major combat operations. This is no more evident than in PACOM where military assets organic to PACOM are most heavily utilized in Humanitarian Assistance Disaster Relief operations. Therefore, our initial use case for demonstrating the Enterprise framework was focused on a Humanitarian Assistance Disaster Relief operation.

Specifically, we looked at Operation Tomodachi which was a United States Armed Forces assistance operation to support Japan in disaster relief following the 2011 earthquake that took place off the coast of Japan, and the ensuing tsunami. The operation took place from 12 March to

4 May 2011 and involved 24,000 U.S. service members, 189 aircraft, and 24 naval ships at a cost of $90 million.

Operation and Mission Objectives

Given that the use case is focused on a specific operation in a specific operating environment, the use case will begin with defining mission objectives (in a completely comprehensive and populated enterprise framework this mission would be one of many that would be considered when evaluating portfolio capabilities).

The Tōhoku earthquake and tsunami in combination were an extreme natural disaster and in addition it included a radiological component that further complicated disaster relief activities. The principal mission elements were:

- Transport/Delivery
- Refueling
- Survey
- Search and Rescue
- Heavy Lift
- Route Clearing

The missions that dominated the operation were Transport/Delivery, Refueling, and Heavy Lift.

If we look back at the mission decomposition for PACOM (Figure 5.2) we see that these missions will fall predominantly within the "Logistics" function. As we move to the next step in the enterprise framework of assessing alternative capabilities (in performing missions) we can focus on the units both within PACOM and those that reside outside of PACOM, that support Logistics functions such as Transport/Delivery. In addition, we can look at units that support other functions within the mission decomposition and identify those that can be repurposed within the relevant "logistics" functions and operations – for example a Carrier Strike Group can be repurposed to serve as a refueling platform (which was the case for CSG Ronald Reagan in Operation Tomodachi).

Assessing Operation and Mission Capabilities

Following is a description of the primary units involved in the operation (drawn from the Congressional research Service report: "Japan 2011 Earthquake: Department of Defense Response March 22, 2011)

Naval Fleet Logistics Support Squadron Six Two and Five Nine (VR-62 and VR-58, respectively) from Naval Fleet Logistics Support Wing Joint reserve Base Fort Worth, which were in theatre (PACOM) were available to assist immediately to deliver 127 tons of material aid. The Navy VR-62 is stationed at Naval Air Station (NAS) Jacksonville, FL and has Lockheed C-130T Medium Lift Cargo Aircraft. VR-58 is stationed at NAS Jacksonville and has Boeing C-40A Clipper Aircraft, which delivered 366,000 pounds of food and water as well as transported 1,400 passengers. Eight additional Naval Fleet Logistics Squadrons were deployed to assist as well during the mission: VR52, VR53, VR54, VR55, VR56, VR57, VR61, and VR64. Nuclear Aircraft Carrier (CVN) 76 (USS Ronald Reagan) Battle Group moved to east coast of Honshu and served as a refueling platform for CVN-76 Battle Group helicopters and Japanese Self-Defense Force helicopters. Carrier Air Wing Five (CVW-5) ferried over 100 tons of food, water, blankets, clothing, and medical supplies from NAF Atsugi to USS Ronald Reagan for distribution by helicopter to local sites in Japan.

Additional unit support included the following:

- P-3 Orion performed damage surveys
- Amphibious Assault Ship (LHD) -2 (USS Essex) – LCU –Expeditionary Strike Group Seven U.S. Seventh Fleet (until 2012) amphibious assault ship deployed utility landing craft (LCUs) – transport of vehicular equipment.
- Dock Landing Ship (LSD)-42 (USS Germantown)– Sasebo, Japan – 31st Marine Expeditionary Unit (Okinawa) moved to east coast of Japan.
- Destroyers (DDG) 85 and 54 – provided helicopters used for search and rescue
- Amphibious Command Ship (LCC)-19 (USS Blue Ridge)– C4I for commander of the U.S. Seventh Fleet – Immediate transport of relief supplies from Singapore.
- Dock Landing Ship (LSD) -46 (USS Tortuga) – embarked 2 MH-53E Sea Dragon Heavy Lift Helicopters – part of Helicopter Mine Countermeasures Squadron 14 (HM-14) detachment Pohang South Korea – transported 800 Japanese civil defense workers and 90 vehicles from Hokkaido to Honshu.
- Military Sealift Command ships – United States Naval Ship (USNS) Carl Brashear (T-AKE 7), USNS Pecos (T-AO 197), USNS Rappahannock (T-AO 204), USS Matthew Perry (T-AKE 9), USNS Bridge (T-AOE 10) - transfer of relief supplies and fuel to other supporting ships.
- USNS Safeguard (T-ARS-50) is a rescue and salvage ship with Explosive Ordinance Disposal Mobile Unit 5 and Underwater Construction team 2 which cleared wreckage from commercial channel.

The Marine Corps was also involved, providing expeditionary units, delivering thousands of pounds of relief supply and thousands of gallons of water. Combat Logistics Battalion 31 and 2nd Battalion 5th Marines also went ashore on Oshima for supply delivery and debris removal. The Air Force also provided support including C-135 transport of initial relief crews and 50 civil engineers to Misawa Air Base from Kadena Air Base, C-17A to transport rescue teams and equipment, Global Hawk UAV for damage assessments, and use of Yokota Air Base. Finally the Army provided UH-60 Blackhawk helicopters for relief supplies transport, I Corps set up forward logistics base for supplies, and a logistics team helped to reopen Sendai airport.

By far, the dominant required capability for Operation Tomodachi was transport and delivery capabilities. Many different units were used in fulfilling this function (as suggested by the above list of involved units). However, the VRC-30, VR-58, and VR-62 logistics air wing units were the most heavily utilized. VRC-30 includes two primary transport systems: C-130T and C-2A Greyhound aircraft and over the duration of Operation Tomodachi transported over 100 tons of material. Similarly, VR-58 includes C-40A Clipper aircraft and transported 68 tons of material and 1400 passengers. Lastly, VR-62 includes C-130T and C-9B aircraft and transported 58 tons of material. VRC-30 is unique in that it is a carrier group logistics air wing organic to PACOM and the C-2A Greyhound transport aircraft, within VRC-30, perform the Carrier Onboard Delivery (COD) mission – the C-2A is a cargo transport aircraft that can land on an aircraft carrier. The COD mission is particularly critical when large volumes of material must be transported over long oceanic distances – as was the case in Operation Tomodachi. The C-2A is also an ageing aircraft (first fielded in the 1960s) and replacement systems are being considered for the COD mission.

In the context of our Enterprise Framework, the Assessing Capabilities step could be employed to evaluate the C-2A within the COD mission (as baseline) versus other potential systems that could perform the COD mission such as the V22 Osprey. The V22 Osprey has roughly twice the cargo capacity of a C-2A but also costs $69M per unit as opposed to $39M per unit for a C-2A. However, the V22 has other advantages in that it is a more flexible platform such as performing a Heavy Lift mission when operating in helicopter mode. Within our framework we would utilize performance simulation models that would allow us to evaluate the C-2A and the V22 performing similar missions and compare impacts. Notional comparative results would be such as those in Figure 5-3.

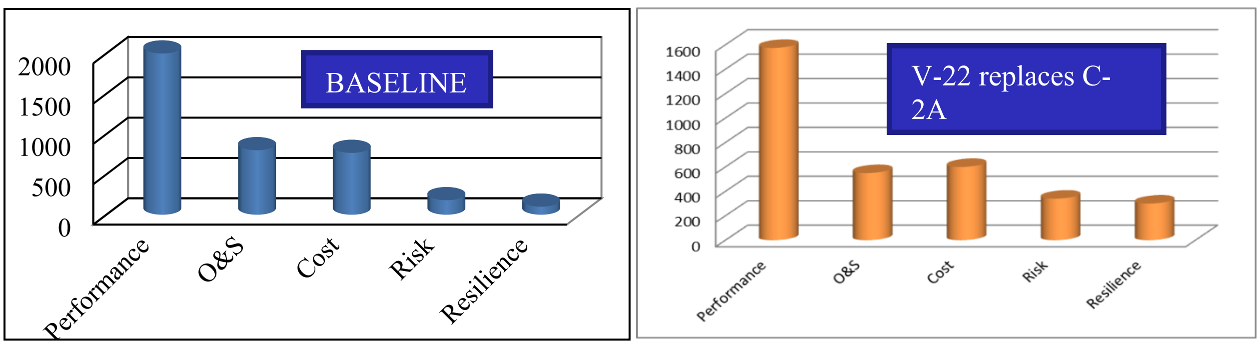


Figure 5-3 Comparative Results for Two Competing Capabilities

In this case, performance would roll up measures such as rate of movement (e.g., tons per day), system range (e.g., nautical miles), and reliability (e.g., mean time between failure). Once we have set up the value model for our entire enterprise functional decomposition and mapped units and capabilities to those functions, we can evaluate contribution to overall enterprise performance each potential variant would import. For example, if the relative importance of the COD mission, with respect to other missions, is very high it may drive the decision to invest in the V22 as it is superior in performing the COD mission even though it is more costly.

5.1.6 Major Combat Operation Use Case

Our second use case for demonstrating the utility of the Enterprise Framework is a Major Combat Operation (MCO) involving a Joint Suppression of Enemy Air Defense Systems

(JSEADS) operation. Due to the sensitivity of this use case it is documented in a separate Offical Use Only controlled document.

5.2 Description of Capability Evaluation

The general evaluation framework shown in Figure 3-2 illustrates the complex set of dynamical interactions among the natural, economic, and political systems that determine the outcome of a particular decision sequence. The framework defines a systematic approach for comparing the consequences of alternative investment paths considering a broad range of secondary effects. Some elements of this evaluation, such as estimating the probability of various conflict outcomes in particular circumstances, are well-understood in principle: improving such elements has not been the focus of our research. Other elements, such as estimating the behavior of strategic actors, are areas of active research. We have therefore allowed for various theories of behavior to be used within the framework rather than selecting one, or attempting to create another. A full application of the framework requires coordinating information flows among a set of simulation systems, collecting sets of possible investment sequences for evaluation, performing the requisite simulations, and processing the results. A full application of the framework is therefore as large an undertaking as its development has been.

It is not necessary to consider all of the interactions in Figure 3-2 to make a considerable advance on current practice: the framework is not meant to be used either in its entirety or not at all. Instead, it defines the components of a comprehensive analysis and their logical arrangement. In addition, some core simulation capabilities, such as the ability model potential global resource and economic dynamics over a range of future conditions, were developed as necessary components of a comprehensive implementation.

We can illustrate a partial application of the framework that highlights some of the novel capabilities developed for it. A particularly challenging problem is to develop a rich set of possible strategic scenarios that future capability mixes would be required to meet. The ideal approach to this problem is to define capabilities in such a way that the material requirements for their production and the material effects of their use can be represented in the Exchange model, and can also be reasoned about in the model of decision-makers. This would allow the spontaneous development of novel strategic challenges, against which the performance of specific capability investments can be judged. Ultimately, the value of a capability would depend both on its performance in possible future situations and on the likelihood of those situations arising.

The ability to produce novel conflict scenarios depends on having a general formalism for describing capabilities. Without that formalism the existing approach of factoring possible futures into a set of missions can still be accommodated by the framework. This would be necessary in any case because of the strong institutional commitment to mission-based capability valuation. In the context of the framework, missions define a kind of basis set for describing future conditions. Rather than generating specific conflict scenarios, future conditions project to some degree on each of the defined missions. The weight given to each mission in assessing capabilities is then determined by the number of possible futures that strongly align with it.

5.3 Results – Comparative Value of Capabilities

As an illustration, we simulated the evolution of 20 interacting nations, each having distinctive technological capabilities and resource endowments. These differences create dynamics in the availability of key resources within each nation. Figure 5-4 shows the dynamics of selected state variables within a single simulation in a single nation. We take 2000 samples of possible future configurations of the global economy, each producing a set of coupled indicators for each nation.

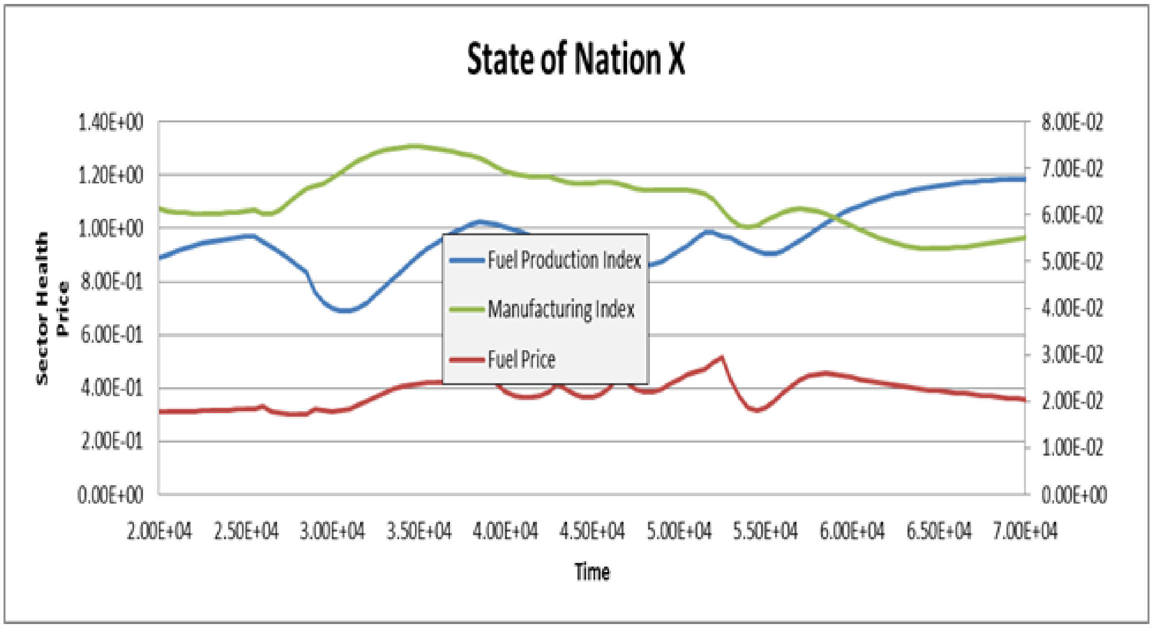


Figure 5-4 Trajectories of Selected State Variables in a Simulated National Economy.

We can analyze those indicators to understand how differences in economic configuration, as well the contingencies of interaction dynamics, might produce conditions provocative of conflict, such as abrupt changes in living conditions or strong contrasts in living conditions across nations. For example, strong contrasts in household consumption across neighboring countries may precipitate unrest. Figure 5-5 shows a distribution of household health indicators among three nations over the set of realized conditions.

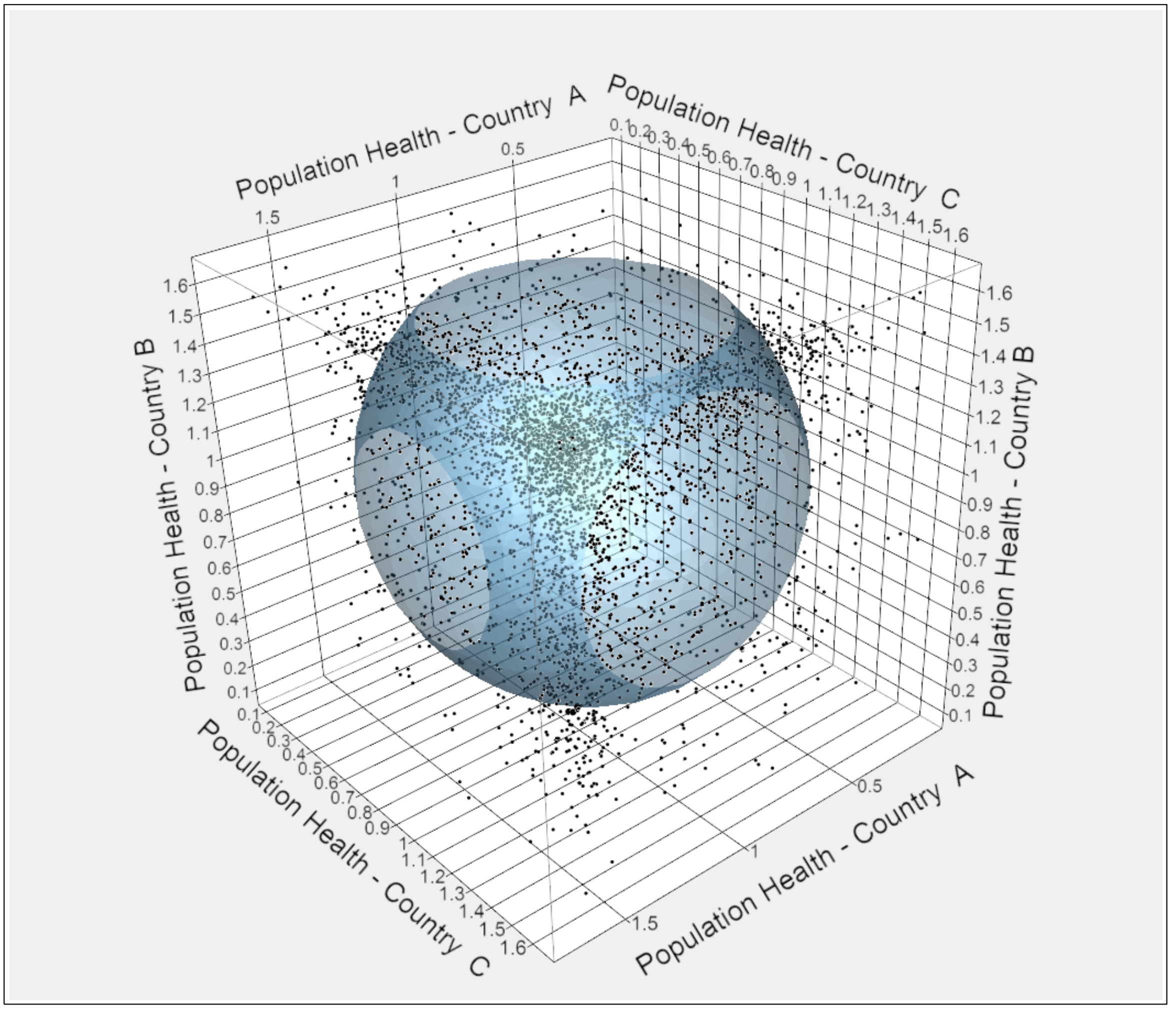


Figure 5-5 Distrbution of Household Health in 3 of 20 Interacting National Economies.

Strong contrasts in conditions, in which one nation is very wealthy and the neighboring two very poor, are plausible precursors of conflict. Such conditions obtain in the simulation results falling outside the shaded solid. This conflict might manifest as territorial aggression, as mass migration, or in some other way. The comparative likelihood of those outcomes may be assessed through a behavioral model of the actions available to each relevant actor. Cases of mass migration confer value on humanitarian relief missions, and therefore on the capabilities that support such missions. Figure 5-6 summarizes this procedure for deriving capability value contributions.

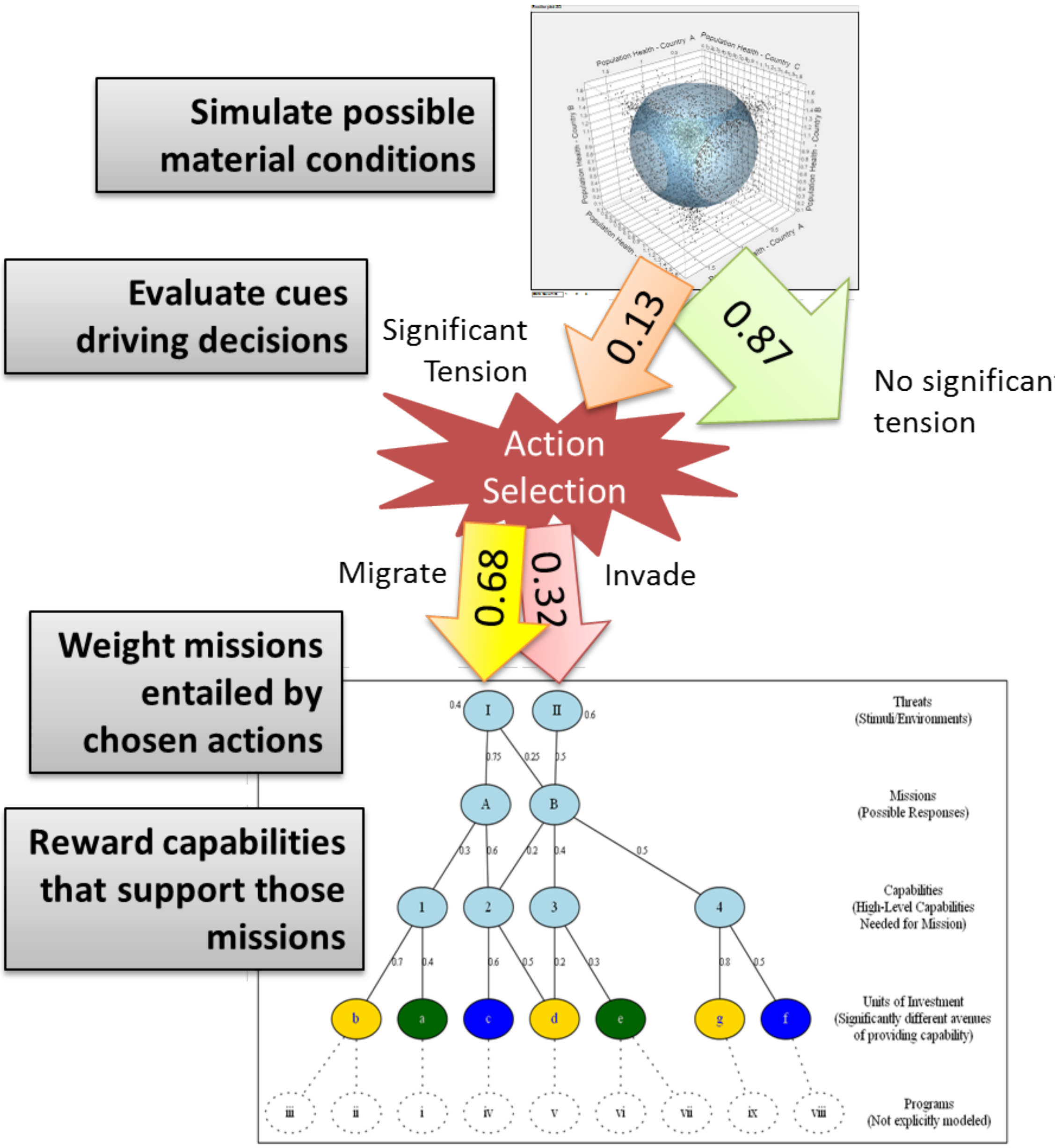


Figure 5-6 Illustration of Applying the Framework to Derive Capability Value Weights by Projecting Future Conditions onto Missions.

6 SUMMARY AND PATH FORWARD

Capability investment decisions are becoming increasingly difficult due to many factors: a rapidly shifting security environment, the tremendous cost and inertia of technology-rich systems, and the prospect of economic parity with strategic rivals and the associated "second-mover" advantages they will have. Traditional methods need rethinking because the costs and consequences of poor decisions may be unbearable.

We have defined a framework to formalize enterprise evaluation so that it is explicit, rational, and therefore open to review, assessment, criticism and refinement. We have built key analytical and simulation elements that are not currently available, and have integrated them with other distinctive capabilities to create a framework for enterprise evaluation.

Ultimately, this framework can provide the basis for structured, enterprise optimization such as that depicted in Figure 6-1. In Figure 6-1 enterprise elements such as the capabilities and units of investment are assembled into optimal enterprise configurations based on multiple dimensions of value (in this case, performance, cost, operation and sustainment cost (O&S), risk, and resilience).

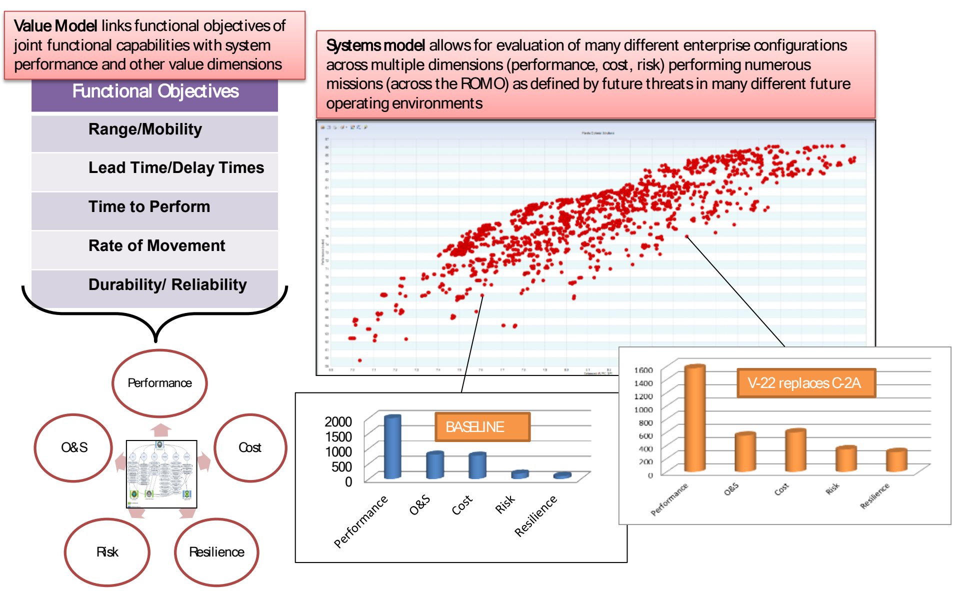


Figure 6-1 Enterprise Optimization

After building a repository of enterprise elements, associated functional decomposition, capability mappings and respective simulation of capabilities and associated characteristics (cost, etc.), a Pareto frontier in multiple dimensions can be constructed to allow for insight into desirable capability investments.

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APPENDIX B: PRESENTATIONS AND PUBLICATIONS

The modeling and analytical capabilities developed in the course of this research have led to several technical communications of specific components, and of their experimental application to subsidiary problems. The presentations and publications summarized below, although derivatives of this LDRD, were not explicitly funded by the LDRD.

1. **Studying the Relationship between System-Level and Component-level Resilience.** Michael D. Mitchell, Walter E. Beyeler. Manuscript under consideration for publishing in the Journal of Complex Systems.

Abstract. The capacity to maintain stability in a system relies on the components which make up the system. This study explores the relationship between component-level resilience and system-level resilience with the aim of identifying policies which foster system-level resilience in situations where existing incentives might undermine it. We use an abstract model of interacting specialized resource users and producers which can be parameterized to represent specific real systems. We want to understand which features of a system, such as input resource stockpiles, demonstrate the efficacy of system-level resilience policies. Systems are subject to perturbations of varying intensity and frequency. For our study, we create a simplified economy in which an inventory carrying cost is imposed to incentivize smaller inventories and examine how components with varying inventory levels compete in environments subject to periods of resource scarcity. The results show that policies requiring larger inventories foster higher component-level resilience but do not foster higher system-level resilience. Inventory carrying costs reduce production efficiency as inventory sizes increase. JIT inventory strategies improve production efficiency but do not afford any buffer against future uncertainty of resource availability.

2. **Help from Hoarders: How Storage Can Dampen Perturbations in Critical Markets.** Marshall A. Kuypers, Walter E. Beyeler, Matthew Antognoli, Michael Mitchell, Robert J. Glass, October 2012 (2012-8506 C). 2nd International Conference on Complex Sciences: Theory and Applications, December 2012, Santa Fe, NM.

Abstract. Critical resource supply chains are vulnerable to manipulation because of the un-substitutability of their goods. When a monopoly controls all or part of a market, it has the ability to profit from a reduction in supply of a critical resource. We model this complex adaptive system (CAS) using an agent-based model (ABM) and investigate a strategy to mitigate the potential for exploitation of a market by a monopoly. We find that when entities increase their input resource buffer, they decrease the reactivity of resource prices to supply disruptions, which limits the amount by which monopolies benefit from price fixing. This storage strategy also reduces total system losses due to a perturbation.

3. **To Trade or Not to Trade: Analyzing how Perturbations Travel in Sparsely Connected Networks.** Marshall A. Kuypers, Walter E. Beyeler, Matthew Antognoli, Michael Mitchell, Robert J. Glass, October 2012 (2012-8507 C). 2nd International Conference on Complex Sciences: Theory and Applications, December 2012, Santa Fe, NM.

Abstract. In global economics, nations are often faced with the opportunity to open or close new avenues of trade or to join new markets. These actions can be beneficial or harmful for a nation because entering a market exposes that nation to the perturbations caused by others in the market. However, joining a new market offers the benefit of lower prices and increased security against domestic perturbations because shocks are spread across all trading partners. This risk/benefit tradeoff is relatively straightforward for one market, but the effects are more complicated when multiple markets are introduced. We use an agent-based model to analyze how the connection pattern of markets affects perturbations that travel across networks. We find that shocks are not easily transmitted across networks unless the perturbed resource is directly traded and we discuss the tradeoffs associated with opening new international market connections.

4. **The Crossover Point: Comparing Policies to Mitigate Disruptions.** Matthew Antognoli, Marshall Kuypers, Rowan Copley, Walter Beyeler, Michael Mitchell, Robert Glass, October 2012 (2012-9319P). 2nd International Conference on Complex Sciences: Theory and Applications, December 2012, Santa Fe, NM.

Abstract. Companies, industries, and nations often consume resources supplied by unstable producers. Perturbations that affect the supplier propagate downstream to create volatility in resource prices. Consumers can invest to reduce this insecurity in two ways; invest in and impose security on the suppliers, or can invest in self-sufficiency so that shocks no longer present devastating consequences. We use an agent-based model of a complex adaptive system to examine this tradeoff between projecting security and investing in self-sufficiency. This study finds that the significance of tradeoffs correlates with the dependence of the consumer on the supplier.

5. **Behaviors of Actors in a Resource-Exchange Model of Geopolitics.** Curtis S. Cooper, Walter E. Beyeler, Jacob A. Hobbs, Michael Mitchell, Z. Rowan Copley, and Matthew Antognoli. 2nd International Conference on Complex Sciences: Theory and Applications, December 2012, Santa Fe, NM.

Abstract. We present initial findings of an ongoing effort to endow the key players in a nation-state model with intelligent behaviors. The model is based on resource exchange as the fundamental interaction between agents. In initial versions, model agents were severely limited in their ability to respond and adapt to changes in their environment. By modeling agents with a broader range of capabilities, we can potentially evaluate policies more robustly. To this end, we have developed a hierarchical behavioral module, based on an extension of the proven ATLANTIS architecture, in order to provide flexible decision-making algorithms to agents. A Three-Layer Architecture for Navigating Through Intricate Situations (ATLANTIS) was originally conceived for autonomous robot navigation at NASA's JPL. It describes a multi-level approach to artificial intelligence. We demonstrate the suitability of our reification for guiding vastly different types of decisions in our simulations over a broad range of time scales.

6. **A Policy of Strategic Petroleum Market Reserves.** Michael D. Mitchell, Walter E. Beyeler, Matthew Antognoli, Marshall Kuypers, Robert J. Glass, October 2012 (2012-

9372C). 2nd International Conference on Complex Sciences: Theory and Applications, December 2012, Santa Fe, NM.

Abstract. Unexpected price spikes in petroleum can lead to instability in markets and have a negative economic effect on sectors which rely on petroleum consumption. Sudden rises in the price of petroleum do not have to be long-term to cause negative, cascading impacts across the economy. Firms which make futures purchases or hedge against a higher price during a price spike can become insolvent when the price spike deflates. A policy is needed to buffer short-term perturbations in the petroleum market to avoid short-term price spikes. This study looks at the effects of implementing a Strategic Petroleum Market Reserve within a multi-agent Nation-State model which would utilize trading bands to determine when to buy and sell petroleum reserves. Our analysis indicates that the result of implementing this policy is a more stable petroleum market during conditions of resource scarcity.

7. **Sizing Strategies in Scarce Environments.** Michael D. Mitchell, Walter E. Beyeler, Robert J. Glass, Matthew Antognoli, Thomas W. Moore, December 2011 (2011-8675C). 2012 International Conference on Social Computing, Behavioral-Cultural Modeling, & Prediction (SBP12), April 2012, College Park, MD.

Abstract. Competition is fierce and often the first to act has an advantage, especially in environments where there are excess resources. However, expanding quickly to absorb excess resources creates requirements that might be unmet in future conditions of scarcity. Different patterns of scarcity call for different strategies. We define a model of interacting specialists (entities) to analyze which sizing strategies are most successful in environments subjected to frequent periods of scarcity. We require entities to compete for a common resource whose scarcity changes periodically, then study the viability of entities following three different strategies through scarcity episodes of varying duration and intensity. The three sizing strategies are: aggressive, moderate, and conservative. Aggressive strategies are most effective when the episodes of scarcity are shorter and moderate; conversely, conservative strategies are most effective in cases of longer or more severe scarcity.

8. **The Impact of Network Structure on the Perturbation Dynamics of a Multi-agent Economic Model.** Marshall A. Kuypers, Walter E. Beyeler, Robert J. Glass, Matthew Antognoli, Michael Mitchell, December 2011 (2011-8676 C). 2012 International Conference on Social Computing, Behavioral-Cultural Modeling, & Prediction (SBP12), April 2012, College Park, MD.

Abstract. Complex adaptive systems (CAS) modeling has become a common tool to study the behavioral dynamics of agents in a broad range of disciplines from ecology to economics. Many modelers have studied structure's importance for a system in equilibrium, while others study the effects of perturbations on system dynamics. There is a notable absence of work on the effects of agent interaction pathways on perturbation dynamics. We present an agent-based CAS model of a competitive economic environment. We use this model to study the perturbation dynamics of simple structures by introducing a series of disruptive events and observing key system metrics. Then, we generate more complex networks by combining the simple component structures and

analyze the resulting dynamics. We find the local network structure of a perturbed node to be a valuable indicator of the system response.

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